

THE PAST, PRESENT AND FUTURE OF NEUTRINO NEAR DETECTORS

Novel pixelated charge readout in Liquid Argon Time Projection Chambers
& ν_μ induced charged-current resonant pion production cross-section on
hydrocarbon with 4π acceptance

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Abstract

This thesis covers two accelerator-driven long-baseline neutrino experiments. The Tokai-to-Kamioka (T2K) experiment uses a 0.6 GeV neutrino beam produced at the J-PARC beamline in Tokai, Japan to measure neutrino oscillation parameters. These parameters can be found by comparing the neutrino interaction rates at the ND280 near detector and the Super-Kamiokande far detector at 280 meters and 295 kilometers from the neutrino beam source, respectively. Accurately measuring these interaction rates and subsequently the oscillation probability is limited by the systematic uncertainties associated with the neutrino-nucleus interaction cross-sections. Hence, these interactions are studied in the high event rate environment of the ND280 near detector.

In muon-neutrino-induced charged-current single positive pion production on hydrocarbon, both a muon and a positively charged pion are produced in the final state. The four dimensional differential cross-section for this process has been measured in muon and pion kinematic parameters for the full solid angle in the past, but has always been statistically limited. Here it is presented with the full available statistics including the use of pion properties derived from Michel electrons of their subsequent decay, which improved the statistics for pion momenta between 50-400 MeV by 50%. The cross-section extraction is done with a binned log-likelihood minimization returning a χ^2/Ndf of 1.25, showing good agreement with the nominal Monte Carlo models.

The future Deep Underground Neutrino Experiment (DUNE) relies on liquid argon as target material for the neutrino interactions in the near and far sites. The liquid argon near detector (NDLAr) has been given a modular design consisting of 35 modules (70 time-projection chambers) in a 7 by 5 array with novel pixelated charge readout systems in order to deal with the high interaction rates in the world's most intense neutrino beam. To understand the behavior of the drift fields and the pixel charge collection efficiencies inside these time-projection chambers, a series of prototypes have been studied. These studies ultimately converged into a diagnostic tool capable of identifying misbehavior in pixel trigger rates during operation.

Contributions

None of the work presented in this thesis would have been possible without the groundwork that was laid by both the T2K and DUNE collaborations for the cross-section measurement and the prototype charge readout tests, respectively. It is all a collaborative effort, but in this section, I would like to elaborate on the contributions I personally made to these experiments as a whole.

Optical Transition Radiation Monitor: The York University group used to be responsible for the T2K optical transition radiation monitor, which provides the last beam profile measurement before the proton beam hits the T2K graphite target. At the start of my PhD, I assisted in transitioning the OTR simulation from a predominantly C++ codebase to a more accessible Python program. Upon completion, I used the revamped simulation to study the presence of background scintillation light coming from excited atoms in the helium enclosure that inflated the observed proton beam spot size at the OTR compared to the beam monitors that preceded it.

Pion Secondary Interactions: One of the leading detector systematic uncertainties at T2K comes from pions leaving the nuclear medium and interacting with the detector environment. This can impact both their kinematic properties, as well as the final state topology as a whole. This systematic uncertainty was previously developed for specific versions of the Monte Carlo simulation (production) by the T2K systematics working group. In the most widely used version, the tables describing this process were incorrectly implemented. After running a diagnosis and figuring out where the mistakes were made, I successfully tested the framework in the newest Monte Carlo production.

Analysis sample selection: The sample selection used in this thesis is the combined effort of several analyzers in the T2K cross-section group over many years. The data and Monte Carlo simulation comparisons for these samples are shown in the thesis. The selections (and detector systematics propagations) are performed with the analytical framework, High-Level-Analysis-at-the-Near-Detector (HighLAND), developed by the

ND280 software group. I have contributed by writing a technical note (TN490), which details the inclusion of pion kinematic properties derived from the subsequent decay Michel electron into the selection that covers muons propagating in all directions covering the full 4π solid angle.

Likelihood Fitter Framework: The binned log-likelihood fitter framework used in this analysis comes from the Generalized and Unified Neutrino Data Analysis Methods (GUNDAM) created by T2K Cross-Section group. Due to the four-dimensional differential cross-section measurement, a lot of time was spent on validating the binning scheme for this analysis. These validation procedures can be adapted to future endeavors utilizing more appropriate binning.

Operation of liquid argon prototypes: In order to test the new pixelated charge readout system for the modular design of the liquid argon near detector for the DUNE experiment, several prototypes were built. The research groups at the Universities of Bern and Berkeley put together four smaller scale modules to assess the validity of this concept. I took shifts and supported the testing phases of three of the modules at the University of Bern. At Fermilab, I assisted in quality assurance and quality control tests and the design of the high voltage system to support the TPC drift fields.

Pixel charge collection efficiency: In addition to hardware related activities, I assessed the pixel charge collection efficiency from cosmic ray data taken by the NDLAr consortium with these four modules. Ultimately, I developed an algorithm that can be used in-situ to assess the pixel efficiency in real-time.

Building the 2x2 detector: The DUNE modular design has been tested by placing the four modules in a neutrino beam at Fermilab. Surrounding this structure is a set of 44 refurbished MINERvA scintillation planes that detect charged particles (mainly muons) coming from the liquid argon and the surrounding cavern. Together with scientists from the University of Rochester, we set up these planes.

Contents

Abstract	ii
Contributions	iii
List of Figures	ix
List of Tables	xvii
List of Acronyms	xx
1 Introduction	1
1.1 The “terrible” inception	2
1.2 The first detection	3
1.2.1 So it exists, but what now?	5
1.3 A third neutrino	7
2 Neutrino physics	11
2.1 Neutrinos from the Sun	11
2.2 The solar neutrino anomaly	12
2.3 Neutrino oscillations	17
2.3.1 Antineutrino oscillations	22
2.3.2 Matter effect	23
2.4 Accelerator neutrino beams	29
2.4.1 Target	32
2.4.2 Focusing horn system	34
2.4.3 Decay Pipe	38
3 Neutrino Interactions	42
3.1 Charged-Current Quasi-Elastic Scattering	44
3.2 Resonant pion production	46

3.3	Deep-inelastic scattering	48
3.4	Coherent pion production	49
3.5	Interacting with the entire nucleus	49
3.5.1	Nuclear initial state	51
3.5.2	Nuclear correlations	55
3.5.3	Final state interactions	56
3.5.4	Secondary interactions	56
3.6	Pion production measurements	57
4	The DUNE Experiment	61
4.1	The DUNE Far detector complex	67
4.1.1	Module 1: Horizontal Drift LArTPC	71
4.1.2	Module 2: Vertical Drift LArTPC	74
4.2	The DUNE Near detector complex	75
4.2.1	DUNE PRISM	76
4.2.2	SAND	77
4.2.3	TMS	78
4.2.4	ND-GAr	79
4.2.5	ND-LAr	80
5	Liquid Argon Detector prototyping	86
5.1	The SingleCube	87
5.2	The Single Modules	88
5.2.1	Module-0	88
5.2.2	Module 1, 2 and 3	94
5.3	Charge readout tests	97
5.3.1	Hough Transform	98
5.3.2	MIP response map	102
5.3.3	Pixel efficiency	112
5.4	ArgonCube 2x2	121
6	The T2K Experiment	122
6.1	The J-PARC Accelerator	122
6.2	The Optical Transition Radiation monitor	125
6.3	The Target station	128
6.3.1	Focusing Horns	128
6.3.2	Decay pipe	129
6.3.3	Neutrino flux	130

6.4	The T2K Near Detector complex	131
6.4.1	On-Axis: INGRID	132
6.4.2	WAGASCI-BabyMIND	133
6.4.3	ND280	134
6.5	The T2K Far detector	140
7	The Cross-Section Analysis Strategy	142
7.1	Motivation	142
7.2	Signal definition	145
7.3	Cross-section definition	145
7.4	Cross-section extraction	146
7.4.1	Binned maximum likelihood fit	147
8	The CC1π^+ Selection	152
8.1	Event quality	153
8.1.1	Event time quality	153
8.1.2	Time of flight flipping	153
8.1.3	Total multiplicity cut	154
8.1.4	Sort tracks action	154
8.1.5	Track general quality and FV	154
8.1.6	Broken track rejection	155
8.2	Muon PID	155
8.3	Pion PID	158
8.3.1	Topology criteria	160
8.3.2	Zero ECal photons cut	161
8.3.3	Common vertex cut	161
8.4	Signal and control samples	165
8.4.1	Signal distributions	166
8.4.2	Background samples: Quasi-Elastic like	174
8.4.3	Background samples: Signal with an additional pion	179
9	Systematic Evaluation	191
9.1	Detector systematic uncertainties	192
9.1.1	Reconstruction systematic uncertainties	192
9.1.2	Weight systematic uncertainties	196
9.1.3	All systematic uncertainties combined	200
9.2	Cross-section systematic uncertainties	206
9.3	Flux systematic uncertainties	210

9.4	Analysis binning	212
9.4.1	Template binning	214
9.4.2	Sample binning	219
10	Validating the fitter	223
10.1	The Basic Checks	225
10.1.1	Asimov fit	225
10.1.2	Monte Carlo fluctuations	237
10.2	Fake Data Studies	240
10.2.1	Signal enhancement	240
11	Discussion	250
11.1	Conclusion and future improvements	265
	Appendices	280
A	Package implementation	281
B	Analysis binning	285
B.1	Flux binning	285
B.2	Template binning	285
B.3	Signal samples binning	288
B.3.1	The TPC&FGD sample	288
B.3.2	The ME sample	292
B.4	Sideband samples binning	295
B.4.1	The signal + $\pi^\pm$ sample	295
B.4.2	The signal + π^0 sample	295
B.4.3	The CC0 π sample	296
B.5	Truth to reconstruction smearing	300
C	Detector systematic uncertainties	302
C.1	B-Field Distortions	302
C.2	TPC momentum resolution	303
C.3	TPC momentum scale	303
C.4	TPC particle identification	303
C.5	Momentum by range resolution	307
C.6	Momentum bias by vertex migration	307
C.7	FGD particle identification	309
C.8	FGD pion momentum from ME resolution	309

C.9	ECal EM scale & ECal EM Resolution	310
C.10	Time of flight resolution	311
C.11	Neutrino Parent Decay Vertex Position	311
C.12	TPC Charge identification efficiency	311
C.13	TPC cluster efficiency	313
C.14	TPC tracking efficiency	313
C.15	FGD hybrid tracking efficiency	314
C.16	Ecal tracking efficiency	314
C.17	ECal Photon Pile-up	315
C.18	ECal PID & ECal EM hip PID	315
C.19	Michel electron efficiency	317
C.20	Pile-up	318
C.21	Out of fiducial volume background	318
C.22	Sand muon background	318
C.23	TPC-FGD matching efficiency	320
C.24	TPC-ECal matching efficiency	320
C.25	TPC-P0D matching efficiency	321
C.26	FGD-ECal matching efficiency	322
C.27	FGD-ECal-SMRD matching efficiency	322
C.28	Pion Secondary interactions	323
C.29	Proton Secondary Interactions	324
D	Fake Data Studies	325
D.1	Basic Checks	325
D.1.1	Random Template Priors	325
D.2	Fake Data Studies	333
D.2.1	Out-of-phase-space enhancement	333
D.2.2	Out-of-fiducial-volume reduction	341
D.2.3	CCOther reduction	348
E	DUNE Analysis addendum	355
E.1	Track properties Module-0	355
E.2	ArgonCube 2x2 event displays	357

List of Figures

1.1	Cross-section for e^+e^- annihilation to hadrons (LEP experiments)	8
2.1	Predicted and measured SNU's by neutrino oscillation experiments	13
2.2	Muon and electron neutrino flux at Super-Kamiokande	14
2.3	Feynman diagrams for the weak interaction	17
2.4	Possible configurations of the neutrino mass hierarchy	26
2.5	CP Asymmetry as function of baseline for first (black) and second (green) oscillation maxima [63]	28
2.6	Oscillation probability for muon (anti-)neutrinos to electron (anti-)neutrinos at a baseline of 1300 km for normal mass ordering [63].	29
2.7	Oscillation probability for muon (anti-)neutrinos to electron (anti-)neutrinos at a baseline of 295 km for normal mass ordering [65].	30
2.8	Schematic overview of the NuMI beamline at Fermilab showcasing the different neutrino production elements [67].	32
2.9	Proton impinging on segmented target and producing a pion [68].	32
2.10	Pion and Kaon transverse momenta	33
2.11	Focusing effects for a parabolically shaped inner conductor [68].	35
2.12	The focusing effects caused by a conical shaped inner conductor [68].	36
2.13	Meson decay chains producing a neutrino with branching ratios [75]	39
2.14	Neutrino energy for parent particle energy at different decay angles.	40
3.1	Neutrino interaction cross-sections for charged-current processes [78].	43
3.2	Feynman diagram for CCQE scattering of neutrinos	45
3.3	Feynman diagram for CCRES scattering of neutrinos	46
3.4	Feynman diagram of the CCDIS process [82].	48
3.5	Feynman diagram for the neutrino induced coherent pion production	50
3.6	Charged-current quasi-elastic differential cross-section	51
3.7	Schematic overview of final state interactions after charged-current quasi-elastic scattering [97].	52
3.8	Nuclear model implementation in NEUT neutrino event generator	54

3.9	Schematic overview of the 2p2h process	55
3.10	Fluxes of past, present and future neutrino experiments	57
3.11	Flux-integrated differential cross section	58
3.12	MINERvA CC1Pi cross-section results in Q^2	59
4.1	Overview of the DUNE experiment [127].	61
4.2	Overview of Fermilab’s accelerator complex [128].	62
4.3	Overview of the LBNF target station	63
4.4	Engineering drawing of the cantilevered graphite target [132].	63
4.5	Horn A: Outer conductor (left), Inner conductor (right) [133].	64
4.6	Cross-sectional view of Horn B [133].	65
4.7	Cross-sectional view of Horn C [133].	65
4.8	Cross section of the decay pipe [134].	66
4.9	Geant4 simulated LBNF neutrino flux (FHC left, RHC right) [127].	66
4.10	DUNE far detector complex at the SURF site in South Dakota [127].	68
4.11	Mean energy loss in various media as a function of momentum [136].	70
4.12	Liquid argon TPC operating principle	71
4.13	Engineering drawing of the horizontal drift module’s cryostat [139].	71
4.14	Engineering drawing of the far detector’s inner geometry [139].	72
4.15	Schematic overview of the wire planes integrated into the APA	73
4.16	Engineering drawing of the vertical drift far detector module [143].	74
4.17	Electrode strip configuration for the vertical drift module	75
4.18	The DUNE near detector complex for phase 1 [144].	76
4.19	DUNE near detector flux for different prism off-axis configurations [145][146].	77
4.20	SAND engineering drawing (left), operation principle (right) [148].	77
4.21	TMS engineering drawing [151].	78
4.22	Schematic overview of ND-GAr [152].	79
4.23	ND-LAr detector overview	81
4.24	A simulated beam spill in ND-LAr [146].	81
4.25	Schematic of single module for the liquid argon near detector [154].	82
4.26	Charge readout tile; Pixels (left), ASICS (right) [154].	83
4.27	Schematic overview of ArCLight light trap [156].	84
4.28	Schematic overview of LCM light trap [156].	84
5.1	SingleCube field cage (left), LArPix-V2 and ArCLight tiles (right).	87
5.2	A schematic overview of the Module-0 prototype [159].	89
5.3	Established hydra network (left), disabled channels (right)	91

5.4	Module-0 without its G10 sleeve (left), above the liquid argon cryostat (right).	93
5.5	An overview of the first run period for Module-0	94
5.6	Four Module-0 event display	95
5.7	An overview of the different properties for Modules 0 through 3.	96
5.8	Images representing the steps for a 2D hough transform.	98
5.9	Module-0 reconstructed hits (left), Hough lines (right)	99
5.10	Midpoints and angles for data from the first drift volume of Module-0.	101
5.11	Result of the containment study	103
5.12	Procedure of constructing a MIP response map.	104
5.13	Illumination maps for first TPC drift volume	106
5.14	Illumination maps for second TPC drift volume	107
5.15	Hough line illumination maps for first TPC drift volume	108
5.16	Hough line illumination maps for second TPC drift volume	109
5.17	MIP response maps for first TPC drift volume	110
5.18	MIP response maps for second TPC drift volume	111
5.19	Pixel pad efficiency method using randomized segmentation.	112
5.20	Pixel pad efficiency in both TPC drift volumes of Module-0	116
5.21	Pixel pad efficiency in both TPC drift volumes of Module-1	117
5.22	Pixel pad efficiency in both TPC drift volumes of Module-2	118
5.23	Pixel pad efficiency in both TPC drift volumes of Module-3	119
5.24	Pixel pad efficiency in both TPC drift volumes for the simulation of Module-1	120
5.25	MINERvA 2 by 2 in the MINOS underground hall at Fermilab.	121
6.1	Overview of the near and far sites for the T2K experiment [65].	122
6.2	The RCS and LINAC in the J-PARC accelerator facility [164].	123
6.3	Overview of primary and secondary beamline at J-PARC [165].	124
6.4	The locations of different monitors along the beam's path [166].	124
6.5	Overview of the SSEMs and the OTR monitor [166].	126
6.6	Drawing of optical transition radiation principle	127
6.7	Overview of the OTR optical system	128
6.8	Oscillation probabilities at the T2K far detector	131
6.9	ND Complex with ND280, INGRID and WAGASCI-BabyMIND [171].	132
6.10	The Interactive Neutrino GRID on-axis near detector for the T2K experiment with the designed beam center marked in yellow [163].	133
6.11	WAGASCI-BabyMIND detector [174].	134

6.12	ND280's three-layered substructure of individual detectors [163].	135
6.13	A drawing of the ECAL module highlighting the scintillator bars [163]. .	136
6.14	A schematic overview of the side of the P0D.	137
6.15	ND280 time-projection chambers [179].	138
6.16	Deposited energy in FGD1 as a function of distance traveled	140
6.17	The massive water Cherenkov detector Super-Kamiokande [181].	141
6.18	Super-Kamiokande event display	141
8.1	Time of flight between FGD1 and FGD2 for tracks that start in FGD1 [187].	154
8.2	The muon and minimum ionizing particle likelihoods	156
8.3	ECal PID for muon candidates reaching the ECal	157
8.4	ECal PID for HA FWD and BWD muon candidates reaching the ECal .	158
8.5	Pre-common vertex cut muon momentum distributions	162
8.6	Pre-common vertex cut cosine of the muon angle distributions	163
8.7	Distance between the neutrino interaction vertex and the muon decay vertex.	164
8.8	Distance between the neutrino interaction vertex and muon decay vertex	165
8.9	CC1 π^+ selection muon momentum in topological breakdown	166
8.10	CC1 π^+ selection muon angle in topological breakdown	167
8.11	CC1 π^+ selection pion momentum and angle in topological breakdown . .	169
8.12	CC1 π^+ selection muon momentum and angle in true particle breakdown	170
8.13	CC1 π^+ selection pion momentum in true particle breakdown	171
8.14	CC1 π^+ selection pion angle in true particle breakdown	172
8.15	CC1 π^+ selection efficiencies as a function of 4D kinematics	173
8.16	True vertex position for the out-of-fiducial volume events.	175
8.17	CC0 π selection muon momentum and angle in topological breakdown . .	176
8.18	CC0 π selection muon momentum and angle in true particle breakdown .	177
8.19	CC0 π selection efficiencies as a function of muon kinematics	178
8.20	CC1 π^+ &1 $\pi^\pm$ selection muon momentum in topological breakdown	179
8.21	CC1 π^+ &1 $\pi^\pm$ selection muon angle in topological breakdown	180
8.22	CC1 π^+ &1 $\pi^\pm$ selection pion momentum and angle in topological breakdown	182
8.23	CC1 π^+ &1 $\pi^\pm$ selection muon momentum and angle in true particle breakdown	183
8.24	CC1 π^+ &1 $\pi^\pm$ selection pion momentum and angle in true particle breakdown	184
8.25	CC1 π^+ &1 $\pi^\pm$ selection efficiencies as a function of 4D kinematics	185
8.26	CC1 π^+ & π^0 muon momentum and angle in topological breakdown	186
8.27	CC1 π^+ & π^0 pion momentum and angle in topological breakdown	187
8.28	CC1 π^+ & π^0 muon momentum and angle in true particle breakdown	188
8.29	CC1 π^+ & π^0 pion momentum and angle in true particle breakdown	189

8.30	CC1 π^+ & π^0 selection efficiencies as a function of 4D kinematics	190
9.1	Relative errors as functions of muon momentum and angle for all systematics	201
9.2	Relative errors as functions of pion momentum and angle for all systematics	202
9.3	ND280 detector covariance matrix	203
9.4	Cross-section covariance matrix	208
9.5	Systematic uncertainties on the ND280 flux prediction in neutrino mode	211
9.6	Hadron and non-hadron interaction model uncertainties	211
9.7	The flux covariance matrix binned in neutrino energy in neutrino mode .	213
9.8	True event distributions for all CC1 π^+ signal samples combined	214
9.9	Selection efficiency for all CC1 π^+ signal samples combined	215
9.10	Selection purity for all CC1 π^+ signal samples combined	216
9.11	Smearing from truth to reconstructed space for the CC1 π^+ sample. . . .	217
9.12	Expected event distribution for all CC1 π^+ signal samples combined. . . .	217
9.13	Expected selection efficiency for CC1 π^+ samples combined.	218
9.14	Expected event distribution for the CC1 π^+ TPC and FGD-tagged pion signal sample	219
9.15	Expected event distribution for the CC1 π^+ ME-tagged pion signal sample	220
9.16	Expected event distribution for CC1 π^+ +1 $\pi^\pm$ and CC1 π^+ +1 π^0 control samples	220
9.17	Expected event distribution for CC0 π control sample	222
10.1	Asimov: Pre- and post-fit comparison for truth bins	228
10.2	Asimov: Pre- and post-fit comparison for flux parameters	229
10.3	Asimov: Pre- and post-fit comparison for detector parameters	230
10.4	Asimov: Pre- and post-fit comparison for cross-section model parameters	231
10.5	Asimov: post-fit correlation and covariance matrices for truth bins and flux parameters	232
10.6	Asimov: post-fit correlation and covariance matrices for detector and cross- section parameters	233
10.7	Asimov: Pre- and post-fit comparison for signal event numbers	234
10.8	Asimov: Pre- and post-fit comparison for background event numbers . .	235
10.9	Asimov: Calculated cross-section in true 4D kinematic variables	236
10.10	Post-fit χ^2 for statistically varied MC	238
10.11	Extracted cross-section χ^2 for statistically varied MC	238
10.12	Post-fit χ^2 for stat+syst varied MC	239
10.13	Extracted cross-section χ^2 for stat+syst varied MC	239
10.14	Signal enhanced: Pre- and post-fit comparison for truth bins	241

10.15	Signal enhanced: Pre- and post-fit comparison for flux parameters	242
10.16	Signal enhanced: Pre- and post-fit comparison for detector parameters .	243
10.17	Signal enhanced: Pre- and post-fit comparison for cross-section parameters	244
10.18	Signal enhanced: post-fit correlation and covariance matrices for truth bins and flux parameters	245
10.19	Signal enhanced: post-fit correlation and covariance matrices for detector and cross-section parameters	246
10.20	Signal enhanced: Pre- and post-fit comparison for signal event numbers .	247
10.21	Signal enhanced: Pre- and post-fit comparison for sideband event numbers	248
10.22	Signal enhanced: Calculated cross-section in true 4D kinematic variables	249
11.1	Data: Pre- and post-fit comparison for signal event numbers	253
11.2	Data: Pre- and post-fit comparison for sideband event numbers	254
11.3	Data: Pre- and post-fit comparison for truth bins	255
11.4	Data: Pre- and post-fit comparison for flux parameters	256
11.5	Data: Pre- and post-fit comparison for detector parameters	257
11.6	Data: Pre- and post-fit comparison for cross-section parameters	258
11.7	Data: Calculated cross-section in bin numbers	259
11.8	Data: Calculated cross-section in 4D kinematic binning Part 1	260
11.9	Data: Calculated cross-section in 4D kinematic binning Part 2	261
11.10	Data: Calculated cross-section in 4D kinematic binning Part 3	262
11.11	Data: Calculated cross-section in 4D kinematic binning Part 4	263
11.12	Data: Calculated cross-section in 1D muon angle	264
A.1	Overview of the processing steps to form an efficiency map in-site	282
B.1	Truth to reconstructed smearing for the $CC1\pi^+$ signal sample (Part 1). .	300
B.2	Truth to reconstructed smearing for the $CC1\pi^+$ signal sample (Part 2). .	301
C.1	Relative errors in muon kinematics for the TPC momentum resolution. .	304
C.2	Relative errors in pion kinematics for the TPC momentum resolution. . .	304
C.3	Relative errors in muon kinematics for the TPC momentum scale.	305
C.4	Relative errors in pion kinematics for the TPC momentum scale.	306
C.5	Relative errors in muon kinematics for the TPC particle ID.	306
C.6	Relative errors in pion kinematics for the TPC particle ID.	307
C.7	Relative errors in muon kinematics for the momentum bias from vtx migration.	308
C.8	Relative errors in pion kinematics for the momentum bias from vtx migration.	309
C.9	Relative errors in muon kinematics for the neutrino parent decay position.	312
C.10	Relative errors in pion kinematics for the neutrino parent decay position.	312

C.11 Relative errors in muon kinematics for the ECAL EM HIP ID.	316
C.12 Relative errors in pion kinematics for the ECAL EM HIP ID.	317
C.13 Relative errors in muon kinematics for the OOFV.	319
C.14 Relative errors in pion kinematics for the OOFV.	319
C.15 Relative errors in muon kinematics for the TPC-P0D matching.	321
C.16 Relative errors in pion kinematics for the TPC-P0D matching.	322
C.17 Relative errors in muon kinematics for the pion SI.	323
C.18 Relative errors in pion kinematics for the pion SI.	324
D.1 Random template prior: Pre- and post-fit parameter comparison	327
D.2 Random template prior: post-fit correlation and covariance matrices for truth bins and flux parameters	328
D.3 Random template prior: post-fit correlation and covariance matrices for detector and cross-section parameters	329
D.4 Random template prior: Pre- and post-fit comparison for signal event numbers	330
D.5 Random template prior: Pre- and post-fit comparison for background event numbers	331
D.6 Random template prior: Calculated cross-section	332
D.7 OOPS enhanced: Pre- and post-fit parameter comparison	335
D.8 OOPS enhanced: post-fit correlation and covariance matrices for truth bins and flux parameters	336
D.9 OOPS enhanced: post-fit correlation and covariance matrices for detector and cross-section parameters	337
D.10 OOPS enhanced: Comparisons between the pre-fit and post-fit signal event numbers	338
D.11 OOPS enhanced: Comparisons between the pre-fit and post-fit sideband event numbers	339
D.12 OOPS enhanced: Calculated cross-section	340
D.13 OOFV reduced: Pre- and post-fit parameter comparison	342
D.14 OOFV reduced: post-fit correlation and covariance matrices for truth bins and flux parameters	343
D.15 OOFV reduced: post-fit correlation and covariance matrices for detector and cross-section parameters	344
D.16 OOFV reduced: Comparisons between the pre-fit and post-fit signal event numbers	345

D.17 OOFV reduced: Comparisons between the pre-fit and post-fit sideband event numbers	346
D.18 OOFV reduced: Calculated cross-section	347
D.19 CCOther reduced: Pre- and post-fit parameter comparison	349
D.20 CCOther reduced: post-fit correlation and covariance matrices for truth bins and flux parameters	350
D.21 CCOther reduced: post-fit correlation and covariance matrices for detector and cross-section parameters	351
D.22 CCOther reduced: Comparisons between the pre-fit and post-fit signal event numbers	352
D.23 CCOther reduced: Comparisons between the pre-fit and post-fit sideband event numbers	353
D.24 CCOther reduced: Calculated cross-section	354
E.1 Midpoints and angles for data from the second drift volume of Module-0.	356
E.2 Event display of MINERvA 2x2 for through-going muons	358
E.3 Event display of MINERvA 2x2 for stopping muon	359

List of Tables

2.1	Oscillation parameters taken from [54].	26
6.1	Extrapolation uncertainty on beam properties	129
8.1	Summary of POT (Protons On Target) for various T2K runs.	166
9.1	Summary of the relevant detector systematic uncertainties and their types	204
9.2	Integrated relative errors (in %) for each source of detector systematic parameter split by kinematic variable	205
9.3	Overview of the relevant cross-section model parameters with type and prior values	207
10.1	Description of the different validation fits	224
11.1	Summary of post-fit χ^2 values	252
B.1	Flux binning in neutrino energy.	285
B.2	4D template parameter bin edges	286
B.2	4D template parameter bin edges (<i>continued</i>)	287
B.2	4D template parameter bin edges (<i>continued</i>)	288
B.3	TPC & FGD identified pion sample bin edges	288
B.3	TPC & FGD identified pion sample bin edges (<i>continued</i>)	289
B.3	TPC & FGD identified pion sample bin edges (<i>continued</i>)	290
B.3	TPC & FGD identified pion sample bin edges (<i>continued</i>)	291
B.3	TPC & FGD identified pion sample bin edges (<i>continued</i>)	292
B.4	ME-tagged pion sample bin edges	293
B.4	ME-tagged pion sample bin edges (<i>continued</i>)	294
B.5	CC1 π^+ +1 $\pi^\pm$ sideband sample bin edges	295
B.6	CC1 π^+ +1 π^0 sideband sample bin edges	295
B.7	CC0 π sideband sample bin edges	296
B.7	CC0 π sideband sample bin edges (<i>continued</i>)	297

B.7	CC0 π sideband sample bin edges (<i>continued</i>)	298
B.7	CC0 π sideband sample bin edges (<i>continued</i>)	299
C.1	TPC tracking efficiencies	314
C.2	POT effect on ECal pile-up efficiencies	315
C.3	TPC tracking efficiencies	320
C.4	FGD-ECal matching efficiencies for several muon angles	322

List of Acronyms

2p2h 2-particles 2-holes

ABS ABSorption

AGS Alternating Gradient Synchrotron

ALEPH Apparatus for LEP PHysics

APA Anode Plane Assembly

ArCLight ArgonCube Light

ASICs Application-Specific Integrated Circuits

BabyMIND Magnetized Iron Neutrino Detector

BH Benhar-Fantoni

BLM Beam Loss Monitors

BWD Backward-going

BY Bodek-Yang

CC Charged-Current

CE Charge Exchange

CK scheme Chau-Keung scheme

CNO Carbon–Nitrogen–Oxygen

CPA Cathode Plane Assembly

CRP Charge Readout Planes

CRS Charge Readout System

CRU Charge Readout Units

CSA Charge-Sensitive Amplifiers

CT Current Transformer

DAQ Data Acquisition

DELPHI DEtector with Lepton, Photon and Hadron Identification

DIS Deep-Inelastic Scattering

DoF Degrees Of Freedom

DONUT Direct Observation of the Nu Tau experiment

DUNE Deep Underground Neutrino Experiment

DUET Dual Use Experiment

ECal Electromagnetic Calorimeter

ESM Electrostatic Monitors

ESM Segmented Secondary Emission Monitors

FD Far Detector

FGD Fine-Grained Detector

FH Forward-Hand Current

FHC Forward-Hand Current

FSI Final-State Interactions

FV Fiducial Volume

GRAIN Granular Argon for Interaction of Neutrinos

HABWD High-Angle BWD

HAFWD High-Angle FWD

HTA Hough Transform Algorithm

HV High Voltage

IA Impulse Approximation

IC Inner Conductor

IH Inverted Hierarchy

INGRID Interactive Neutrino GRID

INEL INELastic scattering

KLOE K LOnG Experiment

L3 Third LEP experiment

LArTPC Liquid Argon Time Projection Chambers

LBNF Long Baseline Neutrino Facility

LCM Light Collection Module

LEP Large Electron-Positron Collider

LFG Local Fermi Gas

LINAC LINear ACcelerator

LRC Long-Range Correlations

LRS Light Readout System

ME Michel Electron

MEC Meson-Exchange Current

MF Mean-Field

MIGRAD Minimum GRADient descent algorithm

Micromegas MICRO-MEsh-GAseous

MIP Minimum Ionizing Particle

MPPC Multi-pixel Photon Counter

MR Main Ring

ND Near Detector

ND-GAr Gaseous Argon Near Detector

NDLAr Liquid Argon Near Detector

NH Normal Hierarchy

NuMI Neutrinos at the Main Injector

OA Oscillation Analyses

OOPS Out-Of-Phase-Space

OOFV Out-Of-Fiducial-Volume

OPAL Omni-Purpose Apparatus for LEP

Optical Transition Radiation OTR

PACMAN Pixel Array Control, Message and Network

PIP-II Proton Improvement Plan II

PID Particle Identification

PDF Probability Density Function

PE Photo-Electrons

PPM Parts-Per-Million

POT Protons On Target

PRISM Precision Reaction-Independent Spectrum Measurement

QA Quality Assurance

QC Quality Control

QE Quasi-Elastic

RCS Rapid-Cycling Synchrotron

RES Resonant

RFG Relativistic Fermi Gas

RHC Reverse-Hand Current

RMS Root-Mean-Squared

ROC Rate Of Change

RS Rein-Sehgal

RTD Resistive Temperature Detectors

SAND System for on-Axis Neutrino Detection

SAND System for on-Axis Neutrino Detection

SF Spectral Function

SiPM Silicon Photomultiplier

SK Super-Kamiokande

SLAC Stanford Linear Accelerator Center

SM Standard Model of Particle Physics

SMRD Side Muon Range Detector

SNO Sudbury Neutrino Observatory

SNU Solar Neutrino Unit

SRC Short-Range Correlations

SRF Superconducting Radio-Frequency

STT Straw Tube Target

SURF Sandford Underground Research Facility

T2K Tokai-to-Kamioka

TMS Temporary Muon Spectrometer

ToF Time-Of-Flight

TPB Tetra-Phenyl-Butadiene

WAGASCI WAter-Grid-SCIntillator-Detector

INTRODUCTION

”Neutrinos, with their tiny masses and evasive nature, have challenged our understanding of the universe and pushed the frontiers of science.”

— Takaaki Kajita

Physicists spend a lot of time and energy studying complex theories and phenomena that may have little direct impact on the daily lives of the general public. Our pursuit of knowledge often takes us into the realm of the abstract and theoretical, where we seek to explain the underlying mechanisms of the universe. While this work is crucial for advancing our understanding of the world, it is often far removed from the more practical concerns of the average person. We are driven by a passion for discovery regardless of whether the outcomes of our research are immediately life-changing. In this sense, our dedication to exploring the mysteries of the universe is an end in itself, rather than a means to an end.

We have made tremendous progress in grasping intricacies of the physical world around us extending all the way from the magnitude of stellar objects down to the subatomic level. We have utilized the laws of nature in many different ways to make life on Earth more sustainable, comfortable and safe. However, not everyone needs a thorough understanding of the methods that scientists use to communicate with the universe. Most people lead fulfilling and productive lives without detailed knowledge of the latest advancements in research. It is usually sufficient and perhaps more useful to have a general understanding of physical concepts recurring in one’s daily life, such as understanding how a car works

or the principles of electricity, rather than being able to calculate the number of particles that travel through one's finger every second. It allows them to make informed decisions and appreciate the wonders of the material world without needing to explain or justify them.

That is not to say that the impact of our discoveries are nonexistent. It is almost impossible to forecast what future applications might arise from present day research. No one could have foreseen that Einstein's general theory of relativity would one day be used for accurate timing in the global positioning system. It took decades to invent this technology, but now we can't imagine a world without it. So even if the theories or results seem useless on a short timescale, they could have major impact later on and will always serve as a form of guidance in our interactions with the universe. Neutrinos are the perfect example for this train of thought.

Neutrinos are the most abundant massive particles in our universe and yet the most difficult to observe. Tiny, neutral and hardly interacting with anything, neutrinos carry with them the answers to the earlier stages of our world. Their existence and behavior have been puzzling mankind for close to a hundred years now. However, we are nearing an era in which some of the long lasting mysteries will finally be resolved. This thesis will take you from the neutrino's postulation, through all of the incremental discoveries, to our present day view of their nature and our outlook on the future.

Any great neutrino-physics-related thesis ever has started by introducing the solution that brought along with it many new puzzles. This is not an uncommon thing in the world of physics and as discouraging as it may sound initially, it also incentivizes the continuous development of our field. From the way Pauli described his prediction of the neutrino, it seems as if he had at least a slight idea of the trouble that it would be accompanied by [1].

1.1 THE “TERRIBLE” INCEPTION

To understand how this particle came into existence and why its name is so eerily similar to another one we know, we have to go back to the end of the 19th century. It was Ernest Rutherford who discovered that there were both positively and negatively charged particles emanating from radioactive sources in 1898 [2], only two years after Henry Becquerel found the existence of natural radioactivity by studying uranium salts [3]. Rutherford named these particles, ‘alpha’ and ‘beta’ respectively and it would not take

long before physicists realized that the beta particle had in fact the same properties as the electron and positron.

With the decaying nucleus losing some of its mass, it made sense at the time to assume that the emitted radiation would carry away this energy. The alpha particle certainly upholds that law, but in 1911 the first hints of a continuous spectrum for beta decays started to appear. It was Lise Meitner and Otto Hahn who measured the kinetic energy distribution of the decay electron first, expecting to find a narrow energy distribution as the particle should carry away the energy difference between initial state neutron and final state proton. To their surprise, as well as to the surprise of the entire physics community, they found a spread of values [4]. James Chadwick later confirmed this in 1914 with more accurate equipment [5]. A new mystery was born; the apparent violation of conservation of energy. Energy went missing and it took multiple decades for it to be found again!

Austrian physicist Wolfgang Pauli was one of the key players in this search. He proposed that there had to be a third particle involved in beta decay, one that the previous employed methods did not manage to observe. He correctly postulated this particle to be neutral, but his initial assessment of it being the ‘neutron’ was proven wrong two years later by Chadwick showing that the real neutron was too massive to explain the beta decay spectrum [6].

Pauli did not stop there and in 1930 came up with the existence of a new elementary particle, one we now know as the neutrino. He described it in a letter sent to the attendees of a convention organized to discuss potential solutions to the missing energy problem. After opening with “Liebe Radioaktive Damen und Herren”, translated as “Dear Radioactive Ladies and Gentleman”, he continued to characterize his ‘neutron’ and its properties [1]. A neutral spin- $\frac{1}{2}$ particle, which obeys the exclusion principle, does not travel at the speed of light and should have a mass in the same order of magnitude as an electron. He himself called this a desperate remedy and said he had done something terrible as he postulated a particle that could not be detected. Perhaps he foreshadowed what the next century was going to bring.

1.2 THE FIRST DETECTION

Enrico Fermi ultimately was the one to publish the theory on beta decay, as is known now, in 1933 [7]. In order to avoid any confusion with James Chadwick’s neutron, the particle was called the neutrino. In Italian the suffix *-ino* is used as a diminutive, marking the

birth of the “little neutral one”. Its addition would lead the equation for beta decay to take on the following and final form:

$${}^A_ZX \rightarrow {}^A_{Z+1}Y + e^- + \bar{\nu}_e, \quad (1.1)$$

in which a neutron is converted to a proton, which releases an electron and an electron antineutrino. The satisfaction of how well this theory matched all that time’s available data did not last long as they had to now set out and detect the neutrino.

While Pauli’s fear was justified by the cross section prediction from Bethe and Peierls in 1934 [8], showing that it was in fact incredibly small, at the order of 10^{-44} cm² for neutrino energies around 2 MeV, it was only temporarily true. By 1950 nuclear reactor technology had advanced far enough to allow for neutrino fluxes sufficiently large to reignite the hope of detecting this illustrious particle.

Bruno Pontecorvo, unfazed by Pauli’s message and the conclusions drawn by Bethe and Peierls, proposed to detect electron neutrinos through the conversion of chlorine-37 to argon-37 accompanied by the release of an electron [9]. His statement on the viability of such an experiment marked the start of the neutrino detection race.

Raymond Davis Jr., who went on to share the Nobel Prize in 2002, was one of the pioneers when it came to using Pontecorvo’s method of neutrino detection. He installed a tank containing chlorine atoms at the Brookhaven National Lab’s fission reactor in the hope of observing the radioactive argon coming from the neutrino-chlorine reaction. This first iteration of his detector in 1954 did not yield any results [10]. The reactor flux was not large enough for the size of the tank that was being used (38000 liters). He did what any sane individual would do and that is to seek a more intense reactor with a more massive detector. The next experiment ran with a 11400 liter carbon tetrachloride volume at the 0.8 GW Savannah River reactor in South Carolina, the most intense in the world at that time. The second effort turned out to be unsuccessful as well when no significant amount of argon was found upon inspection. But while they did not show the actual existence of the neutrino, their results did suggest that there might be a difference between neutrinos and antineutrinos as neutrinos are required for the chlorine to argon conversion, but antineutrinos are provided by the nuclear reactors [11].

In that same era, Fred Reines and Clyde Cowan Jr. set out to launch project Poltergeist named after the illusiveness of the particle they were trying to find [12]. With the

Manhattan project still being very recent history and with both men having worked on it, the idea to use an atomic bomb to produce a high level of neutrino flux was introduced. As the blast time and the neutrino emission would be rather short, the detector would not amass a significant amount of background events like when it ran for several months in the reactor experiments. The target material was changed from chlorine to liquid scintillator as the inverse beta decay process now became the signal that was sought.

$$p + \bar{\nu}_e \rightarrow n + e^+ \quad (1.2)$$

This in turn also provided a method of understanding the deposited energy by the resulting electron through studying the scintillation light. For reasons that are not entirely clear, Reines and Cowan Jr. decided to abandon the idea of using a nuclear weapon to study neutrinos after all components were approved by the Los Alamos Laboratory already. Instead they followed in the footsteps of R. Davis and switched to a reactor-based source. First they studied the flux coming from the Hanford reactor, where they improved the detection mechanism [12]. They now not only looked for the signal of the outgoing electron, but also utilized the high neutron capture rate of cadmium through which more photons are emitted. This was achieved by dissolving some cadmiumbichloride into the scintillator. The effort at Hanford ended with a probable detection published in 1953 [12].

Following in the footsteps of their predecessor, they too moved to the Savannah River reactor. Utilizing a similar strategy as before, they now dissolved the CdCl₂ in water to have a more transparent medium for the released photons to travel through and reach the photomultiplier tubes [13]. The water containers were encircled by tanks of liquid scintillator. Using the expected time delay between photons from the annihilation of the positron and the deexcitation of the cadmium after it absorbed the lone neutron, the neutrino signal could be distinguished from the background, leading to its official discovery in 1956 [14]. The initial search had come to an end, but the understanding of the neutrino's intricacies had only just begun.

1.2.1 So it exists, but what now?

The lepton number conservation law states that the total number of leptons minus the total number of antileptons should be consistent for all particle interactions. In the case of the nuclear reactors used in the aforementioned experiments, it is beta decay that provides the neutrinos. The final state consists of an electron (+1 lepton number) and in order to conserve the lepton number, the neutrino has to be an electron antineutrino (-1 lepton number). This of course does not preclude the idea that particles and antiparticles are

identical. So, was the neutrino in fact its own antiparticle? Well, even though Raymond Davis Jr. was unable to discover the antineutrino in his inverse beta decay experiment, his failure to do so did provide evidence that suggested they are not one and the same. In a more extensive search for this phenomenon, he managed to show that the probability of this process occurring at a reactor source was less than 10 percent of the expected probability had they been the same particle [11]. As we will see later, this question is still unanswered and takes center stage in a wide variety of neutrino-related experiments.

The ‘is-the-particle-its-own-antiparticle’-narrative only covered half of the questions the discovery of the neutrino brought along. The other half revolved around figuring out if the neutrinos in this process, where electrons are involved, are the same as those in interactions between leptons of other families. At the time, only one of those other families had been identified. The muon, known as the heavier brother of the electron, had its own set of neutrino related interactions. This motivated Melvin Schwartz, Jack Steinberger and Leon Lederman in the late 1950s to propose an experiment in which they would attempt to detect the neutrinos coming from pions decaying into muons [15].

The experiment used the Alternating Gradient Synchrotron (AGS) at the Brookhaven National Laboratory to accelerate a proton beam up to 15 GeV. These protons then impinged on a beryllium target to produce pions. As the pions propagated through space, they would decay into muons and neutrinos in line with equation 1.3. As we will see later, this strategy is still being used in present-day experiments as well.

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu/\bar{\nu} \tag{1.3}$$

To see if the produced neutrinos are identical to the ones in the β -decay experiments, the idea was to look at the reaction products. If these neutrinos interacted with matter and predominantly produced muons instead of electrons, the argument could be made that the particles are different. The directly produced muons would obviously interfere with this observation, so before reaching the detector these muons had to travel through a 13.5 meter iron wall. The neutrinos would flow through almost freely before reaching the aluminium spark chamber. Here a spark is recorded every time a charged particle is produced. If the neutrinos interact, the charged lepton coming from the process would thus be identifiable. If the neutrinos were in fact identical, the muon and electron rate should be similar, but instead Schwartz, Steinberger and Lederman found that nearly all of these charged particles were muons and concluded that the neutrino, as with the charged leptons, can belong to different families [15][16]!

1.3 A THIRD NEUTRINO

Now you might wonder how many of these families and consequently how many neutrinos exist in our universe. That is exactly what kept the field's interest for the years to come. Halfway through the seventies, hints of a third generation started popping up after the discovery of yet an even heavier brother of the electron. The tau lepton was discovered in 1975 at the Stanford Positron Electron Asymmetric Rings collider at the Stanford Linear Accelerator center (SLAC) and sparked the search for another neutrino different from those accompanying electrons and muons [17]. Although there were several experiments showing the existence of the tau neutrino indirectly, it would take until 2001 to find it through direct observation [18]. This was done by the aptly named Direct Observation of the Nu Tau experiment (DONUT) at Fermilab.

Employing a similar strategy as for the muon neutrino, DONUT scientists shot 800 GeV protons from the TeVatron at a tungsten beam dump [18]. The higher energy allows for the creation of heavier mesons, such as the 'D-strange' (D_S), a meson that consists of a strange and anticharm quark, which decays into a tau meson and tau antineutrino in $(5.48 \pm 0.23)\%$ of the cases [19]. The decay of the tau itself provides the tau neutrinos. Direct observation refers to the fact that these neutrinos are identified in a nuclear emulsion tracker. The signature of a charged-current interaction is an outgoing tau lepton, which due to their short lifetime, can be identified by searching for 'kinks' in the emulsion tracks of outgoing particles, indicating a decay to a charged daughter particle. DONUT discovered the third neutrino and presented the three generational system.

The number 'three' finds its way into the Standard Model (SM) of Particle Physics, the most accurate and comprehensive description of nature as of the 1970s, more often. The SM integrates principles from quantum mechanics and special relativity to explain the universe at the smallest scales. In the SM, matter consists of three generations of elementary particles, three quarks, three generations of electrons and now there were three neutrino families. The three fundamental forces, the strong, the electromagnetic, and the weak (the latter two unified as the electroweak force) are mediated by bosons [20]. Does that mean that the addition of this third neutrino had finally completed the SM or was there perhaps more to be found?

A systematic way of testing the number of neutrino species arose a couple of years after the

indirect detection of the tau neutrino. In 1989 at the Large Electron Positron Collider at CERN, the number of (light) neutrinos was found to be $N_\nu = 3.27 \pm 0.30$ by the Apparatus for LEP PHysics (ALEPH) collaboration [21]. The method is a delicate one and finds its origin in the resonance width of the weak-interaction-mediating Z^0 boson, one of the three massive gauge bosons predicted by Glashow, Salam and Weinberg, three recurring names throughout this document, in their concept of the electroweak theory [22]. This constitutes the unification of the electromagnetic and weak nuclear force. The $W^\pm$ and the Z^0 bosons were speculated to have a mass of 80 and 90 GeV, respectively [23].

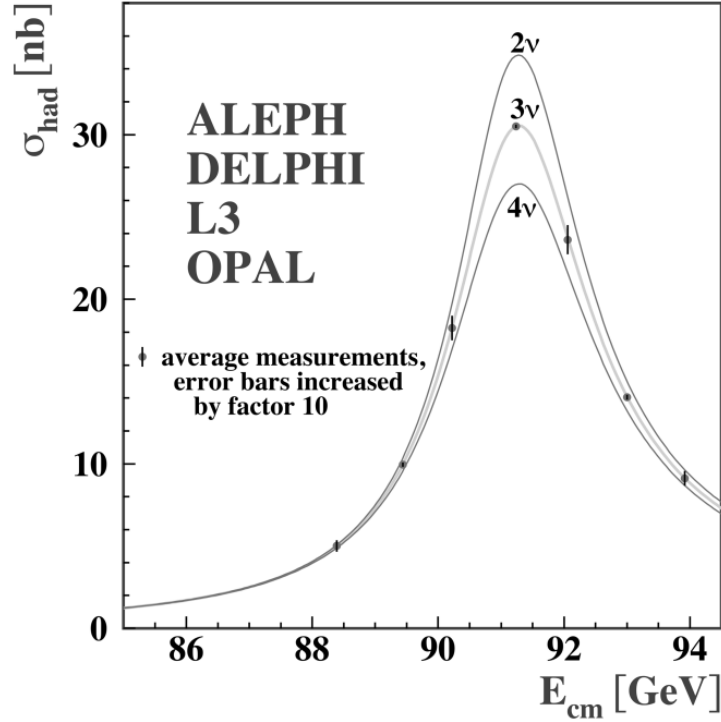


Figure 1.1: Cross-section for e^+e^- annihilation to hadrons as a function of the centre of mass energy for several Large Electron-Positron Collider (LEP) experiments. The curves indicate the Standard Model prediction for two, three and four light neutrinos, while the data points represent the averaged experimental measurements. [24].

After the upgrades to the CERN colliders allowed for the discoveries of the $W^\pm$ and Z^0 bosons, the incentive to use the latter as a measuring technique for the number of neutrinos was born. This does, of course, only include the neutrinos that actually couple to the Z^0 boson. By producing collisions at energies around the Z^0 pole, the Z^0 decay width can be studied [25]. Leaving the mathematical details for later chapters, this width can be described in the following manner here: $\Gamma_Z = \Gamma_{\text{had}} + \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + N_\nu \Gamma_{\nu\nu}$. From this, the influence of the number of neutrinos can immediately be distilled in the final term of the equation. With the result of the ALEPH collaboration, a fourth neutrino type

was ruled out at the 98% confidence level [21][26]. Combining their result with the other experiments at the time yielded an even more satisfying result of $N_\nu = 2.9840 \pm 0.0082$. The LEP experiments' combined result agrees with the three light neutrino hypothesis, as shown in figure 1.1.

With that number fresh in our memory the introduction into the world of neutrinos comes to an end, but as you might have guessed from the existence of this thesis the mysteries only just began. The Standard Model of particle physics looks and feels idealistic, it operates beautifully and seems symmetric across families. Thus in the next chapter, that facade will be lifted and more exotic phenomena will be discussed. Chapter 2 dives into neutrino oscillations, whereby neutrinos move between families as they propagate in space. The probabilities of this happening as well as the mixing framework and its parameters will be laid out by describing the areas in which they are most prevalent. How neutrinos interact with the world around them will also be a key element of the theoretical background.

Then it is onward to chapter 3, where the connection will be made to the experimental realm. In the specific subset of neutrino oscillation experiments of interest, accelerators are the starting point. Contrary to other experiments, the source in this case is thus a man-made one specifically designed to emit neutrinos. In this work the focus will lie on Tokai-to-Kamioka (or T2K) and the Deep Underground Neutrino Experiment (or DUNE). The two experiments will be covered from their starting proton beam all the way up until the observations in the detectors. The goal is to relay the design choices and considerations that go into each of these experiments and explore their differences before moving on.

Chapter 4 will elaborate on the actual detection of neutrinos in the DUNE experiment. In order to assess the parameters describing oscillations, the neutrinos have to be measured at at least two separate positions along the beam's path. This thesis will analyze interactions in the detectors closest to the source (i.e. the 'Near' Detectors). For DUNE, this is a modular configuration of liquid argon time projection chambers coined *NDLAr*. To show the feasibility of this modular approach, the light detection and the charge collection systems, a series of prototypes have been developed to serve as a proof of concept. This is perhaps jargon at this stage, but please refer to chapter 5 in order to learn more.

That concludes the DUNE section and opens the discussion on T2K. For T2K, the near

detector consists of an assembly of different subsystems named *ND280*. As these are truly at the core of the succeeding analyses, each will receive a detailed description in chapter 6 before moving on to the analysis.

As T2K has been operating for many years, there is data readily available. To study the oscillatory behavior, one has to take into account several different factors that influence it. The neutrino cross-section, the flux and detector performance all play a key role. Better understanding of these factors will reduce the uncertainty by which oscillation parameters are recorded. Here, the focus lies on the cross-section and more specifically on the cross-section of a neutrino interacting with hydrocarbon through the charged-current resulting in a muon, proton and pion. The strategy to do so will be discussed in chapter 7. For this, a selection needs to be made to ensure a high-signal purity in exactly those events. The selection is described in chapter 8, while the systematic uncertainties for the flux, cross-section and the detector parameters will be described in chapter 9.

The following chapter 10 will cover all the necessary information to understand the fitting framework in which we try to match the simulation to the data. A log likelihood technique that is utilized to do so will be thoroughly covered in this chapter, accompanied by several studies that show the robustness of the method at hand. When that is all said and done, the cross section will finally be extracted and discussed in chapter 11, along with a set of recommendations and thoughts on what to improve in future iterations of this work.

NEUTRINO PHYSICS

2

Throughout the introduction some of the neutrino’s peculiarities have already started to surface. The chapter ended with an outlook on neutrino oscillations, a phenomenon that goes beyond the laws and definitions of the Standard Model. Hints suggesting the existence of these oscillations started showing up at the end of the 1960s during the operation of the Homestake experiment [27]. This was yet another endeavor led by Ray Davis, who, after missing his shot in discovering the neutrino itself, had not given up. Together with John Bahcall, they designed an experiment capable of measuring the neutrinos coming from the sun [28].

2.1 NEUTRINOS FROM THE SUN

The sun has a well understood nuclear fusion chain governing the energy output in its core. Although there are several paths this process can take, the initial steps from hydrogen to helium are the same. This ‘proton-proton chain’ dominant in stars around the solar mass, starts off by combining two protons into deuterium (at higher masses than 1.3 times the solar mass, the CNO-cycle becomes more prevalent [29]). One of the protons undergoes β^+ decay, releasing a positron and the cycle’s first neutrino. The positron then annihilates with an electron from the surrounding medium to produce photons [30]. The process is summarized by equation 2.1,

$$p + p + e^- \rightarrow {}^2_1\text{D} + \nu_e + 1.442 \text{ MeV}. \quad (2.1)$$

The deuterium can in turn interact with another proton to produce the stable isotope helium-3. This is the point at which the different fusion chains start to diverge. The key take-away is that every individual path produces exactly two neutrinos (the main method is through fusion of two helium-3 atoms into one helium-4 atom), two electron neutrinos to be precise under the lepton conservation constraint [31]. From the hot and dense environment that is the center of a star, most particles would not be able to escape. This would make detecting them at Earth impossible. Neutrinos, however, are not faced by this challenge. Their weakly interacting nature allows them to travel through these intense conditions and find their way to mankind’s detectors.

The detector used by R. Davis and J. Bahcall was based on the methodology from Bruno Pontecorvo in that electron neutrinos interacting with chloride should produce argon and the corresponding lepton [32]. The expertise that Davis had garnered from his studies on neutrinos and antineutrinos in the previous decade again proved very valuable here. A staggering volume of 390 cubic meters of perchloroethylene comprises the Homestake experiment [33]. With this size and naturally occurring chlorine being composed of roughly 25% ^{37}Cl , the detector provided enough material for a maximum of seven captures per day. With each interaction, more and more argon atoms would be present in the mixture. To count the number of argon-37 atoms, the tank was flushed with helium while simultaneously polluted with a preset amount of argon-36. This way argon-36 could be used as a performance metric for helium flushing. Afterwards the sample was purified and the argon-37 atoms were counted. At this stage, Davis was adamant that he could achieve an accuracy of a few dozen in a sea of 10^{30} atoms and so the first solar neutrino counting experiment was born.

2.2 THE SOLAR NEUTRINO ANOMALY

The caveat here is that the threshold for the inverse beta decay reaction between the electron neutrino and the chlorine-37 atom lies above a neutrino energy of 0.814 MeV. The proton-proton chain responsible for producing helium-3 does not actually produce neutrinos of that energy and thus it is only those from other proton fusion branches that Homestake was capable of detecting. One might argue that this was the reason for the measured flux being around three times smaller than predicted (first bar plot in figure 2.1), but that would not do the so-called ‘solar neutrino puzzle’ the justice it would soon deserve. The solar puzzle lasted from 1967 to 2002; during this period, multiple measurements were made (figure 2.1), but nothing wrong was ever found on the experimental side. Even after refining the theory and improving the detector’s sensitivity,

lack of agreement persisted. In fact, even when the target material was changed from chlorine to gallium by the SAGE and GALLEX experiments, lowering the threshold from 0.814 to 0.233 MeV and allowing for more of the solar cycle neutrinos to be seen, it still remained [34].

Back in the 90s when abbreviations were still straightforward, SAGE or the Soviet-American Gallium Experiment, began its data taking and has never stopped [35]. In SAGE, the volume is not filled with C_2Cl_4 but instead with liquid gallium metal kept just above its melting point. By extracting and counting the gallium atoms, an indication can be given on the total neutrino rate coming from the sun. This is summarized in the third bar plot in figure 2.1 and equates to around 55-60% of the expected rate.

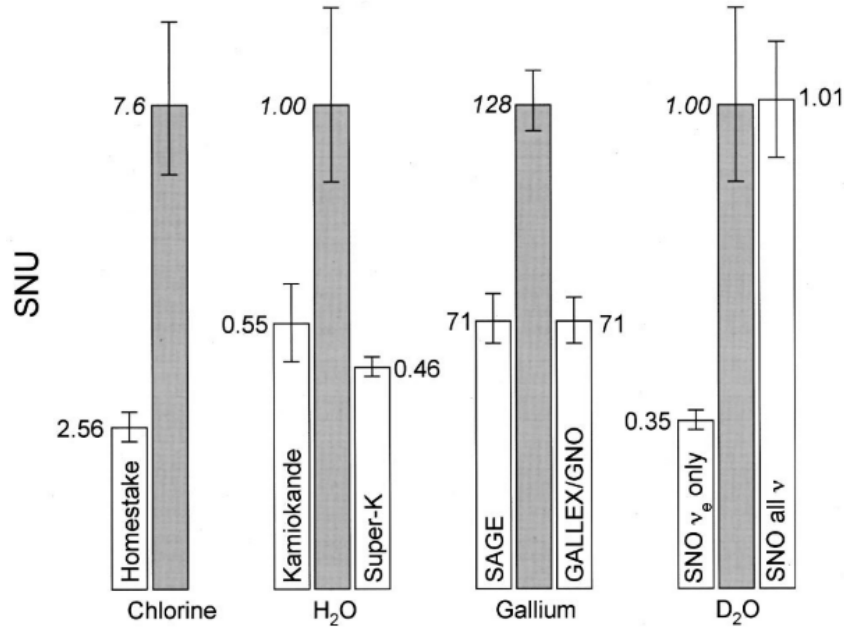


Figure 2.1: Overview of the predicted (grey) and measured (white) solar neutrino units (SNUs), which are equal to a neutrino flux that produces 10^{-36} captures per atom per second, for several neutrino oscillation experiments across the globe [36].

GALLEX, or the gallium experiment (arguably an even simpler name than before), started running in 1991 and stopped in 1997 [37]. Located at the Gran Sasso Laboratory in Italy was the equivalent of a 30.3 ton gallium target volume. The $GaCl_3$ solution was flushed every three to four weeks with nitrogen and the germanium atoms were then counted, constituting one cycle. The results were reported in terms of solar neutrino units, which are equal to a neutrino flux that produces 10^{-36} captures per atom per second. For GALLEX, the SNU was determined after 53 extraction cycles, also corresponding to around 55% of the expected rate during the six years of operation (see figure 2.1).

Although the discrepancy was smaller than measured by Homestake, it still remained significant and thus helped discard any theories that tried to argue that the original observation was simply a mistake. In years to come many more experiments (e.g., Kamiokande-II in 1987 [38]) proved the existence of this discrepancy, but it was not until thirty years later that the idea of neutrino oscillations started to take off. The truth was uncovered by discovering that both the observed solar neutrino deficit and the theory behind proton-proton cycles were true at the same time. This indicated that both production and detection were correct and that something must have had happened in between those two stages.

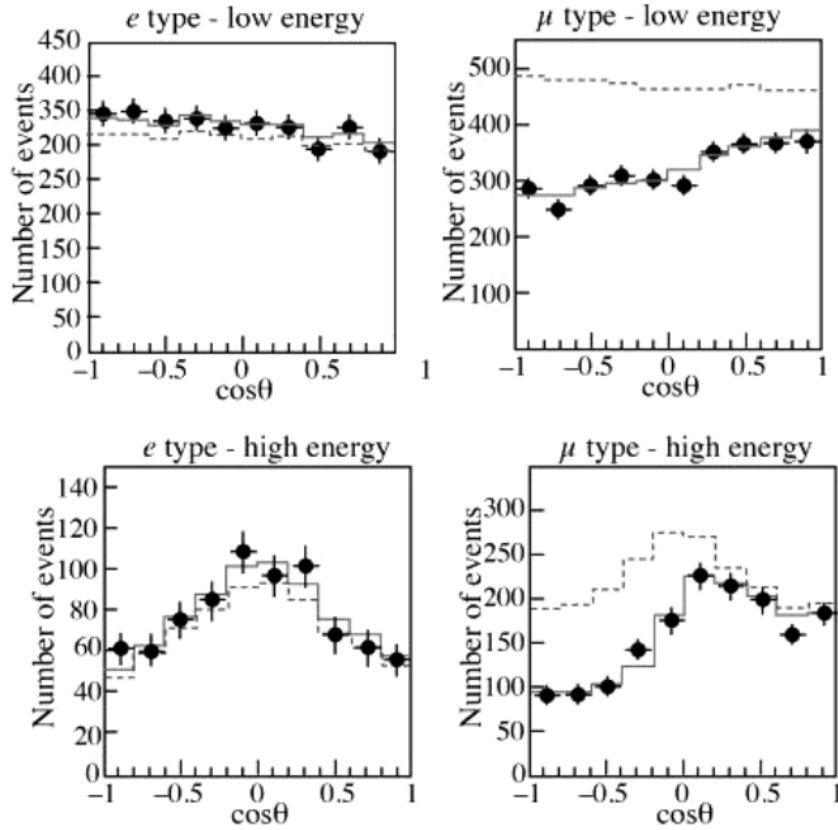


Figure 2.2: Muon and electron neutrino flux at Super-Kamiokande. Expected rate without oscillations (dotted line), with oscillations (solid line) [39].

It was a combination of measurements from the Sudbury Neutrino Observatory (SNO) and SuperKamiokande (which also serves as a motivation for the analysis of this thesis) that provided this final piece of the puzzle. Super-K supplied another estimate on the observed to expected neutrino rate of around 0.473 (figure 2.1). It also looked at the dependence of this rate on the neutrino arrival angle (zenith angle) for neutrinos created in the atmosphere. In contrast to the sun, interactions in the atmosphere lead to the

creation of a wide variety of particles, some of which are mesons like pions and kaons. When these decay, they produce muons and muon neutrinos. When the muons decay, they in turn produce electrons, electron neutrinos and even more muon neutrinos. When atmospheric neutrinos are mentioned, the term refers to both of these types. Looking at the atmospheric rates for different energy regions and zenith angles in figure 2.2, it can be seen that the electron neutrino rate matches the prediction without oscillations. The muon neutrino rate, however, shows a large discrepancy, indicating that they must have been lost somehow, perhaps lost to oscillations [40].

SNO provided the last nail in the coffin for the validity of the Standard Model to describe neutrino behavior. In 2002, SNO measured the electron neutrino flux in addition to the total neutrino flux. With their heavy water target, they were sensitive to neutral-current interactions as well as the charged-current ones. The electron neutrino measurement once again showed the solar anomaly, while the total neutrino measurement did not show that pattern (figure 2.1). With all of this evidence, there was no other explanation than that the neutrinos change flavour in flight. They oscillate and this discovery earned both Takaaki Kajita and Arthur McDonald the 2015 Nobel Prize in Physics.

As the equations for the probabilities for neutrinos to oscillate will show at the end of the next section, one of the major consequences of observing oscillations is that the squared mass difference Δm_{lk}^2 between neutrino mass states l and k can not be zero. If the difference can not be zero, at least one of these states has to be massive meaning that the neutrino has mass constituting the first experimental evidence of physics beyond the Standard Model.

In the Standard Model of particle physics, fermions acquire mass through their interactions with the Higgs field via the Higgs mechanism [41]. This interaction is described by the Yukawa coupling that is represented by the following term in the Standard Model Lagrangian:

$$\mathcal{L}_{\text{Yukawa}} = -g_f \bar{\psi}_L \phi \psi_R + \text{h.c.}, \quad (2.2)$$

where g_f is the Yukawa coupling constant for a fermion, $\bar{\psi}_L$ and ψ_R are the left-handed and right-handed components of the fermion field and ϕ is the Higgs field. After the spontaneous breaking of the electroweak symmetry (on which more can be read in [42]) through the acquisition of the non-zero vacuum expectation value by the Higgs field, this interaction term is what generates the mass of the fermions. The handedness refers to the projection of the field based on their chirality, which is a fundamental property

related to the particle's spin and momentum that determines how they transform under the Poincaré group. Fermion fields can be decomposed into left-handed and right-handed components using projection operators shown in equation 2.3:

$$\psi_L = \frac{1 - \gamma^5}{2} \psi, \quad \psi_R = \frac{1 + \gamma^5}{2} \psi, \quad (2.3)$$

where γ^5 is a gamma matrix satisfying $(\gamma^5)^2 = 1$. To describe the orientation of a particle's spin and momentum vectors with respect to one another, the helicity h can be used. It is described by equation 2.4.

$$h = \frac{\vec{S} \cdot \vec{p}}{|\vec{p}|}, \quad (2.4)$$

where $\vec{S}$ is the spin vector, $\vec{p}$ is the momentum vector and $|\vec{p}|$ is its magnitude. Right-handed particles have their vectors oriented in parallel resulting in a positive helicity (+1), whereas left-handed particles have a negative helicity (-1). For massless particles, chirality and helicity are the same. For massive particles, they differ due to the possibility of reference frame changes [43]. From the Lagrangian in equation 2.2, it becomes obvious that both components are necessary for the fermions to acquire their mass through the Higgs mechanism.

The weak interaction acts only on left-handed fermions and right-handed antifermions. Neutrinos only interact through the weak force, so while they can be both right-handed or left-handed, all the neutrinos that have ever been observed are left-handed and all of the antineutrinos are right-handed. Hence the neutrinos must have obtain their mass through a phenomenon that is not the Higgs mechanism hinting at new physics.

Models for this phenomenon take several different approaches categorized by: Dirac masses, Majorana masses and the Seesaw mechanism. In the first approach, right-handed neutrinos are introduced as singlets under the Standard Model gauge groups. The neutrinos then acquire mass through the Higgs mechanism in the same way as other fermions, with a Yukawa coupling. However, this approach requires extremely tiny Yukawa couplings (on the order of 10^{-12}) to match observed neutrino masses. In the Majorana case, neutrinos may be their own antiparticles, allowing for mass terms that do not require right-handed neutrinos. Majorana masses can arise through effective terms violating lepton number conservation, such as those generated by the seesaw mechanism. In the Seesaw mechanism, heavy right-handed neutrinos are introduced. Their large masses suppress the masses of the observed left-handed neutrinos. The mass scale is then

given by $m_\nu = \frac{m_D^2}{M_R}$. Here m_D is the Dirac mass and m_R is the Majorana mass.

But the field did not stop there as more was still to be understood about how neutrinos oscillate. And then? Well then, oscillations will be used to find the values of other parameters defining our universe and so the complexity of experiments will keep on progressing until further development is deemed impossible by mankind or until nature shows its true colors.

2.3 NEUTRINO OSCILLATIONS

There are three known neutrino flavours ν_e , ν_μ and ν_τ , corresponding to the three types of leptons e , μ and τ . This relationship shows itself when we study the weak interaction. Produced or consumed neutrinos are in their flavour eigenstate in the sense that they are always accompanied by the corresponding charged lepton mentioned above when exchanging a W boson. If a neutrino is generated alongside a muon, it is called a muon neutrino by conservation of lepton number [44]. The same holds for the other two families as shown schematically in the Feynman diagrams of figure 2.3. In addition

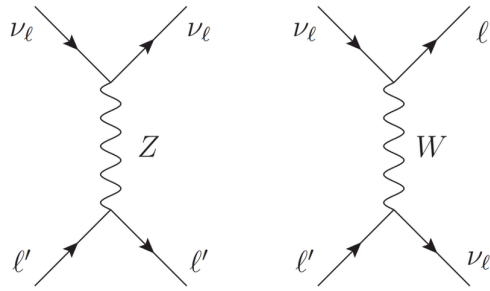


Figure 2.3: Leading order Feynman diagrams displaying the neutral-current and charged-current interactions [45].

to their flavours, neutrinos have three mass eigenstates, ν_1 , ν_2 and ν_3 , generated by the free particle Hamiltonian. Similarly to what happens in the quark sector, these mass eigenstates do not coincide with the flavour ones. However, unlike in the quark sector, neutrino masses can't be resolved in a similar fashion, being orders of magnitude smaller. This means that the mass state can't be perceived after its creation, leaving its identity uncertain [46].

Since the produced neutrinos are by default in their flavour eigenstates, they are not in a definite mass eigenstate. Hence, by the laws of quantum mechanics, each is composed of a combination of the possible states connected through a mixing matrix much like the

CKM-matrix in the manner described in equations 2.5 and 2.6:

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i}^* |\nu_i\rangle, \quad (2.5)$$

$$|\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i} |\nu_\alpha\rangle. \quad (2.6)$$

where $\alpha = e, \mu, \tau$ represents the flavour and $i = 1, 2, 3$ the mass eigenstates [47]. The asterisk simply indicates the complex conjugate of the matrix at hand. The full equation is shown in equation 2.7,

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \underbrace{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix}}_{U_{PMNS}} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \quad (2.7)$$

The form of the superposition in terms of the mixing matrix becomes clear. U is described by the Pontecorvo–Maki–Nakagawa–Sakata matrix or PMNS in short [48]. This matrix is subject to a couple of constraints, all of which can be derived from the unitary condition enforced in order to conserve probability. This means that $U^\dagger U = I = U U^\dagger$, where I is the identity matrix. What follows is that the probability to find one of the neutrinos in any of the three mass eigenstates should be one. The sum of squared elements in one row or column should add up to one, e.g., $|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$. Additionally each row of the PMNS matrix must be orthogonal to every other row and each column must be orthogonal to every other column, e.g., for rows: $U_{e1}U_{\mu1}^* + U_{e2}U_{\mu2}^* + U_{e3}U_{\mu3}^* = 0$ [47].

Incorporating these requirements, the PMNS matrix can be evaluated in a couple of ways, depending on the nature of the neutrinos. Are they Dirac or Majorana particles? In the Dirac framework the neutrinos and antineutrinos would be two distinct particles, whereas in the Majorana framework, they would be the same. In case they are of the first type, the matrix can be parameterized by three rotation angles, θ_{13} , θ_{12} , θ_{23} , and one CP-violating phase δ_{cp} . Two additional phase angles are needed if the neutrinos are of the Majorana type. However, these extra phase angles do not affect the absolute values of the entries in the PMNS matrix and are therefore not represented by any observables in neutrino oscillation physics. Oscillation measurements, which are the main physics goals for both DUNE and T2K, do not assist in resolving the particle’s type at all. Therefore, the focus will lie on relevant mixing and the most common parameterization following

the Chau-Keung (CK) scheme will be used in equation 2.8:

$$\begin{aligned}
U_{PMNS} &= \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\theta_{23}} \underbrace{\begin{bmatrix} c_{13} & 0 & e^{-i\delta_{cp}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{cp}} s_{13} & 0 & c_{13} \end{bmatrix}}_{\theta_{13}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\theta_{12}} \\
&= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{cp}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{cp}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{cp}} & s_{23}c_{13} \\ s_{12} - c_{12}c_{23}s_{13}e^{i\delta_{cp}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{cp}} & c_{23}c_{13} \end{bmatrix}
\end{aligned} \tag{2.8}$$

Here c_{ij} and s_{ij} correspond to the cosine and the sine of the mixing angles θ_{ij} , respectively. The least well-known factor in this matrix is represented by δ_{CP} , the CP-violating angle. If there turns out to be no CP violation in the neutrino sector, δ_{CP} will be 0. If mixing is maximal, δ_{CP} will either be $\frac{1}{2}\pi$ or $\frac{3}{2}\pi$. If the matrix turns out not to satisfy the unitarity constraint, the introduction of a fourth ‘sterile’ neutrino could solve this puzzle. Sterile refers to the fact that they would not interact with matter at all, except possibly through gravity. However, that concept will not be covered here.

Consider neutrinos propagating in free space over a distance L . In the absence of matter, the matter potential can be set to zero $V(x) = 0$. With the mass states ν_i evolving according to the time-dependent Schrödinger equation, the solution is given by that of a plane wave. This gives rise to the phase factor in equation 2.9:

$$|\nu_k(x, t)\rangle = e^{-i(E_k t - p_k x)} |\nu_k(0, 0)\rangle = e^{-i\phi_k} |\nu_k(0, 0)\rangle \tag{2.9}$$

The time-evolving phase ϕ_k can be simplified in the limit of ultra-relativistic neutrinos; as their velocity approaches the speed of light, $t \approx L$.

The second approximation is due to the neutrino’s very small mass and thus $m_i^2 \ll E_i^2$, which in turn affects the dispersion relation: $E_k - p_k = m_i^2/2E$. With the momentum described by $p_i = \sqrt{E_i^2 - m_i^2} = E_i \sqrt{1 - \frac{m_i^2}{E_i^2}}$, the Taylor series follows the logic of $\sqrt{1 - x}$ (with $x = m_i^2/E_i^2$). Hence, we obtain $p_k = E - m_k^2/2E$.

Plugging the momentum p_k , the energy E_k and the simplification for the time t into equation 2.9, the phase looks like $\phi_k = L * m_k^2/2E$ at position L away from the source. Baseline L and energy E are defining characteristics for the design of many of the world’s neutrino oscillation experiments. Combining this result with equation 2.5 gives the flavour

eigenstate at position x and time t in terms of the state at the source $x = 0$ and $t = 0$:

$$\begin{aligned} |\nu_\alpha(x, t)\rangle &= \sum_{k=1}^3 U_{\alpha k}^* |\nu_k(x, t)\rangle = \sum_{k=1}^3 U_{\alpha k}^* e^{-i\phi_k} |\nu_k(0, 0)\rangle \\ &= \sum_{k=1}^3 U_{\alpha k}^* e^{-i\phi_k} \sum_{\beta=e,\mu,\tau} U_{\beta k} |\nu_\beta(0, 0)\rangle. \end{aligned} \quad (2.10)$$

One finds the general formula for the probability through the bracket notation:

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\gamma) &= |\langle \nu_\gamma(0, 0) | \nu_\alpha(x, t) \rangle|^2 \\ &= \left| \sum_{k=1}^3 U_{\alpha k}^* e^{-i\phi_k} \sum_{\beta=e,\mu,\tau} U_{\beta k} \langle \nu_\gamma(0, 0) | \nu_\beta(0, 0) \rangle \right|^2. \end{aligned} \quad (2.11)$$

Due to orthonormality of the different flavour states, the bracket turns into a delta function:

$$\langle \nu_\gamma(0, 0) | \nu_\beta(0, 0) \rangle = \delta_{\gamma\beta} \quad (2.12)$$

Plugging this into equation 2.11 above yields:

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\gamma) &= \left| \sum_{k=1}^3 U_{\alpha k}^* e^{-i\phi_k} U_{\gamma k} \right|^2 \\ &= \sum_{k=1}^3 U_{\alpha k}^* e^{-i\phi_k} U_{\gamma k} \sum_{l=1}^3 U_{\alpha l} e^{i\phi_l} U_{\gamma l}^* \\ &= \sum_{k=1}^3 \sum_{l=1}^3 U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^* e^{-i(\phi_k - \phi_l)} \\ &= \sum_{l,k} U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^* e^{-i(\frac{L \Delta m_{kl}^2}{2E})} \end{aligned} \quad (2.13)$$

where l and k sum over all mass states. This holds for every parametrization of the mixing matrix, independent of phases. Rephasing would result in $U_{\alpha k} \rightarrow e^{i\psi_\alpha} U_{\alpha k} e^{i\psi_k}$, but this does not affect the probability. So, the previous statement about the Majorana phases not being of interest here is justified. To obtain a result that displays the physics behind the process more clearly, we can rewrite equation 2.13 by separating the sum in

two parts and then applying the following relationship: $Re(z) = \frac{1}{2}(z + z^*)$.

$$\begin{aligned}
P(\nu_\alpha \rightarrow \nu_\gamma) &= \sum_{l,k} U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^* e^{-i(\frac{L \Delta m_{lk}^2}{2E})} \\
&= \sum_{k=l} U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^* e^{-i(\frac{L \Delta m_{lk}^2}{2E})} + \sum_{k \neq l} U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^* e^{-i(\frac{L \Delta m_{lk}^2}{2E})} \\
&= \sum_k |U_{\alpha k}|^2 |U_{\gamma k}|^2 + 2\Re[\sum_{k>l} U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^* e^{-i(\frac{L \Delta m_{lk}^2}{2E})}]
\end{aligned} \tag{2.14}$$

The first term in equation 2.14 can be rewritten with the unitarity condition regarding the mixing matrix:

$$\sum_k U_{\alpha k} U_{\gamma k} = \delta_{\alpha\gamma}, \tag{2.15}$$

$$\sum_k |U_{\alpha k}|^2 |U_{\gamma k}|^2 = \delta_{\alpha\gamma} - 2\Re[\sum_{k>l} U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^*]. \tag{2.16}$$

Thus,

$$P(\nu_\alpha \rightarrow \nu_\gamma) = \delta_{\alpha\gamma} - 2 \sum_{k>l} \Re(U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^* [1 - e^{-i(\frac{L \Delta m_{lk}^2}{2E})}]). \tag{2.17}$$

By implementing the rule $\Re(ab) = \Re(a)\Re(b) - \Im(a)\Im(b)$, the exponential can be divided in an imaginary and real part. The need for this will become more clear towards the end of this chapter where the neutrino and antineutrino oscillation probabilities will be compared.

$$\begin{aligned}
P(\nu_\alpha \rightarrow \nu_\gamma) &= \delta_{\alpha\gamma} - 2 \sum_{k>l} \Re(U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^*) [1 - \cos\left(\frac{L \Delta m_{lk}^2}{2E}\right)] \\
&\quad + 2 \sum_{k>l} \Im(U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^*) \sin\left(\frac{L \Delta m_{lk}^2}{2E}\right)
\end{aligned} \tag{2.18}$$

The trigonometric identity $\sin^2(\theta) = \frac{1}{2}(1 - \cos(2\theta))$ simplifies the second term making the final expression for a generic oscillation process look like:

$$\begin{aligned}
P(\nu_\alpha \rightarrow \nu_\gamma) &= \delta_{\alpha\gamma} - 4 \sum_{k>l} \Re(U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^*) \sin^2\left(\frac{L \Delta m_{lk}^2}{4E}\right) \\
&\quad + 2 \sum_{k>l} \Im(U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^*) \sin\left(\frac{L \Delta m_{lk}^2}{2E}\right)
\end{aligned} \tag{2.19}$$

Here, E again represents the neutrino energy or momentum and L represents the distance from the source. U_{ij} are PMNS matrix entries. Δm_{lk}^2 is the squared mass difference between mass states l and k , which also indicates that the individual neutrino masses can't be resolved by measuring the probability. A more detailed description of the parameters

and experimental decisions constraining those will be given after derivation of oscillations in matter.

The focus now shifts to one particular result important for T2K and DUNE. By changing γ to μ and α to e and evaluating the sums over k and l in equation 2.19, the probability in vacuum to find an electron neutrino with energy E after a distance L in a primarily muon neutrino beam is obtained.

2.3.1 Antineutrino oscillations

The second step in determining the level of CP violation is comparing this probability to its CP conjugate. One finds the probability for antineutrinos by applying the Charge-Parity operator to the original. CP can be dissolved into two distinct operators $\hat{C}$ and $\hat{P}$. Individually, these transformations work in the following way:

C = Charge conjugation, this reverses all internal quantum numbers, e.g., the electric charge and essentially transforming the particle into its antiparticle:

$$\hat{C} : |\psi\rangle \rightarrow |\bar{\psi}\rangle \quad (2.20)$$

P = Parity, this reverses the space coordinates (valid for Cartesian coordinates):

$$\hat{P} : \begin{bmatrix} x \\ y \\ z \end{bmatrix} \rightarrow \begin{bmatrix} -x \\ -y \\ -z \end{bmatrix} \quad (2.21)$$

The charge and parity symmetries are violated in the weak interaction. More useful in the case of neutrinos is the combination of $\hat{C}$ and $\hat{P}$:

$$\hat{C}\hat{P} : P(\nu_\alpha \rightarrow \nu_\gamma) \rightarrow P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\gamma) \quad (2.22)$$

Applying this to the right-hand side of equation 2.19 leads to a difference in sign for the imaginary third term:

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\gamma) = & \delta_{\alpha\gamma} - 4 \sum_{k>l} \Re(U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^*) \sin^2 \left(\frac{L * \Delta m_{lk}^2}{4E} \right) \\ & - 2 \sum_{k>l} \Im(U_{\alpha k}^* U_{\gamma k} U_{\alpha l} U_{\gamma l}^*) \sin \left(\frac{L * \Delta m_{lk}^2}{2E} \right), \end{aligned} \quad (2.23)$$

which can be understood by realizing that the flavour states still consist of superpositions between the mass states, but are now linked through the CP conjugate of equation 2.5. This leads to particles becoming antiparticles and the mixing matrix losing its asterisk.

$$|\bar{\nu}_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i} |\bar{\nu}_i\rangle \quad (2.24)$$

Following the same derivation as in the previous subsection leads to the result shown above. Recall that equation 2.17 was decoupled in a real and imaginary part corresponding to a cosine and sine, respectively. The even and odd nature of these functions leads to the difference in sign of the imaginary (odd) part of the probability amplitude. If the neutrinos turn out to conserve CP symmetry and the δ_{CP} actually is zero, the entries of the PMNS matrix are real. Moreover, the imaginary contributions in equation 2.18 and 2.19 disappear and the two oscillation probabilities become equal. So, by studying the discrepancies between these two amplitudes, conclusions can be drawn regarding the level of CP violation.

Now, one could pose the question: what symmetry is preserved by neutrino oscillations? One more transformation has to be added to this story, which is known as $\mathbf{T}$ = Time. This changes the direction in which time flows, interchanging the initial and final states:

$$\hat{T} : P(\nu_\alpha \rightarrow \nu_\gamma) \rightarrow P(\nu_\gamma \rightarrow \nu_\alpha) \quad (2.25)$$

If the PMNS matrix turns out to be real, neutrino oscillations are time reversible. By observing $\delta_{CP} \neq 0$, the PMNS matrix turns out to be complex and time symmetry has to be broken accordingly. If the CP operator is followed by the time operator, this broken symmetry is restored and the arrow becomes an equal sign. CPT is conserved in general field theories, which the SM belongs to.

$$\hat{C}\hat{P}\hat{T} : P(\nu_\alpha \rightarrow \nu_\gamma) = P(\bar{\nu}_\gamma \rightarrow \bar{\nu}_\alpha) \quad (2.26)$$

Hence, if this CPT symmetry is somehow broken it will support the statement that the SM model is incorrect. However, looking for a violation of CPT will not be the focus of neutrino experiments discussed in this work.

2.3.2 Matter effect

Now that all the details of vacuum probabilities have been shown, matter effects can be investigated. The detected neutrinos will have traveled through a significant portion of

the Earth's crust upon reaching the T2K or DUNE far detector after all. This derivation has been done in a very elaborate fashion in a paper by L. Wolfenstein [49]. It goes beyond the scope of this thesis, but the main arguments will be given below. Remember that free space had no potential: $V(x) = 0$. As matter mainly consists of electrons and nucleons, the muon and tau neutrino channels do not contain charged-current contributions to $(\nu_e e \rightarrow \nu_e e)$ as lepton number would not be conserved. The charged current interaction constitutes an exchange of the $W^\pm$ boson. The only exchange of this type that can take place in the Earth's crust is that between a ν_e and an electron. The other two flavours can't participate in this process, meaning the interaction potential due to matter should only affect electron neutrinos as shown by the factor of δ_{ae} in equation 2.27.

$$V_a(x) = \sqrt{2}G_F \left(\delta_{ae}N_e(x) - \frac{1}{2}N_n \right) \quad (2.27)$$

in which N_e and N_n are the electron and neutron number densities of the crossed medium at position x , respectively, and G_F is the Fermi constant. For the neutral current, however, the incoming neutrino can exchange a Z^0 boson with an electron, proton or a neutron, meaning that any flavour neutrino can do this. At zero momentum transfer the Z coupling to electrons and protons is equal and opposite. Under the assumption that there is equal amount of protons and electrons in the traversed matter, the contribution to the interaction potential should thus cancel, leaving only the effect due to the presence of neutrons, as can be seen from the second term in equation 2.27 [50].

Clearly, for $a = \tau, \mu$ the contribution is purely from the second term. As the physical relevance for the oscillatory behavior lies within the difference between these potentials, a few simple conclusions can be drawn. For instance, $V_\tau - V_\mu = 0$ and the non-vanishing potential is the result of charged current interactions for electron neutrinos:

$$V(x) = V_e - V_b = \sqrt{2}G_F N_e(x) \quad (2.28)$$

for $b = \tau, \mu$. This changes the Hamiltonian and therefore affects the eigenstates [51]:

$$H(x) = H_0 + V(x) = U \begin{bmatrix} m_1^2/2E & 0 & 0 \\ 0 & m_2^2/2E & 0 \\ 0 & 0 & m_3^2/2E \end{bmatrix} U^\dagger + \begin{bmatrix} V_x & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \quad (2.29)$$

From this point, a similar treatment to what was done in vacuum follows. In addition to the conjugation of the PMNS matrix, the potential becomes negative if antineutrinos are considered in equation 2.27 [52].

Obviously, neutrinos and antineutrinos do not harness the same interaction cross section when traveling through matter, mainly consisting of electrons and hardly any positrons. Therefore P, CP and CPT are all violated in matter by default, which means that the asymmetry between neutrinos and antineutrinos is now caused by two effects: the matter effect **and** the CP-violating effect quantified by δ_{CP} . It is very important that these two are disentangled as it would be impossible to resolve the CP angle otherwise.

Equation 2.30 shows the inclusion of both effects in the probability that a muon neutrino ends up as an electron neutrino when traveling through a certain amount of matter for a distance L as described by [44].

$$\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \simeq & \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \\
& + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \cos(\Delta_{31} + \delta_{cp}) \\
& + \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2
\end{aligned} \tag{2.30}$$

Here, $a = G_F N_e / \sqrt{2}$ and $\Delta_{ij} = \Delta m_{ij}^2 L / 4E_\nu$. L is the baseline defined in kilometers. E_ν is the neutrino energy in GeV [53].

To study the probability for antineutrinos $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$, the following substitutions have to be made to equation 2.30:

$$a \rightarrow -a, \quad \delta_{CP} \rightarrow -\delta_{CP}. \tag{2.31}$$

The first is caused by the change in potential, while the second is the result of the conjugation in the PMNS matrix, as seen in the previous section on antineutrino oscillations. In vacuum, this probability is observed to be equal for neutrinos and antineutrinos in the cases where the CP angle is 0 or π . When considering the matter effect a as well, a discrepancy is observed between the two probabilities even without CP violation.

The best fit values for the mixing angles appearing in the equation for the probability amplitude above along with the other parameters governing neutrino oscillations are summarized in table 2.1.

The mass squared difference Δm_{21}^2 is chosen to be positive by giving the lighter state

Parameter	Value	Measurement methods
θ_{12}	$33.44^{+0.77}_{-0.74}$	Solar ν_e disappearance
θ_{23}	$49.2^{+0.9}_{-1.2}$	Accelerator ν_μ disappearance
θ_{13}	$8.57^{0.12}_{-0.12}$	Reactor $\bar{\nu}_e$ disappearance
Δm_{21}^2	$(7.42^{+0.21}_{-0.20}) \times 10^{-5} \text{eV}^2$	Reactor $\bar{\nu}_e$ disappearance
Δm_{31}^2	$(2.517^{+0.026}_{-0.028}) \times 10^{-3} \text{eV}^2$	Reactor/Accelerator $\bar{\nu}_e$ disappearance
$\delta_{CP}(NO)$	197^{+27}_{-24}	Accelerator ν_μ disappearance

Table 2.1: Oscillation parameters taken from [54].

the label 1. Given the magnitude of Δm_{31}^2 , neutrino masses could be ordered in either of two ways: $m_1 < m_2 < m_3$ (NH) and $m_3 < m_1 < m_2$ (IH), of which a visual representation is given in figure 2.4.

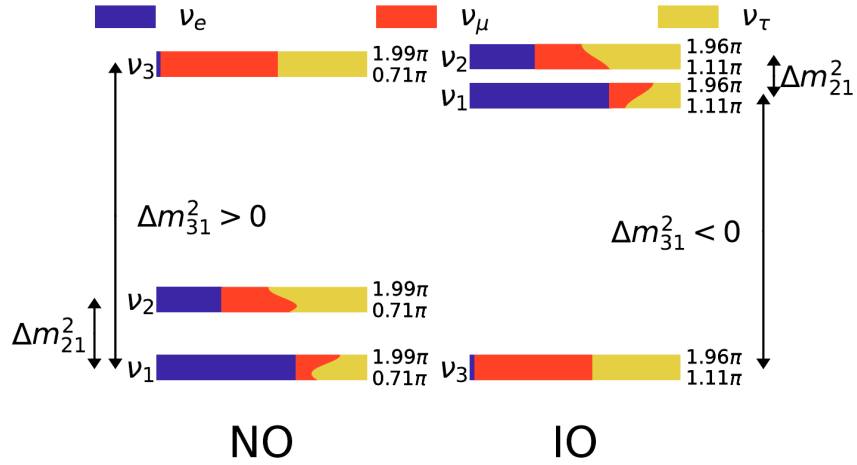


Figure 2.4: Possible configurations for the neutrino mass hierarchy, normal ordering (NO) on the left and inverted ordering (IO) on the right [55].

The latest global oscillation analysis, which combines data from long-baseline, atmospheric and reactor experiments, reported a 2.5σ preference for NO with respect to IO [56]. If by the time DUNE is operational, the combined fit for all these different experiments is not able to determine the neutrino mass ordering at 5σ confidence level, DUNE will be capable of doing so with its extremely long baseline, allowing it to use the matter effect to find the hierarchy.

Oscillation experiments are not capable of resolving the absolute neutrino masses. To find these values, several other experiments have been conducted in the past setting upper

limits on what the masses could be. These include direct measurements of the neutrino mass and observations from cosmology. The former determine the neutrino mass by studying the kinematics of beta decay. The Karlsruhe Tritium Neutrino Experiment or KATRIN in short focuses on measuring the electron energy spectrum near the endpoint of tritium decay. It places an upper limit on the effective electron neutrino mass: $m_{\nu_e} < 0.8$ eV at 90% confidence limit [57]. Cosmological measurements constrain the sum of the neutrino masses by studying the effects of neutrinos on the large-scale structure of the universe, the cosmic microwave background, and galaxy surveys. Observations from Planck Satellite and large-scale structure data provide: $\sum m_\nu < 0.12$ eV at 95% confidence limit [58][59]. Neutrinoless double-beta decay experiments aim to probe whether neutrinos are Majorana particles and provide complementary insights into the mass scale, though no signal has been observed to date [60]. Future endeavors such as Project 8 and advances in cosmological surveys aim to improve sensitivity to neutrino masses, potentially reaching levels below 0.1 eV [61].

Although the value of $\sin^2 2\theta_{23}$ is known to be close to 1, data so far has been inconclusive as to whether θ_{23} is less than or greater than $\frac{\pi}{4}$. NO ν A is one of the experiments that looks to resolve if θ_{23} is in the lower octant ($\theta_{23} < 45^\circ$) or the higher octant ($\theta_{23} > 45^\circ$) [62]. Going back to the PMNS matrix in equation 2.8, it can be seen that the resulting value of θ_{23} impacts the contribution of ν_3 to the muon and tau flavours. If it turns out to be exactly $\frac{\pi}{4}$, ν_μ and ν_τ will consist of the third neutrino in equal amounts. This hints at a previously unknown hidden symmetry. Furthermore, the octant determines the fractions of ν_1 and ν_2 in those two flavours.

It can be shown that by focusing on values for L and E simultaneously and thus producing a proper L/E ratio, the contributions from matter and CP-violating effects can be disentangled. In figure 2.5 the CP asymmetry on the y-axis is defined by

$$A_{CP}(E_\nu) = \left[\frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \right]. \quad (2.32)$$

For this system specifically, it can be approximated to leading order by [64]

$$A_{CP}(E_\nu) \approx \frac{\cos \theta_{23} \sin 2\theta_{12} \sin \delta_{CP} \Delta m_{21}^2 L}{\sin \theta_{23} \sin \theta_{13} 4E_\nu} + \text{matter effects}. \quad (2.33)$$

For $A = 0$, the probabilities for neutrino and antineutrino oscillations are equal. This happens if the baseline goes to zero and there is no CP violating effect. More interesting is the notion that the CP-violating effect is constant over the wide range of baselines for

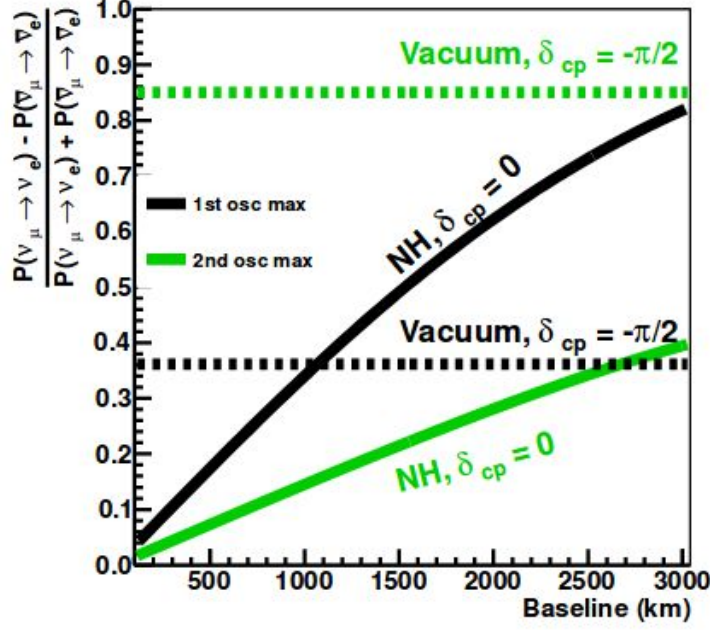


Figure 2.5: CP Asymmetry as function of baseline for first (black) and second (green) oscillation maxima [63]

the value of $-\frac{1}{2}\pi$ in the absence of matter effects.

The green and black lines in figure 2.5 indicate the asymmetry at the first and second oscillation maxima, which correspond to peaks in the probability amplitude spectra. Hence, these are the most effective regions to study. For the first oscillation maximum the asymmetry is dominated by the matter effect (solid black line) at baselines longer than 1000 km. For the second oscillation maximum, however, the asymmetry is governed by $\delta_{CP} \neq 0$ for all baselines (dashed green line).

In addition, to acquire similar sensitivity at shorter baselines (order of kilometers) the energies would have to decrease by a significant amount (eventually reaching the MeV range) so as to preserve the L/E ratio. This is an energy regime that is not practical for pion decay in flight-related experiments. Not only is the initial proton beam required to have enough energy to produce the secondary pions and kaons at rest energies of 135 MeV and 493 MeV, respectively, but these particles also have to be boosted in the forward direction. More importantly, the neutrinos need to be able to produce muons in the detectors downstream. Hence altogether, it is more difficult to do experiments in the several 100 MeV range than in the multiple GeV range. By requiring $L > 1000$ km, the desired disentanglement of the two factors can be achieved [63].

For a baseline or L of 1300 km, the oscillation probability can be plotted as a function

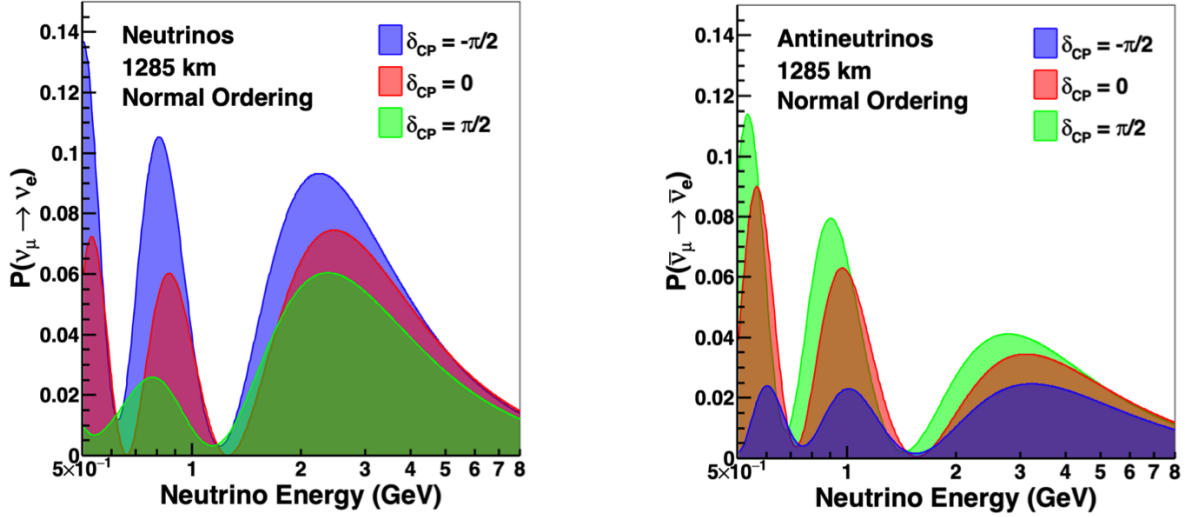


Figure 2.6: Oscillation probability for muon (anti-)neutrinos to electron (anti-)neutrinos at a baseline of 1300 km for normal mass ordering [63].

of the neutrino energy. This can be seen in figure 2.6 for normal ordering: $m_1 < m_2 < m_3$.

The largest influence on the sensitivity to charge-parity violation will come from the neutrinos that have energies close to the peaks in this spectrum. As stated before, the energies on the far left side and the corresponding baseline are not optimal and therefore the focus lies on optimizing the equipment to produce neutrinos around the first two peaks from the right.

The same oscillation probability with a baseline of 295 km as used in the T2K experiment can be seen in figure 2.7. As will be shown in chapter 6, the strategy employed here is different. Instead of covering multiple oscillation maxima, the detector is placed off axis, which compresses the neutrino energy spectrum as will be shown later. The narrower peak covers only the singular maximum out to the right.

In the next section, the instruments responsible for producing a neutrino flux with certain characteristics will be discussed.

2.4 ACCELERATOR NEUTRINO BEAMS

When evaluating the left-hand side of equation 2.23, the key components for neutrino oscillation experiments are revealed. For a given exposure of the detector to a muon neutrino beam, the number of electron neutrino appearance events $N_{\nu_e}^{appear}$ can be related

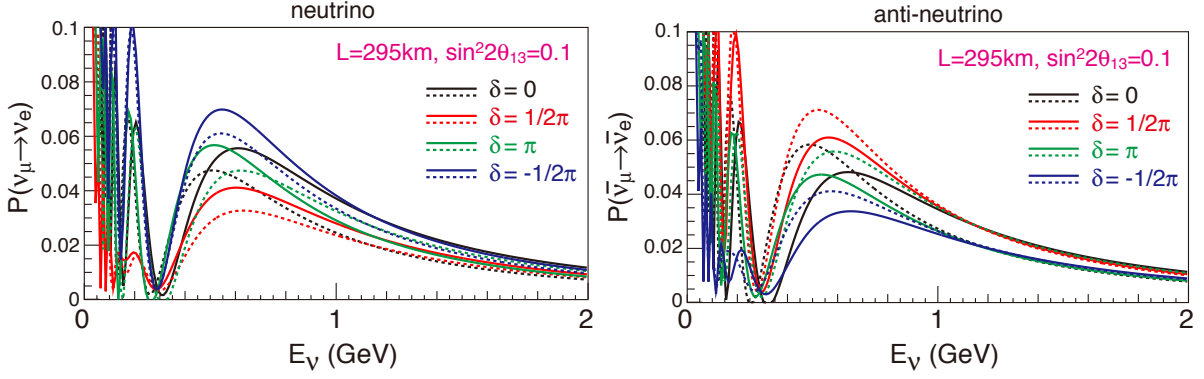


Figure 2.7: Oscillation probability for muon (anti-)neutrinos to electron (anti-)neutrinos at a baseline of 295 km for normal mass ordering [65].

to the probability $P^{\nu_\mu \rightarrow \nu_e}$. It is given by formula 3.3 [63].

$$N_{\nu_e}^{appear} = N_{target} \int \Phi^{\nu_\mu}(E_\nu, L) P^{\nu_\mu \rightarrow \nu_e}(E_\nu, L) \sigma^{\nu_e}(E_\nu) \epsilon dE_\nu \quad (2.34)$$

The far detector houses a total of N_{target} nucleons per kiloton of fiducial volume. By using the per kiloton convention, $N_{\nu_e}^{appear}$ is expressed in terms of $\frac{\text{events}}{\text{kt} \cdot \text{MW} \cdot \text{yr}}$. These units will later be used to evaluate the detector's exposure window. Electron neutrinos passing through the detector medium interact proportionally to the cross section $\sigma^{\nu_e}(E_\nu)$. These neutrinos came from a muon neutrino flux $\Phi^{\nu_\mu}(E_\nu, L)$ of which some have oscillated. Electrons produced in neutrino interactions are a function of those factors in combination with the detector's efficiency ϵ to see them, in addition to electrons coming from the intrinsic ν_e in the beam.

The cross-section for neutrinos interacting with nuclei is not equally well understood for all targets. As will be shown in chapters 4 and 6, the targets consist of argon (Ar), and hydrocarbon and water (H, C, O) for DUNE and T2K, respectively. Especially the neutrino-argon cross-section is not well defined and DUNE relies on other experiments like MINERvA, MiniBooNE and MicroBooNE, also conducted at Fermilab, to shed more light on this quantity. T2K also performs analyses at its own near detector to uncover the behavior of neutrino-nucleus interactions at its far site. The second part of this thesis will cover the cross-section for neutrinos on hydrocarbon. The flux is another quantity of which the uncertainty needs to be heavily reduced compared to previous neutrino experiments in order to ensure DUNE's success.

The use of a near over far ratio, rather than an absolute number, makes a lot of systematic uncertainties cancel. However, this trick does not work for the flux nor fully for the cross

section. Hence a thorough understanding of these quantities will help in determining the oscillation probability. In equation 2.35, the result from dividing the near and far neutrino numbers is shown [66]. We see that the equation can be simplified by using the same target material in both detectors. This is something that will be employed by DUNE, but is only partially valid for T2K.

$$N_{\nu_e}^{FD} \approx \frac{N_{target}^{FD}}{N_{target}^{ND}} \frac{\epsilon^{FD}}{\epsilon^{ND}} \int N_{\nu_\mu}^{ND} \frac{\Phi_{FD}^{\nu_\mu}(E_\nu, L)}{\Phi_{ND}^{\nu_\mu}(E_\nu, L)} * P^{\nu_\mu \rightarrow \nu_e}(E_\nu, L) \frac{\sigma_{FD}^{\nu_e}(E_\nu)}{\sigma_{ND}^{\nu_\mu}(E_\nu)} dE_\nu \quad (2.35)$$

Here, FD and ND represent the far and near detector variables, respectively. Obviously the ND neutrino number is not affected by an oscillation probability amplitude, as this is the starting point of the measurement and hardly any neutrinos will have oscillated. A baseline of approximately 0 also results in no oscillations, as stated before. The integration variable dE_ν is similar in both the far and near case and the boundaries are similar as well; the integral variables cancel and the integration drops out. This is motivated additionally by the FD neutrino number being an extrapolation of the near detector one.

With the theory in the rear-view mirror, it is time to focus on the experimental side. Considering DUNE's baseline, figure 2.6 shows that the oscillation probability peaks at neutrino energies of around 2.4 GeV and 0.8 GeV. These points are also known as the first and second oscillation maxima. For T2K, figure 2.7 shows that the singular peak lies around 0.6 GeV. The task at hand is for the beamline facility to produce a neutrino energy spectrum that peaks around these maxima.

This machinery has been built in the past with great success. One example is the NuMI beamline, which is also stationed at Fermilab and currently generates a ν_μ beam for the NOvA experiment. In the past, it did so for MINERvA and MINOS as well. However, these detectors have been replaced with the ArgonCube 2x2 demonstrator, which will serve as a prototype for the future DUNE liquid argon near detector (see chapter 5). That is the reason it was used as a starting point when people first began designing the long baseline neutrino facility, the production complex for DUNE.

Every accelerator-based neutrino experiment consists of a few crucial elements, as shown in figure 2.8. First, there is the target, which serves as an interaction volume for the incoming protons to create hadrons. Second is the magnetized horns that focus the charged hadrons. Third is a long hollow pipe, usually filled with some type of low-Z gas. Low-Z elements have a small amount of protons in their nucleus, which minimizes the

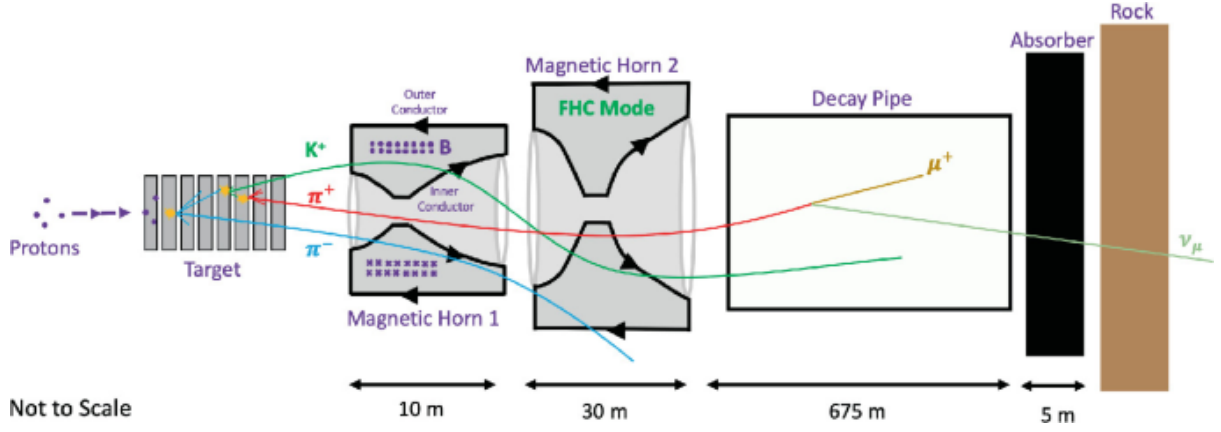


Figure 2.8: Schematic overview of the NuMI beamline at Fermilab showcasing the different neutrino production elements [67].

exposure of the focused particle to interaction processes such as absorption and multiple scattering. Finally, there are absorber walls and layers of rock between the decay pipe and the near detector to get rid of all the muons that are left in the beam. This entire process is initiated by accelerating protons. This is usually done in several stages beginning with a linear accelerator followed by synchrotrons of varying sizes depending on the desired energy level.

2.4.1 Target

After extraction from the accelerator, the protons in both DUNE and T2K impinge on graphite targets. These usually come with dimensions of at least three proton beam widths thick and several interaction lengths long. With the incoming beam having a Gaussian profile, σ_{beam} indicates the spot size that corresponds to one standard deviation, meaning that 68.3% of the beam is contained within that circle. Three standard deviations therefore ensures that most of the beam will go through the target ($\approx 99.7\%$). The interaction length λ_i is a measure of how far particles travel before interacting with the medium. After one λ_i approximately $\frac{1}{e}$ of the protons are left. At the T2K graphite target length of 1 meter, which is around two interaction lengths in graphite, on average 86.5% of protons will have undergone reactions with the carbon nucleons.



Figure 2.9: Proton impinging on segmented target and producing a pion [68].

Through these strong interactions, a sea of hadrons is produced. The heavier ones have lifetimes too short for the focusing process and will decay before ever reaching the horns, so it is the lighter hadrons that do survive. These mainly consist of pions, with a smaller fraction of kaons, both charged and neutral. The angle θ with which the secondary particles leave the target depends on the transverse momentum p_T gained during the collisions as shown in figure 2.9. Higher p_T particles will leave the target at higher angles and vice versa. These angles are a measure of how close secondaries move to the central beam axis after their initial interaction and determine how much more material they will have to cross before exiting the active graphite containing region.

In figure 2.10, the π^+ and K^+ transverse momentum distributions are shown [68] for different $x_F \approx p_z/p_0$. p_0 is the incoming proton momentum and p_z is the secondary's momentum in the direction parallel to the beam axis. This fraction resembles the amount of longitudinal energy that is transferred to the pions or kaons. Strikingly, the peak of the transverse momentum lies around the same values for every x_F . This is very convenient as increasing the accelerator's energy (and increasing that of the secondaries) does not imply the necessity of a larger p_T kick by the magnets following the target. Ergo, p_T does not scale with pion energy [69].

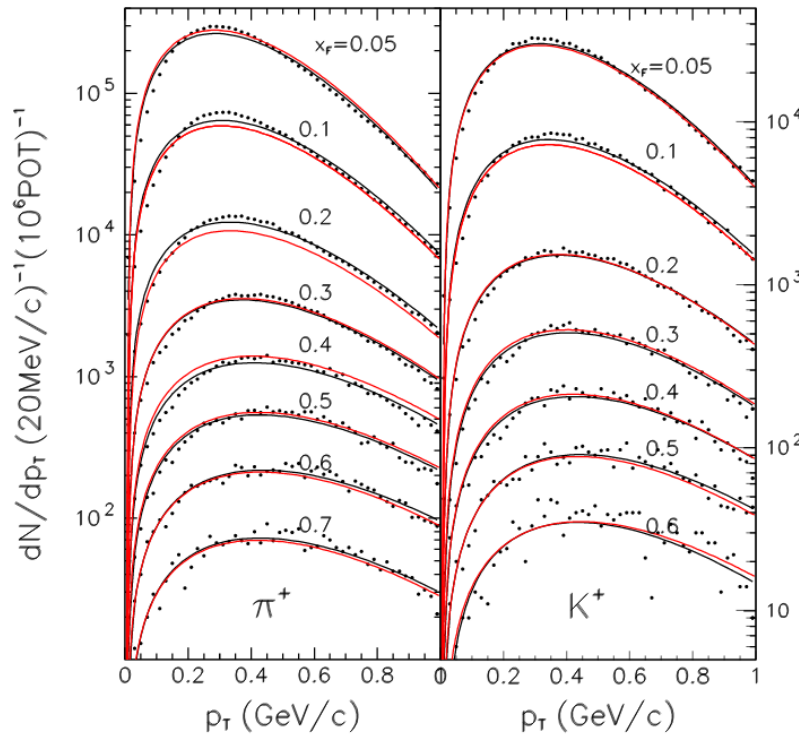


Figure 2.10: Pion and Kaon transverse momenta for different fractions of longitudinal energy transferred from the proton to the mesons [68].

One can understand that the radius or thickness of the active material influences the amount of re-interactions taking place as there will be more material for the pions or kaons to travel through before leaving the target. A similar argument holds for the target length. As most of the high energy particles will be emitted at small angles, a longer target would thus cause them to interact multiple times.

With every subsequent collision, increasingly more energy is converted to heat or used to produce daughter particles, ultimately leading to low energy secondaries leaving this region. The yield of highly energetic particles can be improved by dividing the target as is shown in figure 2.9. By incorporating gaps in between subsequent segments, the low transverse momentum particles have a shorter path length through the active region and can therefore escape more easily. In the end this results in a more energetic neutrino beam. On top of that it assists with the relief of stresses caused by the thermal expansion due to the irradiation. The gaps in the target essentially leave room for the material to push outward when heating up.

The importance of a proper cooling mechanism becomes even more apparent when considering damage by this radiation. Graphite has the ability to slightly anneal itself when operated at high temperatures [70]. Hence the cooling substance that is used plays an important role. There are two commonly used substances, one being gaseous helium and the other being liquid water. One of the largest benefits of a helium system is that its incredibly low boiling point (4.2 K) supports operation at significantly lower temperatures than water, which is limited by its freezing point (273 K). Helium cooling might therefore increase the target's lifetime by limiting the damage, as it would be able to cool the graphite at higher temperatures than water would.

2.4.2 Focusing horn system

The next elements in the hall are magnetized horns. Without these complementary components, most of the high- p_T particles originating from the target would be lost during their travel over the long baseline. As neutrinos are not affected by a magnetic field, due to them being neutral, it is only the charged parent particles that can be subject to this focusing mechanism. Depending on what energies the neutrinos ought to have, the horns come in a variety of shapes and sizes. Higher energetic proton beams will require longer horns and vice versa. Every horn serves a different purpose as the magnetic field will be shaped differently based on the chosen geometry. Before describing two of these shapes, it is important to understand the general focusing idea [71].

The trajectory of particles is close to the beam axis when leaving the target. The horns house a magnetic field that is generated by a current loop of several hundreds of kilo-amperes. This loop is made up of an aluminum inner and outer conductor. The resulting field's direction is toroidal, as shown in figure 2.11 for a parabolically shaped inner conductor. In figure 2.12, the same picture is drawn for a conical conductor. The conductor's shape determines the gradient of the magnetic field $\vec{B}$. This can be

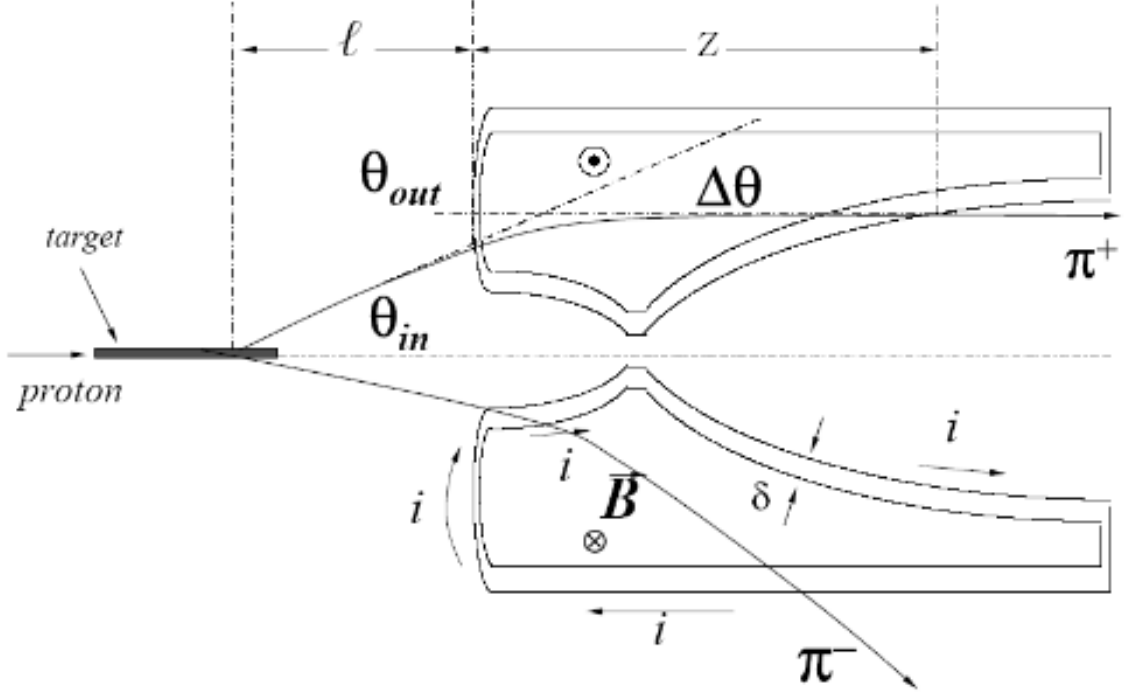


Figure 2.11: Focusing effects for a parabolically shaped inner conductor [68].

understood most easily by comparing the two shapes and taking into account that $B \propto \frac{1}{r}$, where r is the distance to the central beam axis. In the 2D figure, the radius of the parabola increases as $y = \sqrt{z/b}$, while the cone's radius increases as $y = bz$. From Ampere's law it is evident that there is no field without any enclosed current. Hence, particles going through the region between the beam axis and the first conductor will travel in a straight line. Furthermore, the ones that go through the horn's volume will experience less or more of the field depending its shape. The distance between the target and the first horn is described by ℓ . This does not influence the gradient of the magnetic field, however. Hence, it is left out of this discussion and will return later.

In the simplified case where the velocity is along the z direction, the combination of B with v gives rise to a magnetic force in the radial direction as shown in equation 2.36. This force $\vec{F}$ can point to the central beam axis or away from it, depending on the charge

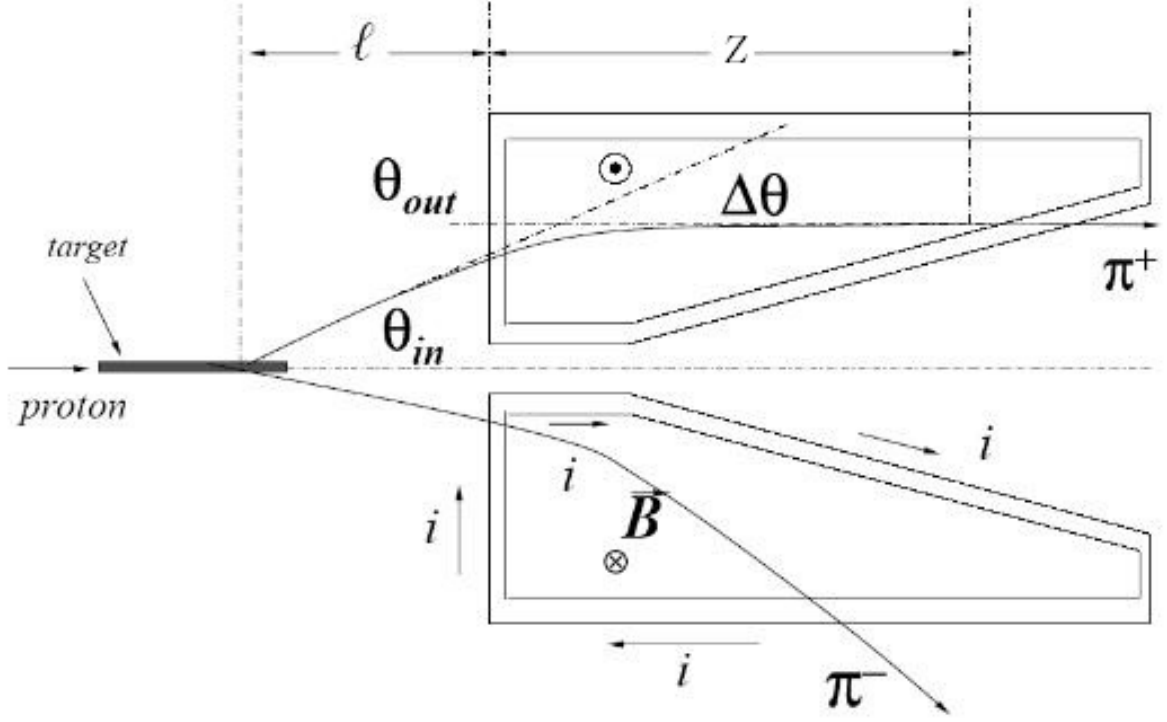


Figure 2.12: The focusing effects caused by a conical shaped inner conductor [68].

q of the particles:

$$\vec{F} = q\vec{v} \times \vec{B}. \quad (2.36)$$

In reality, the velocity will have components along the x and y axis. Due to B_ϕ being the only component, the force will consist of a F_r and F_z part by law of the cross product. Here $F_r = -qv_z B_\phi$ and $F_z = qv_r B_\phi$. In figure 2.11, the π^- is curved away from the beam axis while the π^+ is directed towards it. Therefore, the system not only enhances the signal, but suppresses the background at the same time. Recall that oscillation experiments want to study the difference in probabilities between pure neutrino and anti-neutrino beams, which makes this a very convenient feature. The system can run in two modes by reversing the current, allowing for the creation of both ν_μ and $\bar{\nu}_\mu$ beams.

The amount by which the trajectory of a charged particle is affected can be quantified by the p_T kick. This follows from the change in transverse momentum: $|\delta p_T| = \int \vec{B}(r) d\vec{l}$, with $d\vec{l}$ the distance traveled through magnetic field B . The horns should be constructed such that particles at bigger incoming angles or radii feel more of the field or experience it over a larger distance. As the field is inversely proportional to the radius, geometry plays a significant part in the magnitude of the kick through the dependence on $d\vec{l}$.

Naively assuming that the field looks the same everywhere at a given radius leads to a change in p_T on the order of

$$|\Delta p_T| = \int \vec{B}(r) d\vec{l} = \frac{\mu_0 I}{2\pi r} z. \quad (2.37)$$

To obtain the corresponding $\Delta\theta$, one simply divides by the longitudinal momentum for small angles p_z . In the ideal case, the field aligns pions or kaons with the beam axis upon leaving this region, equating to a $\theta_f = 0$. This means that the focusing effect has to offset the angle by which particles enter the horn:

$$\Delta\theta = \theta_i - \theta_f = \theta_i. \quad (2.38)$$

The incident angle may vary depending on the particle's position inside the target from which they were emitted. For a single particle, the emission angle will be given by the ratio of its transverse to its longitudinal momentum. By taking all particles coming from the target, the equation looks more like $\bar{\theta}_i = \langle p_T \rangle / p$, with the brackets indicating an average value. Filling out equation 2.37 yields equation 2.39:

$$z = \langle p_T \rangle \frac{2\pi}{\mu_0 I} r, \quad (2.39)$$

which is very similar to the gradient at the conical horn's surface with $b = \langle p_T \rangle \frac{2\pi}{\mu_0 I}$. The longitudinal momentum does not appear in this relation meaning that this horn can be used to focus beams with a large momentum spread.

A different substitution regarding the distance from source to horn and the entrance radius leads to $\theta_i = r/l$, which would in turn give equation 2.40:

$$\frac{\mu_0 I}{2\pi r} z = \frac{r}{l} \rightarrow z = \frac{2\pi p r^2}{l \mu_0 I}. \quad (2.40)$$

Here, the more straightforward geometric shape is the parabola for $b = \frac{\pi}{\mu_0 I} \frac{p}{l}$. The inner conductor of the horn shown in figure 2.8 consists of two parabolic sections extending from both sides of the neck (section with smallest radius). This means that the z coordinate depends on both of them, which in the simplified case leads to $z = 2ar^2$.

$$l = \frac{\pi}{\mu_0 I} p \quad (2.41)$$

By assuming that l is the focal length, it can be seen that the parabolic lens works for particles at all angles for a given momentum p . This is contrary to the conical lens, which

focused all momenta for a single angle $\bar{\theta}_i$. The lenses thus serve different purposes [68]!

By implementing multiple horns on different positions along the beam axis, the system is able to focus a larger range of energies. Highly energetic particles that do not diverge enough to cross the first horn's conductor might still do so at a consecutive horn depending on the relative distances between the focusing objects. In general the first focusing element has a rather small aperture to be able to catch most of the particles, while the other elements have increasing inner conductor radii. This complements the goal of not disturbing the well-focused particles coming from horns that lie further upstream [72][73].

2.4.3 Decay Pipe

Upon leaving the target hall, the $\pi^\pm$ and $K^\pm$ mesons will enter a separately enclosed volume: the decay pipe. Often, this pipe is kept at a vacuum or filled with low density material. The main objective here is for the particle to decay without interacting. This is an important fact, because any other pion or kaon interactions might lead to a deflection from the, at this point, well focused path. The obvious option is a vacuum tube. However, it is accompanied by a lot of technical risks. In the NuMI beamline, for instance, the pipe is filled with helium at atmospheric pressure [74].

Charged mesons largely end up as muons and their respective $(\bar{\nu})_\mu$ through their weak decays. Only small fraction of the decays of charged pions (0.0123%) and kaons (5.07%) yield electrons/positrons accompanied by their neutrinos $(\bar{\nu})_e$ despite the resulting phase space being much larger due to the electrons' smaller masses. This arises from the interplay between the weak interaction's chiral nature and helicity suppression. As stated before, the weak force couples only to left-handed particles and right-handed antiparticles.

In the pion decay, the final state must conserve angular momentum. This means that the outgoing neutrino has to be in a left-handed chiral state, while the lepton has to have the correct helicity (opposite to the neutrino's). For massless particles, helicity and chirality are the same, but for massive particles, they differ. This difference introduces the helicity suppression. The pion is a spin-0 particle, so the total spin of the decay products must be zero. The neutrino is always left-handed (helicity -1). To conserve total spin, the charged lepton must have helicity +1, which corresponds to a right-handed state. However, the weak interaction prefers left-handed chiral states for particles. A massive particle like a muon has some right-handed component as there are more Lorentz boosted frames available from which the helicity is observed to be flipped. For the electron having a

much smaller mass, this effect is miniscule and the decay width for the electron channel is thus suppressed. The appearance of electron neutrinos in a muon-neutrino beam causes a background signal in the detectors.

Decay	Chanel	Branching ratio (%)
1	$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	99.9877
2	$\pi^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e)$	0.0123
3	$K^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	63.55
4	$K^\pm \rightarrow \pi^0 + e^\pm + \nu_e(\bar{\nu}_e)$	5.07
5	$K^\pm \rightarrow \pi^0 + \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	3.353
6	$K_L^0 \rightarrow \pi^\pm + e^\mp + \nu_e$	40.55
7	$K_L^0 \rightarrow \pi^\pm + \mu^\mp + \nu_\mu$	27.04
8	$\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$	100.0

Figure 2.13: Meson decay chains producing a neutrino with branching ratios [75]

Particles follow the chains shown in table 2.13 with the branching ratios summarized by the Particle Data Group. It is true that the process $\mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu + \bar{\nu}_e$ provides for electron neutrinos as well. However, by comparing the 2.2 μs muon lifetime to the 26 ns lifetime of charged pions in their own rest frames (where the kaons have an even shorter lifetime), it can be understood that most muons will travel through the pipe without decaying, as observed in the lab frame. The remaining muons will meet a set of absorber walls and rock, stopping them in their tracks and saving the beamline from heavy contamination by electron neutrinos. To protect the surrounding environment, there are aluminum, steel and concrete blocks installed downstream of the decay pipe exit window.

The neutrinos, having a very low interaction cross section, will pass right through the absorber material, leaving a predominantly muon neutrino beam. The pipe is designed to be long enough for the majority of pions and kaons to decay, while also designed to be short enough for muons to survive.

In the case of two-body decays, a fairly simple formula can be derived to describe the neutrino daughter energy E_ν in terms of parent energy $E_{\pi/K}$ and the angle between the

two momenta θ_ν [76].

$$E_\nu \approx \frac{(1 - \frac{m_\mu^2}{M_{\pi/K}^2})E_{\pi/K}}{1 + \gamma^2 \tan^2 \theta_\nu} \quad (2.42)$$

Where γ is the Lorentz factor for the pion. In figure 2.14, the neutrino energy as described by formula 2.42 has been plotted as a function of parent energy at off-axis angles ranging from 0 to 2.5 degrees.

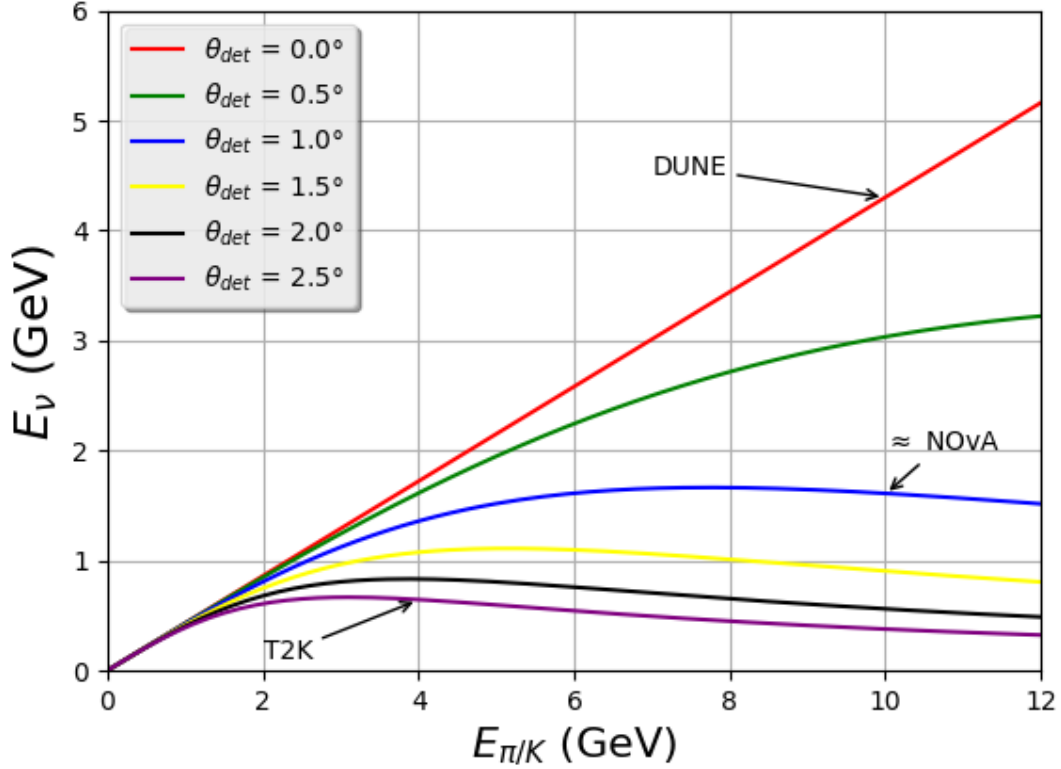


Figure 2.14: Neutrino energy for parent particle energy at different decay angles.

At small pion energies, the detector's location does not have a significant effect on the neutrino energy spectrum. At larger energies, its influence becomes more apparent. E_ν starts to peak more narrowly with increasing angles, i.e., the dependence of the neutrino energy on that of its parent when moving away from the central beam axis starts to get smaller. T2K, which is situated at an angle of 2.5° (in purple), therefore has a very narrow peak between 0 and 1 GeV [77].

DUNE's large baseline compared to the size of the detectors in combination with the parent particles being heavily focused indicate that the measured neutrinos are produced

in decays with a θ_ν close to zero. In that approximation, this formula simplifies to a linear relationship between the two energies (i.e., $\tan^2 \theta_\nu \rightarrow \theta_\nu^2 \approx 0$). Hence DUNE will be operated with an on-axis beam. On-axis means that the mesons are focused in the direction of the far detector, producing a wide-band energy beam upon arrival. It allows for the coverage of both oscillation maxima, which leads to a better resolution between δ_{CP} and the matter effect a .

That concludes the key components for accelerator-based neutrino production. The measurements of oscillations, however, while being influenced by the creation, is done by the detectors and more specifically through the signatures neutrino interactions leave behind in those machines. As they are energy dependent, T2K and DUNE will be dominated by different types of interactions. In chapter 3, several of them will be discussed before proceeding to the detector infrastructure and measurement techniques.

NEUTRINO INTERACTIONS

3

The previous chapters have laid out how different components are used in detectors to observe neutrino interactions. To keep the discussion concise, these interactions were described in a generic way without delving deeper into the variety of final states. In reality there is a wide array of possible reaction modes each yielding its own signatures. By better measuring the rate of each of these modes, the uncertainty on the associated cross-section can be reduced which in turn leads to a more accurate measurement of the parameters governing neutrino oscillations (see equation 2.35).

The capability of the detector to reconstruct what truly happened inside of it (efficiency), as well as the actual number of neutrinos passing through (the flux) are the other key factors in determining the number of oscillations.

In figure 3.1, the charged-current (CC) reaction has been broken down into charged-current quasi-elastic (QE) (in red), charged-current resonant pion production (RES) (in blue) and charged-current deep-inelastic scattering (DIS) (in green) from several hundreds of MeV to around half a TeV covering the oscillation maxima for both T2K (at 0.6 GeV) and DUNE (at 0.8 and 2.4 GeV). As the energy increases, the neutrino is able to probe more of the nuclear structure ranging from liberating single nucleons from the target in CCQE to exciting them to a baryonic resonance in the CCRES region (Δ or N^*) all the way up to interacting with the nucleon's constituents in CCDIS.

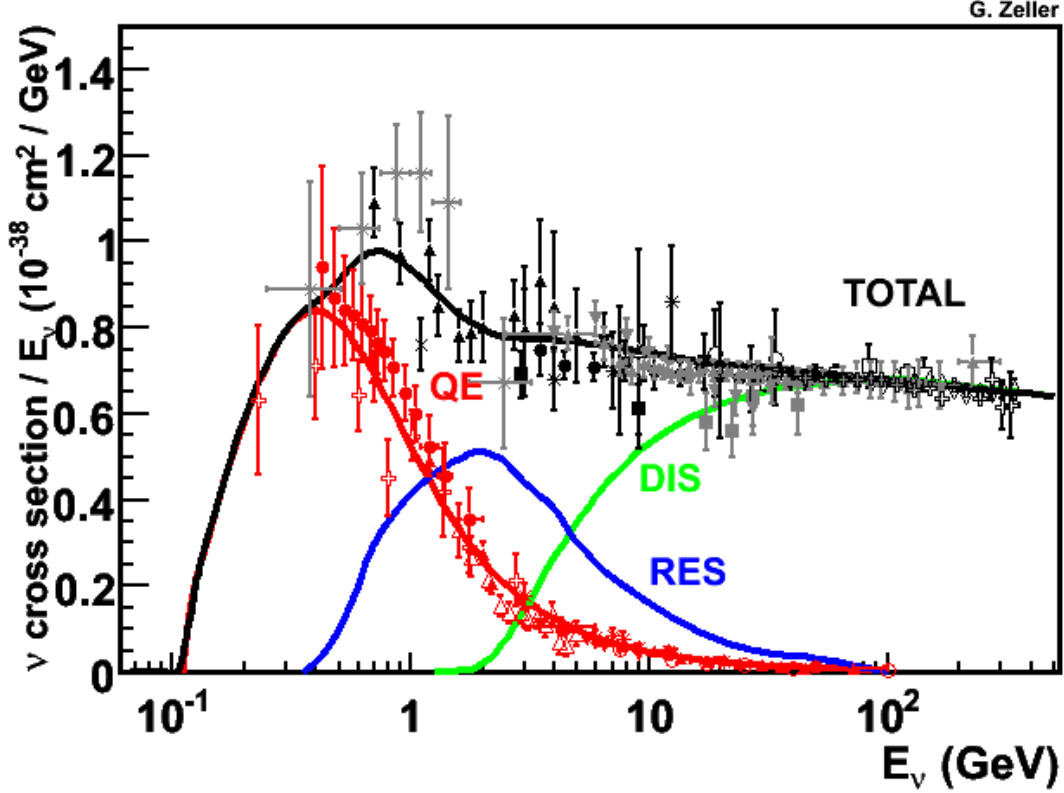


Figure 3.1: Neutrino interaction cross-sections for charged-current processes [78].

This is also reflected in the graph, as the likelihood of any of these processes happening is heavily dependent on the energy of the incoming neutrino. So, while the flux may peak at a specific value, the width of the spectrum will still enable different interactions. For T2K, CCQE is dominant at the peak but the tail covers resonant and deep-inelastic scattering as well. For DUNE, the opposite is true; CCRES and CCDIS will be most prevalent, but quasi-elastic scattering will also be present. In those regions of overlap, modeling is extremely difficult. The gradual transition between the interactions types requires the CCQE, CCRES and CCDIS models that are developed independently to be blended. Testing of these models is impacted by experimental limitations and other nuclear effects that lead to inaccuracies in detecting the final state particles.

Even though these situations contribute the most to the overall events, as will be shown later, they cover only the exchange of a W boson. The neutrino could interact through the neutral-current as well, leading to a new set of final-state products. However, as this specific interaction is not relevant for the upcoming analysis it will not be covered here and the reader is instead referred to [79]. What the detector will observe in the end relies on its capabilities, but also on the particles that are left within it. As the neutrino interacts and

new particles are created, these new particles could interact again, potentially leading to a final state different from the original one. There are two possible scenarios. On one hand, there are final-state interactions (FSI) when the secondaries are trying to leave the nuclear medium and on the other hand, there are secondary interactions when the particles interact with the detector material. Both will also be covered here as they introduce a significant level of uncertainty in the path to understanding what truly happened.

3.1 CHARGED-CURRENT QUASI-ELASTIC SCATTERING

The ‘simplest’ of the interactions described above, if one dares to call it that, is the case where an (anti)neutrino scatters off of a single nucleon, exchanging a $W^\pm$ resulting in the conversion of protons to neutrons or vice versa (adhering to the charge conservation laws) while producing the neutrino’s leptonic counterpart. The nucleus stays intact and there are no additional particles created. These interaction channels are described by:

$$\nu_l + n \rightarrow l^- + p, \quad (3.1)$$

$$\bar{\nu}_l + p \rightarrow l^+ + n. \quad (3.2)$$

The Feynman diagrams for these processes are shown in figure 3.2. As the nucleon itself consists of quarks, it can’t be considered a point-like particle. This means that the conventional strategy of deriving the scattering amplitudes and subsequently the interaction cross-section is not valid. Instead, the resulting formula should represent the nucleon’s inner structure. This is done with form factors in the Llewellyn-Smith formalism to arrive at equation 3.3 [80]:

$$\frac{d^2\sigma}{dQ^2} = \frac{m_N^2 G_F^2 \cos^2 \theta_c}{8\pi E_\nu} \left[A(Q^2) \pm B(Q^2) \frac{(s-u)}{m_N^2} + C(Q^2) \frac{(s-u)^2}{m_N^4} \right], \quad (3.3)$$

where the $\pm$ symbol reflects the differences between neutrinos and antineutrinos. Outside the rectangular brackets, m_N is the nucleon mass, G_F is the Fermi coupling constant, θ_c is the Cabbibo angle and E_ν is the neutrino energy. Inside the brackets is where the nucleon structure is hidden in terms of A , B and C , with s and u being the Mandelstam variables. s is the centre-of-mass-energy-squared and u is the four-momentum-squared. $s-u$ is understood as being equal to $4m_N E_\nu - Q^2 - m_l^2$ in which m_l is the charged lepton mass and Q^2 the momentum-transfer-squared. The alphabetical factors are described by four different form factors. There are the two vector form factors F_1 and F_2 , the axial form factor F_A , and the pseudo-scalar form factor F_P (which only shows up in the expression for A). Together, they describe the behaviour inside the nucleon.

The vector form factors are associated with the vector current and describe the distribution of electric charge within the nucleon as probed by the weak interaction. It determines the strength of the neutrino-nucleon interaction mediated by the exchange of $W^\pm$ bosons. This hints at why F_1 and F_2 can also be obtained through electromagnetic experiments, the most reliable of which is electron scattering [81].

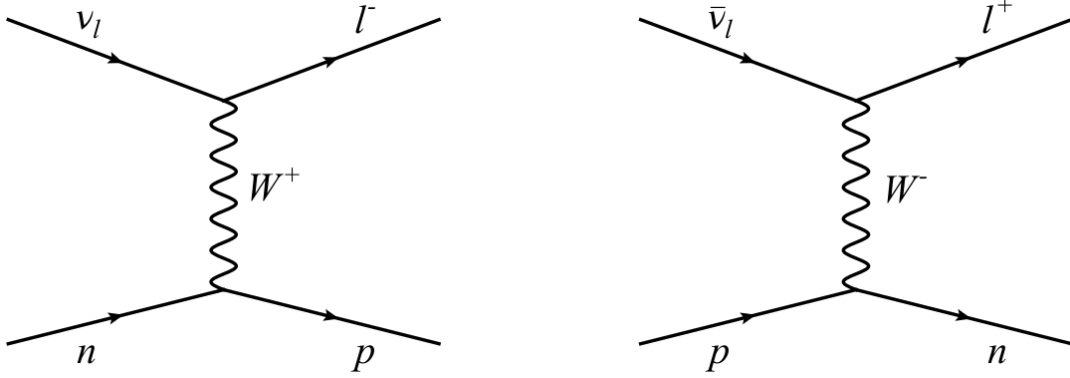


Figure 3.2: Feynman diagrams for charged-current quasi-elastic scattering of neutrino (left) and antineutrino (right) [82].

The axial form factor is linked to the axial vector current, which characterizes the nucleon's spin or axial charge. It is particularly important for the neutral current, where the neutrino couples to the nucleon's spin without changing its charge. This explains why F_A can't be measured through electromagnetic processes and instead has to be found in neutrino-deuterium or neutrino-hydrogen scattering experiments where the influence of surrounding protons and neutrons is limited and the structure of an individual nucleon can be probed [83]. The axial form factor is often assumed to behave like a dipole, as shown in equation 3.4:

$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}, \quad (3.4)$$

where g_A is the axial coupling constant and M_A is the axial mass. At a Q^2 of zero, $F(0) = g_A$. This situation has been accurately evaluated in nuclear β decay [84]. Determination of the axial mass has been more elusive, especially in more recent decades. It was initially measured in bubble-chamber experiments using the light nuclei mentioned before and in charged pion electro-production off of protons, resulting in world averages of around a value of 1 GeV. However, with the rise of accelerator-driven neutrino scattering experiments such as MiniBooNE, K2K and T2K, discrepancies in the CCQE cross-section were observed on the order of 20 to 30%. These discrepancies can be solved by having an effective axial mass of around 1.3 GeV, which would then disagree with the bubble

chamber experiments [85]. In chapter 9, this parameter will return.

3.2 RESONANT PION PRODUCTION

As the available energy in the neutrino-nucleon system grows, so too does the possibility of producing additional or higher mass final state particles. In figure 3.3, two Feynman diagrams are shown for neutrino (left) and antineutrino (right) interactions in which a pion is found in the final state. This pion is accompanied by a nucleon and both are the result of a baryonic resonance or Δ baryon decay. The incoming neutrino excites the struck nucleon into this state, which is highly unstable with a lifetime on the order of 10^{-24} .

To produce the resonances, the available energy should at least exceed the difference between the Δ and target nucleon rest masses. The first accessible one is the $\Delta(1232)$ state, but in the 1–2 GeV regime where CCRES is dominant, a grand total of 18 resonances can be found [86]. The theoretical models describing their production processes often refer to calculations from Rein and Sehgal, which works up to an invariant mass W of 2 GeV. Ultimately, the cross section in their work is the product of the resonance amplitude $d\sigma^{\text{med}}/d\omega d\Omega'$ and the branching ratio $\Gamma_{R \rightarrow N\pi}/\Gamma_{\text{tot}}$ into the desired final state $N\pi$ (>99%), as shown in equation 3.5, of which the details can be found in [87]. Other decay channels include $R \rightarrow N\gamma$ (<1.0%), $R \rightarrow pe^+e^-$ and the speculated $R \rightarrow \Delta\pi$ [88].

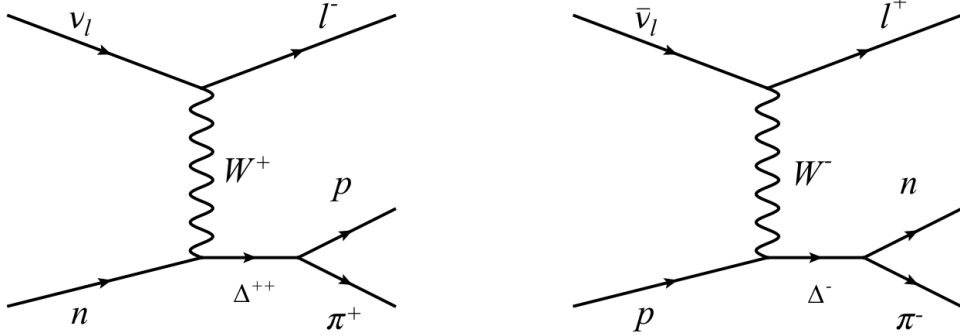


Figure 3.3: Feynman diagram of the charged-current resonant interactions for neutrino (left) and antineutrino (right) [82].

$$\frac{d\sigma^{\text{med}}}{d\omega d\Omega' d\Omega_{\pi}^{\text{CM}}} = \frac{1}{4\pi} \frac{d\sigma^{\text{med}}}{d\omega d\Omega'} \frac{\Gamma_{R \rightarrow N\pi}}{\Gamma_{\text{tot}}} \quad (3.5)$$

The differential cross section is evaluated in ω , $d\Omega_{\pi}^{\text{CM}}$ and $d\Omega_{\pi}^{\text{CM}}$, which represent the energy transfer, the scattering angle of the outgoing lepton and the solid angle between the outgoing lepton and the pion in the center of mass frame, respectively. On the

right hand side, the resonance amplitude shows up with the subscript ‘med’ for medium. Looking at the definition of this variable reveals that this is coming from the spectral function (see eqn. 3.6) of the resonance, which can have different values in a medium versus vacuum:

$$\frac{d\sigma^{\text{med}}}{d\omega d\Omega'} = \frac{|\mathbf{k}'|}{32\pi^2} \frac{\mathcal{P}^{\text{med}}(p')}{\sqrt{[(k \cdot p)^2 - m_l^2 M^2]}} |M_{\mathcal{R}}|^2, \quad (3.6)$$

with p being the nucleon’s four-momentum, p' the outgoing resonance’s momentum, k the incoming lepton’s momentum and k' that of the final state. The scattering amplitude $|M_{\mathcal{R}}|^2$ is what contains the contributions from the leptonic and hadronic part of this interaction. Similarly to the CCQE case, the latter is where the structure functions come into play, in a more complex fashion, as the final state now consists of multiple particles coming from the resonance decay in contrast to the single nucleon conversion. The currents can again be divided into an axial and a vector part. For the most common resonance $\Delta(1232)$ with spin 3/2 and isospin 3/2 in the T2K energy range, they look as follows:

$$A_{3/2}^{\alpha\mu} = - \left[\frac{C_3^A}{M} (g^{\alpha\mu} \not{q} - q^\alpha \gamma^\mu) + \frac{C_4^V}{M^2} (g^{\alpha\mu} q \cdot p - q^\alpha p^\mu) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M^2} q^\alpha q^\mu \right] \gamma^5, \quad (3.7)$$

$$V_{3/2}^{\alpha\mu} = \frac{C_3^V}{M} (g^{\alpha\mu} \not{q} - q^\alpha \gamma^\mu) + \frac{C_4^V}{M^2} (g^{\alpha\mu} q \cdot p - q^\alpha p^\mu) + \frac{C_5^V}{M^2} (g^{\alpha\mu} q \cdot p - q^\alpha p^\mu) + C_6^V g^{\alpha\mu}, \quad (3.8)$$

where C_i^A denotes the axial and C_i^V the vector form factors. Without going into detail on the individual shapes of these parameters, several simplifications can be made. The axial current can be expressed in terms of C_5^A alone as C_3^A is small and C_4^A and C_6^A are fixed by C_5^A . This leads to the dipole parametrization seen before in equation 3.4 for the CCQE interaction:

$$C_5^A(Q^2) = \frac{C_5^A(0)}{1 + \left(\frac{Q}{M_A^{\text{RES}}} \right)^2}, \quad (3.9)$$

with $C_5^A(0)$ describing the normalization of the axial distribution and M_A^{RES} the resonance axial mass.

3.3 DEEP-INELASTIC SCATTERING

In the region between 1 and 2 GeV, neutrinos start becoming able to probe the inner structure of the nucleon and interact with the quarks directly. In doing so, they break up the nucleon, forcing quarks and gluons to rearrange and form hadrons. This hadronization leads to showers in one arm of the Feynman diagram as can be seen in figure 3.4. While this process becomes dominant at energies above the order of 10 GeV, it is particularly poorly understood at the lower end where other reactions are also present. This so-called transition region is found between CCRES and CCDIS and has received more attention during recent years with studies into what is now called Shallow Inelastic Scattering and non-resonant multi-pion production [89].

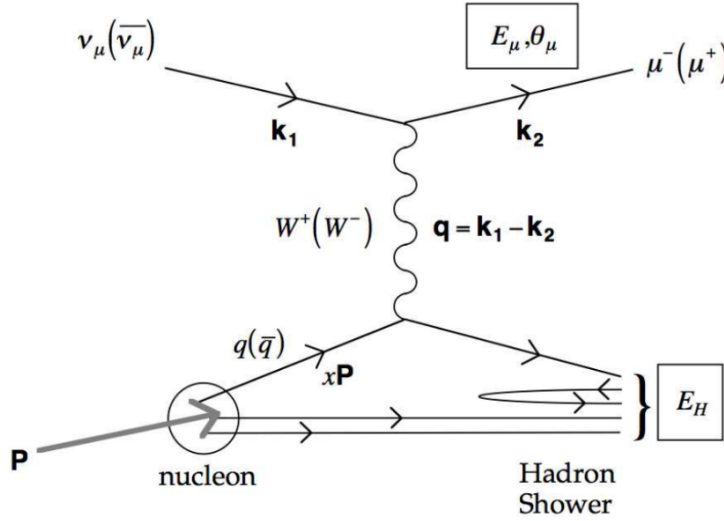


Figure 3.4: Feynman diagram of the CCDIS process [82].

In the higher energy range, the deep-inelastic scattering cross-section can be described by the following formula [90]:

$$\frac{d^2\sigma}{dxdy} = \frac{G_F^2 m_N E_\nu}{\pi(1 + \frac{Q^2}{M_{W,Z}^2})^2} \times \left[\frac{y^2}{2} 2xF_1(x, Q^2) + (1 - y - \frac{m_N xy}{2E_\nu}) F_2(x, Q^2) \pm y(1 - \frac{y^2}{2}) xF_3(x, Q^2) \right] \quad (3.10)$$

Both recurring and debuting parameters can be found in equation 3.10. Again, G_F is the Fermi coupling constant, E_ν the neutrino energy and m_N the nucleon mass. Q^2 is still the momentum-transfer-squared, but now defined as

$$Q^2 = -m_l^2 + 2E_\nu(E_l - p_l \cos(\theta_l)). \quad (3.11)$$

The new parameters are the inelasticity y , which describes the fraction of incident neutrino energy that is carried away by the shower, the Bjorken scaling variable x , which is the fraction of the nucleon momentum that is involved in the scattering, and the mediating boson mass $M_{W,Z}$. While the latter has a unique value, the other two are defined by:

$$y = \frac{E_H}{E_\nu} \quad (3.12)$$

$$x = \frac{Q^2}{2m_N E_\nu y} \quad (3.13)$$

with E_H the energy of the hadronic system and E_l , p_l and $\cos(\theta_l)$ the energy, momentum and cosine of the angle of the outgoing lepton in the laboratory frame. The structure functions F_i are determined through charged lepton and neutrino DIS experiments, where they can be isolated and measured individually. In total there are five of them associated with this cross-section, but they are suppressed by multiplication with the leptonic mass. In DUNE and future experiments where tau leptons become more important, these will need to be included.

3.4 COHERENT PION PRODUCTION

The coherence in this section's title is found in the interaction between a neutrino and the nucleus as a whole. None of the substructure is probed as was the case for other reactions, nor is any nucleon knocked out. The nucleus stays intact and can't be excited. This process can be mediated by either a Z or $W^\pm$ boson, leading to the production of a neutral or charged pion, respectively, as shown in figure 3.5.

As there is no fragmentation occurring here, the momentum transfer $|t|$ to the nucleus A has to be very limited. For coherent processes this transfer is distributed very close to zero, with $|t| = 0$ marking the situation where the pion is ejected at the same angle as the muon. This narrow angle, in addition to the absence of final-state interactions (no nuclear medium to traverse), allows for these pions to be distinguished from those coming from resonant decay. More details on this formalism can be found in work by Rein, Sehgal and Berger in [92], [93] and [94].

3.5 INTERACTING WITH THE ENTIRE NUCLEUS

The story does not end there as in reality none of the nucleons described in the charged-current or neutral-current processes above are free, nor even quasi-free for that matter. They are correlated and affected by each other's presence inside the collectively bound

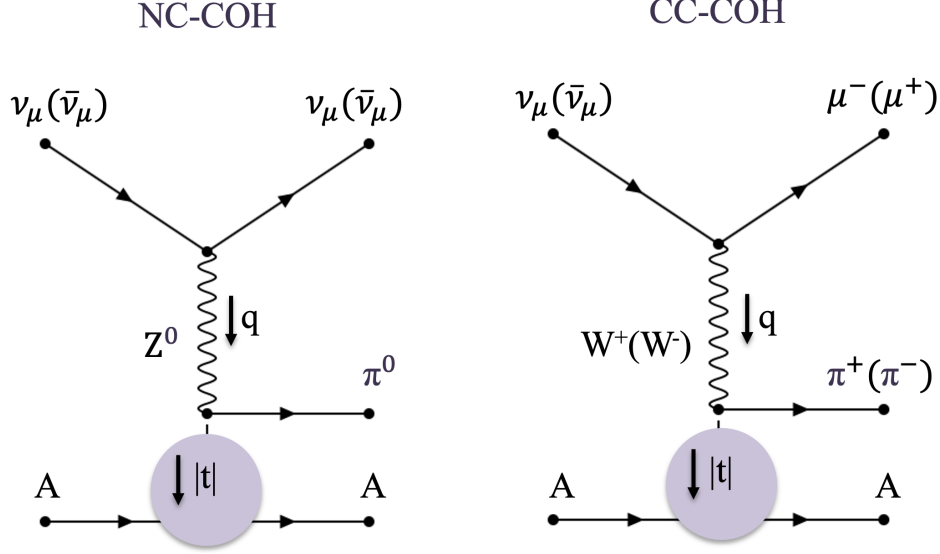


Figure 3.5: Feynman diagram for the neutrino induced coherent pion production via the neutral current (left) and charged-current (right). $|q|$ describes the four-momentum transfer from the leptonic system to the respective boson [91].

nucleus. As neutrino experiments tend to use materials with increasingly higher mass numbers to enhance the interaction probability, the modeling of that structure as a whole becomes essential. The configuration and arrangement of the protons and neutrons vary from one atom to another, affecting the nuclear environment by means of the strong and electromagnetic force and thereby changing the initial state on a case-by-case basis, as will be shown in section 3.5.1.

At the end of section 3.1, discrepancies in the CCQE cross-section between scattering on light (hydrogen, deuterium) and heavier (carbon, oxygen, argon) nuclei were already hinted at. It turns out that by including nuclear effects at the interaction level, agreement between data and MC can be achieved in both scenarios without the necessity of inflating the axial mass value. It is possible for the neutrino to interact with pairs of correlated nucleons. This is often referred to as 2-particles 2-holes (2p2h), the Meson-Exchange current (MEC) or simply ‘Multinucleon’. The process does not scale linearly with Q^2 , however, because the nuclear medium also affects the W propagator. At low values of momentum transfer the nucleons can’t be probed individually and the correlation is suppressed. At higher values, it disappears altogether. The medium’s influence on the interaction is captured by the Random Phase Approximation or RPA [95]. These corrections will be discussed below, but the effects are summarized in figure 3.6. The result for a larger axial mass of 1.32 GeV is shown in black as an improvement to the axial mass of 1.049 GeV in dashed red. However with the RPA and multinucleon nuclear

effects included, agreement can be found even with the lower axial mass in green.

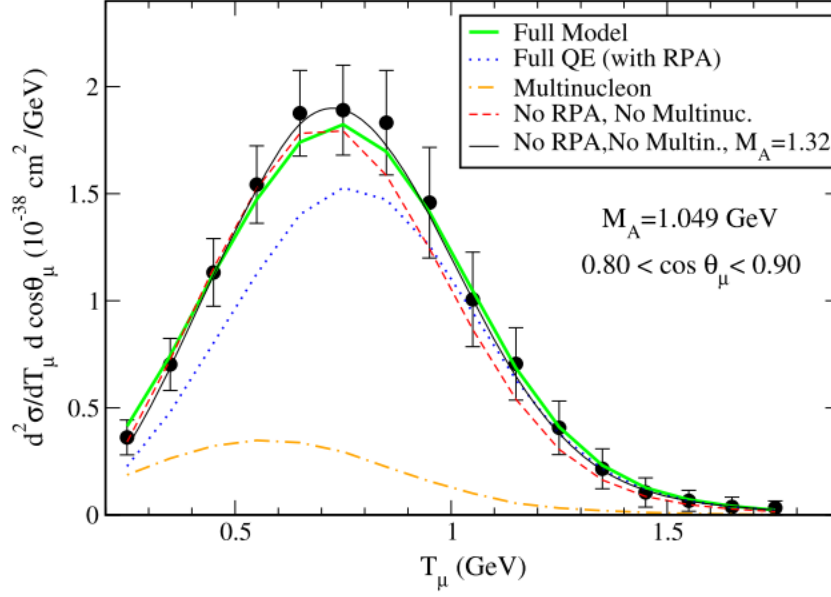


Figure 3.6: Charged-current quasi-elastic differential cross-section with respect to the muon momentum T_μ and muon angle $\cos(\theta_\mu)$ [96].

Lastly, the resistance experienced by particles when leaving the nucleus is denoted by the Final State Interactions or FSI. Larger nuclei will be harder to traverse as the probability of such interactions will be higher. Figure 3.7 shows some of the processes particles could undergo on their way out: charge exchange, pion production, elastic scattering and absorption. In section 3.5.3, each of these will be explained more thoroughly. For now, it is important to realize that they can alter the particles observed outside of the nucleus, making it very difficult (i.e., impossible) to assess the true reaction that took place.

Even after leaving the nucleus, particles can still re-interact with the detector material, further differentiating the observed from the occurred. These interactions are referred to as Secondary Interactions (SI) and will be further detailed in section 3.5.4.

3.5.1 Nuclear initial state

The balance between the attracting strong force (protons and neutrons) and the repelling Coulomb force (protons only) inside the nucleus creates a potential well. In this well, the nucleons occupy different energy levels as the result of Pauli's exclusion principle, which says that two fermions can't exist in identical quantum states. Depending on the nucleus' mass number, fewer or more of these levels can be filled up to a certain maximum or Fermi energy E_F . The amount of energy required to liberate a specific nucleon from the bound

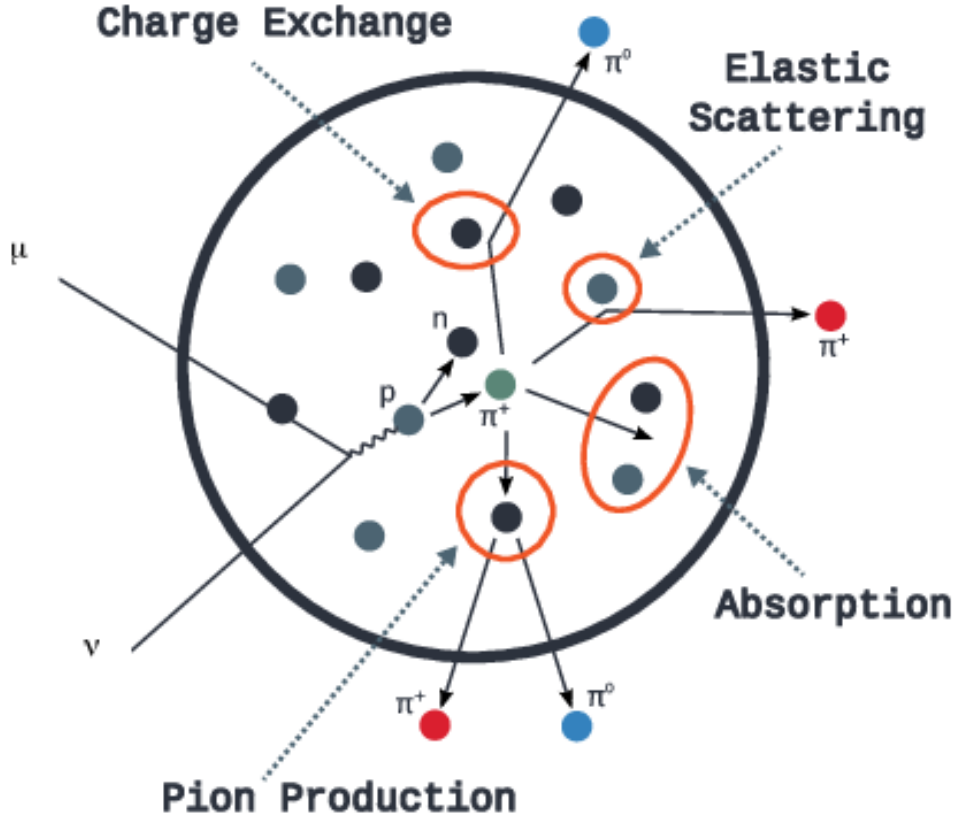


Figure 3.7: Schematic overview of final state interactions after charged-current quasi-elastic scattering [97].

core (i.e., to exceed the potential well) is described by its binding energy E_B [98][99]. Already, the importance of correlations between the nucleus' constituents is starting to become clear.

This potential well model is in stark contrast to the Impulse Approximation (IA), which assumes two things. First, that the incoming neutrino is of high enough momentum to resolve individual nucleons so as to treat them as independent, and second that the products of the subsequent interaction evolve separately with the nuclear remnant ($A-1$) considered a mere 'spectator' to the enveloping particle gala [100]. This would allow the cross-section to be expressed as an incoherent sum of interactions with each nucleon, also known as 1p1h or one particle - one hole. For interactions with a large momentum transfer, this method works very well. At values below 300 MeV, however, it breaks down and more detailed modeling of the nuclear environment is necessary.

This has been done in several layers of complexity, whereby the nucleon's state is defined through a spectral function P depending on the missing momentum p_m and energy

E_m . This function is the joint probability for an ejected nucleon with that specific momentum to leave the nuclear remnant in the excited state $E^* = E_m - E_{\text{sep}}$, with $E_{\text{sep}} = M_{A-1} + M_N - M_A$ the separation energy. Here, three of the spectral functions for T2K's energy range and simulation framework will be briefly discussed [101].

The first model is the Relativistic Fermi Gas Model or RFG [99]. As the name suggests, the nucleons are considered a degenerate gas (i.e., non-interacting). Due to the uniform distributions of particles, a square-well shaped potential is present inside and absent outside the nucleus. As identical fermions can't occupy the same state, energy levels get filled up to the previously mentioned Fermi momentum $\vec{p}_F$ with equal binding energy E_b for each nucleon. This results in the following form for the RFG spectral function [101]:

$$P_{\text{RFG}}(\vec{p}_m, E_m) \propto \Theta(\bar{p}_F - |\vec{p}_m|) \delta(M_A + E_m - m_N - \sqrt{M_{A-1}^2 + |\vec{p}_m|^2}), \quad (3.14)$$

with Θ the Heaviside step function and M_A and M_{A-1} the masses of the nucleus and its remnant, respectively. Equation 3.14 can be improved by moving from a constant nuclear density ρ to a density that scales with the radius $\rho(r)$, ultimately affecting the Fermi momentum via the local density approximation [102]:

$$\bar{p}_F = \int d^3r \rho(r) p_F(r), \quad (3.15)$$

where $p_F(r) = (3\pi^2 A \rho(r)/2)^{\frac{1}{3}}$. This is known as the Local Fermi Gas (LFG) model. While more accurate in its description of the nucleon's state, it fails to capture the intranuclear behaviour. In the Benhar-Fantoni spectral function, an attempt is made to rectify this [103]. The model takes a slightly different approach. It starts from a shell model in which particles move independently in a mean field potential, to which the nucleon-nucleon interactions are added:

$$P_{\text{MF}}(\vec{p}_m, E_m) = \sum_i Z_i |\phi_i(\vec{p}_m)|^2 \bar{F}_i(E_m - E_i^{A-1}) \quad (3.16)$$

where Z_i is the spectroscopic factor and the functions F_i represent the energy width of a level. Electron scattering data showed that the mean field approach alone, as shown in equation 3.16, only explained 80% of the measured cross-section [104]. This is because each individual energy level is strictly defined by E_i , whereas in reality there is interference from the higher-order nucleon interaction potential. An additional term in the probability density is thus required to describe the short-range correlations (SRC) between strongly repulsive nucleons that shift the momentum distribution to higher values. Equation 3.17

represents the origin of the cross-section's remaining 20%:

$$P_{\text{corr}}(\vec{p}_m, E_m) = \int d^3r \rho(\vec{r}) P_{\text{corr}}^{\text{NM}}(\vec{p}_m, E_m; \rho), \quad (3.17)$$

in which $P_{\text{corr}}^{\text{NM}}$ is the correlation part of the spectral function for the uniform matter density mentioned before. The missing energy (removal energy) and probability distributions with respect to the missing momentum (nucleon initial momentum) are summarized in figure 3.8. Here the shortcomings of the simplistic RFG model, which is unable to reveal the underlying nuclear shell structure, are displayed. The Local Fermi Gas model covers parts of the total phase space that the BH spectral function is able to describe. The s- and p-shell of carbon are clearly visible between 16 and 20 MeV and 24 and 50 MeV respectively.

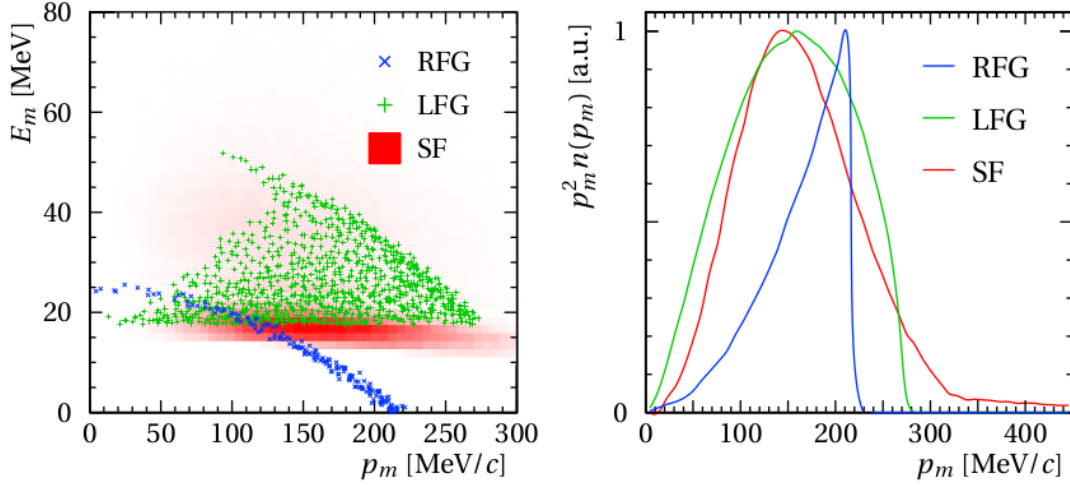


Figure 3.8: NEUT neutrino event generator handling of several nuclear models for carbon (left) and the evolution of the nucleon momentum (right) [105].

In the right hand plot of image 3.8, the Relativistic Fermi Gas model has a sharp cut-off at the Fermi level due to the constant density. When the local density depending on the radius fixes the Fermi momentum as is the case in the LFG model, the spectrum becomes wider and stops less abruptly [106]. However, it still does not manage to describe states at higher missing momentum. This is where the short-range correlations reside and the BH spectral function shines.

That concludes the discussion on different probability density functions, but there is more to the nucleus and neutrino interaction topologies.

3.5.2 Nuclear correlations

Even though interference between nucleons has been taken into account, the interactions described up until this point only involved the ejection of a single nucleon. To further justify the difference in observed cross-sections between light and heavy target experiments, higher order emission has to be considered. This happens when the nucleons form pairs either through the short-range correlations mentioned before, or a process called the Meson-Exchange Current, in which particles inside the nucleus are exchanging mesons (predominantly pions) at the time of impact with the neutrino. The associated topology is the N-particle N-hole mode with N the number of ejected nucleons. The most common form is the 2-particle 2-hole (2p2h, see figure 3.9), which is most relevant in the energy region between CCQE and the first Δ resonance production [107].

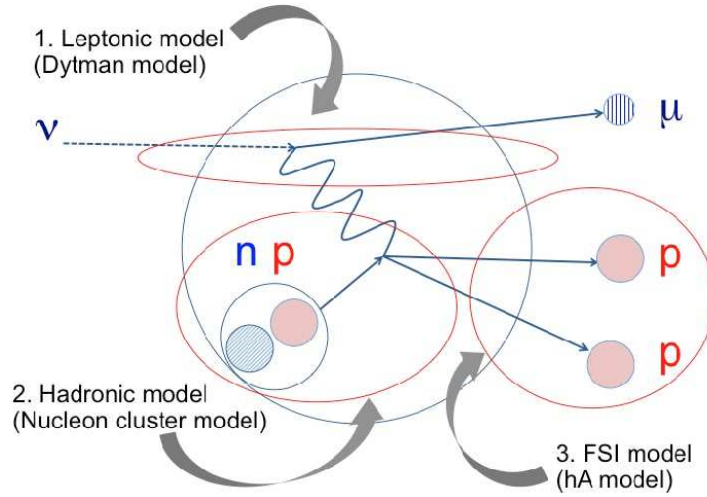


Figure 3.9: Schematic overview of the 2-particle 2-hole process. Numerals refer to different stages in neutrino event generators [108].

To complete the correlations, there is a long range (LRC) variant as well captured by the random phase approximation theory [95][109]. As stated before, the RPA model enhances the 2p2h cross-section in the momentum transfer region where the neutrino is able to resolve the individual nucleons. RPA considers the nuclear response to neutrino interactions in terms of correlated excitations within the nucleus. These can include collective modes such as giant resonances or surface vibrations, as well as particle-hole excitations arising from the promotion of nucleons from filled to empty states within the nuclear potential. These collective excitations are described in terms of fluctuations around the mean-field nuclear potential and differ from short-range correlations with regards to the momentum region they affect (lower for LRC).

3.5.3 Final state interactions

All of these effects combined give a probabilistic description of what the interaction's final state looks like. The issue is that the outgoing particles still have to leave the nucleus before they can be detected. Traveling through the nuclear medium has a larger impact on the characteristics of the hadrons than of the leptons, because the hadrons can also interact via the strong force in addition to the channels available for leptons. Charge exchange, pion production and absorption alter the final state reaction or topology completely, whereas elastic scattering only affects the particle's momentum. Not only does this bias the true interaction type, but also the reconstructed neutrino energy. Both are crucial elements in the oscillation analysis.

Charge exchange is where the produced pion collides with a nucleon and transfers charge towards it (e.g., a positively charged pion would become a neutral pion altering the final state). If the pion gets absorbed by a nucleon, this can result in its excitation to a higher energy state or the production of additional particles (e.g., Δ resonance excitation). The decay of that Δ baryon could then lead to a subset of pions being produced as the result of its decay. In the elastic scattering case, the initial and final states are identical except for the momentum transfer between the pion and nucleon. As it is impossible to measure the kinematics of that specific nucleon, the process still impacts the resulting observation significantly. Each of these final-state interactions is described by the intranuclear cascade model [110].

This model considers individually each particle produced, starting from the interaction vertex and ending when the particle exits the nucleus. In between the starting and exit points, the particle is moved a small distance step by step. At each step, the interaction probability is evaluated based on the mean free path of the particle. This path depends on the density of the surrounding medium (defined according to the nuclear model) and on the total cross-section.

3.5.4 Secondary interactions

Secondary interactions (SI) are quite similar to final-state interactions, but consider only the interactions after particles leave the nucleus and traverse the detector. Here, they can interact with a wide variety of different atoms and nuclei in addition to the original target material. For T2K, these mainly consist of aluminum and iron in addition to carbon and oxygen. The interaction probabilities are determined from a global fit to a collection of pion-on-nucleus cross-section experiments such as the Dual Use Experiment

(DUET [111]) and others [112], [113], [114].

3.6 PION PRODUCTION MEASUREMENTS

As stated at the beginning of this chapter, the neutrino beams for T2K and the future DUNE experiment both operate in the energy region where pion production occurs. In figure 3.10, their fluxes have been overlaid on top of the cross-sections of charged-current and neutral-current processes. In addition, the overview now also includes the NOvA and MINERvA experiments, showing that these also operate in this energy domain.

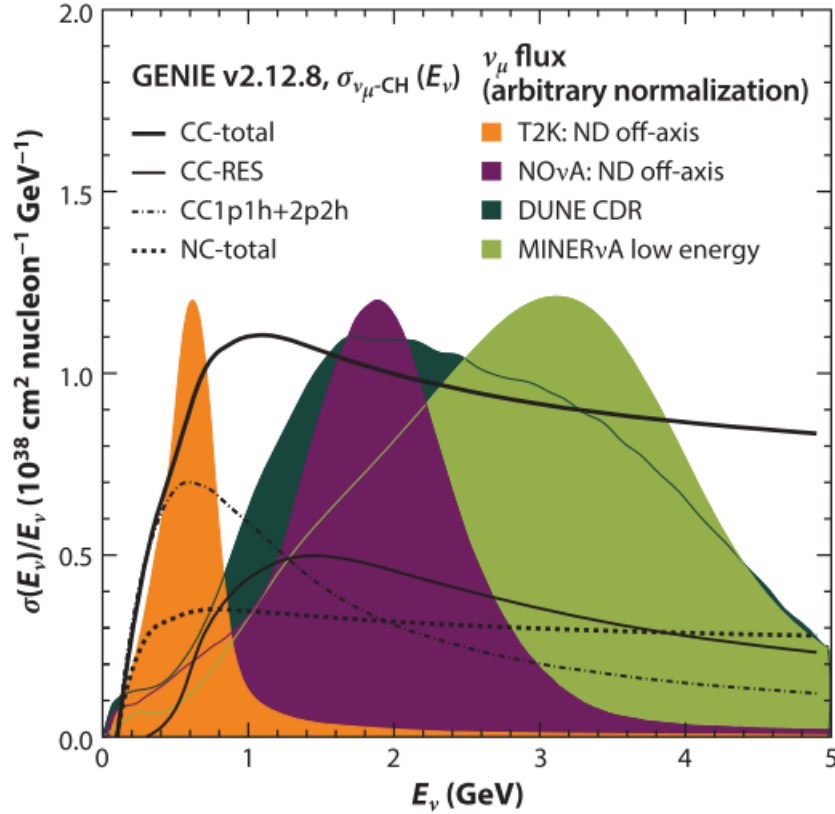


Figure 3.10: Fluxes of past (MINERvA), present (T2K, NOvA) and future (DUNE) neutrino experiments overlaid with CC and NC cross-sections [115].

Pion production is thus an important channel for these neutrino oscillation experiments, but the current agreement between theory and observation is quite poor as there is an uncertainty of around 20%-30% associated with it [116]. Furthermore, at T2K pion production constitutes the largest misidentified background for ν_μ -disappearance and ν_e -appearance measurements. This stems from several factors, but the most influential is the presence of interactions in the nuclear medium and other materials. The process can be recognized by the signature muon and pion coming from the neutrino vertex, often

summarized by the $\text{CC}1\pi^\pm$ final-state topology. While the muon is easily observed in the detector, the pion usually has a harder time to reach the readout equipment. It is more likely to interact again before leaving the nucleus, altering its kinematic properties (e.g., quasi-elastic scattering) or changing the topology as a whole (e.g., absorption, charge-exchange). This strengthens the need for models that include all nuclear effects, so that they properly predict the pion production process. However, even if all these effects are included, none of them can reproduce all the available data. No theoretical model nor MC event generator has successfully managed to describe the MINERvA (CH) [117][118], T2K (water and CH) [119] and MiniBooNE (CH_2) [120] data at the same time.

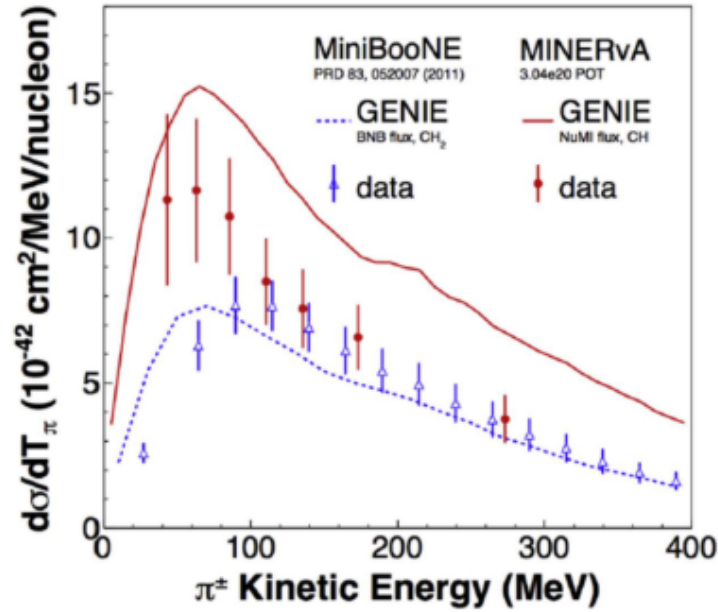


Figure 3.11: Flux-integrated differential cross section as a function of charged-pion kinetic energy for several datasets and GENIE simulation [116].

Comparisons of these datasets to the GENIE simulation shows shape and normalization differences (see figure 3.11 for a comparison between MINERvA and MiniBooNE). Although there seems to be agreement at higher energies, different neutrino beams are used in these experiments making the flux-integrated cross sections presented here not directly comparable. Simulations incorporating the MINERvA flux predict values higher than data, while those with the MiniBooNE flux predict lower values. At lower levels of pion kinetic energy, the discrepancies are even larger.

The axial form factor C_5^A that governs the charged-current resonant pion production reaction mode is constrained by bubble-chamber experiments on deuterium. While these experiments are relatively old and very statistically limited, they still provide a valuable

tool to disentangle the interactions in the nuclear medium from pion production at the neutrino interaction vertex. This is because in contrast to the heavier nuclear target used in more recent experiments, the smaller deuterium nucleus limits the presence of final-state interactions. The assumption that there are no final-state interactions at all in bubble chamber experiments seems to be untrue as well, however. There still seems to be significant disagreement between data and prediction for FSI, meaning that the models have to be refined to accurately describe the behaviour in the nucleus [87].

GENIE FSI models are constrained by MINERvA pion data [121]. While MINERvA managed to reduce the disagreements between model and data, tensions still remain between prediction and observation at low momentum transfer, as shown in figure 3.12. Models overpredict the pion production differential cross section results, something that is also observed by MiniBooNE and MINOS, leading to the need for a suppression of the pion production prediction at low Q^2 [122][123].

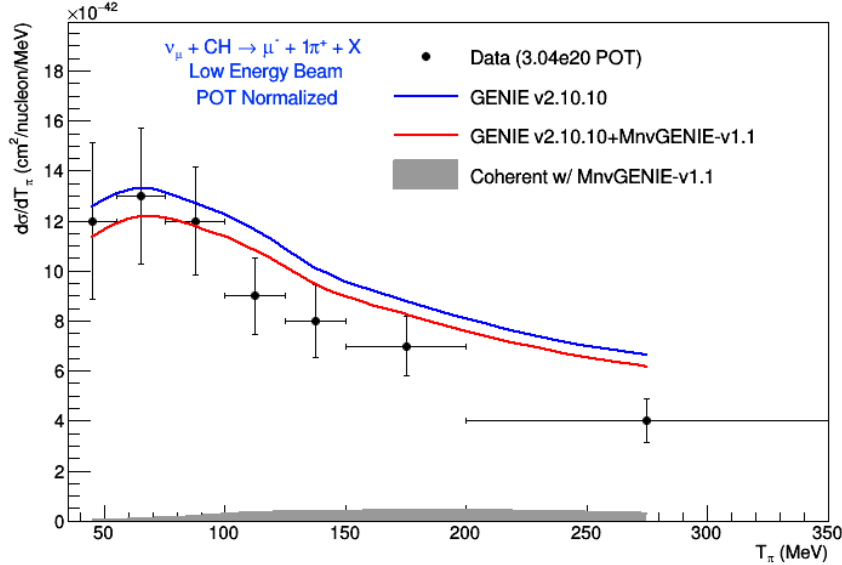


Figure 3.12: MINERvA pion production differential cross sections as a function of pion kinetic energy T_π [124].

Another promising method is selecting events that did not suffer FSI by using the double-transverse momentum imbalance between the final-state π^+ and the proton, where asymmetry between the outgoing pion and proton momenta is a clear indicator of nuclear effects (MINERvA [125], T2K [126]).

Some of the aforementioned differential cross sections results for single pion final states from MINERvA, MiniBooNE and T2K are reported in final-state pion momentum and angle. These final-state kinematics are particularly useful as they allow testing of the

underlying models in a multidimensional space, providing more opportunities to resolve model differences. Measurements of the outgoing pion can provide greater sensitivity to FSI effects, highlighting the importance of collecting all possible statistics in this topological domain.

THE DUNE EXPERIMENT

4

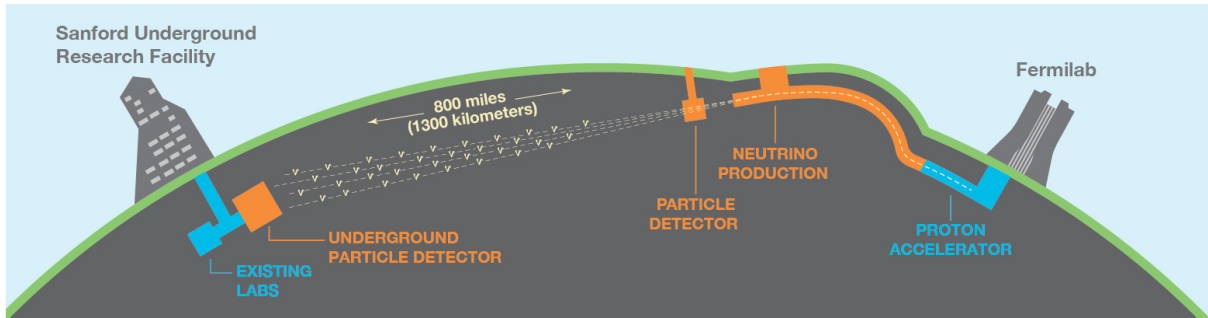


Figure 4.1: Overview of the DUNE experiment [127].

The DUNE experiment's beamline is heavily optimized to produce a neutrino beam that maximizes the detectors' capabilities of observing oscillations. The beam's energy spectrum and profile are tuned by the incoming proton beam, target, horns and decay pipe. For DUNE, the stationary elements reside in the Long Baseline Neutrino Facility (LBNF) hosted at Fermilab near Chicago, USA. As DUNE is yet to be built, the details in this chapter refer to the latest design of the collaboration as of June 2024.

The process of creating a beam at Fermilab starts by accelerating protons in the linear accelerator (LINAC) up to 400 MeV, followed by the 468 meter circumference 'Booster' (a synchrotron) reaching a kinetic energy of around 8 GeV. Before these protons move on to the Main Injector where they reach an energy of 120 GeV, they are inserted into the Recycler.

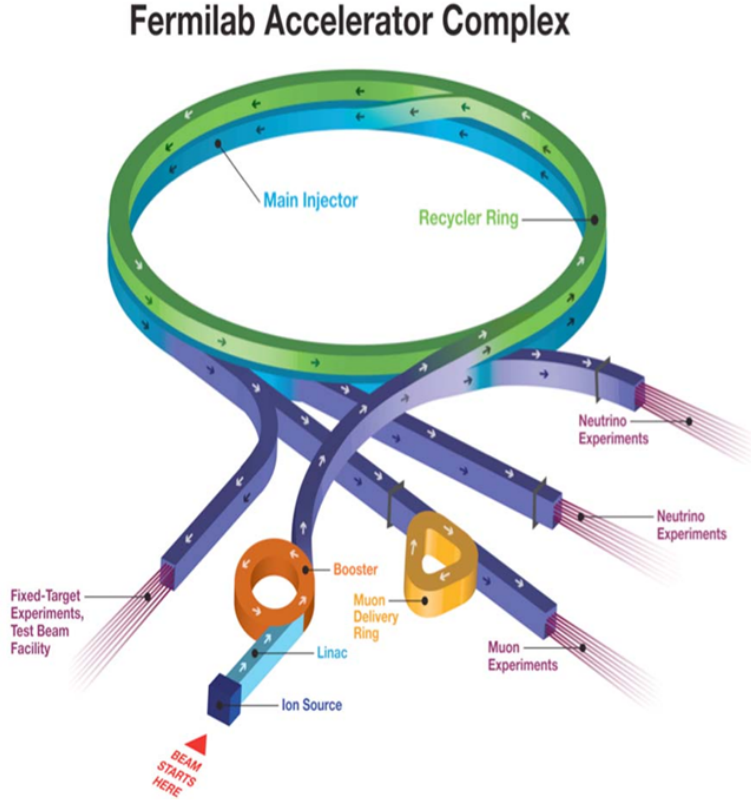


Figure 4.2: Overview of Fermilab’s accelerator complex [128].

Protons enter the Main Injector in ten microsecond spills. These spills consist of 504 bunches (tightly packed groups of protons) divided into six batches. Each batch thus holds 84 bunches, which are separated in time. The total number of protons in each of these spills is approximately 7.5×10^{13} . To achieve the massive 1.2 MW of beam power, that is required for the DUNE experiment, the Main Injector has to supply 1.1×10^{21} 120 GeV protons every year. During the Proton Improvement Plan II (PIP-II), the beam power will increase to 2.4 MW. However, the energy will remain the same. Hence, the number of protons delivered will have to increase. This is why part of this upgrade involves a new superconducting radio-frequency (SRF) LINAC and improvements to the Booster’s beam pulse repetition rate [129].

All protons are extracted by a kicker magnet every 1.2 seconds and guided through the primary beam enclosure towards the LBNF target hall shown in figure 4.3. A total of six key elements can be identified: the baffle, graphite target, horns A through C and the decay pipe. The entire station is protected by water-cooled steel shielding covers that ensure radioactivity in the surrounding soil is well below the maximum allowed amount, the prompt radiation levels are low enough for the sustainability of electronics over longer

periods of time, and the residual radiation sits at a level that allows maintenance on the top of the hall.

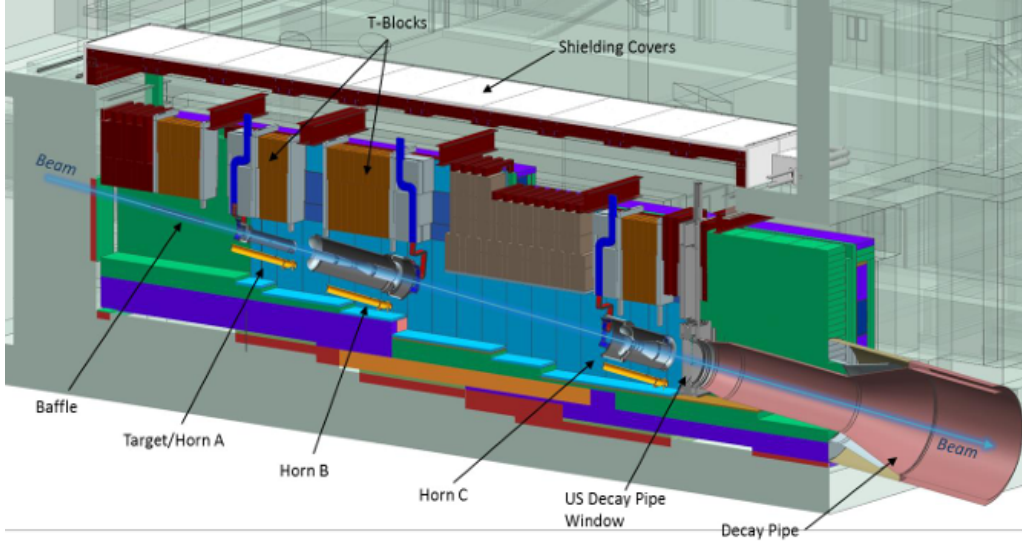


Figure 4.3: Overview of the LBNF target station [130].

Before reaching the target, the protons are led through a 1.5 meter long baffle of the same material. This serves as protection for downstream equipment in the case of beam misalignment or stray protons, as only the ones that are correctly focused will be able to pass through the hole in this structure. In the current design, the target is a helium-cooled 1.5-meter-long segmented graphite rod. It is only supported from one side, which is mounted onto the first horn. Although the length is limited by gravitational bending of the downstream end, the physics performance would improve for more interaction lengths. Hence, studies are ongoing to stiffen the outer container by introducing an extended conical section near the start allowing a length of 1.8 meters (equal to four interaction lengths). The full three-dimensional design can be found in figure 4.4, highlighting the helium gas flow that saves the target from overheating. The temperature changes can go up to 100 degrees Celsius within a time span of only 10 microseconds [131].

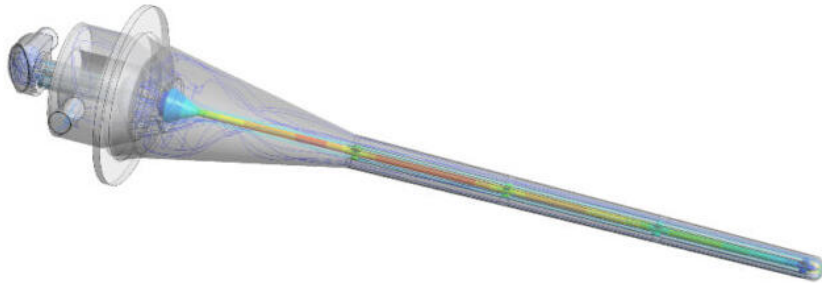


Figure 4.4: Engineering drawing of the cantilevered graphite target [132].

When the protons interact with the carbon nucleons, secondary mesons such as pions and kaons are formed. To ensure a neutrino beam of the right energy, these particles are focused by three conically shaped magnetized horns. The first two are in close proximity of the target (horn A houses the target, horn B sits 3 m downstream), focusing particles with a higher transverse momentum and a smaller longitudinal one. Highly energetic secondaries will pass through the inner conductors' interior and not experience any magnetic bending nor other interactions. Horn C is almost 18 meters downstream. Particles that were exposed to the field in A and B will be aligned with the beam axis and not be affected by the third horn. Its purpose is to focus those mesons at the higher end of the energy spectrum.

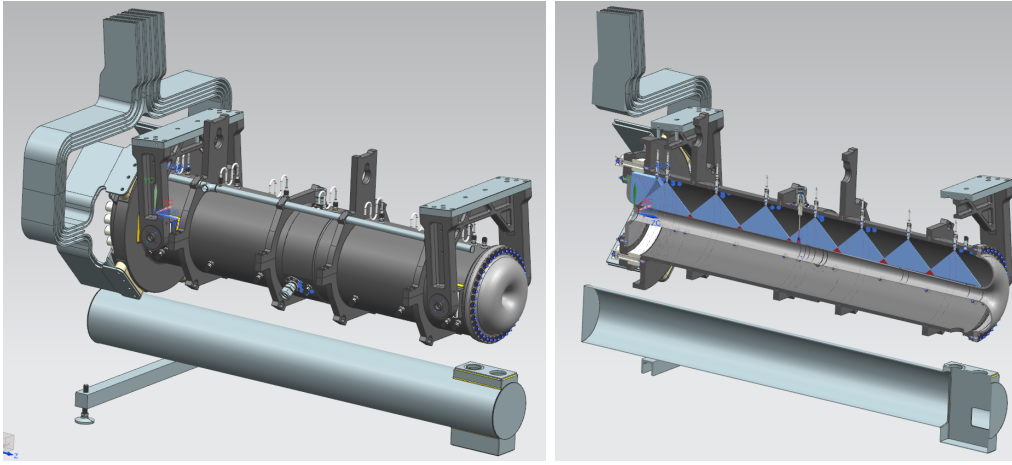


Figure 4.5: Horn A: Outer conductor (left), Inner conductor (right) [133].

Figures 4.5, 4.6 and 4.7 show cross-sectional views of the horns' inner conductors (ICs) to illustrate the variation in length, diameter and shape. With particles leaving the target in all directions (predominantly forward), the angular coverage for focusing is highest in horn A, justifying the tight shape of the inner conductor, with 33 mm at the neck and 43 mm at the upstream end of the cylindrical part. It is 2.2 meters in length.

Horn B is the largest component of the target station at a length of 4 m and a radius varying from 81 mm to 225 mm (159 mm upstream). The outer conductors for B and C have the same diameter at 1268 mm, but the third horn has a larger opening in the inner conductor ranging from 131 mm to 362 mm (284 mm upstream), allowing the well-focused beam to pass through uninterrupted.

The magnetic field through the horns is generated by a 300-kA 800- μ s half-sine wave pulse. As the spills come in for a period of around 4.1 seconds every minute and the horn cycle time is anywhere between 0.7 and 1.2 seconds, the horn can be switched on up to

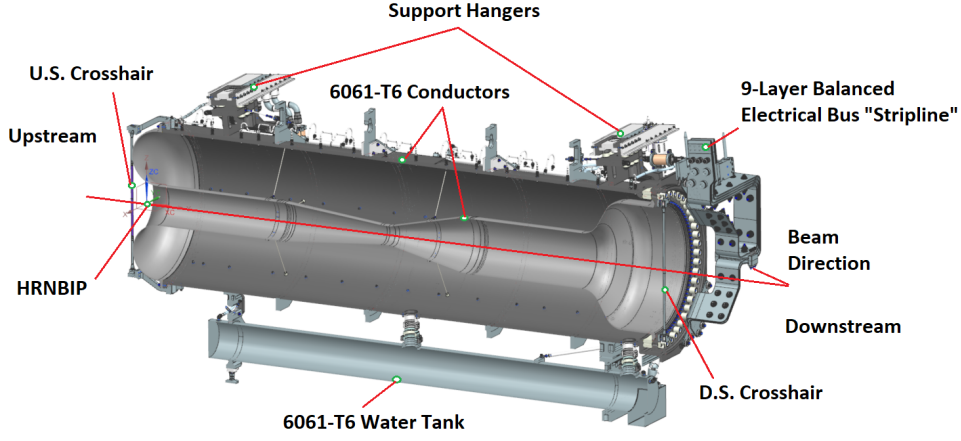


Figure 4.6: Cross-sectional view of Horn B [133].

six times per spill. To reduce the heat-induced stress on the horns, they are water-cooled continuously with water lines integrated into the conducting structure. This leads to local deformations in the magnetic field.

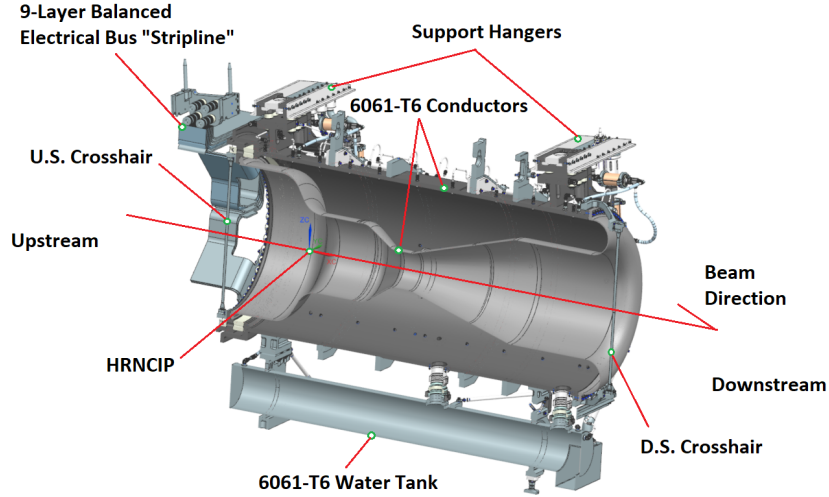


Figure 4.7: Cross-sectional view of Horn C [133].

After the mesons have passed through the horns' magnetic field, the properly focused particles enter a 194-meter-long helium-filled decay pipe of which the cross-sectional view is illustrated in figure 4.8. The pions and kaons decay into muons and muon neutrinos before reaching the absorber walls, leaving a beam predominantly composed of neutrinos, with only a small fraction of surviving muons that will gradually range out further downstream.

The Geant4-based simulated flux resulting from this system at the far detector for both forward-hand (FHC) and reverse-hand current (RHC) is shown in figure 4.9 [135]. The

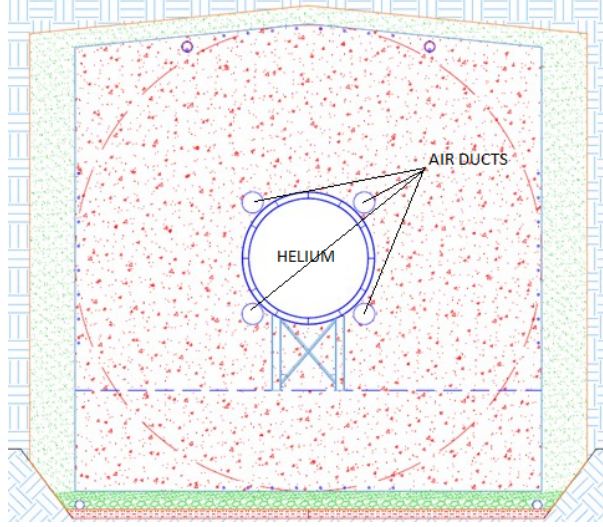


Figure 4.8: Cross section of the decay pipe [134].

different orientations of current flow allow for the creation of a neutrino and anti-neutrino enhanced beam, respectively.

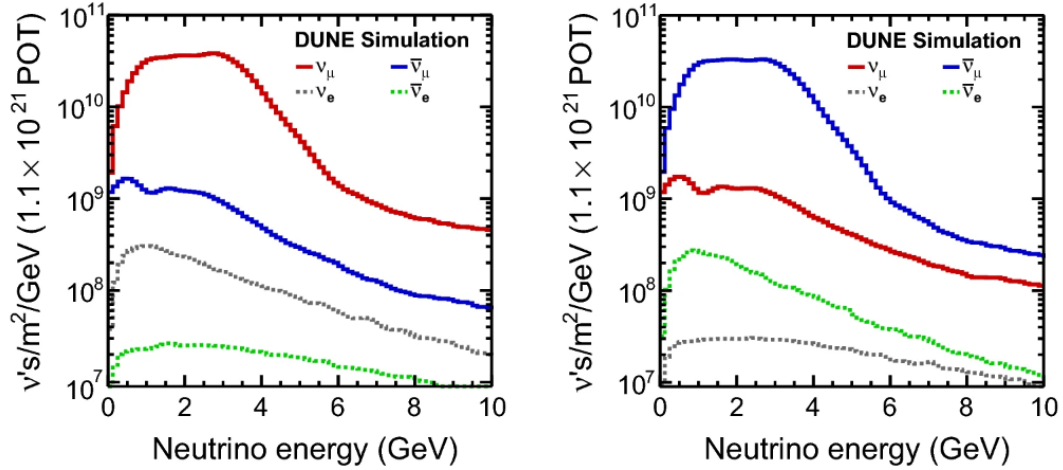


Figure 4.9: Geant4 simulated LBNF neutrino flux (FHC left, RHC right) [127].

Now that the different elements have been shown and the resulting flux has been discussed, the step can be made from neutrino production to detection. Again, this feature will be supported by two key facilities within the Deep Underground Neutrino Experiment: the Near Detector (ND) and Far Detector (FD) complexes. Both of these as well as the beam power will be subject to upgrades as the operating phases progress. In its final form the setup will consist of a 2.4-MW beam with four 17-kton Liquid Argon Time Projection Chambers (LArTPCs) at the far site. At the near site three complementary argon detectors in the form of SAND (a magnetic LAr Target (GRAIN), tracking detector (STT) and electromagnetic calorimeter (ECAL)), ND-LAr (The Liquid Argon ND) and

ND-GAr (Gaseous Argon ND) will provide the necessary capabilities to ensure the success of the extensive physics program.

The studies in this work will solely revolve around the Liquid Argon Near Detector. However, to provide the reader with a full picture of the technological and scientific prowess that all of the other detectors bring to the measurements, they too will be described albeit in less detail. The first section 4.1 will cover the far site’s horizontal and vertical drift modules in subsections 4.1.1 and 4.1.2, respectively. Module 3, which also has a vertical drift design, and module 4, aptly named ‘the module of opportunity’ to reflect its ambitious design goals, will not be elaborated upon. Interactions between particles and the liquid argon will be described in this section as well. In section 4.2 more light will be shed on the intricacies of the near detector complex, which includes the system for on-axis neutrino detector (SAND) beam monitor (subsection 4.2.2), the temporary muon spectrometer (TMS) (subsection 4.2.3), its upgrade ND-GAr (subsection 4.2.4) and the protagonist of this analysis, ND-LAr (subsection 4.2.5).

4.1 THE DUNE FAR DETECTOR COMPLEX

The far detector complex is located at the Sanford Underground Research Facility (SURF) in South Dakota 1285 km away from the production center at Fermilab. After traveling through the Earth’s crust, the oscillated neutrino beam will meet the four far detector modules with a combined active volume mass of 68 kt of which 40 kt is the fiducial mass this facility houses a mile underground. This depth provides sufficient shielding against cosmic rays coming from the sky above. Similarly to the ND complex, the installation will be done in stages starting with the first two modules. The liquid argon time projection chamber technology will be utilized in at least three out of the four modules. However, the readout and orientation of the drift field will vary between them. The equipment’s arrangement within the lab can be found in figure 4.10.

The principle of the LArTPC relies on the effect that the argon atoms have on the charged particles coming from neutrino interactions as they traverse the detector. The most prevalent effect is the scattering off of the bound electrons circulating the atoms. Based on the magnitude of the energy transfer to these electrons, governed by the velocity and mass of the ionizing particle, different processes can follow.

If the transferred energy is below the atomic binding energy, electrons are not released but instead pushed to a higher shell, leaving the atom in an excited state. When such

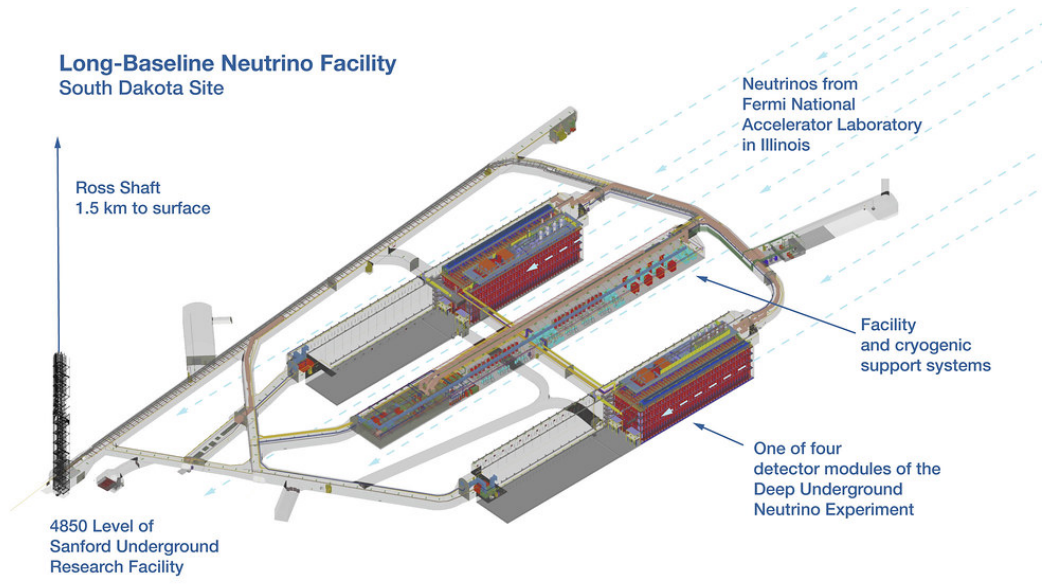
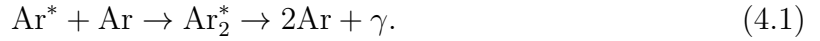


Figure 4.10: DUNE far detector complex at the SURF site in South Dakota [127].

a state couples with an adjacent ground-state argon atom sharing the excited electron, they form a so-called dimer molecule. This happens within a picosecond (10^{-12} s) time frame, which is a valuable asset as will become clear later. The decay of these dimer molecules produces scintillation light according to equation 4.1:



However if the transferred energy exceeds this binding energy, the electron is knocked out of its shell completely. An additional source of scintillation light comes from this released electron finding an ionized argon-neutral argon pair ($\text{Ar}^+ + \text{Ar}$) and recombining. This excites the capturing argon leading to the same situation as before and emitting light through equation 4.2. The electron could also escape causing further ionization if it had gained enough energy.



These dimers are configured in a singlet or triplet state depending on the electron spin state. The distribution of dimer formations within the argon is correlated with the ionization density. This means that the photon emission varies with the energy deposited per unit track length. The decay times for singlet and triplet states are around 7 and 1600 nanoseconds, respectively. A higher energy deposition over a shorter track length thus leads to more singlet states and a larger quickly vs slowly emitted photon spectrum.

On average, around 10000 photons are produced per MeV of deposited energy. With an attenuation length of 1 meter and a refractive index of 1.4, liquid argon is transparent to its own 128-nanometer-wavelength scintillation light, making it the perfect signal to mark the start of an interaction. Electrons that are not recombined can be influenced by an electric field to drift them in a certain direction. If a charged particle releases a substantial number of electrons, this cloud of electrons starts expanding in a manner described by the diffusion parameters parallel and perpendicular to the drift direction. The cloud's length is proportional to the total energy lost by the incoming particle, while its size and intensity are related to the kinetic energy alone. By measuring this charge and comparing it with a particle's characteristic energy loss per unit length, charged particles species can be separated. This energy loss is described by the Bethe-Bloch equation found in 4.3, of which a visual representation can be found in figure 4.11.

$$-\frac{dE}{dx} = N_A \frac{Z}{A} \frac{4\pi\alpha^2(\hbar c)^2}{m_e c^2} \frac{Z_i^2}{\beta^2} \left[\ln \left(\frac{2m_e c^2 \gamma^2 \beta^2 W_{\max}}{I^2} \right) \right] \quad (4.3)$$

The minimum of this curve represents the momentum at which an ionizing particle deposits the minimum amount of energy. This is called a MIP, which means that for muons and charged pions in liquid argon the energy loss is approximately 2 MeV/cm.

Information from the light and charge domains are combined to find the ionizing particle's energy. The choice of liquid argon is primarily motivated by the utility it provides in the far detector. To optimize the neutrino beam's coverage of the oscillation maxima, the baseline of 1300 km was chosen. The flux decreases heavily over such a distance, however, and with it the probability to interact. Having a target medium that is relatively dense is therefore that much more important. Liquid argon serves that purpose, while also providing the inertness inherent to noble gases, meaning it doesn't react with other materials or degrade over time. Combined with being able to be highly purified, the interference from impurities with the released charge or scintillation light is heavily suppressed. Electronegative contaminants such as oxygen or water would absorb drifting electrons, while nitrogen would quench the photons [137]. Lastly, it is the third most abundant gas in the Earth's atmosphere and is the byproduct of commercial oxygen and nitrogen generation, making it relatively affordable, which is essential for a volume of this size.

In the LArTPCs, charge is drifted towards an instrumented wall where it is collected by the readout. In the DUNE far detectors, a set of three differently oriented wire planes are used to perform a two dimensional reconstruction of the track's position as indicated

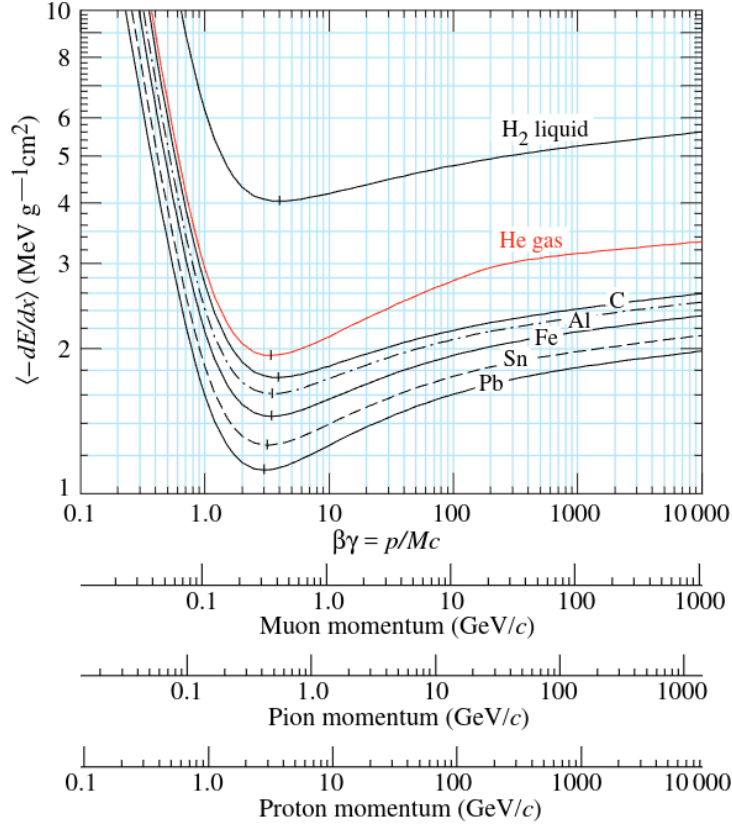


Figure 4.11: Mean energy loss in various media as a function of momentum [136].

in figure 4.12. The first dimension comes from the struck wire's position. Only the final plane in the configuration actually collects electrons. The other two are at a relative voltage that allows the electrons to pass through while producing a bipolar induction signal. While more wires and thus less spacing between adjacent wires would result in more accurate 2D resolution, it affects the signal-to-noise ratio negatively. The increase in number of channels leads to the same amount of ionized charge now being spread out over more channels, which lowers the signal in an individual wire.

The second dimension comes from the time it took the charge to arrive at the respective wire. This time is offset by the so-called t_0 , which is found through the prompt scintillation light coming from the excited argon atoms. This light is in the vacuum ultraviolet regime (120-240 nm) with a wavelength of 127 nm and is shifted towards the visible range before being collected by photon detectors. As the photons travel through the argon with ease, they reach the wall almost instantaneously and set the start time of the event. Alternatively, the start time could be set by the beam clock in case of accelerator-induced interactions. By combining the 2D information from the three individual planes, a three dimensional image is created. Below, the different drift orientations will be discussed.

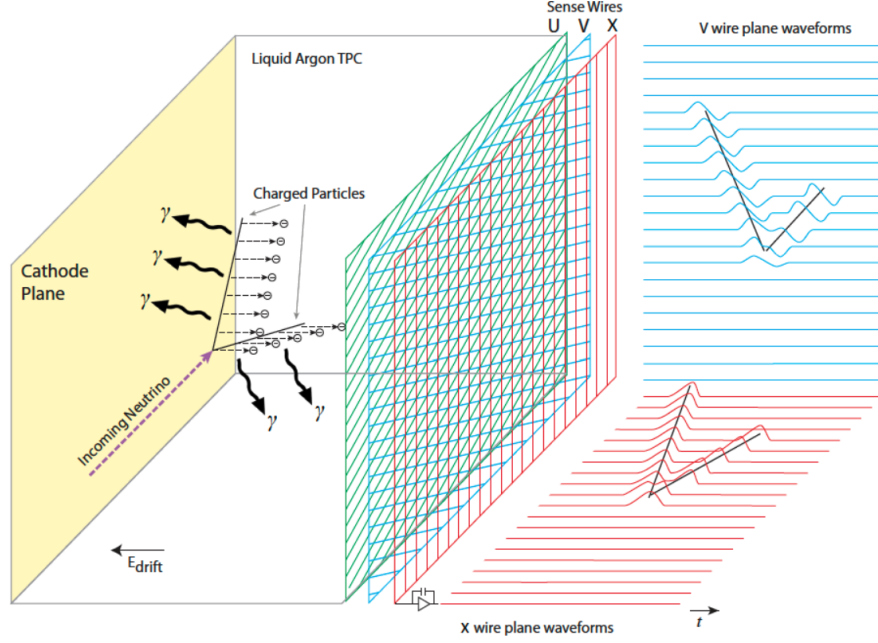


Figure 4.12: Liquid argon TPC operating principle showing released electrons drifting towards the wire collection planes [138].

4.1.1 Module 1: Horizontal Drift LArTPC

With its battle-tested concept from LArTPC neutrino experiments such as MicroBooNE and the FD prototypes ProtoDUNE SP, the most conventional component of the far detector is the horizontal drift module. Figure 4.13 shows the outer shell of the cryostat capable of cooling the 12-m high, 13-m wide and 58-m long active liquid argon volume down to a temperature of 89 K.

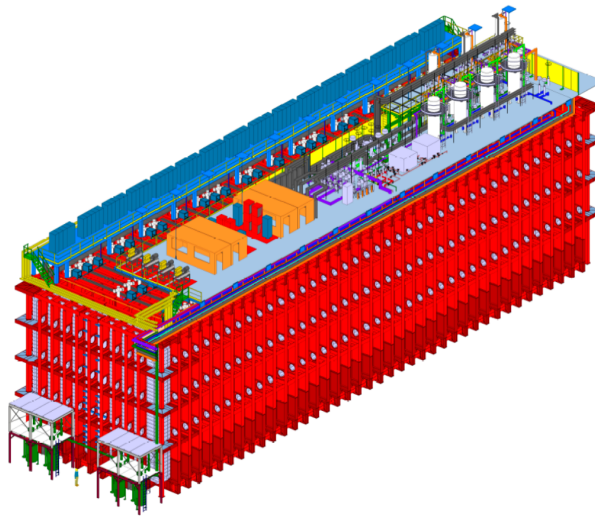


Figure 4.13: Engineering drawing of the horizontal drift module's cryostat [139].

The beam neutrinos arrive at the right hand side perpendicular to the back face. This ensures they see the most target material possible and that the interaction products lose all of their energy within the detector. The inner geometry of the TPC is highlighted in figure 4.14. There are a total of four drift volumes created by three anode planes intersected by two cathodes resulting in drift fields that are horizontally oriented with respect to the incoming beam.

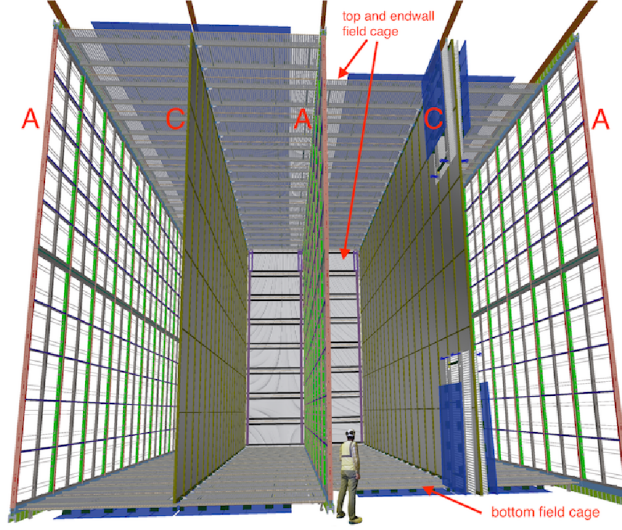


Figure 4.14: Engineering drawing of the far detector's inner geometry [139].

The anodes consist of 50 anode plane assembly units (APAs) with size 6 m by 2.3 m. Two rows and 25 columns are necessary to cover the entire wall. As this is the positively charged side, the negative charge collection happens here on a total of 3500 beryllium-copper wires. While drifting the electrons go through four 5-mm-separated wire layers integrated into the steel frames of the APAs (see figure 4.15).

On their path, the electrons cross the G-layer (grid) or shielding layer first, which is not read out but shields the first induction plane. Next are the induction planes U and V, respectively. These wires makes an angle of $\pm 35.7^\circ$ with the vertical and can sense drifting ionization originating from either side of the APA, which is particularly useful for the central anode.

The collection plane or X-layer is the last readout plane and is followed by a mesh that protects it from through-going ionization particles in addition to shielding the entire charge readout from the light system. The wires are installed in such a way that all channels can be read out from one end, greatly reducing the dead material in the detector.

The electronics responsible for the readout benefit from the low temperatures in terms of improved gain and reduced noise [139].

Each cathode wall serves two drift volumes and is constructed from full-length cathode plane assembly (CPA) modules requiring only 25 of them to span the entire module. Three vertically stacked CPA-units make up a CPA-panel, of which two make up a CPA module. To provide the uniform 500 V/cm drift field over the 3.5 m wide volume, the cathode is kept at a bias of -180 kV (with the anodes grounded). The field cage, also shown in figure 4.14, helps in preserving the uniformity while also preventing the electric field from exiting. The highly resistive material on the surface of the CPA shields the detector from electrical discharges as a result of the high voltage breaking down suddenly.

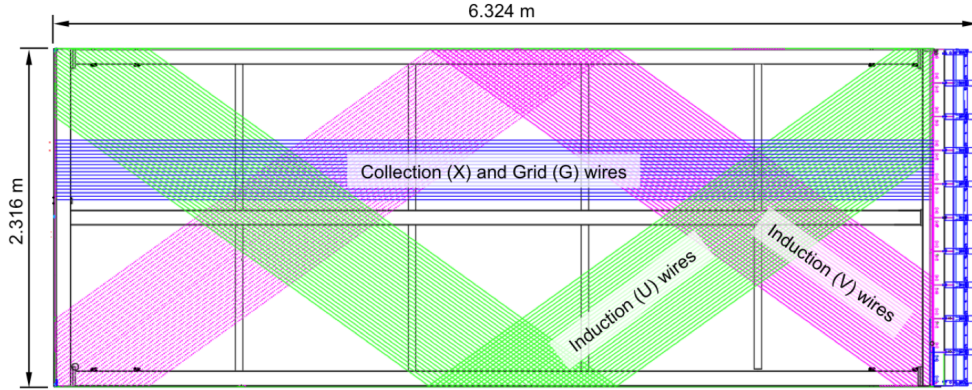


Figure 4.15: Schematic overview of the wire planes integrated into the APA (G-U-V-X): magenta (U), green (V), blue (X) [139].

The light collection system sets the event start time by the prompt scintillation light and it can also provide calorimetric measurements. In immense LArTPCs like the modules described here, light is collected from large areas and channeled towards the sensors in an efficient way. The collection system of choice is the X-ARAPUCA system, an upgrade to the previously used ARAPUCA [140]. After passing through wavelength shifters (made of para-Therphenyl) the photons are re-emitted at 430 nm [141]. Now they can get optically stuck inside the ARAPUCA box. The reflective coating on the walls stops photons with that specific wavelength from exiting, they bounce around until they ultimately end up on silicon photomultipliers (SiPMs). The SiPMs are placed in the inactive region between the wire planes (i.e., only on one side of each drift volume). As the active surface of the SiPMs is quite small, covering the entire detector with them would be challenging and thus the light is collected and trapped first. In total there will be 1500 of these collection modules, 500 per anode.

4.1.2 Module 2: Vertical Drift LArTPC

An overview of the first vertical drift module can be found in figure 4.16. Not only does this reduce the number of drift volumes from four to two, thus requiring only a single cathode (and fewer photon detection systems), it also provides a more uniform electric field and maximizes the active volume compared to its horizontal counterpart. Simplification of both the construction and installation greatly diminishes the overall cost and the time in which such a device can be built [142]. Each of the two anode planes is composed of 80 charge readout planes (CRPs), which in turn consist of two charge readout units (CRUs) held together by a composite structure.

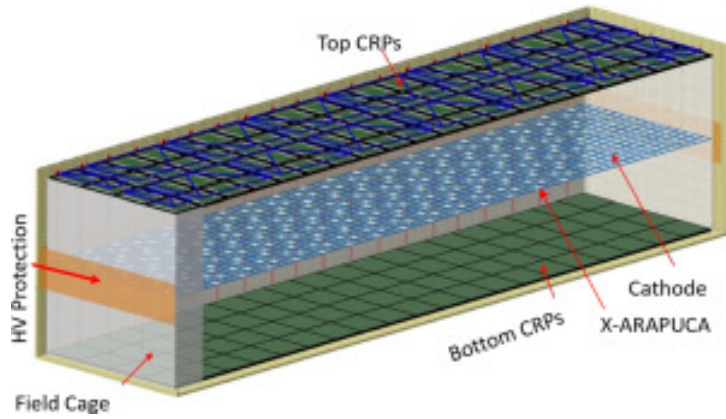


Figure 4.16: Engineering drawing of the vertical drift far detector module [143].

The CRUs house two stacked printed circuit boards (PCBs) that provide a similar charge readout scheme as was the case for the horizontal drift. As the ionized electrons move towards the positively charged walls, they are greeted by four different charge readout layers. The side of the first PCB facing the cathode serves as shielding. The copper guard mounted here absorbs any sudden discharges (e.g., if the high voltage drops). The other side contains the first induction layer. The second board has an induction layer on the inside and collection plane on the reverse pointing at cryostat wall (see figure 4.17). Similarly to the wires in the HD module, the induction planes sit at a ± 60 degree angle with respect to the vertical and are segmented at a pitch of 7.5 mm. The drifting electrons are free to pass through the holes in the perforated PCBs until they are captured by the 5-mm-pitch collection plane at the outermost edge. A 1 kV bias must be maintained across each PCB to guarantee full transmission of the electrons through the holes.

The cathode plane consists of 80 modules formed by highly resistive panels mounted on plastic frames. It has to be held at -294 kV to achieve an electric field comparable to that of the first module over the now increased distance. The field's stability is ensured by

the field cage, which boasts a modular design comprising aluminum rods each separated by a distance of 6 cm.

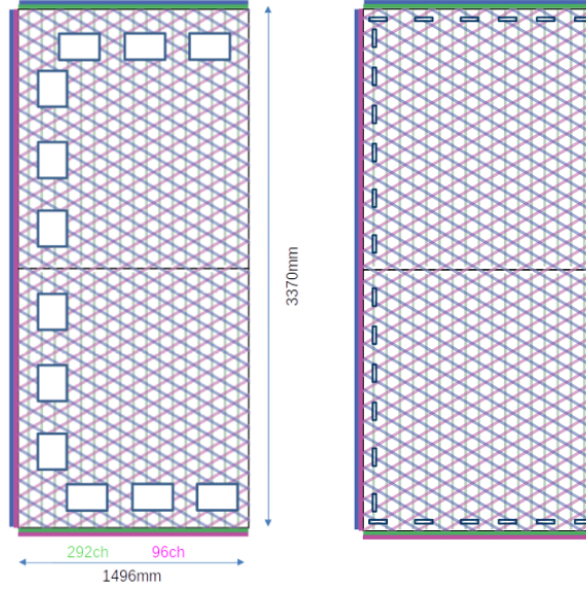


Figure 4.17: Schematic overview of the electrode strip configuration for top charge readout units (left) and bottom charge readout units (right) [142].

The last component to complete the second FD module is the photon detection system. This uses the same X-ARAPUCA light collection elements as in the horizontal drift with slight modifications and different placings. In addition to occupying the anode wall, for the vertical drift they are also mounted on the cathode. Depending on the location, they can either be outfitted with a sensitive window on one of their faces (cryostat wall) or on both (cathode). With this new distribution comes a more uniform coverage of the detector’s light yield albeit suboptimal due to the limited suitable positions on the wall these systems can be placed.

4.2 THE DUNE NEAR DETECTOR COMPLEX

The ND complex sits at 575 m from the target in an underground laboratory at Fermilab located in Chicago, Illinois USA. Its main purpose is to measure the unoscillated neutrino beam and provide a prediction of that spectrum at the far detector where it can be compared to the oscillated beam. Being so close to the production point means that the flux of incoming neutrinos is quite staggering. The facility has to be equipped with machinery suited for handling the high level of event rates in addition to measuring several key parameters that govern the oscillation analysis. The number of neutrino interactions is a convolution between the cross-section, the flux and the detector efficiency, which all

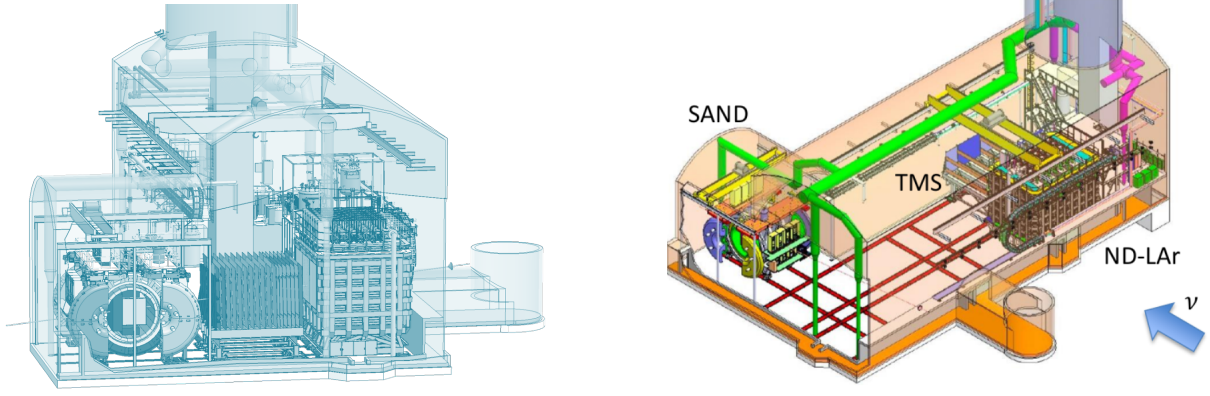


Figure 4.18: The DUNE near detector complex for phase 1 [144].

depend on the neutrino or subsequent particles' energies. The suite of detectors should thus be able to measure the neutrino on argon cross-section, the flux profile and the energy of the final state particles. An overview of the phase 1 setup that is planned to do so can be found in figure 4.18. The image on the left in this figure shows the three initial detectors: SAND, TMS and ND-LAr (from left to right).

In the image on the right, the same can be seen at a different angle with the beam's direction marked on the bottom right. As can be seen, TMS and ND-LAr are not on axis with SAND. This is because those detectors are mounted on rails, which allows for moving them up to a maximum of 3.2° off-axis position with respect to the beam. As shown before, the off-axis configurations allow for a more narrowly peaked energy spectrum. By taking data at multiple positions the DUNE Precision Reaction-Independent Spectrum Measurement (DUNE PRISM) allows for a better understanding of the relationship between true and reconstructed neutrino energy that is less sensitive to the interaction models. Ultimately this helps in disentangling flux, interaction cross-sections and detector response effects.

4.2.1 DUNE PRISM

The main reason the near detectors for both the T2K (2.5°) and NO ν A (0.8°) were positioned at a stationary off-axis angle was to limit the number of high energy neutrinos. Doing so greatly reduces the occurrence of neutral current backgrounds mediated by highly energetic neutrinos while simultaneously tuning the peak to coincide with the peak of the oscillation probability. Figure 4.19 showcases this feature by displaying several off-axis angles and their effect on the energy spectrum.

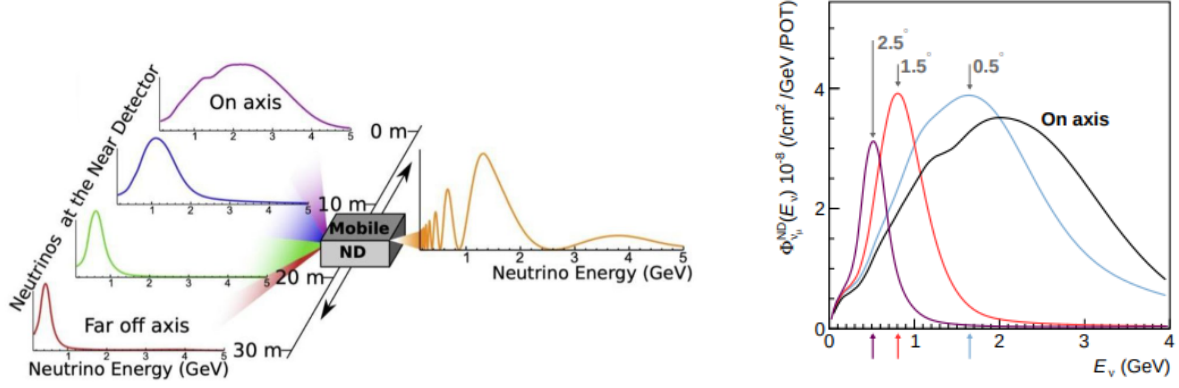


Figure 4.19: DUNE near detector flux for different prism off-axis configurations [145][146].

Being able to compare near detector measurements to Monte Carlo predictions at varying off-axis angles will allow for constraining the underlying neutrino interaction models. This can help identify biases in oscillation parameters as a multitude of spectra now have to agree instead of only a singular one [147].

4.2.2 SAND

Contrary to ND-LAr and ND-GAr, SAND is in a permanently on-axis configuration monitoring the neutrinos before they leave the near detector complex, as can be seen in figure 4.20.

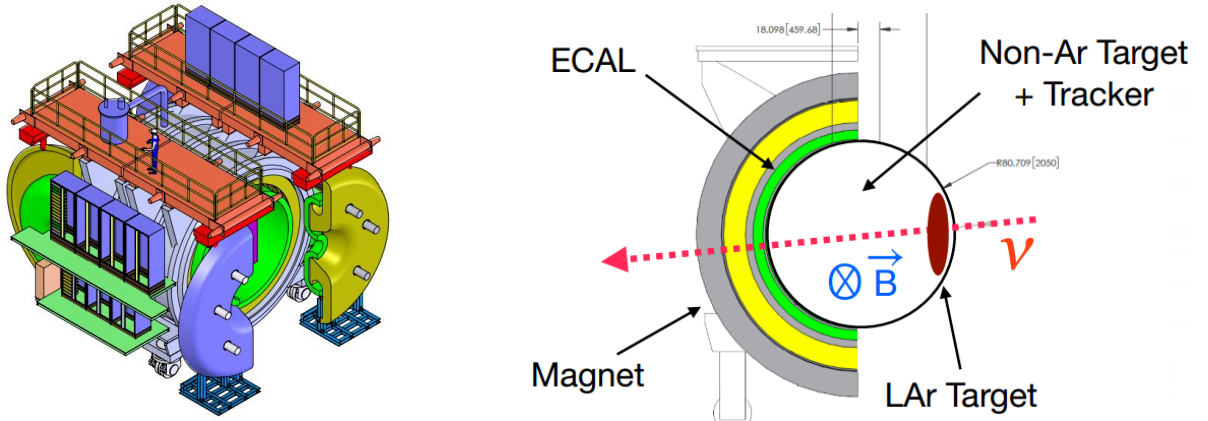


Figure 4.20: SAND engineering drawing (left), operation principle (right) [148].

In this central position, it will receive the largest neutrino flux available and thus notice any beamline changes early on. Deterioration of the target's graphite due to radiation, repositioning of the magnetic horns or alterations in density of the decay pipe gas all affect the flux profile and should be addressed. On top of that, the detector can measure the beam's flavor content, providing additional crosschecks during the off-axis operation

of DUNE prism.

The detector consists of three main components: an inner tracker responsible for particle identification and momentum reconstruction is inserted in an electromagnetic calorimeter (ECAL) housed in a superconducting magnet. The latter two of these are taken from the KLOE experiment [149]. The solenoidal magnet produces a uniform 0.6 T field over a cylindrical volume, which can be seen on the right of figure 4.20 [150]. The ECAL is concentric with the magnet coil and is made up of lead foils alternated with layers of bundled scintillating fibers.

GRAIN or GRanular Argon for Interaction of Neutrinos is a one-ton liquid argon active target at the upstream end of the inner volume allowing for comparisons with the other detectors. The target's thickness is kept to a minimum, ensuring the particles do not lose too much energy as the result of multiple interactions. This is also why the detector relies on scintillation light as opposed to ionized charge for determining particle properties. Targets could be replaced down the line by heavier materials such as Ca, Fe or Pb to further study neutrino on nucleus interactions.

4.2.3 TMS

The temporary muon spectrometer (TMS) is the next detector upstream of SAND. It is a magnetized steel and scintillator plane tracker shown in figure 4.21.

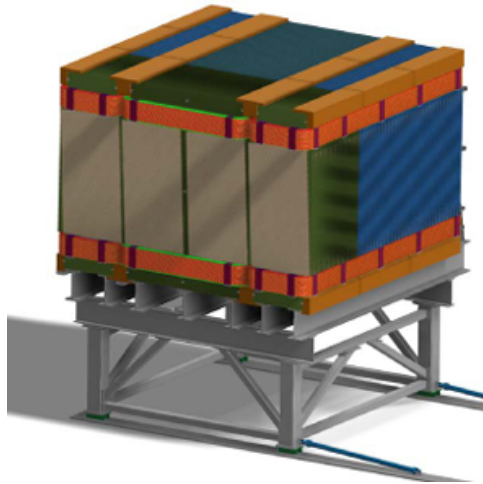


Figure 4.21: TMS engineering drawing [151].

TMS is the next detector upstream of SAND. It is a magnetized steel and scintillator plane tracker. Its ‘thin’ section has 40 layers with a steel thickness of 15 mm, while its

‘thick’ section has 60 layers of 40-mm-thick steel. As TMS does not contain any argon within its design, the main purpose is to measure particles that exit the preceding Liquid Argon Near Detector. These consist predominantly of muons. The bend of the muon track as a result of the magnetic field indicates if the interacting neutrino was a ν_μ or $\bar{\nu}_\mu$.

4.2.4 ND-GAr

In the second phase of the near detector complex, the muon spectrometer will be replaced with the Gaseous Argon Near Detector. ND-GAr is a magnetized, high-pressure gaseous argon time projection chamber and calorimeter, as shown in figure 4.22. At a minimum, it will provide the same information on particle characteristics as the TMS. It will be able to deduce particle momentum and identification and take over the role as muon spectrometer. However in its full capacity, the detector’s geometry not only provides 4π acceptance, but the gaseous state allows for detection at very low threshold and provides very long hadron interaction length, enabling a new level of particle discrimination [152].

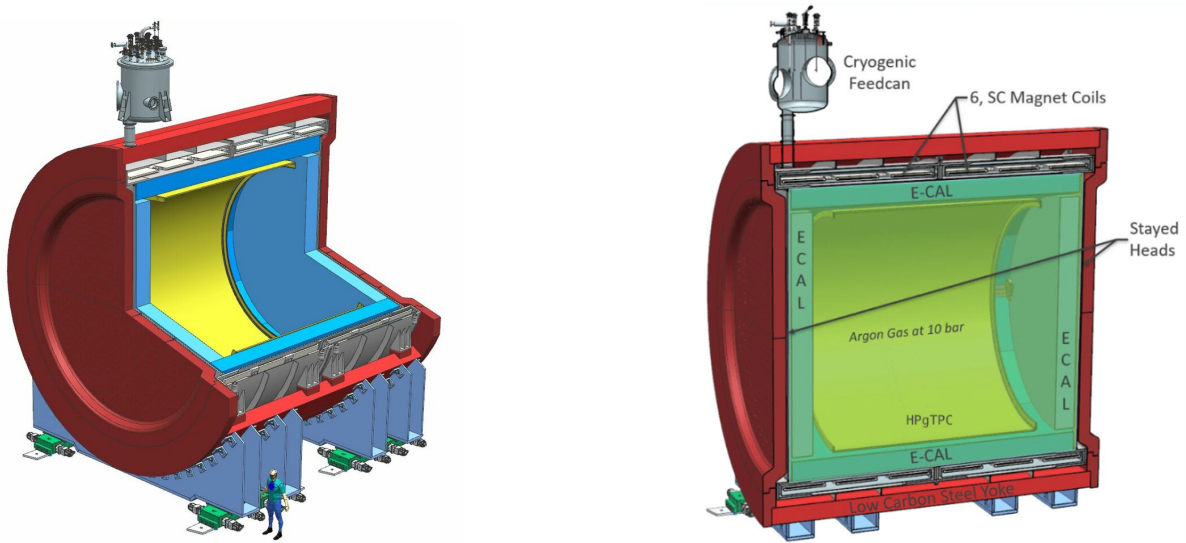


Figure 4.22: ND-GAr engineering drawing (left), cut-away view of detector system (right) [152].

As particles exit ND-LAr, they make their way into the gaseous argon detector. Charged particles traversing through the HPgTPC core ionize the argon. Released electrons are subject to the electric field and forced to drift towards the circular end plates where they will be collected in readout wire chambers [153]. The pressure inside the vessel is kept at 10 atmospheres in order to increase the gas density and boost the interaction probability for neutrinos.

The core is surrounded by the electromagnetic calorimeter. Each of the eight faces in its octagonal shape is made up of combinations of polystyrene scintillator and lead absorbers connected to silicon photomultipliers. The main goal of the ECAL is to be able to measure both the energy and direction of electromagnetic showers. Being able to trace these back to π^0 mesons originating from neutrino interactions in the argon helps in establishing what reaction took place. On top of that, due to its fine segmentation and the time of flight measurements, it is also capable of determining the kinetic energy of neutrons in close proximity to scintillator [152].

Where the ND-GAr really shines is particle identification. By using all of the measurement techniques from separate elements within the detector in terms of energy loss (dE/dx in the TPC), energy (in the ECAL) and momentum (track bend due to the magnet, as well as penetration depth), it is able to distinguish between protons, kaons, electrons, muons and charged pions [147].

4.2.5 ND-LAr

The final detector in the hall takes center stage in the DUNE oscillation analysis as it is the one that most closely resembles the Far Detector in terms of the active target (Liquid Argon). ND-LAr is a modular design of 35 identical LArTPCs in a 7 by 5 array with novel pixelated charge readout systems along with state-of-the-art light collection capabilities (figure 4.23). The studies in chapter 5 will focus on the research and development that have gone into this detector. Here the final design and the prototypes that have been made and tested to show its viability will be discussed.

The choices that went into the conceptualization of ND-LAr's design find their foundation in two essential factors: the detection capability requirements and its environment. As ND-LAr will be placed in the world's most intense neutrino beam with an expected interaction rate of 50 interactions per beam spill, adequate spatial and timing resolution have to be realized. Distinguishing between individual neutrinos in the same spill is of utmost importance for any intended analysis. A single liquid argon volume capable of isolating all neutrino interaction products seems impossible in these circumstances. In figure 4.24, the black lines indicate all deposits that are energetic enough to cause charge to be collected at the pixel planes. The white lines represent the modularization showing why the modular design is necessary to meet the detector's requirements.

By employing a design of this kind, both the scintillation photons and ionized charge are

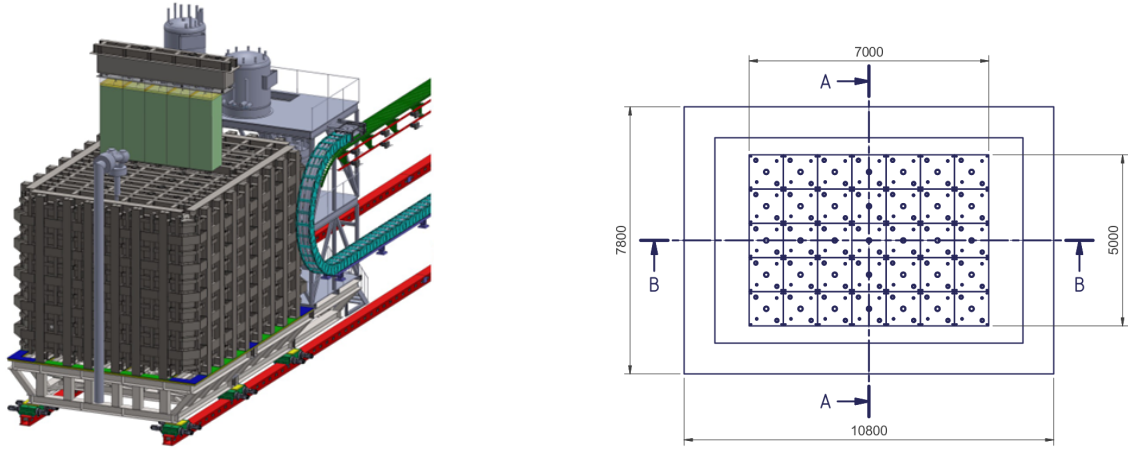


Figure 4.23: ND-LAr detector (left), schematic top-view (right) [152][146].

exclusively propagating in the subset of the detector in which they were produced. With 35 TPCs or 70 drift volumes, the disentanglement in both space and time is simplified (see right image in figure 4.23). To further improve on this new design, the charge readout has been upgraded from a wire-based position reconstruction to a pixel-based one. Where wires only provide a single space and time coordinate, pixels have the inherent property of providing all three dimensions. If one is hit, the charge must have been collected somewhere on their active region.

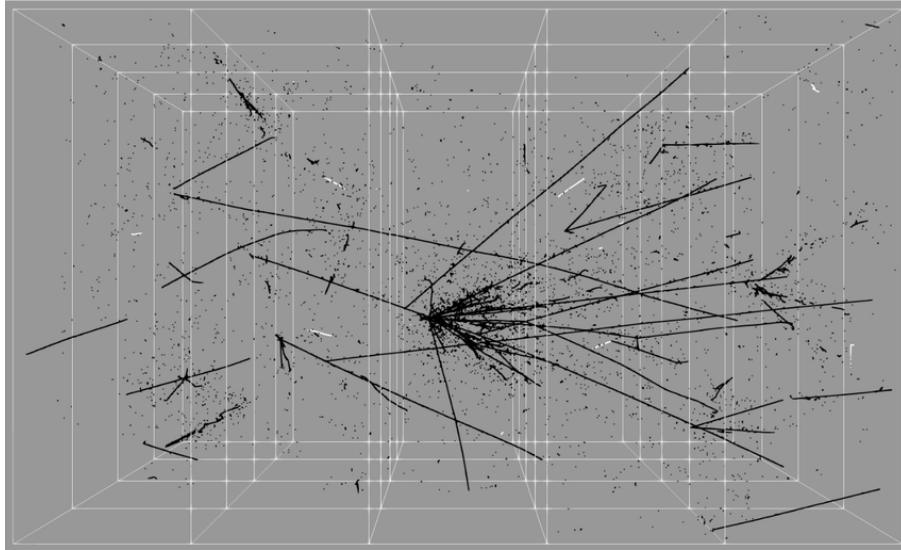


Figure 4.24: A simulated beam spill in ND-LAr [146].

ND-LAr has a fiducial mass of 67 t spread out over the 35 1 m x 1 m x 3 m liquid argon TPCs. In figure 4.25, one of the modules is displayed in expanded view, allowing for the description of the individual parts. Each module will include two optically separated drift volumes separated by the central resistive cathode. The plates at the end of the

TPCs are equipped with a LArPix-based pixelated charge readout system. Perpendicular to these reside the dual light readout systems ArgonCube Light (ArCLight) and the light collection module (LCM), providing fast timing information from the prompt (and slower) scintillation light. The structure is kept in a resistive field shell providing high field uniformity, while also preventing the introduction of additional dead material by the absence bulky field-shaping elements that mitigate the risks of breakdown. Breakdown is the process in which the stored energy in the TPC is suddenly released. The other highlighted elements regulate the argon flow, the purity and temperature.

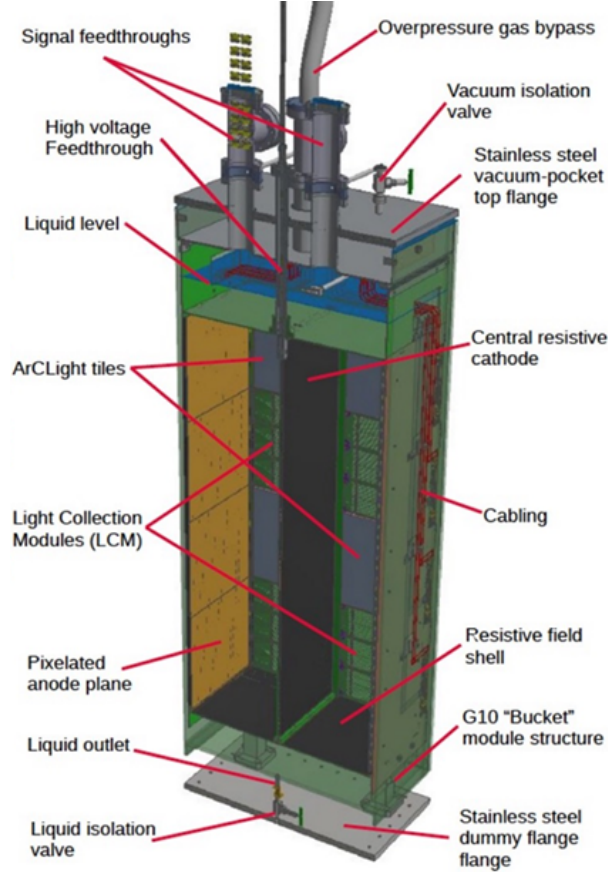


Figure 4.25: Schematic of single module for the liquid argon near detector [154].

The segmentation leads to drift distances of only 50 cm each, heavily reducing the drift times to the hundreds of microseconds regime at the 500 kV/cm electric field [155]. The number of ionized electrons depends on the ionizing particle that traverses the argon. Radioactive Compton scattering typically releases 100's of electrons, whereas with protons and α particles that number could go up to 100k. While the electrons move towards the readout plane, the cloud diffuses, limiting the spatial resolution of the detector to millimeters over the distances used here. Hence, there is no need for the spacing to be finer than that. The charge readout tiles are fully covered by the 4.4-mm-spaced pixels, as

shown on the left-hand side of figure 4.26. The right-hand side shows the surface facing the module's exterior. It houses 100 Application-Specific Integrated Circuits (ASICs) that read out up to 64 channels each.

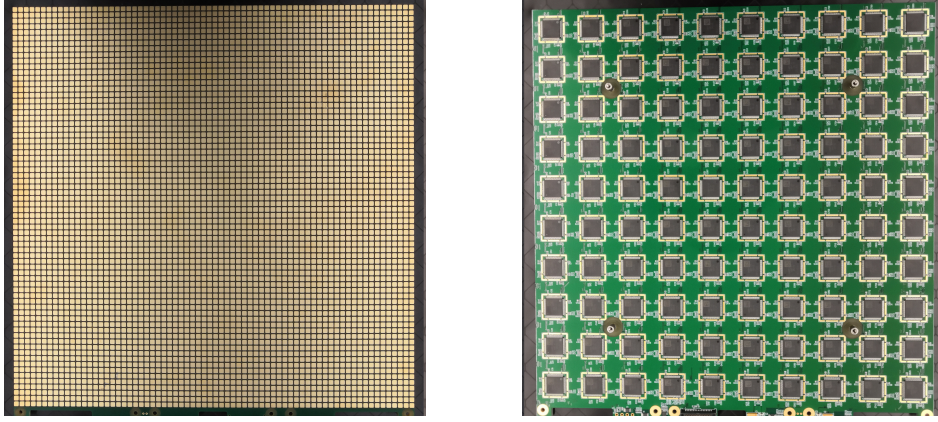


Figure 4.26: Charge readout tile; Pixels (left), ASICs (right) [154].

The charge signals are slow compared to the incoming light. However the timing resolution has to be adequate enough not to limit the spatial reconstruction. With the drift speed of $1.62 \text{ mm}/\mu\text{s}$ at 89K, this sets the boundary at $O(500 \text{ ns})$. To avoid the local boiling of argon, the charge readout must also retain a power output below $100 \mu\text{W}$ per channel. On the opposing face of the PCB, charge-sensitive amplifiers (CSAs) are responsible for providing gain to the incoming electron signal. It is set to 1 mV per 250 electrons. While charge is being collected on the pixel, the output of the CSA grows until it reaches the discriminator threshold. Digitization of the information happens once every 10 clock cycles, which amounts to $1.5 \mu\text{s}$ incorporating the CSA dead time. The outgoing signal is stored in a buffer and transferred by a Pixel Array Control, Message and Network (PACMAN) card. One card provides readout capabilities and power to eight anode tiles simultaneously at a clock cycle of 100 ns .

The two light collection systems ArCLight and LCM are mounted alternately in the vertical dimension, as was already shown in figure 4.25. LCM uses a set of three polyvinyl chloride (PVC) panels with integrated fibers. ArCLight consists of a singular uniform tile. Combined, they cover 30% of the collection area for light emitted within the TPC. When photons arrive at the surface of any of these light-traps, they are wavelength shifted from the 128 nm UV regime towards 400 nm through absorption and re-emission by tetraphenyl-butadiene (TPB). In the case of LCMs, the higher wavelength photons are then captured within wavelength-shifting fibers and trapped through total internal reflection until they reach the SiPM. In the ArCLight design, the 400 nm light undergoes secondary absorption and re-emission, further shifting the light to 500 nm making the walls opaque

and the photon keeps getting reflected until it arrives at the SiPM. Figures 4.27 and 4.28 show the two light collection principles.

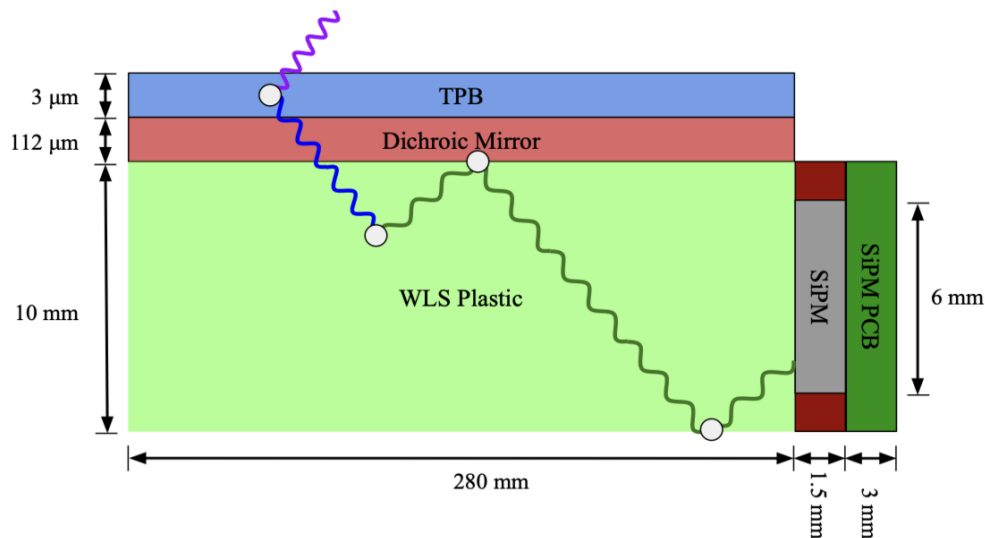


Figure 4.27: Schematic overview of ArCLight light trap [156].

The two light detection systems are complementary in the sense that ArCLight provides better positional sensitivity, while the LCM has higher detection efficiency (2% vs 0.2%). Incoming light in the 10 MeV range provides a signal on the order of tens of nanoseconds with an amplitude of around 200 photo-electrons (PE) for a module with LCMs and 20 PEs for a module with ArCLight.

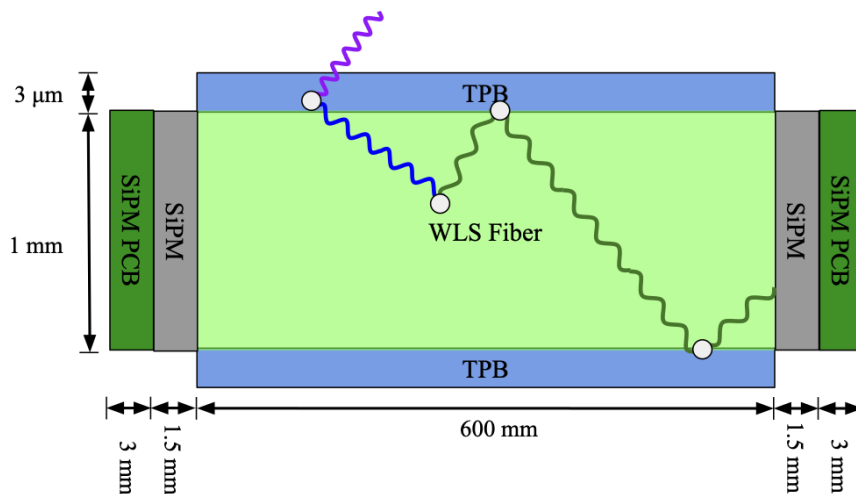


Figure 4.28: Schematic overview of LCM light trap [156].

As ND-LAr comes with a variety of novel concepts such as the modularization, pixelated readout and the light collection systems, massive effort has gone into developing and

testing several prototypes, the latest of which are downsized modules. Four of them were tested by exposing them to cosmic rays to show that the charge and light readout systems operated properly. To evaluate the viability of the modularization, these four have now been assembled in a 2 by 2 array at the NuMI beamline in Fermilab. Not only does this provide data from an actual neutrino beam (increased complexity compared to cosmic rays), it is also the first time the modules have been operated with the majority of the illumination coming from the side instead of the top. Moreover, the track matching in space and time between the different TPC volumes can be put to the test. Chapter 5 will discuss the modules' geometries and the charge read-out tests that were performed to show that pixels are in fact superior to wires and necessary in the environment ND-LAr will be operated in.

LIQUID ARGON DETECTOR PROTOTYPING

5

The liquid argon near detector for the DUNE experiment incorporates several novel technological features that come with their own challenges. The modular approach solves the event pile-up problem in the high intensity environment, but will require precise event reconstruction between drift volumes on top of the charge-light matching in individual modules. The charge collection is done by pixels instead of wires, reducing the 2D spatial ambiguity, but introducing a significant number of additional channels and raising the concern of local LAr boiling as a result of their operation. The drift field's stability is easier to ensure over the now shorter distance, but the resistive field cage might cause non-uniformities. The field could also be distorted by interference with readout equipment such as the dielectric light collectors integrated into the walls.

All of these potential drawbacks have to be studied and evaluated before the final detector is constructed. To this end, a series of prototypes increasing in complexity have been designed and tested both at the University of Bern as well as at Fermilab. Here an overview will be provided for each of these iterations with the goals and lessons learned up until and including the ArgonCube 2x2 neutrino beam test mentioned at the end of the previous chapter.

In total there are three testing stages that serve different purposes. The first two of

these involve single detectors: the ‘SingleCube’ (section 5.1) and ‘SingleModule’ (section 5.2), which were both built and operated at the University of Bern with the goal of collecting cosmic-ray data. Four of these ‘SingleModule’ detectors were then transferred and assembled in a 2x2 array in the NuMI beamline at the end of autumn, 2023. Testing and running of this ArgonCube demonstrator (5.4) in a neutrino beam has been ongoing since the end of spring 2024.

5.1 THE SINGLECUBE

The first ArgonCube LArTPC prototype combining the pixelated charge readout with the ArCLight light collection system was the SingleCube. Both components are shown on the right-hand side of figure 5.1. It consists of a single drift volume with one cathode and one anode plane. The cathode, as well as the entire field cage, are made up of 3.5-mm-thick PCBs equipped with gold-plated copper strips attached to them, as illustrated in the left-hand image of figure 5.1. The four field cage panels have 60 of these strips each, at a 1.5 mm pitch. The individual strips are connected electrically through resistors supplying a $1.5\text{ G}\Omega$ total resistance between the anode and cathode [157].

The field cage spans a 33 cm by 33 cm surface at its base designed in such a way that it can house the same pixel plane and ArCLight tile as in the successive prototypes. The pixelated anode plane hosts 4900 pixels in a 70 by 70 array. Each pixel is 4 mm^2 in size and positioned at 4.434 mm from its neighbors, creating the active area of 30 cm^2 , which is read out by 100 LArPix-V2 ASICs mounted on the backside. With a maximum drift distance of 30.2 cm, the active mass is about 40 kg of liquid argon (30 L) [158].

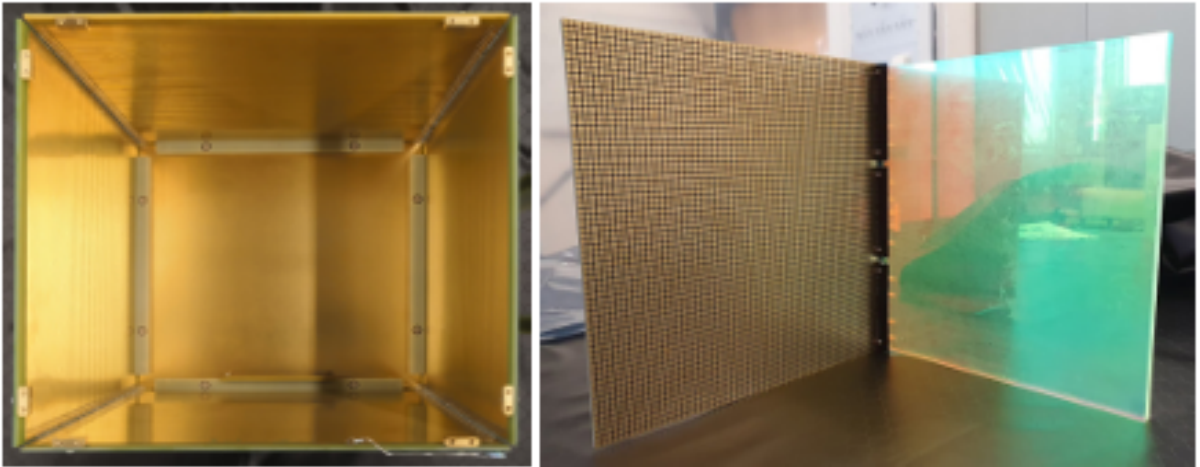


Figure 5.1: SingleCube field cage (left), LArPix-V2 and ArCLight tiles (right).

The ArCLight bulk structure is slightly smaller, at 30 cm by 28 cm, and optically coupled

to six SiPMs. As mentioned at the end of the previous chapter, there are two different light collection systems. Part of the design requirements is the interchangeability of ArCLight with three LCM modules. The signals from the SiPMs were fed to the external trigger input of the charge detection system, allowing for triggering of the LArTPC on the LAr scintillation light produced by particles crossing the TPC. SingleCube was assembled in October of 2020 at the University of Bern in Switzerland, after which it was tested for five days with drift fields ranging from 0.1 kV cm^{-1} to 1 kV cm^{-1} , successfully imaging cosmic rays and operating stably over the entire period [159].

5.2 THE SINGLE MODULES

The next step in the cycle was to assemble multiple of these SingleCube demonstrators into one device. These devices are known as the ‘Single Modules’ with the first iteration being ‘Module-0’ shown in figure 5.2. These machines consist of two LArTPCs around a single cathode, making them the first fully integrated, tonne-scale prototype of the future DUNE ND-LAr. Their drift volume is eight times larger than that of the SingleCube, but the drift distance is of a similar length. Their outer dimensions span 0.7 m by 0.7 m by 1.4 m with the TPCs themselves amounting to a volume of 0.30 m by 0.62 m by 1.24 m. They house the same LArPix 3D charge readout as mentioned earlier and contain both of the light collection systems (ARCLight and LCMs) as well as the low-profile resistive field shaping shell. With this constructed, the beginning has been made for the development of the four modules for the 2×2 ArgonCube demonstrator.

One of the main components for inducing any drifting charge to observe in the first place is the electric field generated by the high voltage (HV) potential difference between the cathode and anode inside the active volume. Preserving the uniformity and stability of this field is key in ensuring that the signals generated by the ionized particles reach the walls in a predictable manner. This is achieved by a series of conductive rings placed at regular intervals and connected through resistors, creating the voltage gradient that helps establish a smooth and uniform electric field between the cathode and the anode. In this way it prevents distortions that could be caused by irregularities in the detector’s geometry and would lead to inaccuracies in particle tracking and measurement.

5.2.1 Module-0

Both the cage and the HV system for Module 0 were designed by the Stanford Linear Accelerator Center (SLAC). The field cage was constructed using 6-mm FR-4 sheets laminated with a 100 μm thick Kapton DR8. To ensure sufficient liquid circulation

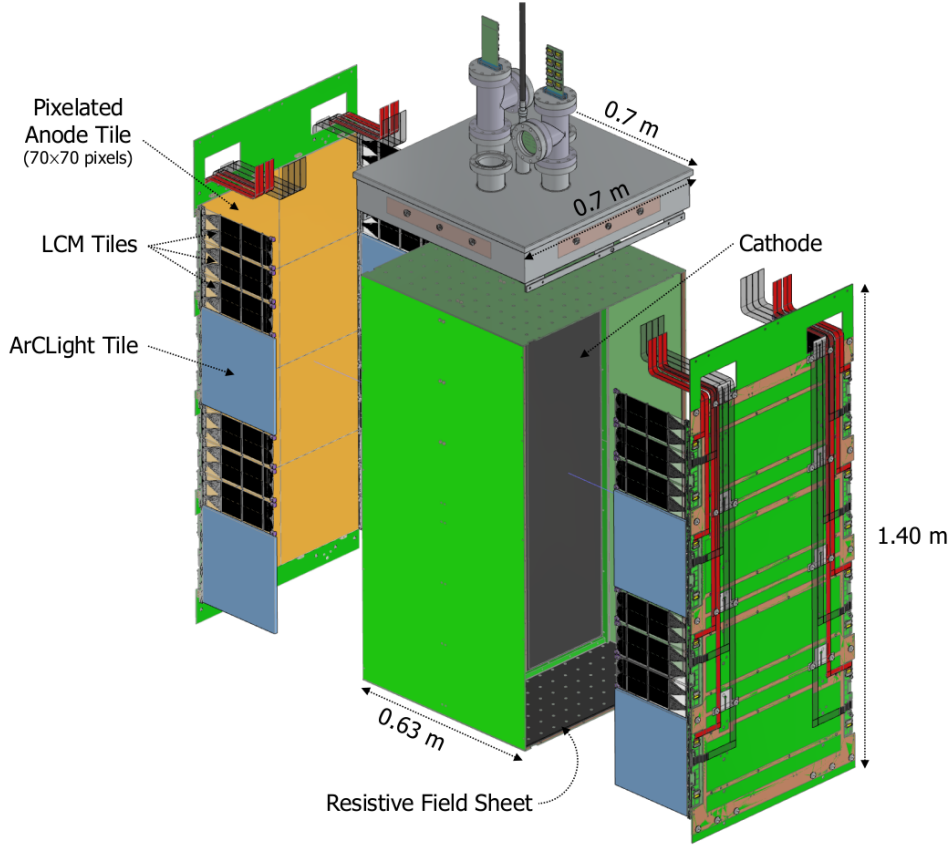


Figure 5.2: A schematic overview of the Module-0 prototype [159].

within the active volume, the top and bottom panels of the field cage were perforated with 4-mm holes. Separate HV ground connections were implemented to isolate the HV supply current from the sensitive detectors and to protect against overvoltage. The field cage was tested with a subset of the charge readout system (CRS) and light readout system (LRS) (one pixel tile, one ArcLight panel and three LCMs) over a wide range of high voltages without any catastrophic breakdown. Moreover, the perforations showed adequate fluid recirculation [159].

The complete CRS for Module-0 consists of eight of these pixel tiles (2 by 4) located at the anodes at the end of the drift path (16 in total). Each of these 16 tiles contains a 70×70 grid of 4900 charge-sensitive pixel pads with a 4.43 mm pitch on one side of a PCB (78400 pixels across the entire detector). Each pixel channel operates as an independent self-triggering detector with nearly 100% uptime, only becoming unresponsive for 100 ns during frontend resets. In the situation where this dead time overlaps with the signal, some of the total charge can be lost. The other side is instrumented with a 10×10 grid of low-power low-noise cryogenic-compatible application-specific integrated circuits

or ASICs as shown previously. These ASICs ensure the translation between incoming charge and outgoing data by amplifying the analog signal and converting it to a digital one through 64 front-end amplifiers and 64 ADC converters. To avoid data collection without any activity, the ASICs have a quiescent mode in which they remain until triggered on ionization above $O(100 \text{ keV})$ [159].

The pixels have two distinct trigger modes. They can be self-triggered or initialized by the light readout system. The first mode is the main method of operation for the LArPix ASICs, meaning that a trigger is supplied on a per-channel basis when the programmable threshold (tuned to a spurious trigger rate below 2 Hz) for that specific channel is exceeded. This results in the most efficient data volumes due to the sparsity of ionization signals in three dimensions even for instances with high amounts of deposited charge. It also induces the lowest amount of dead time. Thresholds were tested in low level regimes to optimize signal sensitivity and in high level regimes to evaluate the trigger stability. In some cases the event rates spike due to high data rate pixels. This can be mitigated by improving threshold setting procedures. In runs where this was unsuccessful the individual pixel was disabled. On the right-hand side of figure 5.3 a few of those can be identified.

The assembly of 100 ASICs on a single pixel tile routes the collected data through a so-called ‘hydra’ network, which allows neighboring elements to receive data packets from one another. Initially, several readout chains are established between the ASICs, ensuring all of them get read out at the end. A procedure that always starts at one of the root chips as can be seen on the left-hand side of figure 5.3. This ensures robustness in case of single channel failure. Packets deeper in the network take longer to exit, but carry a timestamp to allow the chronological order to be reinstated afterwards. The cosmic rays produced a self-trigger rate of around 0.25 Hz per pixel, resulting in a total pixel hit rate on the order of 20 kHz for the entire Module-0 detector and yielding a data rate of 2.5 Mb/s. Trigger rates, timing, channel occupancy, and data corruption checks were all stored.

The LRS is mounted on the walls perpendicular to the cathode as shown in figure 5.2. Due the chosen configuration, the 12 LCMs and four ArcLight tiles dedicated to a single TPC are distributed over two opposing walls in a 1 by 4 format. However, the readout is done for the equipment on adjacent walls by summing the waveforms from six SiPMs for every three LCM panels and singular Arclight tile (96 SiPMs in total). That information was then used for triggering the charge readout and stored to allow for offline charge-

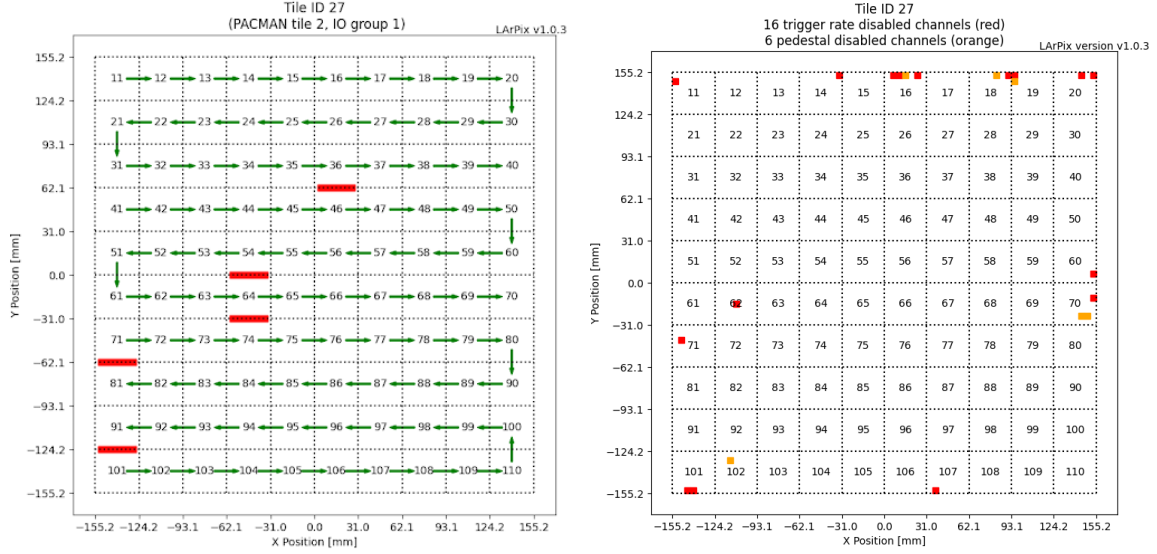


Figure 5.3: Established hydra network (left), disabled channels (right)

light matching. In Module-0 only the LCMs were used to produce a trigger signal as the registered background noise on the ArcLight detectors would occasionally surpass the 1500 ADC count threshold set for a combined signal from the six SiPMs.

As the studies in this analysis revolve around the performance of the charge readout system, its operation will be discussed in more detail. The coverage of the light readout in the previous chapter should suffice for understanding the studies performed here and will not be discussed any further.

Aside from the charge and light readout systems that collect data on particle interactions, the module houses a suite of equipment to monitor its stability during operation.

- Four-wire resistive temperature detectors (RTDs) placed within the detector and cryostat.
 - Monitor cooling rate during the initial fill and provide a redundant liquid level measurement
- Pressure sensors
 - Monitor ullage volume, fill and vent lines, cryostat vacuum insulation
- Capacitive level sensor
 - Continuously measures liquid level near the operational fill level
- Integrated monitoring of the HV power supply.

- Gas Chromatograph
 - Detects trace gases within the ullage volume down to approximately 10 parts-per-million (ppm).
- Continuous purification of the liquid argon
- 5- μm particular filter
 - Removes fine particles of the purifier materials from detector volume.

The fully instrumented Module-0 detector was operated during two run periods, one at the end of March and the other at the end of June 2021. The detector can be seen without its G10 sleeve on the left of figure 5.4. On the right it is being inserted into the cryostat. In the first run period, over 25 million cosmic-ray triggers were collected over an 8-day span, utilizing various field configurations and charge readout thresholds. The effect that these different settings have on the event rates is shown in figure 5.5. It also provides a global overview of the distinct steps in operating the LArTPCs. At this point, three of them have not been covered yet. These include part of the commissioning, pedestal data, the Drift HV Ramp and the diagnostics.

The commissioning was preceded by a 2-day evacuation period, which reduces the amount of outgassing done by detector components during the eventual LArTPC operation. Outgassing is the process whereby gases are released that were previously trapped, dissolved, or absorbed within a material or substance. Once this was completed, the cryostat was ready to be filled with liquid argon. This has to be done in a slow and controlled manner as a high temperature gradient across the components could cause deformations. This is one of the main purposes for the RTDs installed at several positions along the detector’s height. It takes around two days for the environment to reach stable conditions. In the final testing stage of the commissioning one E-board stopped responding in addition to two separate SiPM channels. As it is impossible to replace anything during operation, the active SiPM count was 88 out of 96. Other SiPMs inside the same drift volume can fill the role of triggering the system on incoming light signals.

To estimate the background activity in the detector without high voltage present, so-called ‘pedestal’ runs were taken periodically throughout the data collection, as indicated by the pink strips in figure 5.5. For these calibration runs, each chip was operated in periodic-trigger mode implying that the trigger is set off at fixed intervals instead of being supplied by the light readout or instigated by excess charge on the pixel plane. Because

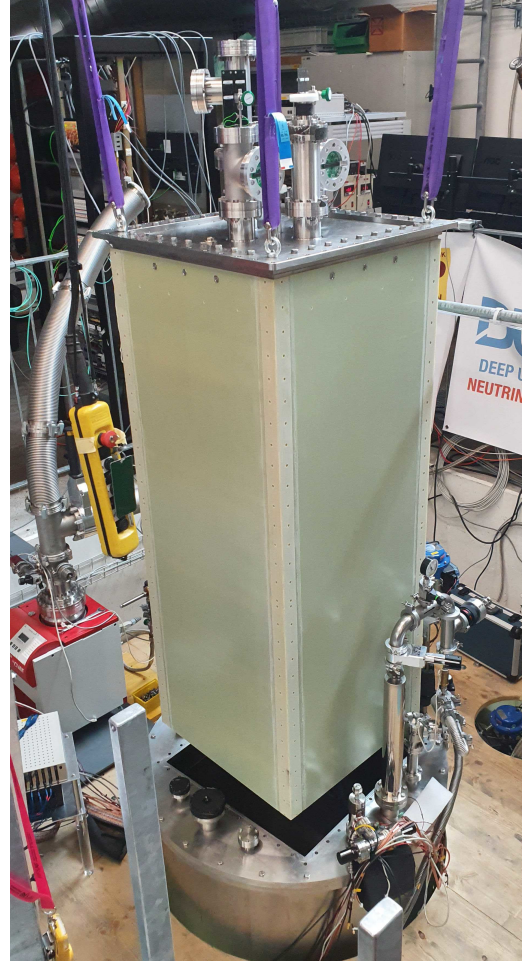


Figure 5.4: Module-0 without its G10 sleeve (left), above the liquid argon cryostat (right).

the sampling is uncorrelated with activity on the pixel, this provides an estimate of the ADC distribution when no signal is present and can therefore be used to define a channel by channel subtraction of any future measured signal when the high voltage is in fact enabled.

The drift field is not immediately ramped up to 500 V/cm. It is done in several steps to ensure the field's stability (halted at 250 V/cm to assess the structural integrity). The drift HV ramp done on April 9th as mentioned in figure 5.5 consisted of increasing the field strength in steps of 50 V/cm up to a maximum of 1 kV/cm. Data was taken for 40 minutes at every interval and for a period of six hours at the maximum. This is valuable information as the field strength affects several factors related to the charge readout such as electron diffusion, recombination and drift speed.

Finally, a diagnostic session was introduced to evaluate the position of broken or malfunctioning

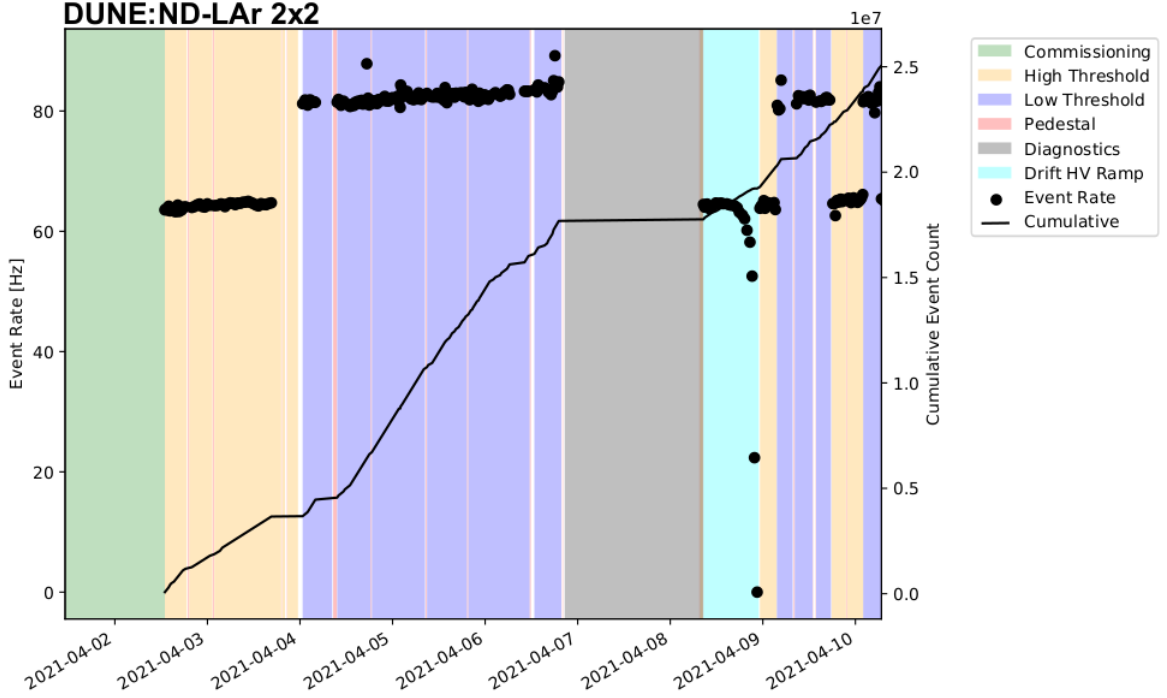


Figure 5.5: An overview of the first run period for Module-0 highlighting the different stages of operation. The event rate and cumulative event count as a function of time are indicated with the black dots and black line, respectively [159].

pixel channels and to optimize the individual trigger thresholds. These studies form the basis for the DUNE analysis and will be described in section 5.3.

The second run period gathered an additional sample of over 14 million cosmic-ray triggers, with data collected under a consistent threshold and field configuration, but with varying fluid recirculation rates. The system exhibited reliable operation and high-fidelity data collection in both runs, that confirmed its readiness to be shipped to Fermilab for further testing and eventual installation into the 2 by 2 ArgonCube demonstrator. Several event displays can be found in figure 5.6 highlighting the capability of the pixelated liquid argon detection system.

5.2.2 Module 1, 2 and 3

The strategy for constructing and testing the three remaining modules was nearly identical to that of Module-0. Similarly to the ND-LAr design, the modules for the 2 by 2 demonstrator have the same outer dimensions in order to stack them together. There are, however, a few key differences in their geometry, with Module-2 having an unique charge

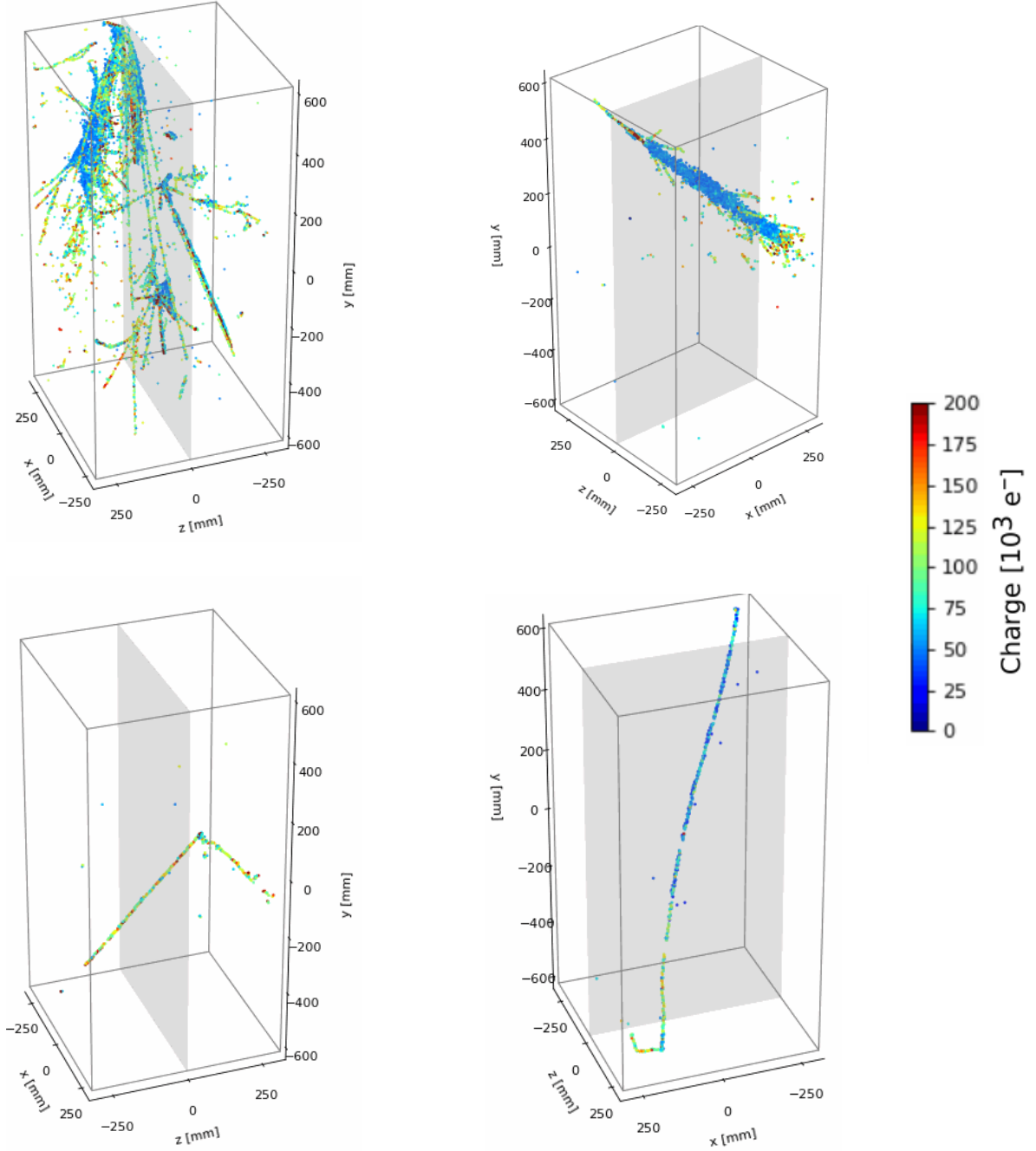


Figure 5.6: Four displays of the Module-0 architecture with its central cathode in grey showcasing different cosmic ray-induced events in terms of collected charge converted to number of electrons as indicated by the color bar on the right-hand side. The plot in the top-left shows a multi-prong shower. The one in the top-right denotes an electromagnetic shower. On the bottom-left, a neutrino-like event can be seen. An ‘invisible’ particle creates two tracks with a common origin or vertex. Lastly, the image on the bottom-right shows a stopping muon and the subsequent Michel electron decay.

readout system in terms of pixel size and pixel coverage. The pitch went from 4.434 mm down to 3.8 mm increasing the number of pixels from 78400 to over 100k, which affects the position resolution in the reconstruction. Other changes between the modules are listed in figure 5.7.

Bern Single module test	Module-0	Module-1	Module-2	Module-3
LArPix ver.	v2A	v2A	v2B	v2A
Pixel pitch,mm	4.434	4.434	3.8	4.434
CRS Threshold	5.8 ke, $\sim 1/4$ MIP	4.5 ke, $\sim 1/5$ MIP	7.5 ke, $\sim 2/5$ MIP	6.1 ke $\sim 1/4$ MIP
Inactive channels	7.8%	2.4%	9%	3.9 %
LRS PDE: LCM	0.6 %	0.6 %	0.6 %	tbd
LRS PDE: ACL	0.06%	0.2 %	0.2 %	tbd
LRS threshold	~ 5 MeV	~ 1.6 MeV	< 1.6 MeV	~ 1.6 MeV
LRS timing	< 2 ns	1.2 ns	1.2 ns	1.2 ns
LRS inactive channels	8.3%	1%	0	2%
Field shell	DR8	DR8	DR8	DR8
R shell	71.193 MΩ	82.582 MΩ	71.285 MΩ	61.791 MΩ
Max E-Field tested	1 kV/cm	0.5 kV/cm	0.8 kV/cm	0.7 kV/cm
Electron lifetime	> 2 ms	> 2 ms	> 2 ms	> 2 ms

Figure 5.7: An overview of the different properties for Modules 0 through 3.

The actual testing procedures followed the same steps as laid out before. Module-1 performed best and only required a single run to be deemed qualified. Module-2 and Module-3 needed two and three runs respectively. During the Module-2 run, we found an excess in the data transfer for the charge readout. This was due to mechanical vibrations as a result of someone walking on the platform surrounding the detector. Post-operation investigation concluded that the G10 sleeve panels were indeed not glued properly.

During the cosmic-ray tests for Module-3, a excessive amount of light was observed to come from a particular location in the detector. Posing a problem to the triggering system, the machine had to be warmed up and taken out of the cryostat enclosure. The first attempt to cover the exposed metal failed as the excess remained. Hence the detector had to be taken out of the cryostat for a second time in order to perform another comprehensive check of the material. This last try showed that the issue had been resolved and thus testing at Bern was completed.

5.3 CHARGE READOUT TESTS

The large influx of data from the individual modules’ cosmic-ray runs at the University of Bern provided ample opportunity to test the performance of both the charge and light readout systems across multiple metrics, with the primary goal of characterizing the detectors and improving the settings, as well as our simulations. Here, the focus will lie only on the former, but the reader is referred to [160] for more information on the LRS as well as on other parts of the detector technology.

As the CRS consists of tens of thousands of pixels per module, simply studying the performance of individual channels would be both time-consuming and memory intensive. This is why methods have been developed to isolate problematic regions on the pixel plane that then can receive more dedicated attention. One of the most basic checks is to find regions that have not been triggered by any incoming charge at all and did not report any signal for the entire run. On top of the so-called ‘dead’ regions found in between the tiles, individual pixels within the tiles could have been totally unresponsive as well. This could have been caused by incorrectly set trigger thresholds, but the more likely scenario is that a pixel or an entire ASIC was broken.

Furthermore, the intent is to understand the detector’s response to charged particles. The ideal case is to select particles exhibiting a well-defined energy deposition pattern (ideally consistent over the entire width of the detector). MIPs provide exactly that. Hence, data cuts are designed to obtain a sample primarily consisting of singular MIP-like tracks for every event. As these cuts rely on track properties, it is important to first reconstruct the tracks from the three-dimensional position that the hit and timing information provide. This is done through a Hough transform algorithm (HTA) discussed in section 5.3.1. Subsequently a map of the pixel plane’s responsiveness is created by using the dead region overview generated before. The minimum ionizing particle (MIP) response maps were constructed for every TPC, as will be discussed in section 5.3.2. The main goal of these studies is to show defective regions in one single glance.

The MIP response map is a global representation of the pixels’ performance, but it does not describe the response or the sensitivity of individual pads. To investigate these metrics, so-called pixel pad efficiency histograms are produced. The 4.434 mm by 4.434 mm pad is subdivided into 400 squares of the same size to see if there is a difference in the trigger rate depending on the distance from the pixel center charge arrived at. The

ionized electrons drift towards the walls in clouds, making it impossible to assess which specific electron induced the signal at what position. Hence, the same Hough transform algorithm is used to reconstruct the particle track. More on this in section 5.3.3.

The chapter will conclude with a discussion on the implementation of these studies in the in-situ diagnostics framework to assess the detector's performance live at any point in time. This will allow for making adjustments to the charge detection thresholds and settings on the fly.

5.3.1 Hough Transform

The Hough Transform is a technique used in image analysis, computer vision, and digital image processing to detect shapes, such as lines, circles, or other parametric curves. While the 2D Hough Transform is commonly used for detecting straight lines in images, the 3D Hough Transform extends this concept to three dimensions, allowing the detection of planes or other 3D shapes.

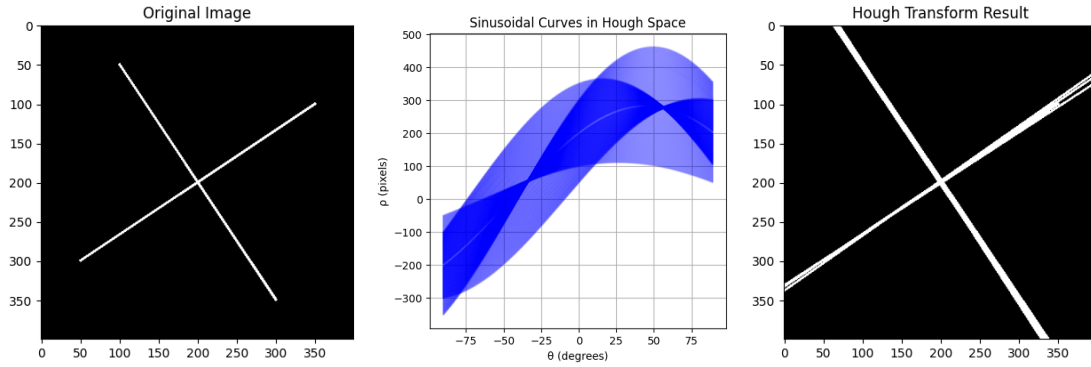


Figure 5.8: Images representing the steps for a 2D hough transform.

In figure 5.8 the steps for the 2D hough transform are represented visually with the starting point shown on the far left. A line in 2D space can be represented by equation 5.1,

$$y = mx + b, \quad (5.1)$$

or in its parametric form by equation 5.2,

$$\rho = x \cos \theta + y \sin \theta + b, \quad (5.2)$$

where ρ is the distance from the origin to the closest point on the line and θ is the angle between the x-axis and the line's normal. In the Hough Transform, each point in

the image space (x, y) corresponds to a sinusoidal curve in the parameter space (ρ, θ) (middle image in figure 5.8). The idea is that all points lying on a particular line in the image space will correspond to curves that intersect at a common point in the parameter space. By identifying this intersection, the presence of a line can be detected (right-most plot in figure 5.8).

The two-dimensional Hough Transform method is extended to detect lines in 3D point clouds using a modified approach described in [161]. This technique involves regularizing the Hough parameter space for effective quantization and employs an iterative process to identify lines with the most supporting points. The method discretizes the infinite space of possible lines, allowing each point to ‘vote’ for the lines it belongs to. Lines that accumulate the most votes correspond to those with the most closest points and are thus the most likely candidates to best represent the particle track.

In figure 5.9, the point cloud for a single event in the liquid argon volume of Module-0 is shown. The x and y positions are reconstructed from the pixels that collected charge above threshold. The z dimension is found by using the timing information coming from the light trigger signal as discussed in the previous chapter. Immediately a distinction can be made between several through-going tracks illustrated by the subcategory’s color. A total of seven lines result from applying the Hough transform on this dataset as can be seen on the right in figure 5.9. The issue here is that several of their point clouds could overlap, making it very difficult to assign the right charge to the right particle, ultimately leading to an incorrect determination of the energy. Hence, tuning of the algorithm is required moving forward.

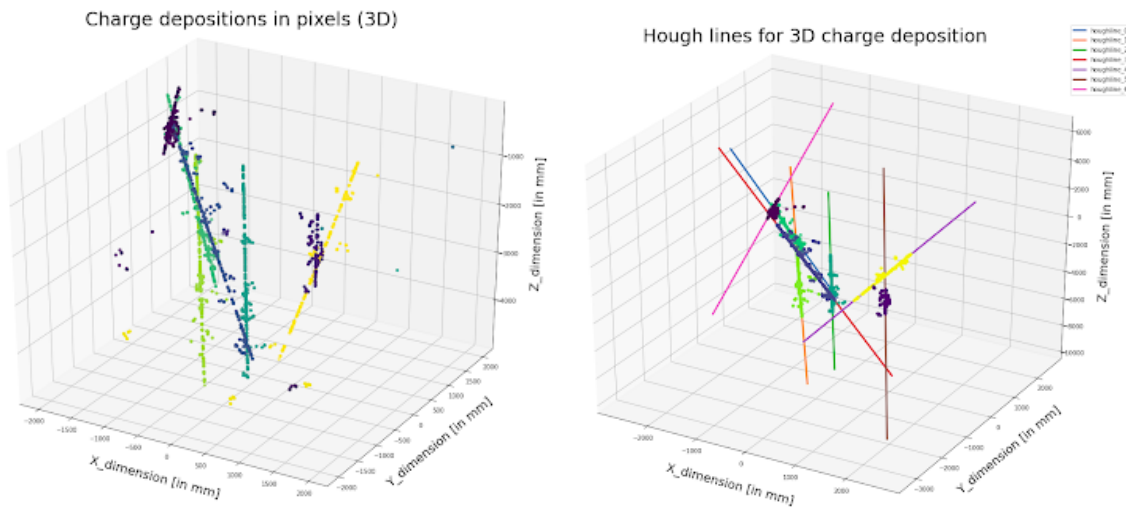


Figure 5.9: Module-0 reconstructed hits (left), Hough lines (right)

The Hough transform algorithm relies on two parameters to determine its success, the minimum number of votes or hits required to be classified as a line and the maximum number of lines it is allowed to find in the dataset. These options are not independent. As the number of particles crossing the detector differs for every measurement period, it is easier to study the minimum number of votes required on the HTA's ability of identifying a track. A minimum of 125 votes was established. This threshold rejects shorter tracks that only clip the detector's edges and it serves as a significant cut-off for tracks reconstructed from noisy channels.

When applying this criteria to the algorithm, identified track properties can be studied in each of the four modules. These properties describe the orientation (angles with respect to different planes xy , xz and yz), midpoints (halfway between edges). The X and Y dimensions describe the horizontal and vertical measurements of the pixel plane. It is important to ensure the data samples consist of similar sets of tracks before conducting any of the diagnostic tests explained in the following sections. This is because any issues or differences should be the result of operational stability or certain detector characteristics and not the result of analyzing variations in selection results.

Figure 5.10 show the midpoints and orientations of 10000 events in drift volume 1 of Module-0 (figure E.1 in appendix E for drift volume 2). These volumes are indicated by **io1** and **io2**, respectively. The full scope of this study also includes the track properties in Modules-1 though 3. The events were only allowed to contain one single track to make sure the statistics were identical between detectors.

The distributions show a few key features that are directly related to the component design and the incoming cosmic ray direction (from above).

- Clear peak at halfway point for each of the midpoints across all detectors. This refers to tracks that cross the entire width of the detector in a certain dimension. The midpoint is then always in the middle of the volume
- No midpoints at the edges
- Two additional peaks at $1/4$ and $3/4$ of the detector's x and y dimensions caused by through-going track that illuminated only half of both drift volumes
- Angular distribution w.r.t. YZ plane peaks only on one hemisphere as algorithm always identifies this particular orientation (by design)

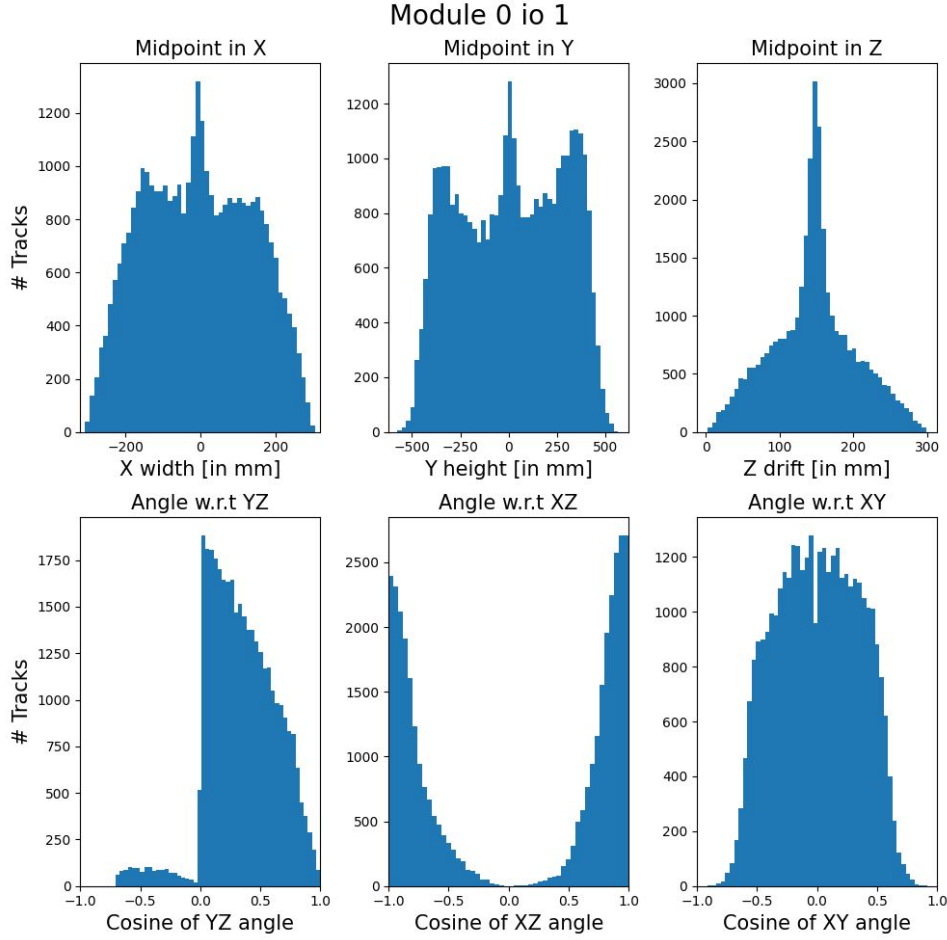


Figure 5.10: Midpoints and angles for data from the first drift volume of Module-0.

- Angular distribution w.r.t. XZ plane decreases as tracks become more horizontal and increases when they become more vertical
- Angular distribution w.r.t. XY plane (pixel plane) peaks as tracks approach parallel path with the exception of exactly 0 degrees
- In general the tracks look alike for all modules with the exception of the skewed Z midpoint distribution for module 2

Moreover, the hits do not necessarily span a perfectly straight line, meaning that there has to be a second step in the algorithm that determines which charge deposits belong to what track. In its simplest form, this step groups all hits within a radius R around a Hough line together and assigns it to that specific particle. The effect of varying this radius R has also been studied. Most of the charge is contained within the first tens of millimeters from the main ionization line, meaning that for tracks far enough apart, one can predict which hit belongs to what track simply based on the distance.

In figure 5.11 the results of containment study can be found. The values on the x-axis refer to the radius of the cylinder that assigns all hits to a certain HTA track. On the y-axis the percentage of the total particle energy this cylinder captures is shown. The horizontal line in the box's bulk indicates the median of the points for that specific radius. The upper and lower edge of the box describe the 1/4th and 3/4th medians. To qualify, the box's bottom should be above 90% containment. This is achieved at cylinder radii of 9, 7, 9 and 7 mm for Module-0, Module-1, Module-2 and Module-3, respectively. As expected, Module-1 and Module-3 show similar behavior, which is the result of their near identical geometry. Module-2 has a smaller pixel size meaning there are more channels within the same distance to the track. As locations on the pixel pad can't be distinguished from one another, the center's position is always returned making the radius for Module-2 larger (tracks are usually three pixels wide in Module-2 vs two pixels wide in Module-0, Module-1 and Module-3).

This radius will not only help in determining the overlap between particle point clouds, but also help understand the straightness of the track. This is a necessary requirement when looking for MIP-like particles.

5.3.2 MIP response map

To test the responsiveness of individual pixels and identify malfunctioning ones in addition to the known dead and inactive pixels mentioned before, a MIP response map of the entire pixel plane is made. This response map consists of the ratio between two other maps. One records hits as measured by the modules, while the second estimates all pixels that could have been hit. Their ratio then identifies regions on the pixel plane that are less responsive than others.

The Hough transform algorithm on the x (the horizontal axis of the pixel plane), y (the vertical axis of the pixel plane) and reconstructed z (the drift direction) dimensions of the hits cloud returns the MIP's central ionization axis in 3D. This axis is then projected onto the pixel plane to result in a 2D line (see the right-most image in figure 5.12). The image on the middle is the simple 2D projection of the reconstructed hits from the event display on the left. Next is a filtering step. All hits within the predefined radius, as found from the study showcased in figure 5.11 (9, 7, 9, 7 mm for Module-0 through Module-3, respectively), from the line are collected and stored. All other hits that do not fall within this cylinder are rejected.

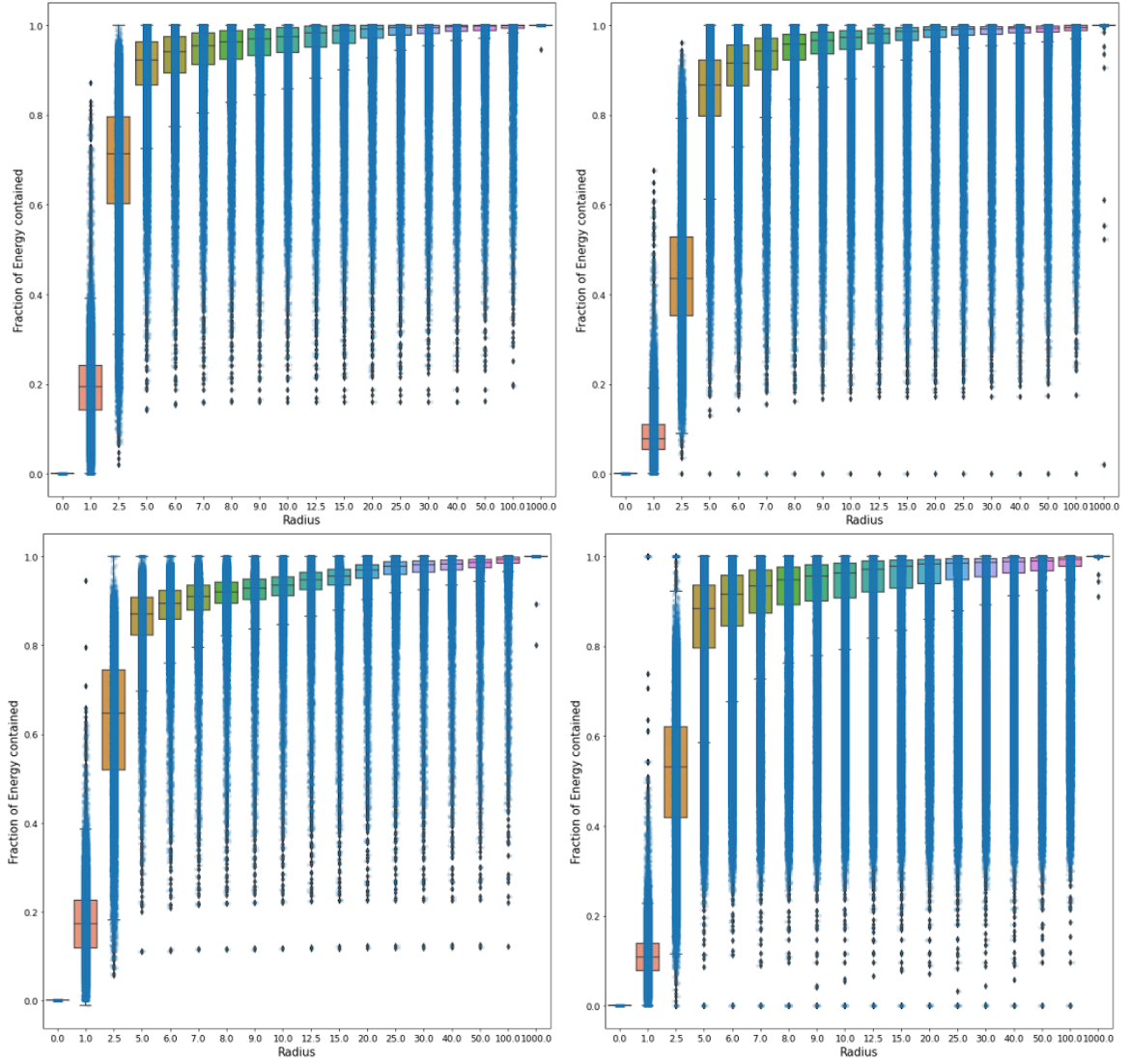


Figure 5.11: Containment study results for Module-0 (top-left), Module-1 (top-right), Module-2 (bottom-left), Module-3 (bottom-right).

Moreover to ensure that the events contain MIP-like tracks, i.e., straight lines with a constant energy deposition, several data quality cuts are made before this analysis is performed. Aside from the ten thousand events required in both drift volumes, each identified particle track should have an entry and exit point. In combination with a minimum of 125 votes this corresponds to a lower bound for the track length.

For events that contain more than one Hough line, the energy within the radius of all lines is summed up and compared with the total event's energy. Tracks that overlap at a rate of more than 1.1 times the total energy are excluded. To determine the straightness of individual particles' tracks, the energy contained within the specified radius is compared

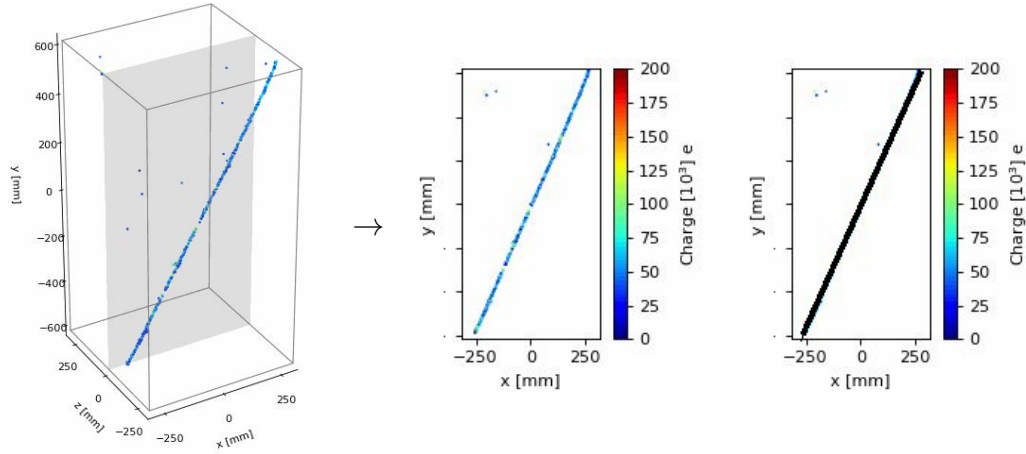


Figure 5.12: Procedure of constructing a MIP response map.

with the energy contained within a 25 mm radius. At ratios below 0.8, a considerable part of the energy is deposited further away from the main axis, indicating secondary effects such as EM showers or delta rays, which are knocked-out electrons that have sufficient energy to further ionize the medium along their path. These are also excluded in this performance study. This will be referred to as the linearity constraint moving forward. Lastly, tracks found to be parallel to the pixel plane are excluded as these are the result of noise. From this point onward the procedures for the two maps diverge.

To obtain the first map, all pixels that recorded hits within that radius from the projected line receive an entry. This is at most one entry per pixel per event (e.g., each pixel bin that has registered a hit in the middle plot of figure 5.12 would accumulate a ‘1’). This is then repeated for 10000 events, which creates the illumination maps shown in figures 5.13 and 5.14, one for each of the eight drift volumes.

The ASICs that collect the pixel data can clearly be distinguished from one another. The broken ones can easily be identified by the large empty squares registering no charge at all. If individual channels are malfunctioning, they show up as the smaller dark blue dots. The sizes of the horizontal and vertical dead regions across the entire width and length of the pixel planes vary with each modular prototype. Module-3 hardly has any dead material left, because the individual pixel tiles were placed more closely together when compared to earlier prototype iterations. Overall it can be seen that there are differences in responsiveness within the modules and even on singular tiles. Due to excessive triggering in some regions of Module-1 and Module-3, the color bars differ from that of Module-0. Yet upon closer inspection the levels of illumination are the same. However, to be sure the Hough line map has to be constructed which will give insight

into what regions were actually hit and which were not.

To construct this second map that will be used as the denominator, all pixels within that same radius receive an entry. It receives an entry if the pixel lies within the specific radius of the Hough line independent of recorded charge. If a pixel is unresponsive, it will not show up in the first but will do so in the second. The ratio will thus be low for this area. This procedure is then repeated for the same 10000 events, which creates the Hough line maps shown in figures 5.15 and 5.16 for each of the eight drift volume pixel planes. Here regions that were not covered by the particle tracks can easily be identified. The known dead regions have been excluded when generating these figures. Any unknown zones will have been filled as the Hough transform algorithm disregards any gaps as long as it can still parametrize the line with a sufficient number of votes. This map indicates all the paths the particles took in crossing the detectors.

The ratio between these two maps will then reveal those areas that were not hit while they should in fact have had some charge cross their surface via equation 5.3:

$$\text{ratio} = \frac{\text{hits only [Illumination]}}{\text{hits and nohits [Hough line]}}. \quad (5.3)$$

In figures 5.17 and 5.18, this ratio is shown for each of the drift volumes, showcasing threshold differences and truly unresponsive areas. An overall response rate exceeding 50% can be seen across all modules with Module-0 leading the group at a consistent level of 90%. Module-1 also exhibits uniform behavior across the pixel planes, with the exception of the top left tile in TPC2. Module-2 and Module-3 do show differences in thresholds apparent from the changes in responsiveness when moving between adjacent ASICs. In general, the MIP maps show that Module-2 should be studied in more detail as values range from 0.3 to 0.8 across the detection walls.

Ultimately, this tool serves the purpose of quickly scanning the planes to localize potential misbehavior, but it lacks the ability to better explain the pixel pad sensitivity.

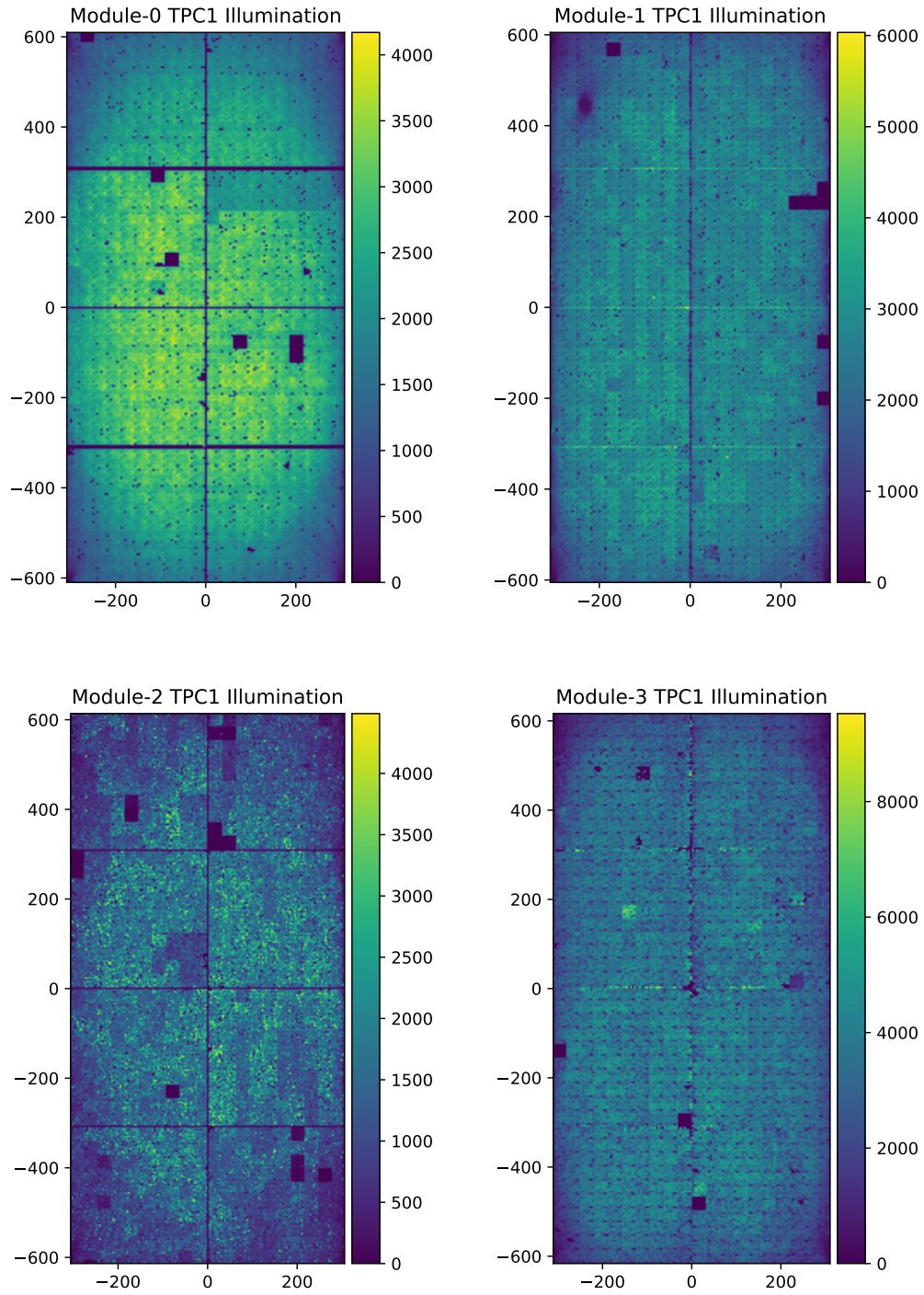


Figure 5.13: Illumination plots for the first TPC drift volume of Module-0 (top-left), Module-1 (top-right), Module-2 (bottom-left), Module-3 (bottom-right). The x-axis and y-axis represent the horizontal and vertical position on the pixel plane, respectively. The color scale indicates the number of times a specific pixel was hit by incoming charge.

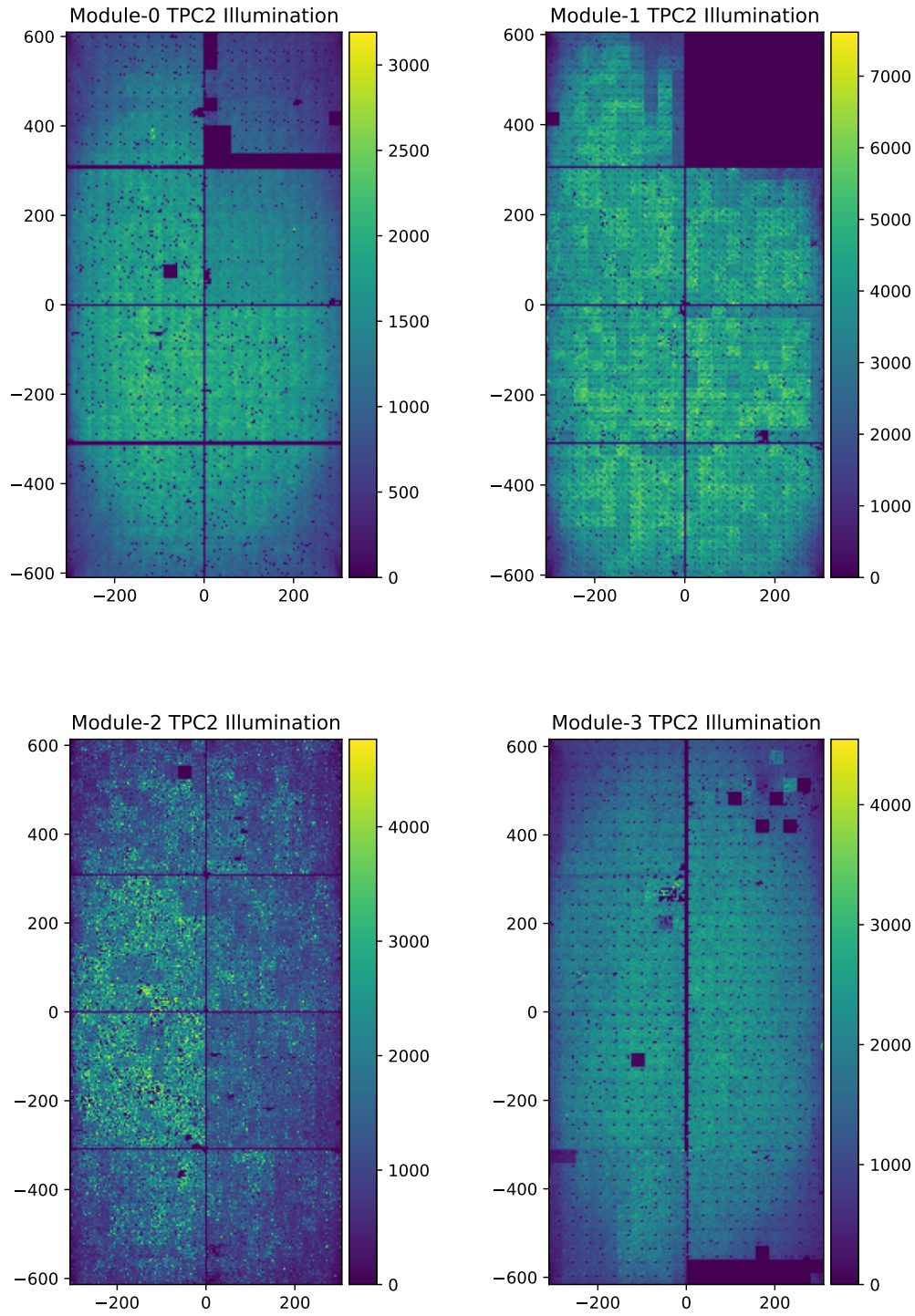


Figure 5.14: Illumination plots for the second TPC drift volume of Module-0 (top-left), Module-1 (top-right), Module-2 (bottom-left), Module-3 (bottom-right). The x-axis and y-axis represent the horizontal and vertical position on the pixel plane, respectively. The color scale indicates the number of times a specific pixel was hit by incoming charge

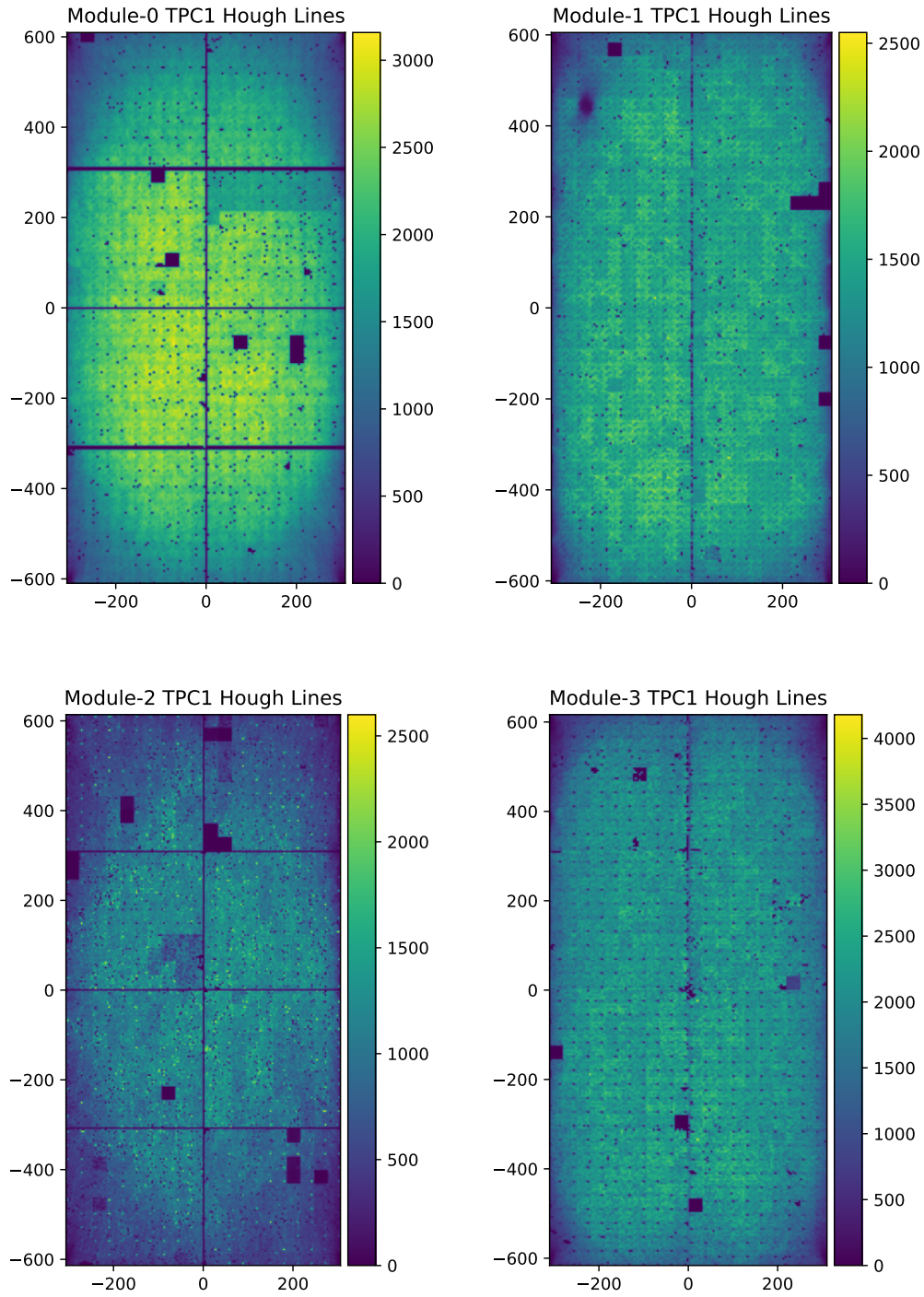


Figure 5.15: Hough line plots for the first TPC drift volume of Module-0 (top-left), Module-1 (top-right), Module-2 (bottom-left), Module-3 (bottom-right). The x-axis and y-axis represent the horizontal and vertical position on the pixel plane, respectively. The color scale indicates the number of times a specific pixel was crossed by the Hough line.

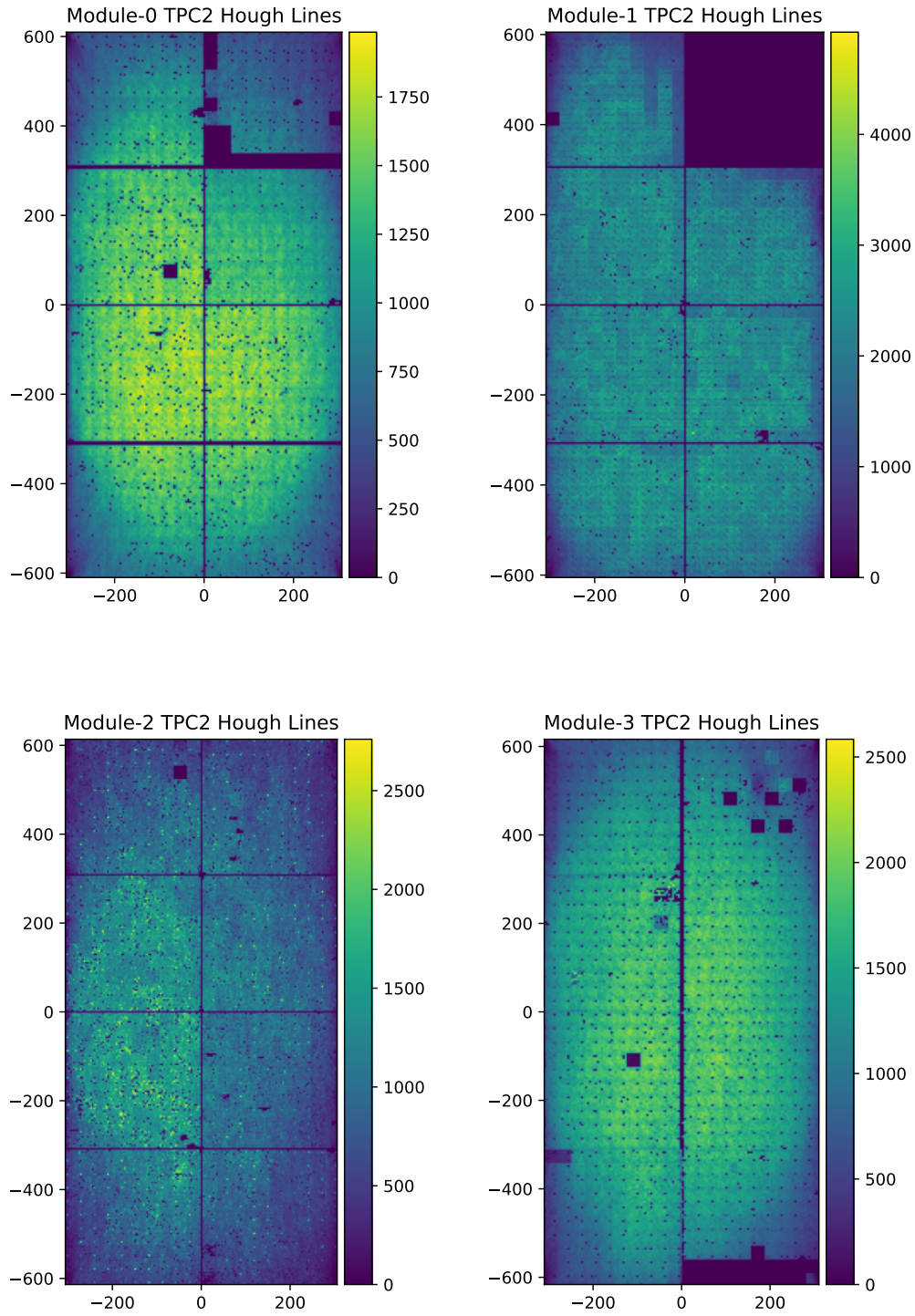


Figure 5.16: Hough line plots for the second TPC drift volume of Module-0 (top-left), Module-1 (top-right), Module-2 (bottom-left), Module-3 (bottom-right). The x-axis and y-axis represent the horizontal and vertical position on the pixel plane, respectively. The color scale indicates the number of times a specific pixel was crossed by the Hough line.

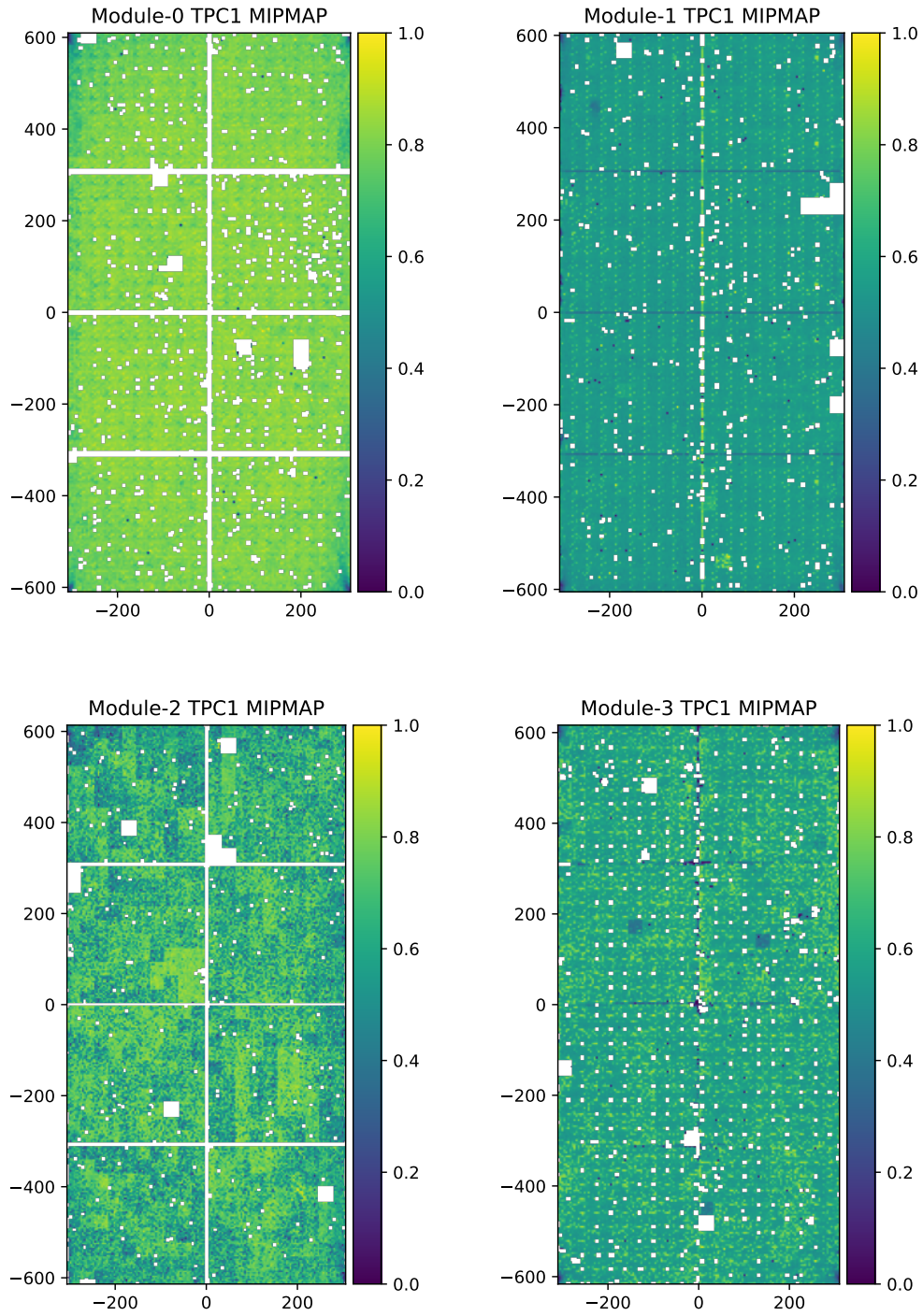


Figure 5.17: MIP response maps for the first TPC drift volume of Module-0 (top-left), Module-1 (top-right), Module-2 (bottom-left), Module-3 (bottom-right). The x-axis and y-axis represent the horizontal and vertical position on the pixel plane, respectively. The color scale indicates the ratio described by equation 5.3.

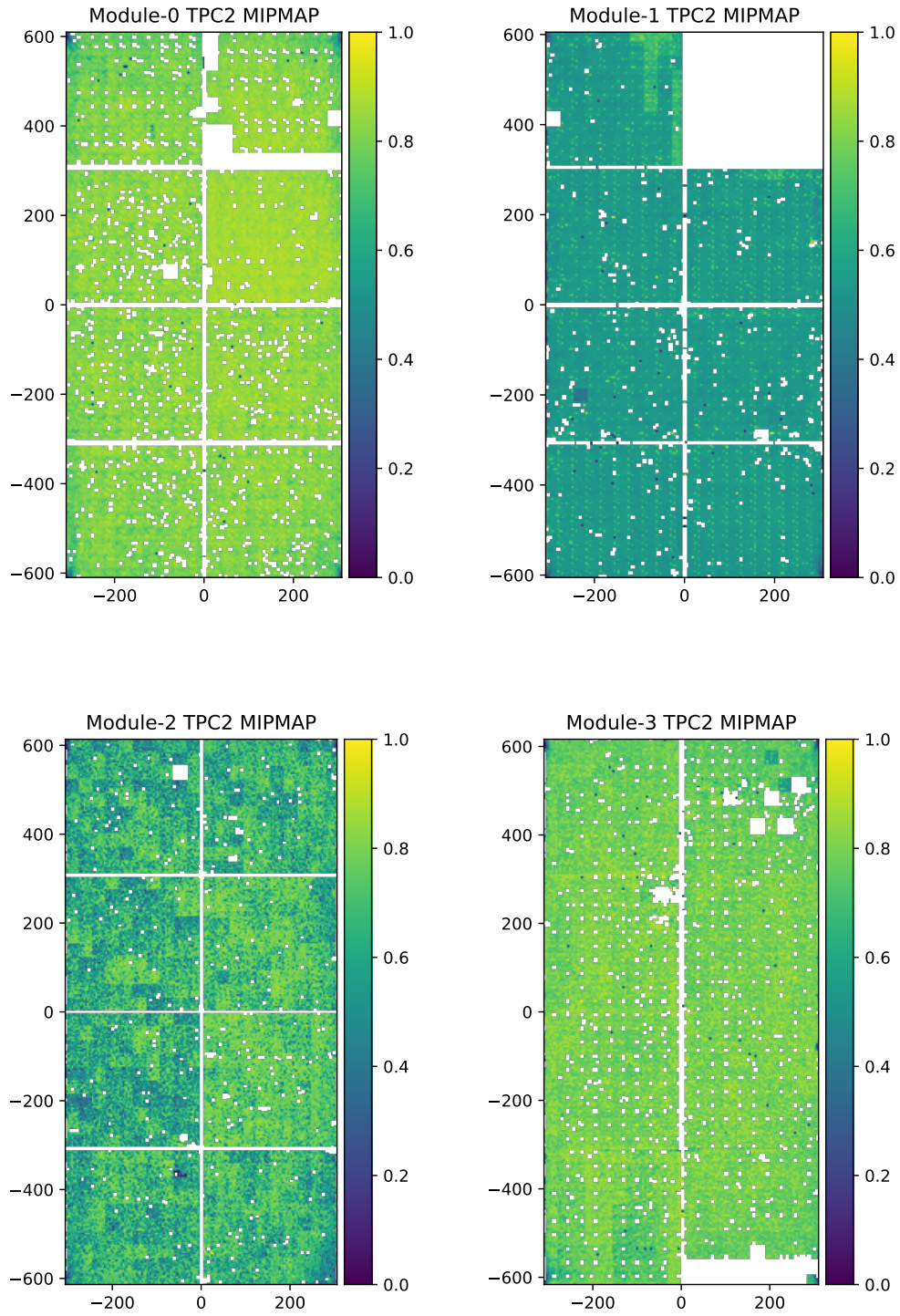


Figure 5.18: MIP response maps for the second TPC drift volume of Module-0 (top-left), Module-1 (top-right), Module-2 (bottom-left), Module-3 (bottom-right). The x-axis and y-axis represent the horizontal and vertical position on the pixel plane, respectively. The color scale indicates the ratio described by equation 5.3.

5.3.3 Pixel efficiency

The pixel efficiency study attempts to make a representation of the pad's sensitivity by relating the distance in x and y separately between its center and the ionization axis to the trigger rate. As the track covers a wide area of the pixel pad, it is impossible to tell what part of the track generated the charge that triggered data taking for the crossed channel. This means that there is some ambiguity in picking a point on the line from which to measure the distance from the pixel's center. Before those are discussed, this ionization axis has to be found first. This is done in exactly the same way as for the previous study (125 votes, crossing tracks only and the linearity constraint) except that only events in which a single line was found are allowed. A visualization of the method to find the efficiency is provided in figure 5.19.

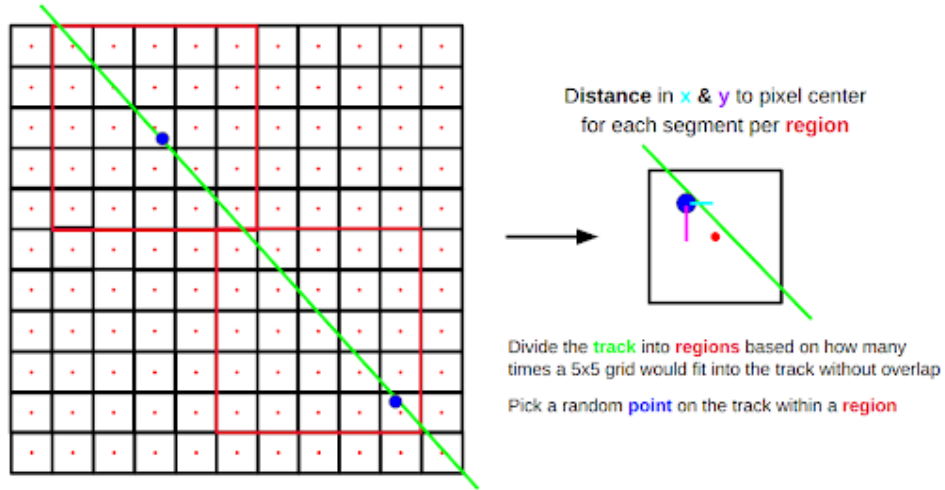


Figure 5.19: Pixel pad efficiency method using randomized segmentation.

The individual steps are outlined below:

- Segmentation of the track into pieces of 0.1 mm.
- Picking the point of closest approach.
- Randomly picking points along the track with a separation of at least several pixels between them in order for double counting to never occur. This seems to be the most viable method as it removes the dependencies introduced by the previous two.

After many rounds of testing, the random segmentation method proved to be the most reliable and unbiased. Hence the discussion will be focused around this method. Similarly to creating the response maps, two separate components will be needed to calculate the pixel pad efficiency. The following steps must be taken. First, all of the Hough lines for

10000 events are collected. An example is indicated by the green line in figure 5.19. The black squares represent a subset of the pixel plane with the red dots marking the centers.

The goal is to understand how often data taking is triggered on a certain pixel when the main ionization axis is at a certain distance away from its center. The assumption is that most of the charge is localized around this axis and that the pixel was thus triggered by the specific part of the cloud. As explained before, by randomly picking points, as marked by the large blue dots, along the axis limits the resulting efficiency bias.

The interest resides in finding the trigger rate for a square of 5 by 5 pixels, which translates to ‘how often does the charge indicated by the blue dot trigger pixels at a distance of at most two neighbors away’. To reduce double counting any of the measured hits, a multitude of grids (the large red squares) is used to subdivide the line into segments. Within these grids, a point is then randomly picked to become the effective charge. If two consecutive blue dots are too close together to the degree that they are within a single grid size distance from one another, one of them is rejected completely. This way the charge recording central pixel (the one containing the dot) is isolated from the next one and no single track segment is considered for two different response maps.

The maximum number of randomly picked points is equal to the track length divided by the grid size scaled by the angle of incidence. For vertical or horizontal lines, this is simply five pixels wide. For any other orientation, the denominator has to be larger, as can be seen in figure 5.19. The green segment within the red square exceeds five pixel widths.

The remaining blue dots after the proximity filter form the basis of this study. As shown in the example of that same image, the residuals in X (cyan) and Y (purple) with respect to the pixel’s center are determined separately. Initially this is only done for the charge-containing pixel. Its surface is divided into 20 by 20 bins leading to lengths and widths of 0.22 mm and 0.19 mm for Module-0, 1, 3 and Module-2, respectively. These are then filled if the previously calculated residuals fit within the bin’s boundaries. So, a residual of $x = 1$, $y = 1$ would fill the histogram bin spanning the surface between 0.8868 – 1.1085 and 0.8868 – 1.1085 with an entry of ‘1’. This would serve the same purpose as the Hough line plot for the MIP response maps.

The numerator in the ratio to produce the efficiency map comes from the same residual calculation, but this histogram is only filled with a ‘1’ in case the pixel actually recorded

a hit. The ratio between those two then shows how often the a trigger is induced for charge arriving at that specific position on the pixel pad. However this description covers only the middle image in each of the plots shown in figures 5.20, 5.21, 5.22, 5.23 and 5.24. To extend this to all 25 pixels shown here, the same principle can be applied over larger distances. So, instead of finding only the residuals as suggested by the example schematic drawing, distances are now calculated between the blue dot and each of the 24 surrounding pixels' centers, which will then cover the entire 5 by 5 grid. The only difference in constructing the histograms for these cases is the 'hit' condition in the numerator. These bins are only filled if the pixel of which the distance to its center is considered, recorded any charge.

Upon studying the figures, it is clear that the pixel pad efficiency goes down as you move away from the center. The drop is more significant in the x-direction than in the y-direction, but it shows similar behavior across all modules including the simulation. This is to be expected and can also be understood from the extreme example in which we would examine a pixel at the other end of the detector from where the charge was located. In that scenario, no trigger would be expected.

In a general sense, the efficiency sits above 80% with Module-1, Module-3 TPC1 and the simulation performing best at a rate of 87% or higher and even peaking above 96% for the central pixel. The shape of the map comes in two forms. There is a diamond pattern revealed by the study of Module-0 and Module-3 TPC2 and a rectangular pattern exhibited by the other drift volumes. The overall values are higher in the latter case. The most striking difference resides within Module-3, where with identical geometry and identical incoming track properties two different efficiency maps are produced in TPC1 and TPC2.

When comparing the individual axes, different behavior is observed. While there is a gradual decrease in efficiency for both dimensions, the drop in x is more substantial than in y. This can be understood when considering the track properties. Cosmic rays come in from above, so the majority will travel along the y-axis (vertical dimension of the pixel plane) ionizing charge along its path. Finding hits in a neighboring pixel to the top or the bottom of the central one is thus more likely by design and is less dependent on the actual track width.

The goal is to understand the differences between these overviews and quantify the bias that is introduced because of it when measuring ionization left behind by crossing charged

particles. Having the capability of running this diagnostic framework while the modules are taking data would then assist in understanding the operating conditions. To this end the aforementioned analysis procedure has been transformed into an executable program that can be incorporated into the overarching system. The next section will shed more light on how it is used.

As all of the work leading up to this point had the end goal of optimizing the ArgonCube 2 by 2, this chapter will be concluded by a first look at its event displays (see [section 5.4](#)) below.

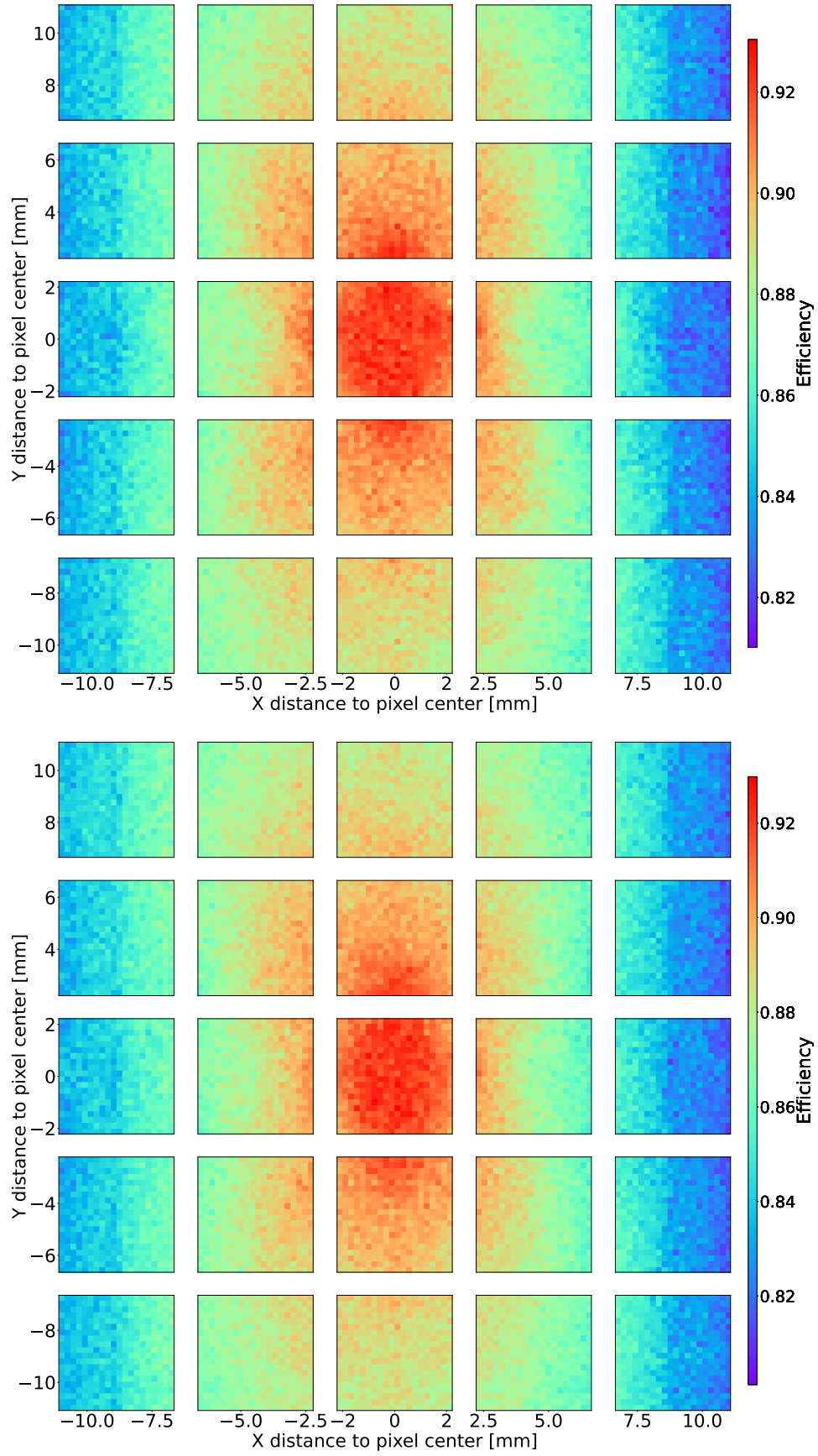


Figure 5.20: Pixel pad efficiency in both TPC drift volumes of Module-0 [TPC1 (top), TPC2 (bottom)].

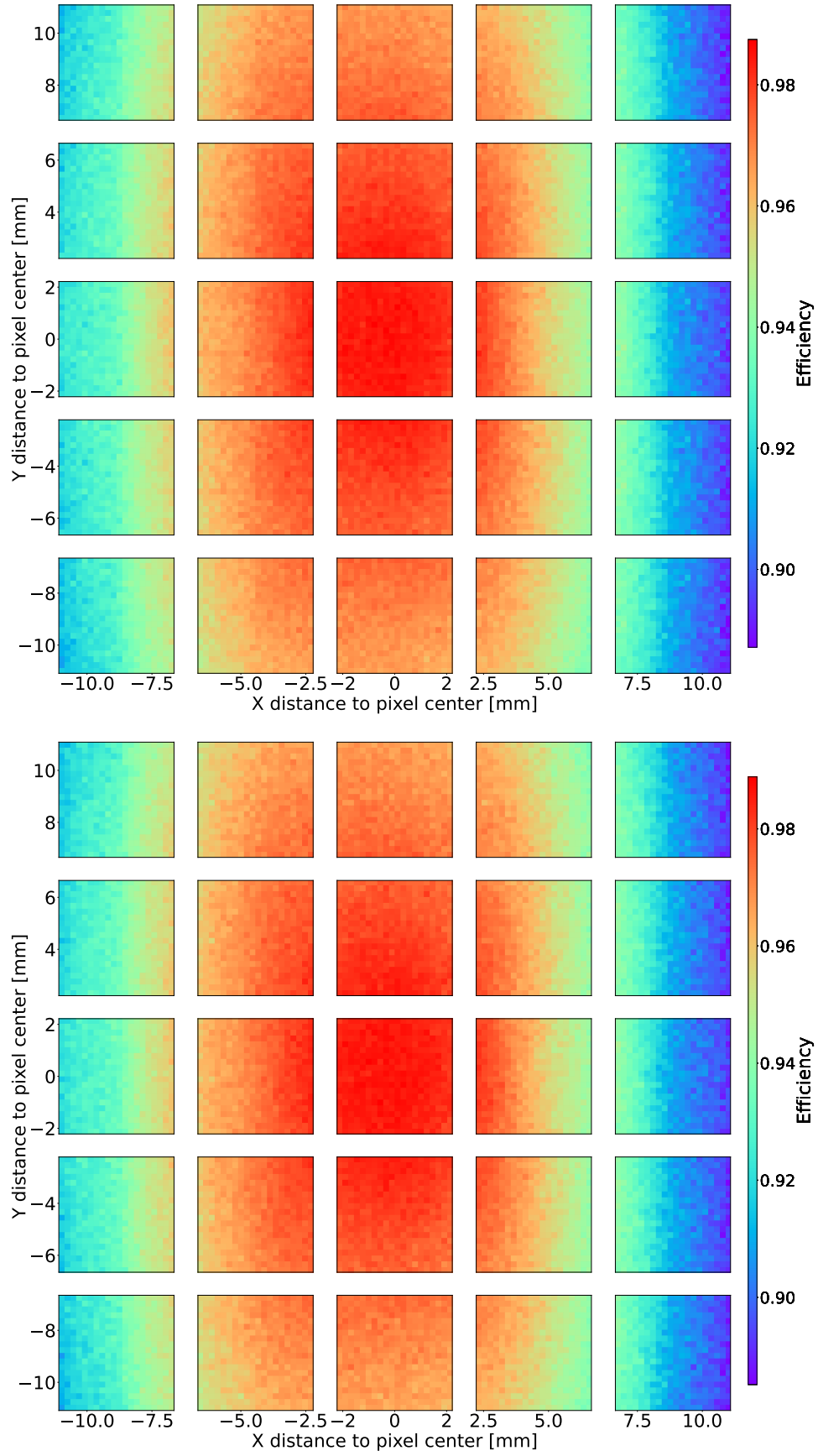


Figure 5.21: Pixel pad efficiency in both TPC drift volumes of Module-1 [TPC1 (top), TPC2 (bottom)].

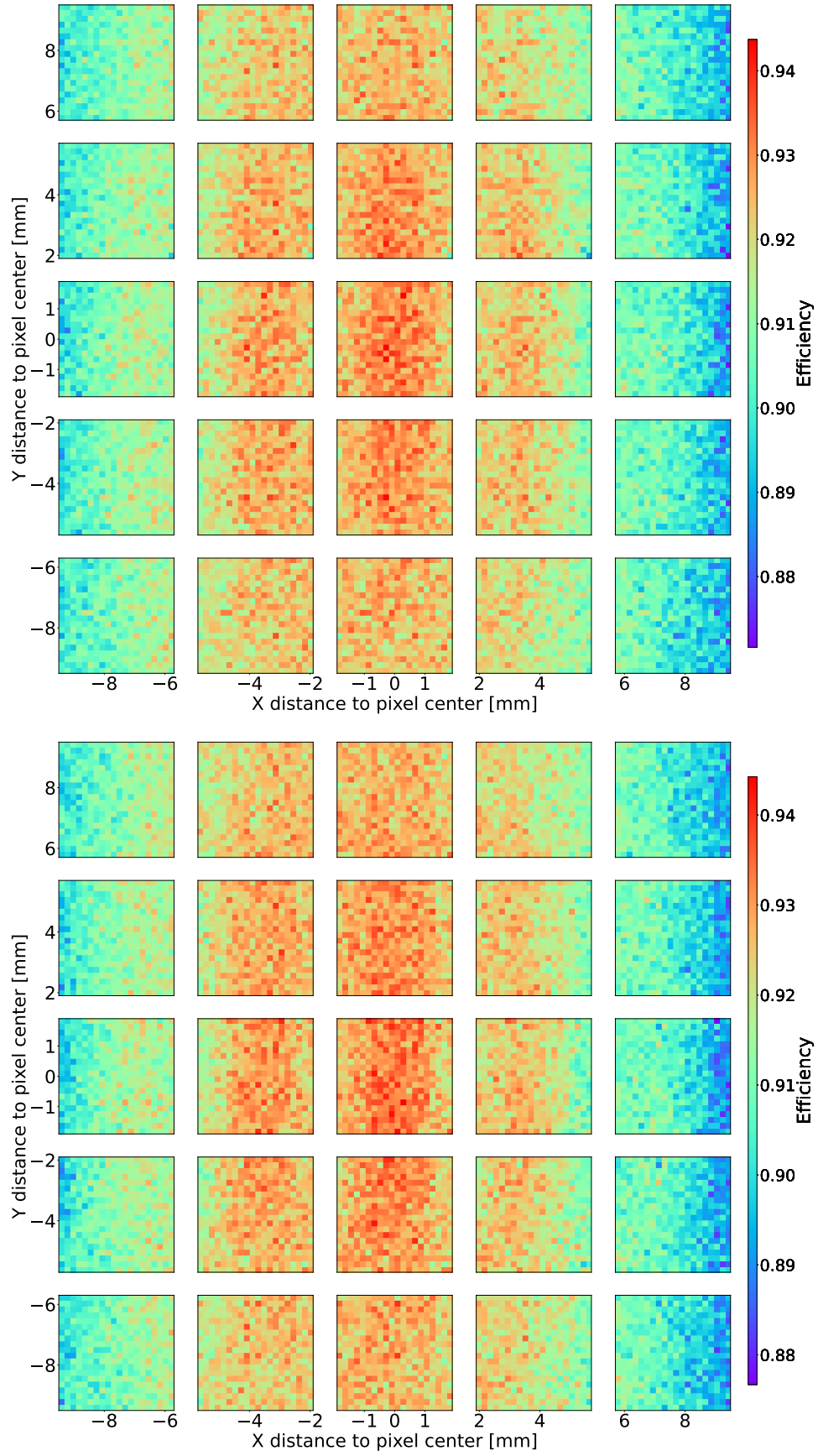


Figure 5.22: Pixel pad efficiency in both TPC drift volumes of Module-2 [TPC1 (top), TPC2 (bottom)].

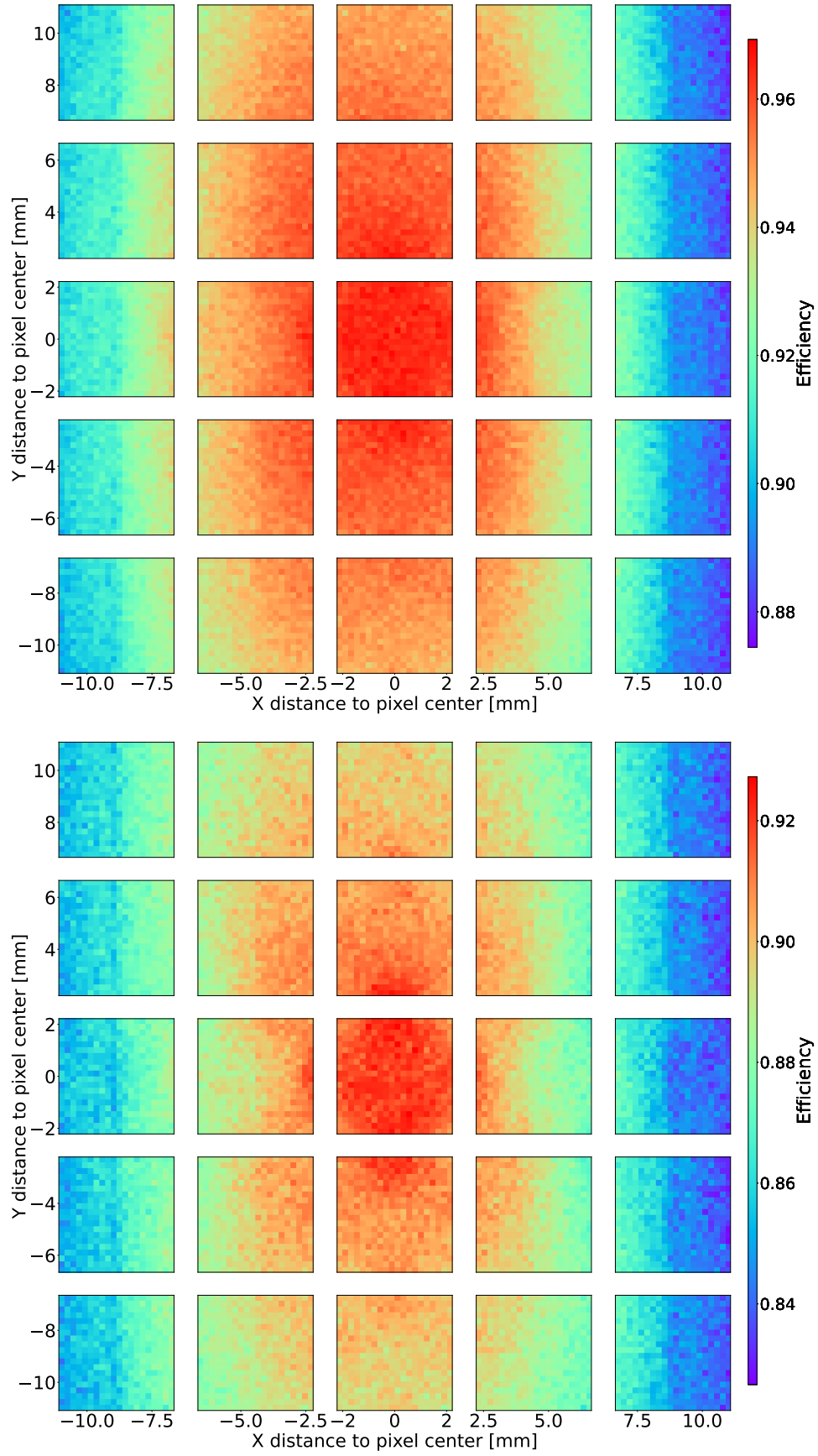


Figure 5.23: Pixel pad efficiency in both TPC drift volumes of Module-3 [TPC1 (top), TPC2 (bottom)].

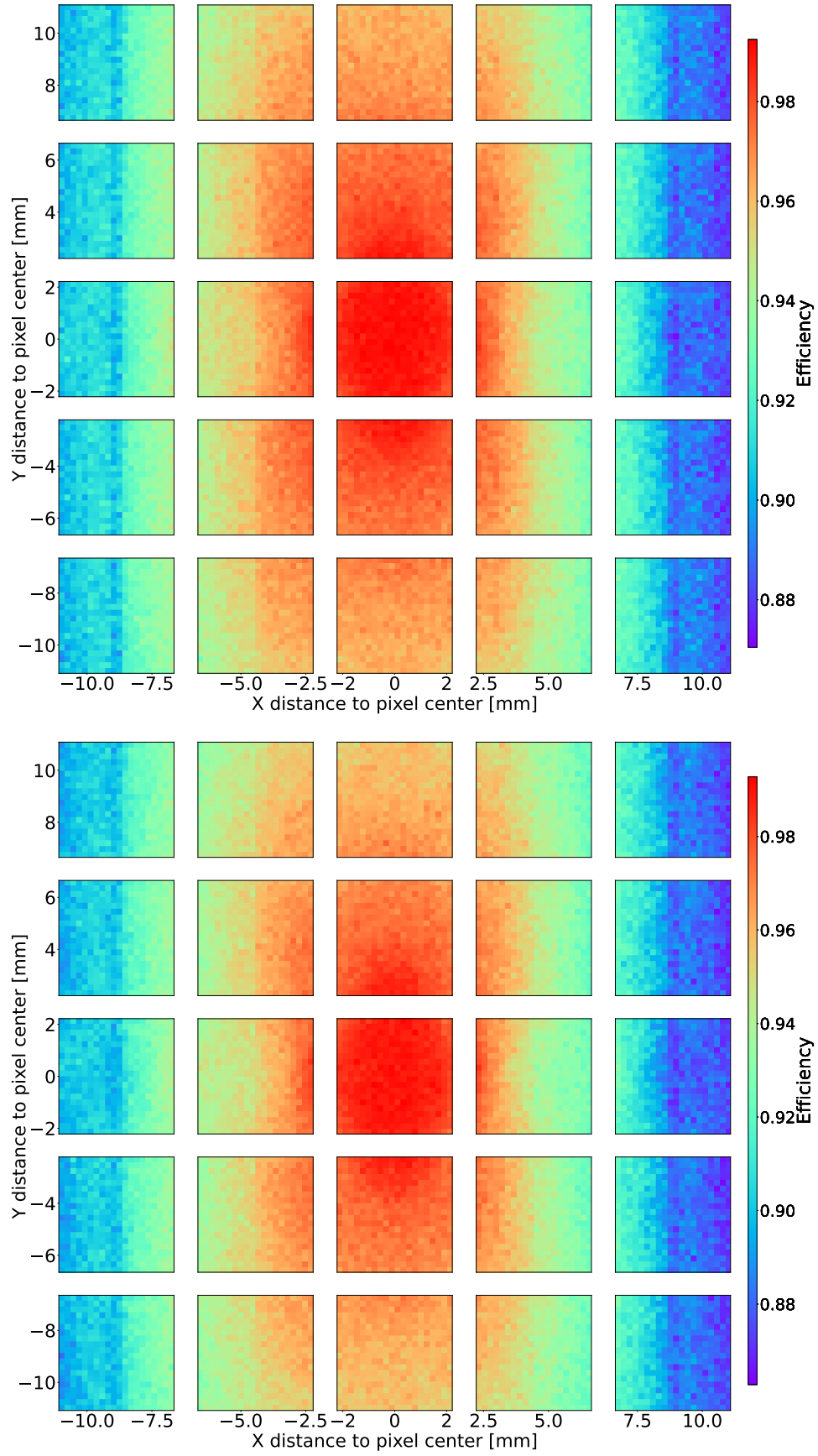


Figure 5.24: Pixel pad efficiency in both TPC drift volumes the simulation of Module-1 [TPC1 (top), TPC2 (bottom)].

5.4 ARGONCUBE 2X2

After completion of cosmic ray runs in Bern, Switzerland, the four modules were shipped to Fermilab in Illinois where they went through another round of quality assurance (QA) and control (QC) tests for both the light and charge readout systems. These were done to assess if the transportation overseas or any of the modifications made to the detector had had any impact on its condition before ultimately being installed into the 2 by 2 cryostat. The QA/QC procedure for the charge readout consists of evaluating the performance of each tile individually by testing the responsiveness of the 100 constituent ASICs. As the readout is chained, it is paramount that a network between the channels be established and data be put through. All of these tests were done without liquid argon, limiting the scope but also the cost.

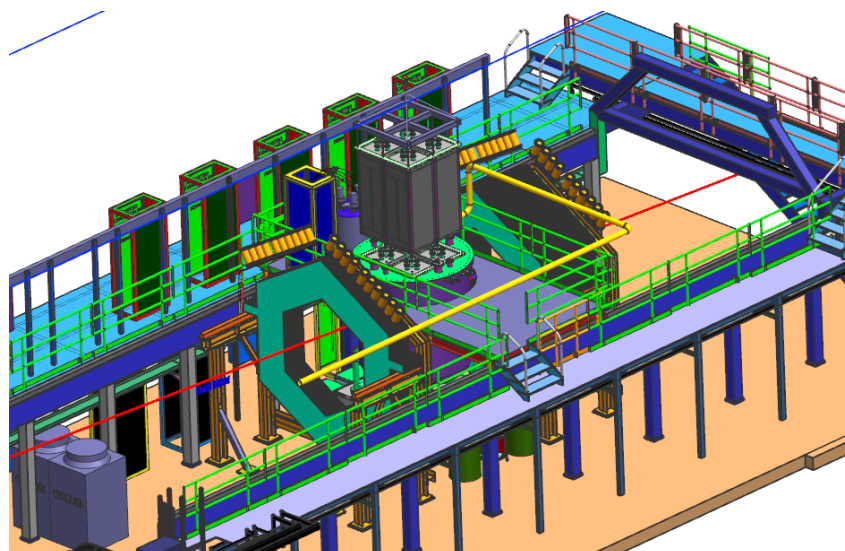


Figure 5.25: MINERvA 2 by 2 in the MINOS underground hall at Fermilab.

After successful completion of these QA and QC tests, the modules were eventually moved underground into the MINOS hall. A full overview can be seen in figure 5.25. The cryostat is fit in between repurposed scintillation detection planes from MINERvA that will serve as trackers for particles exiting the liquid argon enclosure [162]. As of writing this chapter, data taking has started and the first event displays have been produced (see appendix E, figures E.2, E.3).

THE T2K EXPERIMENT

6

As we have seen in the neutrino beamlines section, the accelerator plays a key role in oscillation physics. It sets the energy of the incoming protons and together with the magnetic horns determines the spectrum of the outgoing mesons and subsequent neutrinos. In the Tokai-to-Kamioka, or T2K experiment, the accelerator and the near detector are based at J-PARC, Tokai in the Ibaraki prefecture in Japan [163]. The far site is located in Kamioka. Figure 6.1 shows the distance the neutrinos have to cross to go from one to the other.

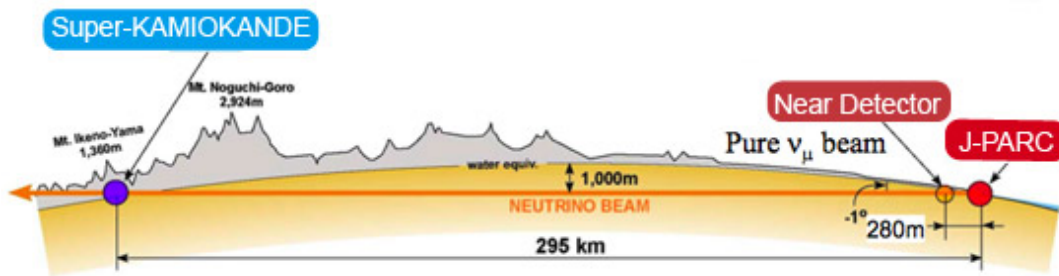


Figure 6.1: Overview of the near and far sites for the T2K experiment [65].

6.1 THE J-PARC ACCELERATOR

The accelerator consists of three separate stages each contributing uniquely to the final energy. First, there is a 249 m linear accelerator where the H^- beam is accelerated up to 400 MeV before it is charge-stripped upon entering the rapid-cycling synchrotron (RCS).

The converted H^+ beam is now circularly accelerated up to 3 GeV. The RCS operates two bunches per 25 Hz cycle. Around five percent of the bunches then make it to the final stage in the Main Ring (MR) synchrotron. The rest is delivered from the RCS directly to the Material and Life Science Facility (figure 6.2) [164]. Perhaps this is where that more direct ‘impact’ written about in the introduction becomes apparent.

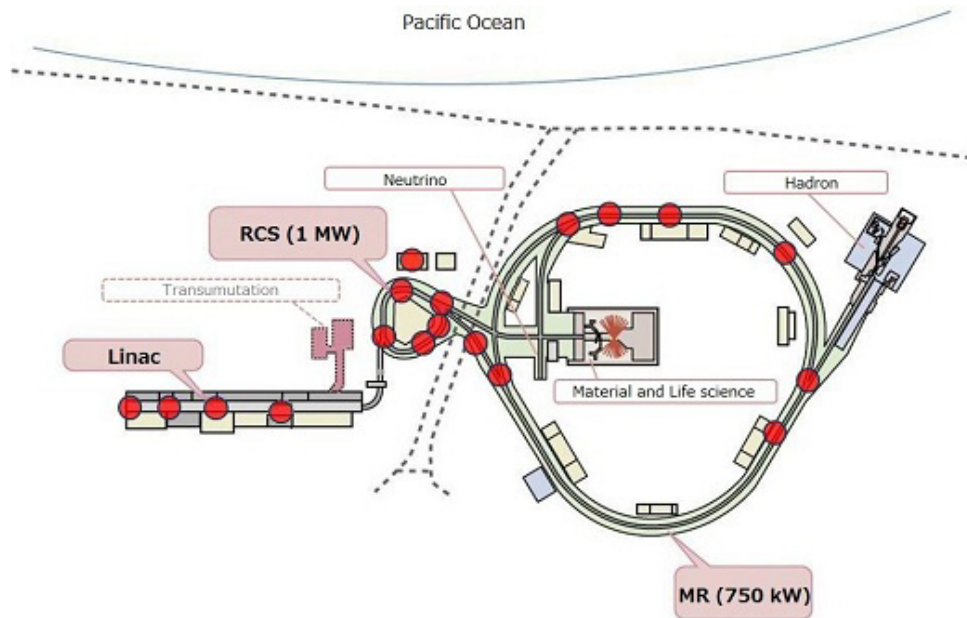
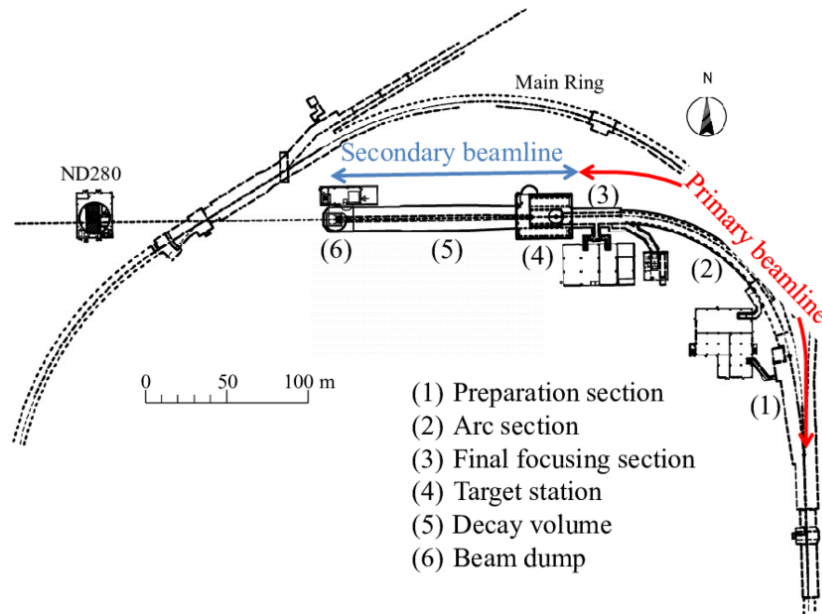


Figure 6.2: The RCS and LINAC in the J-PARC accelerator facility [164].

Nevertheless, the proton beam reaches its ultimate energy of 30 GeV within the Main Ring before being sent off to T2K. The Main Ring runs with eight bunches at a 0.5 Hz cycle and has two separate extraction points using a different methodology depending on the receiving facility. On the one hand, there is the hadron facility that requires slow proton extraction. On the other hand, there is the neutrino beamline that asks for all bunches in one single turn with the help of kicker magnets essentially kicking the protons into the desired beamline [163].

For T2K, the protons arrive in the so-called primary beamline, which is responsible for pointing them in the direction of Kamioka (figure 6.3). It is a three-stage machine whereby the first section ensures the protons are prepared to be received by the bend portion of the beamline. By guiding the beam through a sequence of four steering magnets, two dipole and five quadrupole, over a length of 54 meters, the beam is ready to be curved [165].

The second stage of the arc is composed of 14 doublets of superconducting combined function magnets (SCFMs). The protons leave this part at a 80.7° angle into the direction



of the Super-Kamiokande detector. Before entering the target hall, there is a final focusing section containing four steering, two dipole and four quadrupole magnets that direct the beam 3.657° downwards from the horizontal and onto the target station. The beam is measured all along this portion to monitor the loss, the intensity, the position and the angle. To this end, there is a grand total of five current transformers (CTs), 21 electrostatic monitors (ESMs), 19 segmented secondary emission monitors (SSEMs) and 50 beam loss monitors (BLMs) installed to capture the necessary metrics in an attempt to best estimate the outgoing proton beam flux. In figure 6.4 some of the positions of these monitors are shown [163].

The proton bunches arrive at the target station in 700 ns intervals and last for 58 ns. The target station is the first element of the secondary beamline that the beam comes across (see figure 6.3). It is made up of the beam window, the baffle, the optical transition radiation monitor, the graphite target and the magnetic focusing horns all contained within a helium vessel at a pressure of 50 Pa. Each of these components serves a different purpose. The vessel itself is a 10-cm-thick steel enclosure with a volume of 15 m by 4 m by 11 m. The irradiation of the equipment by the through-going proton beam causes the temperature to rise. Water cooling channels welded to the surface of the vessel prevent the structure from deforming thermally. The 2 meter iron and 1 meter concrete shielding inside the vessel and the 4.5 meter thick concrete wall are necessary to block the radiation from reaching the surface. As none of these components has infinite lifetime and the area is not accessible by humans for a while after operation, there are remote controls installed to deal with any required maintenance [163].

The vessel is entered through the beam window, which consists of two 0.3-mm-thick titanium alloy-skins (Ti-15V-3Cr-3Sn-3Al). This alloy is chosen for its high specific strength, and high thermal shock resistance to pulsed beams, which results from its relatively low modulus and coefficient of thermal expansion. On top of that the window is helium-cooled to counteract the instantaneous pressure rise per pulse of up to 160° [163].

Once the protons are inside, they meet the baffle. The baffle is a graphite block with a 30-mm-diameter hole for the ‘nominal’ beam to pass through. The structure itself is designed to prevent any diverging protons from damaging other components in the target station further downstream.

6.2 THE OPTICAL TRANSITION RADIATION MONITOR

After the beam is collimated by the magnets in the beamline and the baffle, it will reach the final beam monitor. This is the Optical Transition Radiation Monitor, or OTR for short. Its position with respect to the SSEMs can be found in figure 6.5. It is the only one of its kind in this particular system. The other measuring devices are not able to survive in the high radiation enclosure and are thus limited to the primary beamline. Without the OTR, the beam’s shape would have to be extrapolated to the interaction center from a point outside the vessel, limiting the understanding of its characteristics just before colliding with the target [167].

The OTR relies on transition radiation produced from the incoming proton beam passing

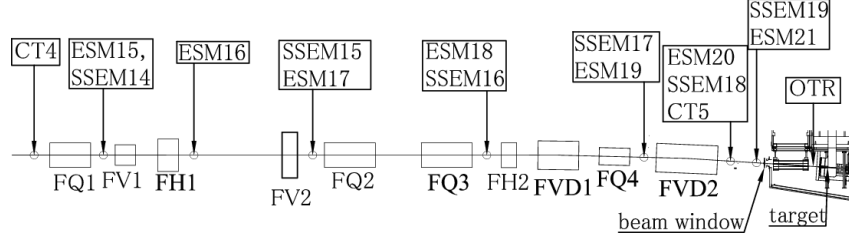


Figure 6.5: Overview of the SSEMs and the OTR monitor [166].

through a thin foil. The OTR houses a total of eight separate foils on its rotatable disk. Of these, one is empty, one is made of ceramic wafer, one consists of aluminum and then there are five titanium ones of 50 micrometer thickness. Two of the titanium foils have holes in them in either a grid or cross pattern.

Transition radiation is created when a charged particle crosses the boundary between two media with different dielectric constants forcing it to reshape its electric field by emitting photons. The visible light coming from this process is produced in a narrow cone around the beam itself with the maximum of the angular distribution at $\theta = \frac{1}{\gamma}$ with $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ representing the Lorentz factor. In cases where the second medium is very thin, there will be an additional lobe in the backward-going direction. The number of photons that this yields can be expressed per frequency range $d\omega$ and solid angle $d\Omega$, assuming relativistic particles, in the reduced form of equation 6.1 [168]:

$$\frac{d^2 N}{d\omega d\Omega} = \frac{2e^2}{\pi \hbar c \omega} \times \frac{\sqrt{\epsilon - 1}}{\sqrt{\epsilon + 1}} \times \frac{2}{\theta^2 (\theta^2 + \gamma^{-2})^2}. \quad (6.1)$$

Having this light emanate in the same direction as the proton beam would still not allow for a beam monitor to observe it. By rotating the aforementioned foils to a 45° angle, the backward-going light is now perpendicular to the beam's direction shown in figure 6.6 [168].

Even a radiation-hard camera would not make it through the entire lifespan of the T2K experiment and hence the OTR light has to be guided through the concrete and iron shielding. This is done with a set of four parabolic mirrors, of which the orientation can be seen in figure 6.7. These mirrors are 90° off-axis, making their effective focal length twice the focal distance of the parent parabolic surface. The OTR lobes move further apart as they travel away from the foil until they hit the first mirror at 110 centimeters away [166].

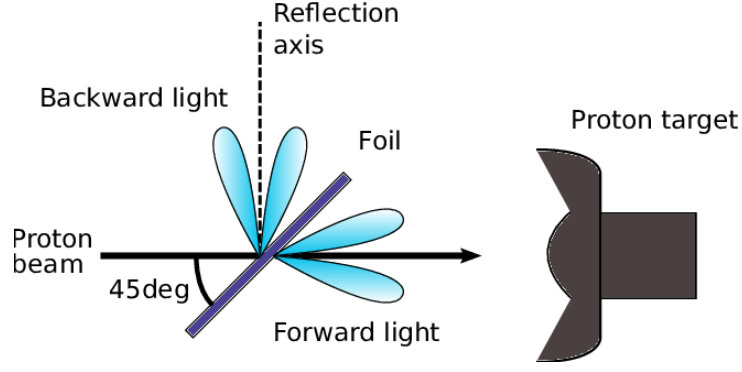


Figure 6.6: Schematic drawing of optical transition radiation coming from a foil oriented at 45° . The backward lobe exits at an angle of 90° [168].

By picking this distance, we ensure that the rays leave Mirror 1 in parallel and are focused by Mirror 2 again reaching the smallest beam width at 110 cm. Mirror 3 is positioned at twice that distance and thus the rays arrive in a similar fashion to how they were reflected off of the first mirror. From Mirror 3 to 4, the rays are parallel again and pass through a 25 cm quartz window that separates the helium from the outside before being focused at a 60 centimeter distance from Mirror 4 onto the radiation tolerant camera. While the first three mirrors have the same focal length, Mirror 4 has a focal length of 30 centimeter. This means that the image at the camera is 45% smaller than what left the foil. The foil sits at a diameter of 5 cm and needs to fit within the 4 cm diameter fiber table that is connected to the camera. The taper reduces the image diameter further from 4 cm to 1.1 cm so it can be accepted by the camera [168].

With this many optical components in the relay chain, the resulting image is not a direct replica of the original one. Each reflection introduces a slight distortion and this has to be taken into account when trying to determine the proton's beam position and angle. In order to retrieve the original image at the foil from the distorted image at the camera, a map describing the transformation has to be produced. To this end, the OTR foil with the grid of holes is used. The calibration process maps points on the foil to positions on the camera and builds a map that can undo the distortion effects when taking data. The impact of the OTR is displayed in table 6.1, where both the angles and positions with and without this additional data point in the extrapolation are mentioned. Now that both of these metrics are measured to their best extent, it is time to collide to protons with the target [168].

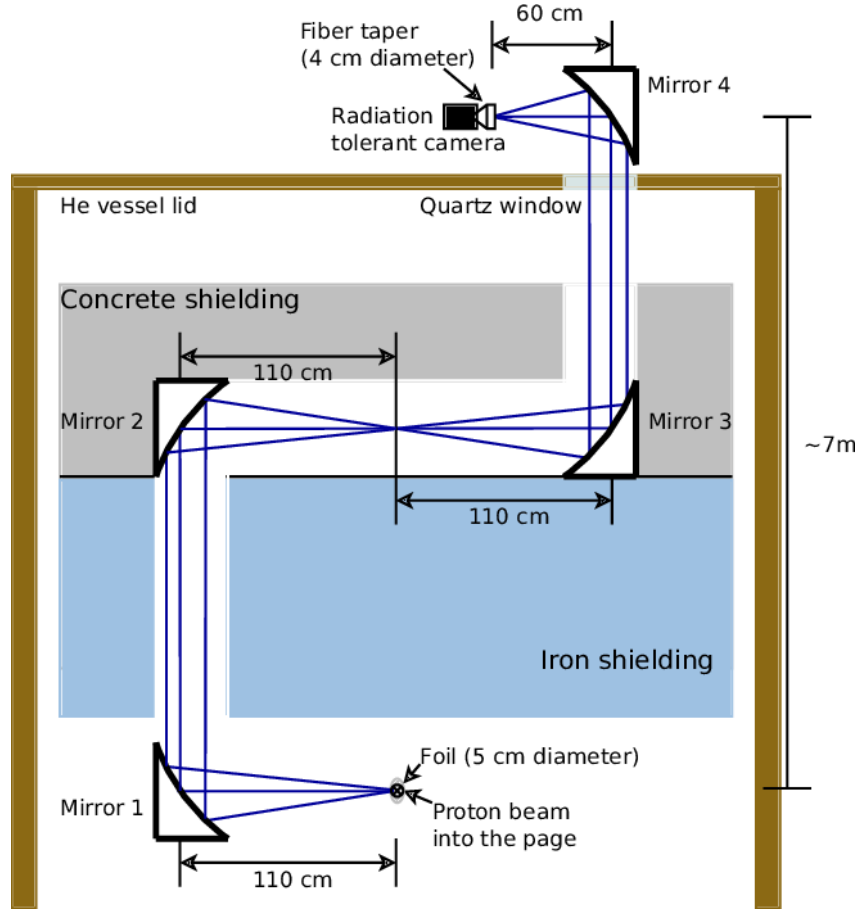


Figure 6.7: Overview of the optical system guiding the OTR light [167].

6.3 THE TARGET STATION

The target is a graphite rod of 1.9 interactions lengths or 91.4 cm long and 2.6 centimeter in diameter. This material is used specifically because of its lower density at 1.8 g/cm^3 as a higher density substance would melt under the heat load of the pulsed beam. The core, along with a surrounding 2-mm-thick graphite tube, is sealed inside a titanium case, which is 0.3 mm thick. Helium gas flows through the gaps between the core and tube and between the tube and case to cool the target and protect it from overheating. And overheat it definitely would as the center reaches temperatures of up to 700 degrees Celsius upon interacting with the 750 kW proton beam.

6.3.1 Focusing Horns

The interactions between the incoming proton beam and the nucleons in the graphite target yield the mesons that were described before. At T2K beam energies of 30 GeV,

	Extrapolation uncertainty	
	With OTR	Without OTR
X pos	0.5 mm	0.5 mm
Y pos	2.3 mm	0.5 mm
X angle	0.08 mrad	0.08 mrad
Y angle	0.5 mrad	0.3 mrad

Table 6.1: Extrapolation uncertainty on beam profile with and without the OTR.

the main contribution to the secondary particles will come from pions with a smaller fraction from kaons. Remember that the mesons provide the last opportunity to focus the beam. The final components in the target hall are thus a set of three magnetic horns to do exactly that. Each horn is made up of two coaxial conductors, which together create a closed volume. A current is run through the conductors to generate a toroidal magnetic field pointing the Lorentz force towards the central axis. The horn conductor is made of 6061-T6 aluminum alloy. The dimensions of the horns are as follows:

- First horn: minimum inside diameter of 54 mm, inner conductor thickness of 3 mm, outside diameter of 400 mm, and length of 1.5 m.
- Second horn: minimum inside diameter of 80 mm, inner conductor thickness of 3 mm, outside diameter of 1000 mm, and length of 2 m.
- Third horn: minimum inside diameter of 140 mm, inner conductor thickness of 3 mm, outside diameter of 1400 mm, and length of 2.5 m.

The sizes of the horns are optimized in such a way as to maximize the neutrino flux. By making the conductor as thin as possible, pion absorption is heavily suppressed and by making the inner diameter as small as possible the magnetic field is maximized. The first horn completely encompasses the target. All the particles resulting from the proton interactions are collected here, while they are focused at the second and third horn. At the operation current of 320 kA, the resulting magnetic field is of the order of 2.1 T. This focusing step improves the neutrino flux at the far detector by a factor of 16 at the neutrino energy peak of 0.6 GeV, truly showing the importance of the horns in this concept [169].

6.3.2 Decay pipe

That concludes the elements within the target station. The bundle of charged mesons is sent down the decay pipe, a 96-meter-long, 1500-cubic-meter concrete-shielded steel tunnel once again filled with helium. The helium is kept at a pressure of 1 atmosphere to

minimize pion absorption during flight and limit the production of tritium and nitrogen oxides. At the end of the decay volume at around 109 meters from the target sits the beam dump. Its core consists of 75 tons of graphite with a density of 1.7 g/cm^3 , a length of 3.17 meters, a width of 1.94 meters and a height of 4.69 m. The beam dump is shielded by fifteen iron plates outside the vessel and two inside at the downstream end of the graphite core, providing a total iron thickness of 2.40 meters. Only muons with momenta above $5.0 \text{ GeV}/c$ sometimes make it through the beam dump to reach the muon pit. The structure is cooled by water to keep it at around 150 degrees Celsius for the 750 kW beam.

Just behind the beam dump, the muon monitor records the direction and intensity of the neutrino beam on a bunch-by-bunch basis by measuring the distribution profile of secondary muons. The direction is determined as the line connecting the target and the center of the muon profile. The center of the profile is measured to a precision of 3 cm, which corresponds to a 0.25 mrad (or 0.014°) precision on the neutrino angle. The beam's intensity should have an accuracy better than 3%.

The nuclear emulsion detector behind the muon monitor measures the momentum and the flux of the muons that are still present at this stage. Paragraphs could be written on both the beam monitor and the emulsion detector, but that is beyond the scope of this work. Here the focus will lie on the near detector, which is the following element along the neutrinos' path. Remember that one of the important factors in determining any neutrino oscillation parameter and related variable is the neutrino flux [169]. So, before the step is made towards detection, let us review what the flux profile looks like at this stage.

6.3.3 Neutrino flux

At T2K, not all detectors are on-axis with the beam direction. The profile thus looks different for each one of them. As discussed in chapter 2, the oscillation probability is a function of the baseline and the energy. Super-K, the far detector, is located at a distance of 295 km from the target. In figure 6.8, the muon neutrino survival probability, the electron neutrino appearance probability and the scaled muon neutrino flux distributions for several beam angle configurations have been overlaid, supporting the design choices of both the baseline and the off-axis angle. The blue shaded region shows the benefit of picking an off-axis angle to minimize the muon neutrino survival probability while simultaneously maximizing the electron neutrino appearance probability at the flux peak of 0.6 GeV. Comparing the 2.0° and 2.5° angles also reflects the necessity for an accurate

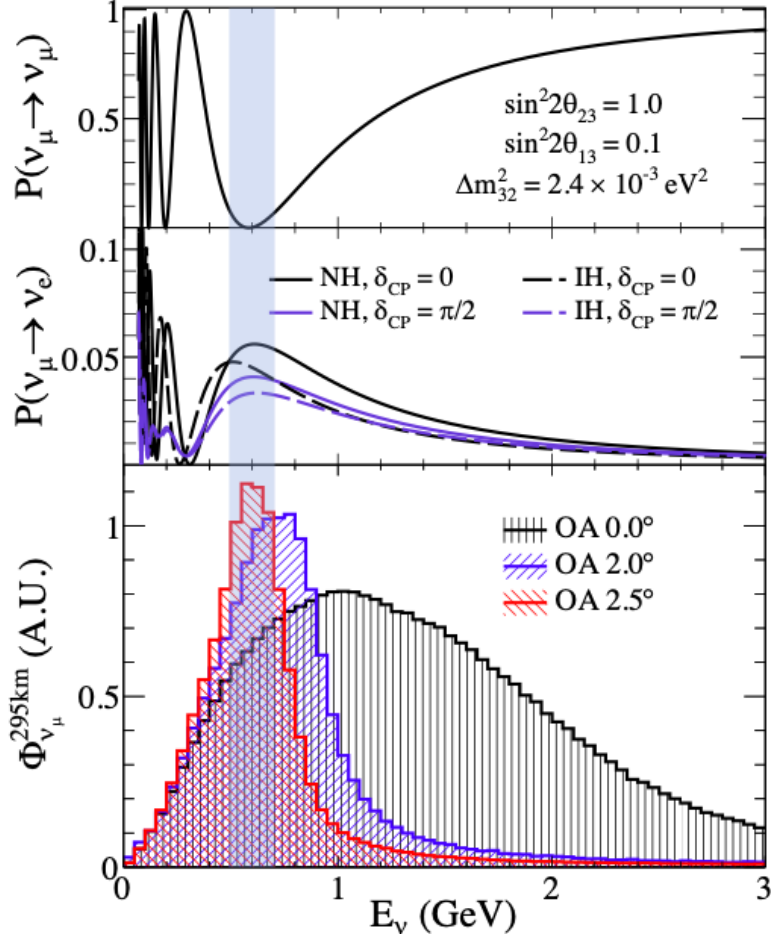


Figure 6.8: Overlay of muon neutrino survival probability, electron neutrino appearance probability and the scaled muon neutrino flux distributions [170].

estimation of the beam's direction as a small change impacts the spectrum quite heavily [170].

6.4 THE T2K NEAR DETECTOR COMPLEX

In order to get a grasp of how many neutrinos have actually oscillated once they have traveled over the 295 km baseline, the neutrinos also have to be characterized in a stage where they have not yet oscillated. This is done at the near detector complex, which houses three separate systems. At 280 meters downstream of the target sits a 37-m-deep and 17.5-m-diameter pit with total of three floors.

As can be seen from figure 6.9, Near Detector 280 referring to its 280 meter distance from the target, sits on the top floor (section 6.4.3). As it takes center stage in the cross-section analysis, it will be discussed in more detail than the other detectors. Yet

it is still worthwhile to mention them briefly. INGRID rests on the level below ND280 and contrary to its upper level neighbor is on-axis (section 6.4.1). On the bottom level WAGASCI-BabyMIND can be found (section 6.4.2). The latter only had its first full data run in 2019/2020 and with that is the latest addition to the framework.

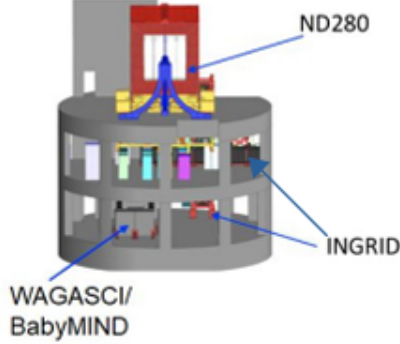


Figure 6.9: ND Complex with ND280, INGRID and WAGASCI-BabyMIND [171].

6.4.1 On-Axis: INGRID

INGRID stands for the Interactive Neutrino GRID. The naming convention can be derived from the grid-like structure formed by the sixteen identical modules aligned around the beam's central axis (figure 6.10). This detector was brought into this world to assist in understanding the characteristics and the intensity of the outgoing neutrinos. It serves as support to the muon beam monitor right after the beam dump. As only muons above 5 GeV make it to that monitor, there is a large region of the kinematic space left uncovered by solely studying those. INGRID solves that problem by directly measuring the neutrinos and thus providing insight into the lower energy (i.e., sub 5 GeV) part of the spectrum [172].

Fourteen out of those sixteen modules are arranged in a seven-by-seven cross, whereas the remaining two are oriented slightly off-axis. The cross extends 5 meters to either side with the purpose of covering the 1σ spatial width of the beam. Each module consists of a sandwiched configuration between 11 scintillator tracking planes and nine iron target plates. When a neutrino interacts in the iron, scintillation light is generated in the tracking bars by the resulting through-going charged particles. This light is then collected by wavelength shifting fibers and the charge is measured by a Multi-pixel Photon Counter (MPPC). The number of photons serve as a proxy for the number of interactions. As the beam is most intense at its core, this setup can be used to pinpoint the central axis with a precision better than 10 cm [173].

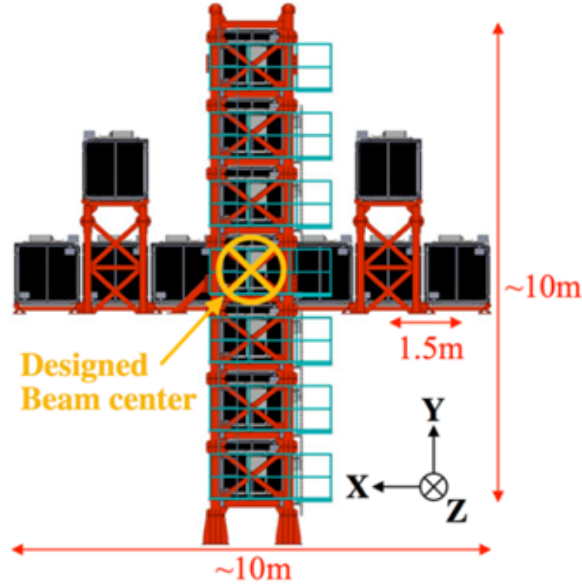


Figure 6.10: The Interactive Neutrino GRID on-axis near detector for the T2K experiment with the designed beam center marked in yellow [163].

6.4.2 WAGASCI-BabyMIND

One might wonder why there were additional detectors added to the T2K framework ten years after first starting the data taking journey. The answer can be found in the goal to build WAGASCI and BabyMIND. Their purpose is to constrain the main non-cancelling systematic uncertainties for the neutrino oscillation analysis caused by the difference in target material between ND280 and Super-Kamiokande along with the difference in angular coverage between the two detectors. WAGASCI or the Water Grid And SCIntillator and the prototype Magnetized Iron Neutrino Detector or Baby-MIND will make an attempt at improving the cross-section measurements for interactions on both carbon and water by receiving the same beam as the other detectors but now at a 1.5 degree angle [174].

In figure 6.11, the WAGASCI-BabyMIND configuration is shown with its surrounding muon range detector referred to as WallMRDs. WAGASCI consists of a segmented target of water and scintillator cells. The grid structure containing the water targets is alternated by horizontally and vertically oriented plane scintillator bars. BabyMIND sits immediately downstream of WAGASCI. It is designed to measure the momentum and charge of muons leaving the previous detector in the forward direction. By running conducting aluminum coils on the surface of each plate, they become magnetized making BabyMIND capable of identifying the traversing particle's charge based on the bend in its

trajectory. Combined, the time of arrival for each hit can be processed and the direction of the reconstructed muon track can be determined. It also enables the identification and measurement of the muon momenta.

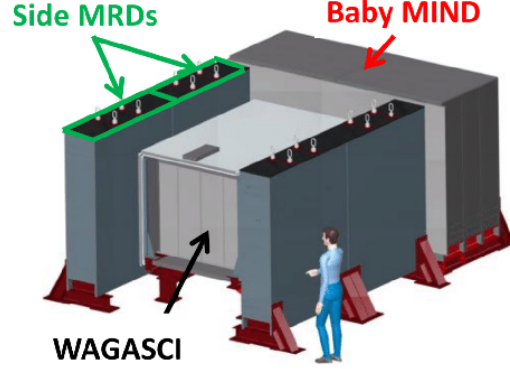


Figure 6.11: WAGASCI-BabyMIND detector with muon range detectors [174].

6.4.3 ND280

The time has now come to give the stage to the key component of this thesis' analysis, the 2.5 degree off-axis near detector ND280. Its full structure comprises three separate elements from the central axis outward. The core containing the neutrino interaction targets consists of the P0D, a π^0 detector, and the tracker, which houses three time-projection chambers interspaced by two FGDs or fine-grained detectors. Downstream of the tracker sits an electromagnetic calorimeter called the DS-ECAL. This first region is encompassed by a metal frame in which more ECALs are embedded, one for the P0D (the P0D ECAL) and one for the tracker (the Barrel-ECAL). This entire structure is inserted into a magnetic coil of which the air gaps are instrumented with muon range detectors (SRMD) in the form of scintillators [163]. In figure 6.12 this three-layered substructure can be seen more clearly.

6.4.3.1 The Magnet

The magnet has been refurbished from the UA1/NOMAD experiment that was located at CERN. Its outer boundaries span a 7.6 m by 5.6 m by 6.1 m volume. This essential piece of equipment allows for the identification of the charge sign for particle tracks inside the detector through the 0.2 T dipole field that generates in the water-cooled aluminum coils. On top of that, it enables the possibility of measuring the momenta of neutrino interaction products with good precision [175].

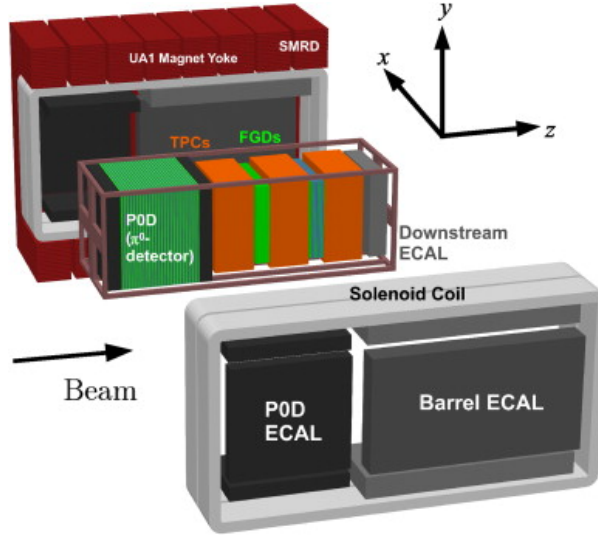


Figure 6.12: ND280's three-layered substructure of individual detectors [163].

6.4.3.2 The side-muon range detector

As with the previously discussed side or wall muon detectors, this too relies on the detection of scintillation light. By placing the SMRD in the outer shell of the magnet, muons escaping the core at high angles are also observed. In addition, it can assist in vetoing events that occurred outside the detection volume and are the result of neutrino interactions in the cavity walls of the iron inside the magnet. This also includes events coming from cosmic rays that find their way into ND280. The side-muon range detector is composed of 440 scintillator modules following a very similar structure to the ones mentioned before and to the upcoming electromagnetic calorimeters and fine-grained detectors described later. The main difference resides in the wavelength shifting fiber that is placed in a snaking groove pattern rather than a hole. By having this pattern instead, not only can a greater area be covered reducing the number of required channels, but the position of the interaction can be reconstructed by looking at the intensity of the light at each end of the fiber [176].

6.4.3.3 The electromagnetic calorimeters

Particles that exit the interior of the tracker region meet one of the electromagnetic calorimeters that surround it. Neutral particles (photons and neutral pions, as well as electron-positron showers are the main contributors to this group and in order to achieve better understanding of the neutrino event, should be precisely measured as well. In combination with the SMRD, they serve as a veto for incoming backgrounds. Any neutral pions leaving the P0D can be fully contained within them and they can provide an extra

particle identification score for charged particles, assisting in the discrimination between muons pions and electrons.

The architecture of the ECALs follow that of the other scintillator detectors in that they have WSF connected to MPPCs on both sides. Each ECAL module is made of layers of 40 mm by 10 mm scintillator bars glued to 1.75-mm-thick lead plates on the side of the barrel and downstream ECALs and 4 mm on the P0D side (figure 6.13). Lead is chosen because of its short radiation length boosting the creation of electromagnetic showers and thus improving the reconstruction of π_0 decays and photon conversions [177].

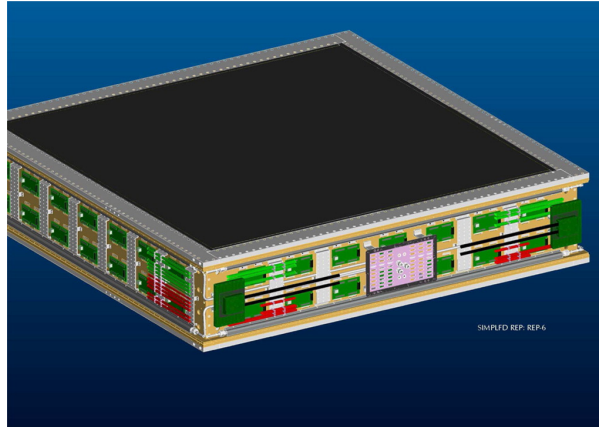


Figure 6.13: A drawing of the ECAL module highlighting the scintillator bars [163].

Each of these lead-scintillator combinations constitutes 50 bars in the similar alternating fashion as shown before. The barrel ECAL consists of 31 of these combinations, amounting to 9.7 radiation lengths. The downstream ECAL has 34 of them totaling 10.6 radiation lengths. The P0D ECAL has only six, giving 3.6 radiation lengths. The lead is wider here as the P0D itself is already optimized to detect neutral pions unlike the rest of the tracker.

The ECALs can discriminate between tracks and showers based on the shape and the distribution of the observed charge clusters. Electron, positrons and photons are separated from muons by looking for MIP-like particles and assessing the energy deposition trend. By looking at HIP-like particles, the stopping protons can be identified.

6.4.3.4 The P0D-detector

Before the neutrinos come across the carbon and water target, they first traverse the P0D. Its primary objective is to combat backgrounds. As has been made abundantly clear in the section on the ECALs and as the name suggests, those backgrounds revolve around

the interference of neutral pions. At the Super-Kamiokande far detector, the observation of electrons indicates the existence of a progenitor electron neutrino through the channel: $\nu_e + n \rightarrow e^- + p$. From the production of the muon neutrino beam, it is understood that there is an intrinsic and unavoidable contamination of electron neutrinos. If these ν_e s interact in the far detector, they would produce electrons that are not the subsequent result of oscillations. The second most infamous background to this signal is caused by neutral-current events producing a single π_0 through the channel: $\nu_\mu + N \rightarrow \nu_\mu + \pi^0 + X$. These pions rapidly decay to a di-photon pair or a photon and electron-positron pair, leaving the same signature as that of the interaction between an electron neutrino and a neutron [178].

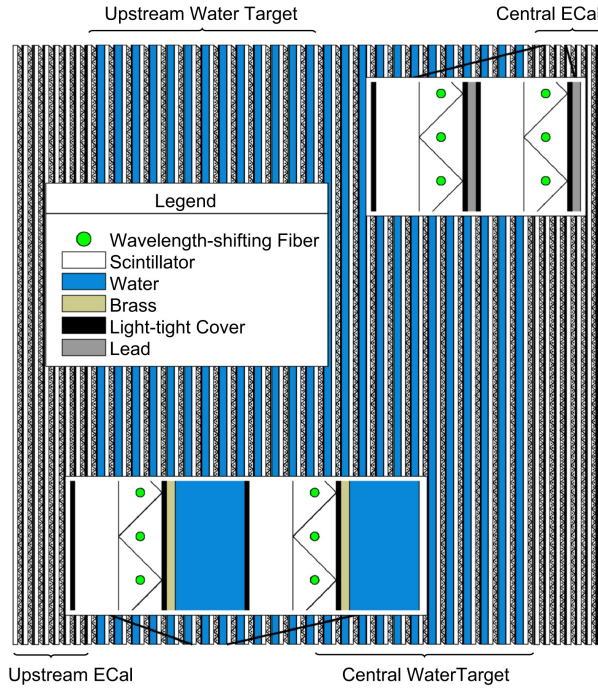


Figure 6.14: A schematic overview of the side of the P0D. The scintillator bar structure in both the ECals and water targets are shown in expanded view [163].

The design of the P0D is tailored to measuring the neutral pion interaction rate in water. The upstream and downstream exterior consists of ECALs following the same structure as the P0D ECAL. The interior houses the water target, as can be seen in figure 6.14. These targets are separated in an upstream and a central part. Both consist of alternating water bags with scintillator planes and brass sheets. Each scintillator plane again comprises horizontal and vertical sections. Instead of lead, here the brass sheets fulfill the role of radiators to boost the formation of electromagnetic showers. There are thirteen of these alternations in the upstream section and 12 in the central one. To amplify the effect of the water targets, the P0D has been drained for some of the T2K data runs.

6.4.3.5 The time-projection chambers

Inside the tracker region, three identical time-projection chambers are stationed to produce the most reliable estimate of momentum, particle identity and charge sign. To this end, the TPCs make use of the fact that charged particles ionize any media they traverse along their path. The released electrons can be studied to reconstruct the trajectory. The magnetic field ensures that these tracks are curved. The level of curvature is directly related to the particle's momentum and the direction of curvature to its charge sign. By combining this information with the amount of charge left behind in the detector per unit length or dE/dx , the particle's type can be identified [179].

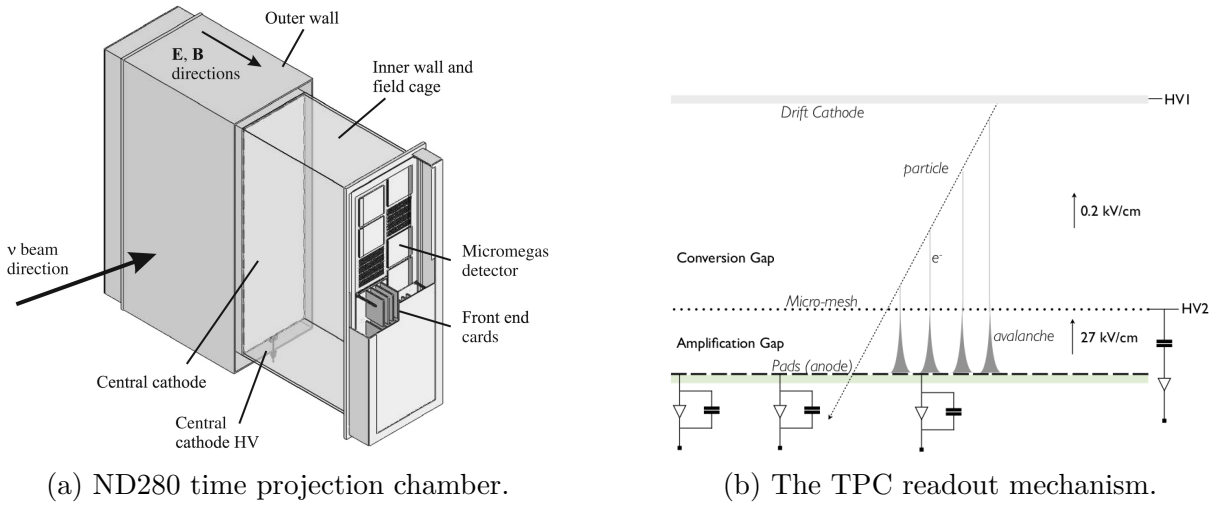


Figure 6.15: ND280 time-projection chambers [179].

So, how is this ionized charge measured? To answer that question, the TPC geometry has to be investigated. The TPCs consist of two concentric rectangular volumes. The outer wall is kept grounded, while the inner box forms the electric field cage shielding the inside from any external electric fields and maintaining a uniform field within. In between the walls, CO_2 is inserted as an insulator. Figure 6.15a displays the TPC architecture. The electric field points in the direction perpendicular to the central cathode. The inner box holds a gas mixture of argon, tetrafluoromethane and isobutane (95-3-2 percent contribution, respectively). The charged particles ionize this gas and the electric field ensures the electrons start drifting towards the anode where the readout plane is located (see schematic overview in figure 6.15b). The readout is done with bulk Micromegas (MICRO-MESh-Gaseous) detectors. Each plane contains 12 of these machines arranged in two vertical columns. Before the electron reaches the readout, it encounters an amplification region where a 27 kV/cm electric field is applied over 128 μm . This causes

the incoming electron to produce an avalanche with a gain of up to 1500, at which point the charge and the time of each individual hit is recorded. The timing of each hit and its location on the Micromegas are used to create a 3D reconstruction of each particle track [163].

6.4.3.6 The fine-grained detectors

Where in the foregoing discussion every scintillation detector relied on a separate material (lead, iron etc) for the neutrino to interact with, in FGD1 the scintillating material also served as target. The configuration of choice here is polystyrene segmented in 5760 individual bars aligned. With 192 bars per layer advanced calculus determines there to be 30 layers in total, with fifteen per direction perpendicular to the neutrino beam (so-called X and Y modules). The bars are equipped with a reflective TiO₂-containing coating, which effectively restricts light propagation between adjacent bars. Additionally, each bar's center is outfitted with a wavelength-shifting fiber, responsible for collecting scintillation light and conveying it to the MPPC on one end [180].

The XY module orientation is designed to optimize the tracking capabilities in order to reconstruct the position of the neutrino interaction vertex. A combination of light arrival time and light intensity can be used to pinpoint its location down the line. The FGD also has the crucial task of detecting and distinguishing low-momentum particles that never make it into the TPC. By studying the decay electron or positron from the pion to muon to electron chain, protons can be differentiated from pions. The muon lifetime of 2.2 microseconds sets a lower bound on how long the detector must remain operational for after the beam spill. If hits in the detector occur more than 100 ns outside of one of the eight bunch time windows in one spill, they are considered delayed.

Unlike the TPC, the FGD is not capable of measuring the momentum through the track bend. Instead it employs a momentum-by-range strategy. Consideration of the length of the particle track and the deposited energy can also be used to identify particles in this detector, see figure 6.16 [163].

6.4.3.7 FGD2

FGD2 houses only seven of the XY-modules, leaving room for 150 mm of water depth spread over six target modules. As one can imagine when handling a water or any other non-solid target, leaks in the container can cause major problems for the surrounding electronics. To counteract that risk, the bags are kept at a pressure below one atmosphere.

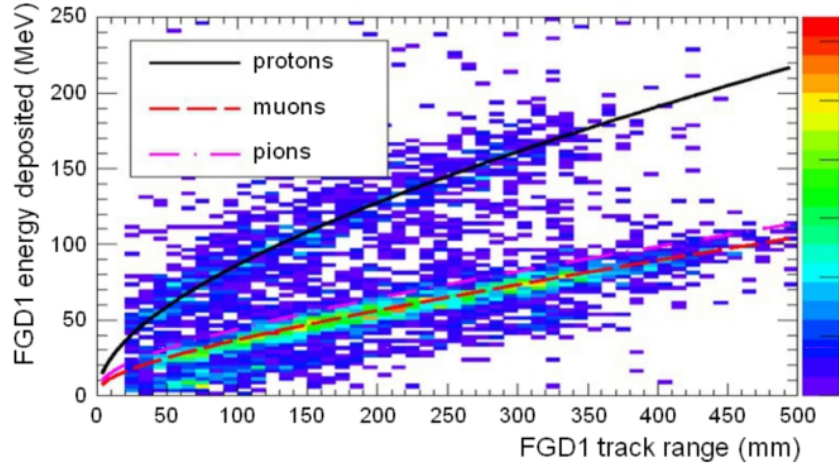


Figure 6.16: Deposited energy in FGD1 for distance traveled, showcasing the capability of distinguishing between protons and pions [180].

This means that any leaks will cause air to be sucked into the bag instead of water leaking out. As FGD2 is not part of this analysis, it will not be discussed in further detail. More information can be found in [180].

6.5 THE T2K FAR DETECTOR

With the last element of ND280 laid out, the move can be made towards the far site located in the Mozumi mine of the Kamioka Mining and Smelting Company in Japan. At a distance of 295 km west of the source, at a depth of 1 km underground resides the world famous water Cherenkov detector Super-Kamiokande [181]. Super-K, shown in figure 6.17, is a cylindrical tank of 42 meters in height and 39 meters in diameter containing 50 kton of water.

With a staggering number of 13000 PMTs spread over the inner and outer detectors, Super-Kamiokande detects the Cherenkov light generated by faster-than-light charged particles coming from neutrino interactions. The outer detector has a thickness of 2 m radially and houses 1885 outward-facing 20 cm diameter PMTs. The inner detector contains the remaining PMTs, which point inward. With their 50 cm radius, they cover around 40 percent of the walls, achieving sufficient spatial resolution to deduce the outgoing particle's kinematics [163].

The generated Cherenkov light is emitted in a cone around the direction of the charged particle. As the light propagates towards the walls of the detector, it will trigger the PMTs in a ring-like structure. Combining the time of arrival for each hit with the amount of

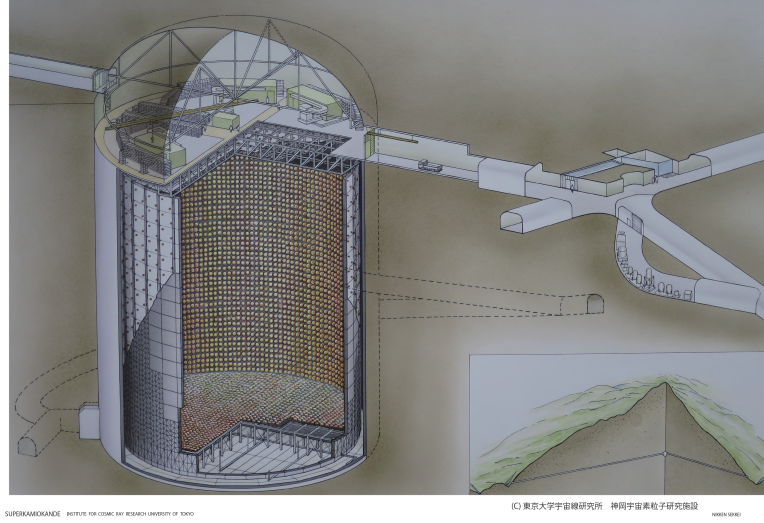


Figure 6.17: The massive water Cherenkov detector Super-Kamiokande [181].

light collected allows for the reconstruction of the energy, the direction and the type of charged particle [182].

In figure 6.18 two event displays can be seen for an outgoing muon (figure 6.18a) and outgoing electron (figure 6.18b), respectively. For the outgoing muon, the pattern is sharp and the boundaries clearly defined. The mass of the muon protects it from major divergence in its path as it interacts with the detector medium. The electron, however, is not as lucky. It is more affected by scattering process and on top of that produces electromagnetic showers. This results in a multitude of Cherenkov cones that overlap and create a fuzzy pattern on the detector wall.

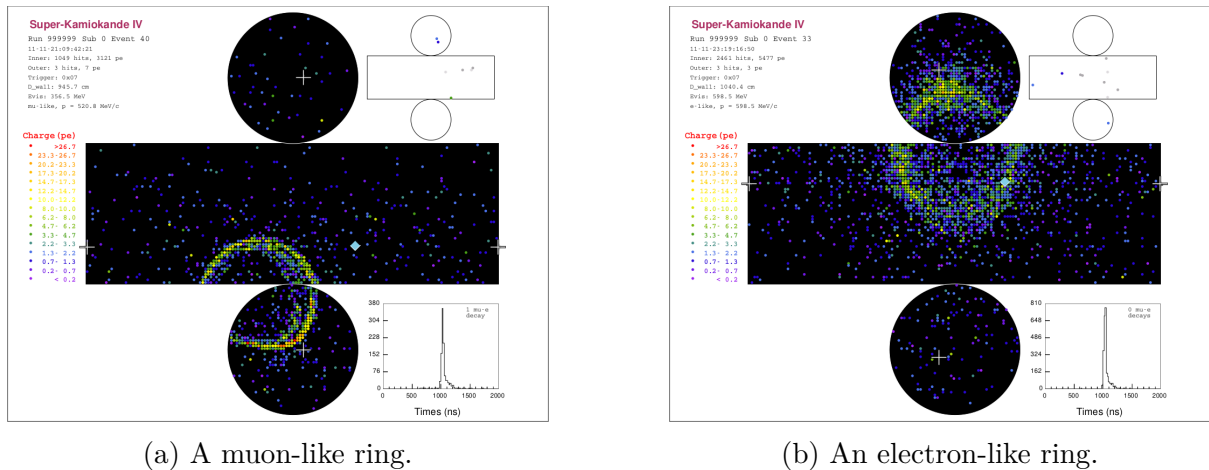


Figure 6.18: Unfolded Super-Kamiokande event display with colors indicating the amount of charge collected. The top right section shows the hits in the outer diameter [183].

THE CROSS-SECTION ANALYSIS STRATEGY

7

In this chapter, the reasoning behind evaluating the $\text{CC}1\pi^+$ cross-section on hydrocarbon and the strategy of extracting it will be discussed. First the observable kinematic ranges will be described by defining the analysis signal region. Next, the four-dimensional differential cross-section in muon and pion momentum and angle will be derived. Methods to incorporate the flux, detector efficiency and cross-section model parameters will be laid out before the chapter will conclude by explaining the binned maximum likelihood fitter framework.

7.1 MOTIVATION

Accelerator-based neutrino oscillation experiments usually utilize a minimum of two detectors conventionally labeled ‘Near’ and ‘Far’ to observe a neutrino beam at two different positions in space. The ‘Far’ detector is used to measure the oscillated spectrum after the beam has traveled for a predetermined well-established distance that maximizes the probability of those oscillations and thus the opportunity to observe them. As neutrinos have an incredibly small interaction cross-section, these devices are generally

massive in order to contain a lot of target atoms. Super-Kamiokande, T2K’s far detector, is a cylindrical stainless steel tank filled with 50000 tons of water. The detector’s shape, its target material and the readout architecture make it symmetric over the entire (4π) solid angle.

The ‘Near’ detector is close to the source, allowing it to observe the neutrinos in their unoscillated form. On top of that, the beam will not have dispersed as much at this distance as it will have once it reaches the far detector, meaning that the flux and thus the event rate will be much larger. These statistics make it possible to study the cross sections and flux properties in great detail with the goal of constraining them. The T2K near detector ND280 consists of both hydrocarbon and water targets specifically designed with that purpose in mind. Oscillation analyses (OA) rely on the separation between oscillatory effects on one side and flux, cross-section and detector effects on the other. The formulas in equations 7.1 and 7.2 show the event rates at both detectors,

$$R_{\text{near}} = \Phi_{\text{near}}(E_\nu) \cdot \sigma_{\text{near}}(E_\nu) \cdot N_{\text{t,near}} \cdot \epsilon^{\text{near}}, \quad (7.1)$$

$$R_{\text{far}} = \Phi_{\text{far}}(E_\nu) \cdot \sigma_{\text{far}}(E_\nu) \cdot N_{\text{t,far}} \cdot P_{\text{osc}} \cdot \epsilon^{\text{far}}, \quad (7.2)$$

where P_{osc} is the probability of oscillation, R is the rate of interactions in the detector, Φ is the neutrino flux, σ is the cross section (both Φ and σ depend on the neutrino energy (E_ν)), N_{t} is the number of target atoms, and ϵ is the respective detector’s efficiency.

By studying neutrinos at the near detector, predictions of their behavior at the far detector improve. In the past most of the selection in ND280 was centered around forward-going muons (i.e., downstream from the beam source). Muons that originated in the hydrocarbon fine-grained detector (FGD1) would be required to pass through TPC2. The events taken into account at the far detector did not have that limitation due to the symmetry described earlier. At the far detector charged particles produce Cherenkov rings when their velocity exceeds the speed of light in water. Depending on the reaction mode, multiple charged particles could arise from a single neutrino interaction (e.g., from resonant or deep-inelastic scattering processes) and multiple rings could be produced.

At earlier iterations of the oscillation analysis, only single rings from the charged lepton or from the charged lepton and its decay products were taken into account. As the detector does not measure the type of reaction that took place, the events can only be categorized by what is actually observed. The reason behind measuring a cross-section in terms of an observed topology rather than a specific neutrino-nucleus interaction mode is to avoid

dependence on the nuclear models used in the MC event generator (NEUT). Accurately determining the true reaction type (such as CCQE, CCRES, DIS, etc.) is challenging due to the way final state interactions affect the topology before particles exit the nucleus. At the near detector, the classification is therefore done based on the presence of a lepton and the number of pions found in the final state. CC0 π , CC1 π^+ and CCOther with 0 pions, a single positively charged pion and any number of pions, respectively, were among the first designed categories. Here the focus will lie on CC1 π^+ events as it is the next step in ring multiplicity after CC0 π with the idea that an additional ring came from the produced pion or its decay products.

Now that the potential improvements have been identified, the revamped selection in this analysis can be described. The forward-going muon selection was extended over previous analyses to cover all angles and better reflect the 4π coverage of SK. The new samples were labeled High-angle Forward, Backward and High-angle Backward, of which the characteristics will be elaborated on below. By means of time-of-flight properties of the detected particles, one can specify the direction the muons propagate in.

The ultimate goal of the work preceding this analysis was to obtain a four-dimensional cross-section in both muon and pion kinematic variables (muon momentum and angle and pion momentum and angle) for the CC1 π^+ topology. This will reveal the combined correlation and effect of these variables on the neutrino interaction cross-section. The downside is that it quickly becomes statistically limited due to the unavoidable higher number of bins. This means that any method of increasing the garnered statistics from the existing Monte Carlo sample should be considered.

In prior work, pion identification was done by the FGD (resulting in so-called isolated FGD pions) or the TPC. However, there is a third method possible in which they are found through the observation of their decay products. Low energy pions coming from neutrino interactions propagate in the FGD and decay into muons after traveling a short distance. These muons will in turn be low energy and thus decay into electrons (i.e., Michel electrons). Using the traveled path of the pion as a parameter for the fitting function, the distance can be related to the pion energy with reasonable accuracy. There are many of these events originating from FGD1, adding up to around 50% of the statistics in the region between 80 and 400 MeV/c in pion momentum. This improves acceptance for low energy pions since making a track in the FGD or entering the TPC requires the pions to have more energy. What is even more beneficial is that these events have a very high purity for the desired signal, as will be shown later.

7.2 SIGNAL DEFINITION

Ultimately, the sought after cross-section for this analysis will include ν_μ charged-current interactions that will lead to a topology containing the leptonic muon and a single positive pion. Other particles present in the final state are not subject to any restrictions, e.g., no limit on the number of nucleons, as there is no attempt made at reconstructing those. Due to how the topology can be affected by final-state interactions before particles exit the nucleus, the interaction is characterized based on the particles observed in the final state rather than the perceived reaction mode (CCQE, CCRES, CCDIS, etc.).

Due to inefficiencies introduced by the detector and inaccuracies in the reconstruction procedure, the signal phase space has to be limited to regions that are well understood. Events in which muons have momenta below 200 MeV/c or above 30000 MeV/c ($p_\mu < 200$ MeV/c, $p_\mu > 30000$ MeV/c) are excluded, as well as events containing pions with momenta below 80 or above 3000 MeV/c ($p_\pi < 80$ MeV/c, $p_\pi > 3000$ MeV/c). The reasoning behind this will be further laid out in the section on analysis binning.

7.3 CROSS-SECTION DEFINITION

The goal is to measure the neutrino flux-integrated ν_μ CC1 π^+ 4D differential cross-section on hydrocarbon for interactions occurring inside the FGD1 detector fiducial volume (FV). This four dimensional phase space is expressed in dp_μ , dp_π , $d\cos(\theta_\mu)$ and $d\cos(\theta_\pi)$. The actual differential cross section is measured by counting the number of selected signal events in each region of observable phase space. In general, the number of signal events N_i we expect to observe in phase space region i can be derived as

$$N_i = N_T \int \sigma_i(E_\nu) \phi_i(E_\nu) \epsilon_i(E_\nu) dE_\nu, \quad (7.3)$$

where σ_i is the cross section we want to measure, ϕ_i is the neutrino flux, ϵ_i is the detection efficiency, and N_T is the total number of target nuclei. As all of the parameters contained in equation 7.3 depend on the neutrino energy (not considering the number of target nuclei as this is a property of the detector itself), an integration over this variable will yield the total number of events.

This measurement can be simplified by considering the energy-averaged counterparts of the cross-section and detector efficiency, allowing these terms to be taken out of the integration. Moreover, by choosing to do a flux-integrated measurement the integral will

be replaced by the total integrated neutrino flux Φ . The downside of this method is that any results will be T2K-specific, since the shape of the neutrino energy spectrum has been disregarded.

With these adjustments and rearranging the variables, the energy-averaged cross-section becomes

$$\langle\sigma_i\rangle = \frac{N_i}{N_T\langle\epsilon_i\rangle\Phi}. \quad (7.4)$$

The transition to a differential measurement for a specific analysis observable bin i is then made in the following way:

$$\frac{d\sigma_i}{dX_i} = \frac{N_i}{\Phi N_T \epsilon_i} \times \frac{1}{\Delta X_i}, \quad (7.5)$$

where dX_i refers to any combination of analysis observables and ΔX_i characterizes the phase space bin size. For this analysis done in muon and pion kinematic properties, the four-dimensional form of the cross-section is written as

$$\left(\frac{d^4\sigma}{dp_\mu d\cos\theta_\mu dp_\pi d\cos\theta_\pi}\right)_{i,j,k,l} = \frac{N_{i,j,k,l}}{\Phi N_T \epsilon_{i,j,k,l}} \times \frac{1}{\Delta p_\mu^i \Delta\cos\theta_\mu^j \Delta p_\pi^k \Delta\cos\theta_\pi^l}. \quad (7.6)$$

As the number of dimensions increase, the statistics in each separate analysis bin decreases. On top of that, visualizing the evolution of a 4D differential cross-section with respect to its binning scheme might not yield a straightforward and intuitive view of the dependencies. For those reasons, the cross-section can also be reported in double-differential form (i.e., in muon kinematic properties or pion kinematic properties only). This is done by integrating over the other two parameters. Equation 7.7 shows this for the pion kinematic properties, but the same strategy could be applied for the muon by interchanging the pions for muons.

$$\left(\frac{d^2\sigma}{dp_\pi d\cos\theta_\pi}\right)_{k,l} = \frac{1}{\Phi N_T \Delta p_\pi^k \Delta\cos\theta_\pi^l} \sum_i \sum_j \frac{N_{i,j,k,l}}{\epsilon_{i,j,k,l} \Delta p_\mu^i \Delta\cos\theta_\mu^j}. \quad (7.7)$$

With the definitions finalized, it is time to discuss how values for each of the parameters in these equations are acquired.

7.4 CROSS-SECTION EXTRACTION

The most important parameter to obtain is the number of signal events in each analysis bin N_i as a function of ‘true’ variables before detector smearing effects. While this allows for comparisons between different interaction models, the actual data is measured in reconstructed space, which is affected by the detector’s resolution, statistical fluctuations and s in the following three ways:

1. **Detector smearing:** Due to limited accuracy in the analysis observables as a result of the detector's performance (e.g., the momentum and direction of a particle are measured with non-zero bias and resolution), events could migrate from one bin to another at the reconstruction level
2. **Statistical fluctuation:** Event rates in each analysis bin follow Poisson distributions, leading to statistical uncertainties
3. **Background:** Events that pass the selection and end up in the signal sample also contain contributions from misidentified background channels

This means that a strategy is required to translate the kinematic information from one space to the other. This procedure is called ‘unfolding’, which can be described by a migration matrix M mapping events from reco to truth space:

$$N_i^{\text{true}} = \sum_j^{\text{reco}} N_j^{\text{reco}} M_{ji}, \quad (7.8)$$

where N_i^{truth} is the number of events in the true analysis bin i , N_j^{reco} the number of events in the reconstructed analysis bin j and M_{ji} represents the migration probability from bin j to i . The sum runs over all reconstructed analysis bins, considering the possibility of contributions from all of them. The transformation from truth to reco space can be achieved by inverting M to find the smearing matrix: $S = M^{-1}$. Hence,

$$N_j^{\text{reco}} = \sum_i^{\text{true}} N_i^{\text{true}} S_{ij}. \quad (7.9)$$

In this analysis a binned likelihood is used to perform a fit of the number of selected events as a function of reconstructed variables to determine the number of true signal events versus true variables. The next section covers the construction of this function, as well as a means of maximizing the binned likelihood to find the set of parameters that best describes the data.

7.4.1 Binned maximum likelihood fit

The likelihood function that will be evaluated to find the most probable weights to scale the signal events in the true bins from Monte Carlo simulations to those in the data takes on the following abstract form:

$$L(\vec{\theta}) = L_{\text{stat}}(\vec{x}; \vec{\theta}) \times L_{\text{syst}}(\vec{x}; \vec{\theta}), \quad (7.10)$$

where L_{stat} refers to the statistical term and L_{syst} to the systematic uncertainty term, both of which will be discussed later. Maximizing this function will then yield the set of parameters $\vec{\theta}$ that best describe the data $\vec{x}$ and thus retrieve the expected number of events in truth space, which can then be used to calculate the cross-section. Parameter $\vec{\theta}$ is the convolution of a template normalization part and a systematic uncertainty part according to $\vec{\theta} = (\vec{\theta}_{\text{temp}}, \vec{\theta}_{\text{syst}})$.

A customary method to simplify maximizing the likelihood function $L(\vec{\theta})$ consists of taking the logarithm and applying Wilks' theorem [184]. The theorem states that in the limit of infinite sample size the minimum of $-2\log L$ follows a χ^2 distribution with a number of degrees of freedom equal to the number of bins minus the number of unconstrained fit parameters, such that $\chi^2(\vec{\theta}) \approx -2\log L(\vec{\theta})$. In this way maximizing the likelihood $L(\vec{\theta})$ is equivalent to minimizing $\chi^2(\vec{\theta})$ according to

$$\begin{aligned}\chi^2(\vec{\theta}) &= \chi_{\text{stat}}^2(\vec{\theta}) + \chi_{\text{syst}}^2(\vec{\theta}) \\ &\approx -2\log L(\vec{\theta}) \\ &\approx -2\log L_{\text{stat}}(\vec{\theta}) - 2\log L_{\text{syst}}(\vec{\theta}).\end{aligned}\tag{7.11}$$

The term $-2\log L_{\text{stat}}(\vec{\theta})$ includes the statistical information, i.e., the event samples collected from data. As a result of the counting nature of this experiment, the event number in each analysis bin will satisfy a Poisson distribution,

$$L_p(\vec{y}; \vec{n}) = \prod_i \exp(-y_i) \frac{y_i^{n_i}}{n_i!},\tag{7.12}$$

where n_i is the number of events in the i^{th} bin, and y_i is the number of events predicted by the model in that bin. Defining the likelihood ratio test value λ as the ratio of the given likelihood to the likelihood of obtaining the true values of n_i if there were no error, and taking $\vec{n}$ as the maximum likelihood estimate of the true values, the ratio becomes

$$\lambda = \frac{L_p(\vec{y}; \vec{n})}{L_p(\vec{n}; \vec{n})} = \prod_i \exp(-y_i + n_i) \frac{y_i^{n_i}}{n_i^{n_i}}.\tag{7.13}$$

Applying Wilks' theorem to this, we obtain the χ^2 approximation in the log-likelihood form:

$$\chi_P^2 \approx -2\ln \lambda = -2\ln \left[\prod_i \exp(-y_i + n_i) \frac{y_i^{n_i}}{n_i^{n_i}} \right] = 2 \sum_i \left(y_i - n_i + n_i \ln \frac{n_i}{y_i} \right).\tag{7.14}$$

Inserting the values for the statistical parameters appropriate for this analysis, yields

$$\chi_{\text{stat}}^2 = 2 \sum_j^{\text{reco bins}} \left(N_j^{\text{exp}} - N_j^{\text{obs}} + N_j^{\text{obs}} \ln \frac{N_j^{\text{obs}}}{N_j^{\text{exp}}} \right). \quad (7.15)$$

Here we sum over all analysis bins in reconstruction space, N_j^{obs} is the observed event number in bin j , which comes from data, and $N_j^{\text{exp}}(\vec{\theta})$ is the expected event number in the same bin, which depends on parameters $\vec{\theta}$ and will be fitted when minimizing the χ^2 function.

The second term $-2 \log L_{\text{syst}}(\vec{\theta})$ incorporates all of the systematic uncertainties coming from the detector, flux, and cross-section parameters in an attempt to constrain them. The systematic part of the log-likelihood parameter θ_{syst} can be described by

$$\vec{\theta}_{\text{syst}} = (\vec{d}, \vec{f}, s : b), \quad (7.16)$$

in which s and b represent the signal and background cross-section model parameters, respectively. The constraint comes in the following multivariate Gaussian form

$$L_G(\vec{\theta}) = \frac{1}{\sqrt{(2\pi)^n |V|}} \exp \left(-\frac{1}{2} (\vec{x} - \vec{\mu})^t V^{-1} (\vec{x} - \vec{\mu}) \right), \quad (7.17)$$

where $\vec{\mu}$ corresponds to the vector of mean values and V to the covariance matrix. Taking the logarithm and neglecting the constant term independent of $\vec{\theta}$ reveals a dependency of the form

$$-2 \log L_G(\vec{\theta}) \propto (\vec{x} - \vec{\mu})^t V^{-1} (\vec{x} - \vec{\mu}). \quad (7.18)$$

And hence, $-2 \log L_{\text{syst}}(\vec{\theta}_{\text{syst}})$ can be expressed as

$$\chi_{\text{syst}}^2 \approx -2 \log L_{\text{syst}}(\vec{\theta}_{\text{syst}}) = (\vec{\theta}_{\text{syst}} - \vec{\theta}_{\text{syst}}^{\text{prior}})^t (V_{\text{syst}}^{\text{prior}})^{-1} (\vec{\theta}_{\text{syst}} - \vec{\theta}_{\text{syst}}^{\text{prior}}), \quad (7.19)$$

in which $\vec{\theta}_{\text{syst}}^{\text{prior}}$ is a vector containing all systematic uncertainties' prior values and $V_{\text{syst}}^{\text{prior}}$ is the covariance between those parameters. This allows prior knowledge from theory and previous experiments to be introduced into the analysis.

With the formulae for χ_{stat}^2 (equation 7.15) and χ_{syst}^2 (equation 7.19) defined, the minimization procedure can start. Every bin in truth space is assigned its own unconstrained template parameter c_i , which gives the fit additional freedom in looking for weights that make the MC distributions match the data in reconstructed space. It also reduces the dependence

on neutrino interaction models used to generate the Monte Carlo simulation. The template parameters are introduced through

$$N_{i,\text{true}}^{\text{sig}} = c_i N_{i,\text{true}}^{\text{sig MC}}, \quad (7.20)$$

where $N_{i,\text{true}}^{\text{sig}}$ is the predicted number of events in truth bin i and $N_i^{\text{sig, MC}}$ the number of events simulated in the MC for that same exact bin. Using equation 7.7, the number of signal events in reco space can now be found with the migration matrix, as can be seen from the first term in equation 7.21,

$$N_{j,\text{reco}}^{\text{sig}} = \sum_i^{\text{true bins}} \left(c_i N_{i,\text{true}}^{\text{sig MC}} + \sum_b^{\text{bkg}} N_{i,\text{true}}^{\text{bkg MC}} \right) S_{ij}. \quad (7.21)$$

The second term indicates the background events that also end up in that specific bin as the result of impure signal samples. Note that this contribution is not weighted by template parameters, but rather constrained by simultaneously fitting the three control samples discussed before. Combining equation 7.21 with the parameters that cover the systematic uncertainties of this analysis $(\vec{d}, \vec{f}, \vec{\beta})$ yields the following result for the number of reconstructed events in bin j , which can then be used as N_j^{obs} to minimize χ_{stat}^2 with equation 7.15:

$$N_{j,\text{reco}}^{\text{sig}} = \sum_i^{\text{true bins}} \left[c_i \left(\prod_s^{\text{model}} \omega(s) \right) N_{i,\text{true}}^{\text{sig MC}} + \sum_b^{\text{bkg}} \left(\prod_b^{\text{model}} \omega(b) \right) N_{i,\text{true}}^{\text{bkg MC}} \right] S_{ij} d_j \sum_n^{E_\nu} h_{\text{in}} f_n, \quad (7.22)$$

with d_j being a weight factor for each analysis bin in reconstructed space representing the detector systematic uncertainty. How to obtain these is thoroughly explained in the first section of chapter 9. Parameter f_n describes the flux uncertainty as a function of true neutrino energy bin n , while ω_{in} are the weights that map the neutrino energy bins n to the corresponding true analysis bins i . Altering the flux parameters causes a change in the number of events in a true neutrino energy bin, which corresponds to multiple true muon+pion kinematic bins. The cross section systematic uncertainty is implemented as a product of systematic parameters related to the underlying neutrino interaction. The response function $\omega(\beta)$ determines the weight given to the input parameter. $N_{i,\text{true}}^{\text{MC sig}}$ and $N_{i,\text{true}}^{\text{MC bkg}}$ are the mean event numbers supplied by the Monte Carlo simulation for the signal and background samples, respectively.

The fit minimizes the χ^2 function with the MINUIT numerical algorithm [185]. The

algorithm explores the multi-dimensional parameter space and finds the best-fit point giving a minimum χ^2 value based on a gradient descent approach (MIGRAD) [186]. The correlations among best-fit parameters at this point are computed by the HESSE algorithm, where it calculates the inverse of the second derivative matrix of the χ^2 with respect to the best-fit parameters.

The final necessary parameter in the cross-section evaluation is the number of target nucleons N_T included in equation 7.6. The number of hydrocarbon target nucleons within the defined fiducial volume of FGD1 is found via

$$N_t^C = N_A \sum_i^{\text{modules}} \frac{m_C^i N_C}{M_C^A}, \quad (7.23)$$

where i runs over the individual XY modules, $N_A = 6.022 \times 10^{23}$ is Avogadro's number, m_C^i is the mass of hydrocarbon targets in the fiducial volume of the i^{th} module, N_C is the number of nucleons in carbon and M_C^A is carbon's relative atomic mass. To account for the presence of additional neutrons from less common isotopes of the two elements, the number of nucleons N_C is set to the weighted average across the possible isotopes, thus canceling with the relative atomic mass $M_{\alpha A}$. With the exclusion of a few layers of XY modules in FGD1 from this analysis, the total number of targets is found to be $N_T^{CH} = (4.76 \pm 0.088) \times 10^{29}$.

THE $CC1\pi^+$ SELECTION

8

This chapter describes the steps that were taken with the Monte Carlo simulations to arrive at signal and background samples that best isolate the specific event topologies that are of interest. Each of these selections shares several common analysis criteria, which can be summarized in two categories. The first contains criteria specifically designed to guarantee event quality. The second is composed of finding the track with the highest negative momentum for each event and separating these events into four different orientations (forward-going, backward-going, high-angle forward-going and high-angle backward-going). It is concluded by the identification of the particle causing the track.

The next section introduces the separation based on the final-state particles. As the separation is done based on the number of pions, these candidate pions should first be identified. The identification is performed in the time-projection chambers, the fine-grained detectors or by studying the Michel electrons coming from the decay of the daughter muon. With the charged and neutral pions collected, the events are split into the desired topologies.

The $CC1\pi^+$ signal sample should contain a positively charged pion in addition to the identified muon. An overview of the shared selection sequence is given first. The topological breakdown of the individual samples along with the criteria will be discussed afterwards.

8.1 EVENT QUALITY

The first few criteria are done under the umbrella of data quality spearheaded by ‘Event Quality’. The main objective here is to prevent event pile-up, a situation in which multiple events are present within the same time frame. Every accelerator spill will provide T2K with several bunches of neutrinos. The time structure of these bunches can be matched to the events occurring in ND280, so that neutrino interactions from different bunches can be seen as separate events. The event passes if this separation is done correctly for the entire spill.

8.1.1 Event time quality

One of the key components of this analysis is the incorporation of the full solid angle of muon directions. The orientation of the tracks is heavily dependent on the time-of-flight measurement accuracy. These measurements are used to flip the tracks in case of a backward-going particle and are thus even more important for those specific samples.

8.1.2 Time of flight flipping

The timing information yields discrepancies between data and Monte Carlo simulation. Every instance in which the MC production is revamped, the corrections that need to be applied to the time of arrival are re-evaluated. The time-of-flight (ToF) correction smears the particle arrival time at the subdetectors and thus changes its time of flight. The adjusted ToF can be found by simple subtraction of time at A from time at B. If that yields a positive result, the track came from element A. With this new information, tracks can be flipped to their correct directional sense. If the start and end position are swapped, the charge is multiplied by -1. The momentum loss in FGD1 will also be affected by the flipping and thus has to be re-investigated as well. In figure 8.1, this has been done for the forward-going sample. As FGD2 is further downstream from FGD1, any forward-going track should arrive at FGD2 after FGD1, which corresponds to a negative time of flight, as defined in figure 8.1. For most of the tracks (that are truly forward-going), this seems to be the case. For a small subset as indicated by the red arrow, the time of flight is positive as the result of the time-of-flight correction. These tracks have to be flipped.

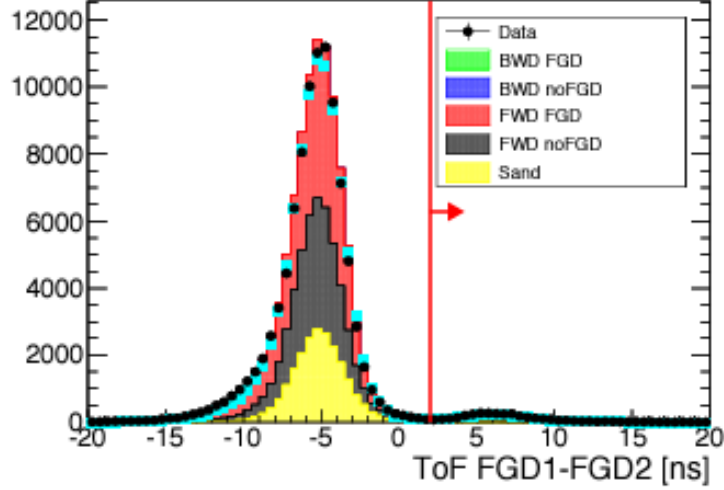


Figure 8.1: Time of flight between FGD1 and FGD2 for tracks that start in FGD1 [187].

8.1.3 Total multiplicity cut

Events must contain at least one reconstructed track in one of the fine-grained detectors, reducing the computational time for the steps that follow.

8.1.4 Sort tracks action

Here all remaining tracks are sorted into two subgroups based on how the candidate particle's momentum and its identity will be determined. Tracks starting or ending in the FGD with a long TPC segment of more than 18 separate clusters are seen as 'low-angle tracks'. In this case the TPC can be used to find both the momentum and the particle's identity. For tracks with a short TPC segment, on the other hand, the momentum is calculated based on the range and the particle is identified through ECal information. This is due to the geometry of the detector, since the TPCs only cover the upstream and downstream ends of the FGDs.

8.1.5 Track general quality and FV

Each neutrino interaction has to have its vertex within the specified fiducial volume of the first fine-grained detector. This fiducial volume is defined by the following ranges: $|x| < 874.51$ mm, $|y - 55| < 874.51$ mm, $125.750 < z < 447.375$ mm, where the 55-mm offset in the y direction reflects the 55 mm shift of the XY modules according to the center of the ND280 coordinate system. These limits translate to rejecting the five outermost bars (≈ 58 mm) on both sides of the XY modules over the entire z range (the beam direction). This results in only considering the central 182 out of the total 192 X

and Y bars. Events with vertices in the most upstream XY module are always rejected. For high-angle tracks, vertices found in the downstream layer are also excluded.

Now the tracks are distributed into the four desired candidate muon directions: forward (FWD), backward (BWD), high-angle forward (HAFWD) and high-angle backward-going (HABWD) muons.

8.1.6 Broken track rejection

Sometimes the reconstruction splits up tracks in the FGD, yielding an apparent start or endpoint within the detector. To combat this, the particle with the highest momentum after the muon candidate is identified. If the ratio between this ‘second highest momentum’ particle and the muon exceeds 0.8 (0.9, 0.9), the event is rejected. Moreover, if the start positions of these two particles fall within 100 mm (-150 mm, -400 mm), the event is rejected as well. The numbers in parenthesis show the values of the criteria for HAFWD and HABWD cases.

BWD events are also rejected if they originate from the second layer of the FGD, essentially defining a tighter fiducial volume for those directions. In the forward-going regime, the condition is slightly more complex. If there is more activity present in the FGD that does not leave a TPC track and the muon candidate started from the final two layers, the event is rejected. This greatly limits the number of instances where we find multiple particles when there truly only was a single particle. This concludes the criteria that are applied in the general quality block of the selection. The next step is to perform particle identification (PID).

8.2 MUON PID

Now that the general data quality has been assured and the highest momentum track been selected, the process of classifying the particle that caused the track can be initiated. To each track, a score is assigned that corresponds to the likelihood of it being a muon. These scores are produced through particle pulls, which describe the difference between measured and expected energy deposition profiles $\frac{dE}{dx}$ normalized by the energy resolution σ_i for particle type i .

$$\text{Pull}_i = \frac{dE/dx_{\text{meas}} - dE/dx_{\text{expected},i}}{\sigma_i}. \quad (8.1)$$

These pulls can be transformed into a Gaussian distribution by computing the exponential of the squared pull:

$$P_i = \exp\left(-\frac{\text{Pull}_i^2}{2}\right). \quad (8.2)$$

The likelihood is finally computed by normalizing the Gaussian probability by all particle probabilities:

$$L_i = \frac{P_i}{\sum P_k}, \quad (8.3)$$

where the sum in the denominator is over all particle hypotheses: muons, protons, electrons, and pions. The likelihood is then calculated for all events and all track orientations, but sees a variety of constraints for each muon direction.

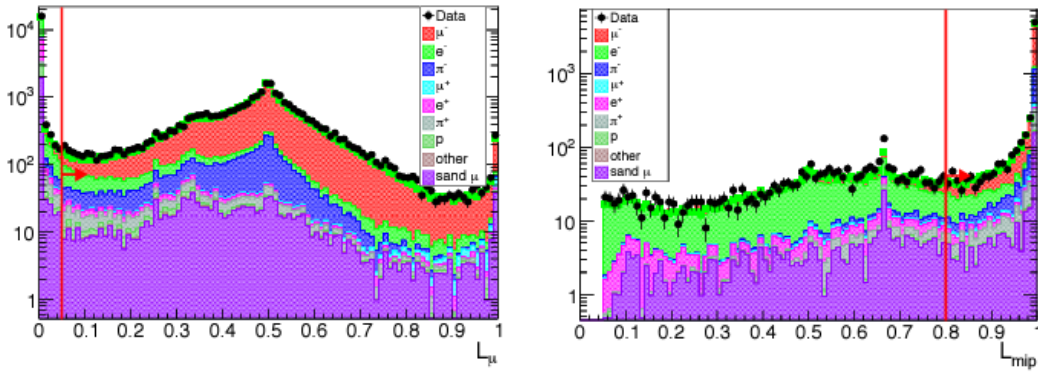


Figure 8.2: The muon Likelihood (left) and the minimum ionizing particle (MIP) likelihood (right) for the muon candidate in the forward-going direction. Colors indicate true particle types [187].

Forward-going muons

- For muons with a momentum above 280 MeV/c, the track should not stop in FGD2
- The likelihood that it is a muon should be higher than 0.05. The other particle types all have values below 0.05. This is mainly used to remove leading pions and protons (see left-hand image in figure 8.2.)
- In case the momentum is below 500 MeV/c, the likelihood to be a minimum ionizing particle should be above 0.8: $L_{MIP} = \frac{L_\mu + L_\pi}{1 - L_p}$. This is essential to the rejection of electrons that were selected as the highest momentum track (see right-hand image in figure 8.2.)
- Lastly, if a muon candidate that fulfills the TPC muon PID criteria enters the barrel ECal or stops in the downstream ECal, it must have an ECal ‘PIDMipEm’

value below 15. This is a score that distinguishes between track-like (muons) and shower-like (hadrons) objects. Negative values indicate track-like behavior and positive values indicate shower-like behavior. Figure 8.3 shows the effectiveness of this requirement.

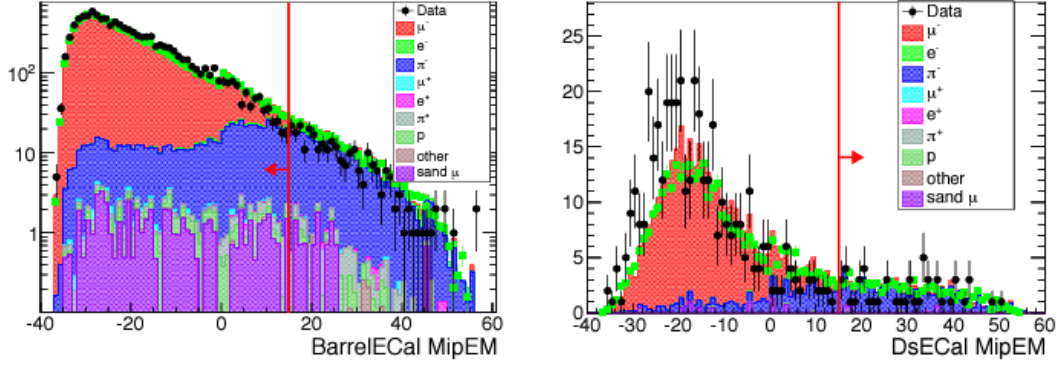


Figure 8.3: ‘PIDMipEm’ criteria for muon candidates reaching the Barrel ECal (left) and downstream (DS) ECal (right) [187].

Backward-going muons

- For backward-going muons with a momentum below 200 MeV/c, the MIP likelihood $L_{MIP} = \frac{L_\mu + L_\pi}{1 - L_p}$ should be above 0.95 and the muon likelihood $L_\mu > 0.65$.
- Backward-going muons with higher momentum should have a MIP likelihood $L_{MIP} = \frac{L_\mu + L_\pi}{1 - L_p} > 0.35$ and a muon likelihood $L_\mu > 0.65$.

For the high-angle tracks, the TPC information is not reliable enough to make a conclusive statement based on the previously discussed likelihood parameters. Instead the ECal and the side muon range detector (SMRD) are used. If tracks enter the SMRD mounted within the magnet yoke, they are classified as muons as most other particles do not make it this far out of the tracker region. If the track stops in the ECal, the same PIDMipEm variable is used as in the forward-going case.

High-angle FWD and BWD muons

- The particle in question has to have been assigned a PIDMipEm between -100 and 0 (see figure 8.4)
- The track length divided by the electromagnetic energy as observed by the ECal has to lie between 1.0 and 2.6

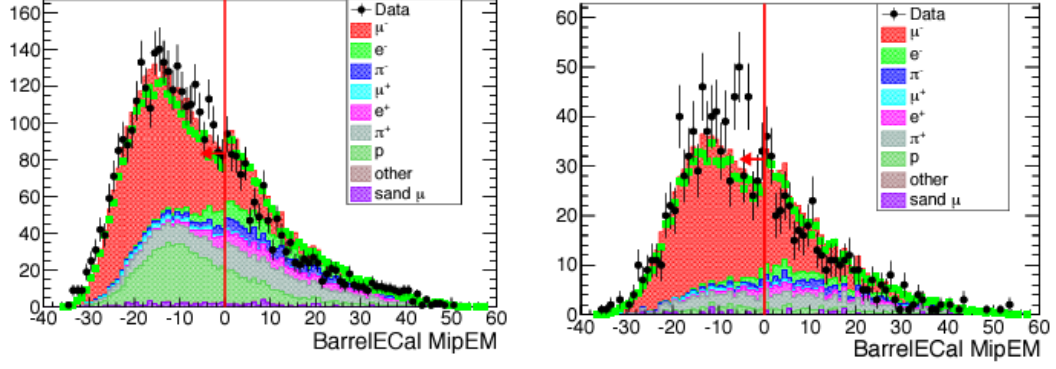


Figure 8.4: ‘PIDMipEm’ values for muon candidates reaching the BarrelECal in the high-angle forward-going direction (left) and high-angle backward-going direction (right) [187].

8.3 PION PID

Now that the muon has been assigned to the highest momentum track, the sample can be split into the pion topologies described above. However, those pions need to be found first. This is done following a similar procedure as for the muon PID. As stated before, the charged pion identification comes from three different sources:

Pion identification methods

- TPC: tracks with good TPC information (at least 19 clusters)
- FGD: tracks that find their origin in the FGD, but never make it out
- ME: pion identified through the resulting Michel electron coming from the decay of its daughter muon

Neutral pions are recognized by the signature electron and positron pair in the TPC coming from the two photon decay.

TPC pions

The pion PID for TPC tracks is determined by the highest probability particle method. Similarly to the muon PID, the likelihood is calculated according to equation 8.3. To ensure the highest probability in correctly assigning the particle, there is an additional step calculating the ratio of likelihood to summed likelihood. This ratio will be referred to as ‘prob’.

$$\text{Prob}_i = \frac{L_i}{\sum L_k} \quad (8.4)$$

In equation 8.4, i is a particle type and k loops over a positive pion, proton or positron in the case of positive TPC tracks and a negative pion or electron in the case of negative TPC tracks.

FGD isolated pions

Both of the remaining identification methods rely purely on the FGD and its timing capability. Time bins in this detector are defined as a collection of hits left behind by particles that traverse it within a rolling time window. It is not a standard set window in the sense that here the hits are all stored in a singular bin as long as each subsequent hit arrives within 100 ns from the previous one. If that limit is exceeded, a new bin is created.

In order to be classified as an isolated FGD track, it must first of all be placed in the same time bunch as the muon candidate. It should only be associated with a single segment in order to avoid broken tracks. It has to be fully contained within the FGD and the cosine of the angle with respect to the neutrino beam must be larger than 0.3. Above this value, the reconstruction and related systematic uncertainties start to behave erroneously.

The final cut is on the pion pull, which is described by equation 8.5.

$$P_i^{\text{FGD}} = \frac{E_{\text{measured}} - E_i(x_{\text{measured}})}{\sigma_i(x_{\text{measured}})}. \quad (8.5)$$

It is analogous to the TPC version described before, but contains the total deposited energy instead of dE/dx . The region between value of -2.0 and 2.5 is selected to remove electrons on the lower end and protons on the higher end. In equation 8.5, the expected total energy E_i and its associated resolution σ_i both depend on the measured track length x_{measured} as there is no TPC information to perform a rigidity study for bend tracks.

ME-tagged pions

Although the concept of tagging pions through the subsequent Michel electron is not new to this analysis, the derivation of the pions' kinematic information from these MEs is. The time bins used in the isolated FGD case can be used here as well. The muon lifetime sits around $2.2 \mu\text{s}$ far exceeding the 100 ns interval between time bins. These decays thus exhibit a characteristic delayed signal that can be used as an identification tool. The event should contain at least one delayed bin with a minimum of seven hits to be considered. The method used for estimating the kinematics of the pion when it is tagged by the presence of a Michel electron is detailed in [188].

With the particle identification done, the sample can now be split into pion multiplicities.

8.3.1 Topology criteria

Stage three of the introduced diagram is where the sample is separated into CC0 π , CC1 π and CCOther topologies. The criteria are summarized below.

- **Zero pions:** Any event for which the likelihood study labeled particles as electrons, positrons or charged pions in the TPC is rejected immediately. Events fully contained in the FGD involving pions or Michel electrons are also rejected.
- **A single positively charged pion:** Events with more than one positively charged pion, any number of neutral pions, electrons, or positrons in the TPC are rejected. Events meeting either of the following criteria are selected:
 - The sum of all positively charged pions identified by the time-projection chamber and tagged by the subsequent Michel electrons must be equal to 1.
 - In the absence of any ME, the sum of all positively charged pions in the time-projection chamber and the fine-grained detector must be equal to 1. Pions could leave both an isolated track in the FGD and decay, so the requirement here ensures there is no double counting.
- **Others:** This cut essentially covers all ‘other’ scenarios. Events with at least one negative pion, any number of neutral pions or more than one positive pion will all pass this selection step. In recent times this sample has been further subdivided by considering the number of protons and photons, but as this selection focuses on specific sidebands that separation will not be covered here.
- **Sidebands:** Subsets of the CCOthers topology can be used as the sidebands for this cross-section analysis. As will be shown in the next chapter, the true composition of the selected signal region consists of CC1 π^+ (as intended) with a substantial amount of CCOther. To better understand this secondary contribution, the interaction modes making up CCOther can be studied. This shows that it consists predominantly of deep-inelastic scattering (DIS) events.

The main background coming from DIS and ending up as CC1 π^+ is from situations where any of the particles aside from the muon and the pion are not observed in ND280. Intuitively, the most common of these background topologies would be the ones where there is an additional pion in the final state. These samples can be constrained by looking at events where the extra pions are identified, resulting in the CC1 $\pi^+ \& \pi^+$ and CC1 $\pi^+ \& \pi^0$ sidebands.

In the high-angle forward-going sample, the $CC0\pi$ topology dominates the background contribution. This is the result of protons being misidentified as positively charged pions and thus passing the signal selection criteria. Hence the sideband has been specifically designed to contain one identified proton in addition to the candidate muon. More details will be given in the dedicated sections on control samples.

8.3.2 Zero ECal photons cut

To further purify the $CC0\pi$ and $CC1\pi^+$ samples, an additional measure is taken to reduce the contamination from events with neutral pions. Especially in the region of interest between 200 and 800 MeV/c, in around a third of the $NC1\pi^0$ events, the neutral pion undergoes photon conversion in the barrel ECal. After finding the photon cluster pairs, their paths can be traced back to a π^0 decay vertex in the FGD. It is paramount to simultaneously have low activity in the tracker region. Photons are selected if there is an isolated object in the ECal in the same time bunch as the muon candidate. Something similar was discussed before when considering the pion PID. Moreover, the most energetic ECal object gets selected and has to have a $PIDMipEm > 0$ in combination with fewer than six upstream layers hit.

8.3.3 Common vertex cut

Looking at the kinematic distributions for the final $CC1\pi^+$ sample up until this point in the selection in figure 8.5 for muon momentum and figure 8.6 for the cosine of the muon angle with respect to the incoming neutrino beam, a concerning observation is made for the backward-going regions. The out-of-fiducial-volume (OOFV) contribution overshadows the signal by 51% in the BWD and 46% in the HABWD directions. As a crucial part of this analysis revolves around the extension of the solid angle, a higher level of purity within those regions is important. The common vertex cut is an attempt at reducing the out-of-fiducial-volume contribution while retaining the signal events. As the name suggests, it looks for a shared vertex between the muon and pion tracks by finding the starting position of those two particles and checking if they are found within a certain distance from one another.

Muon-Pion Vertex

- The coordinates transverse to the beam direction have to be within 200 mm from each other.
- The beam direction coordinate of the muon and the pion have to lie within 60 mm.

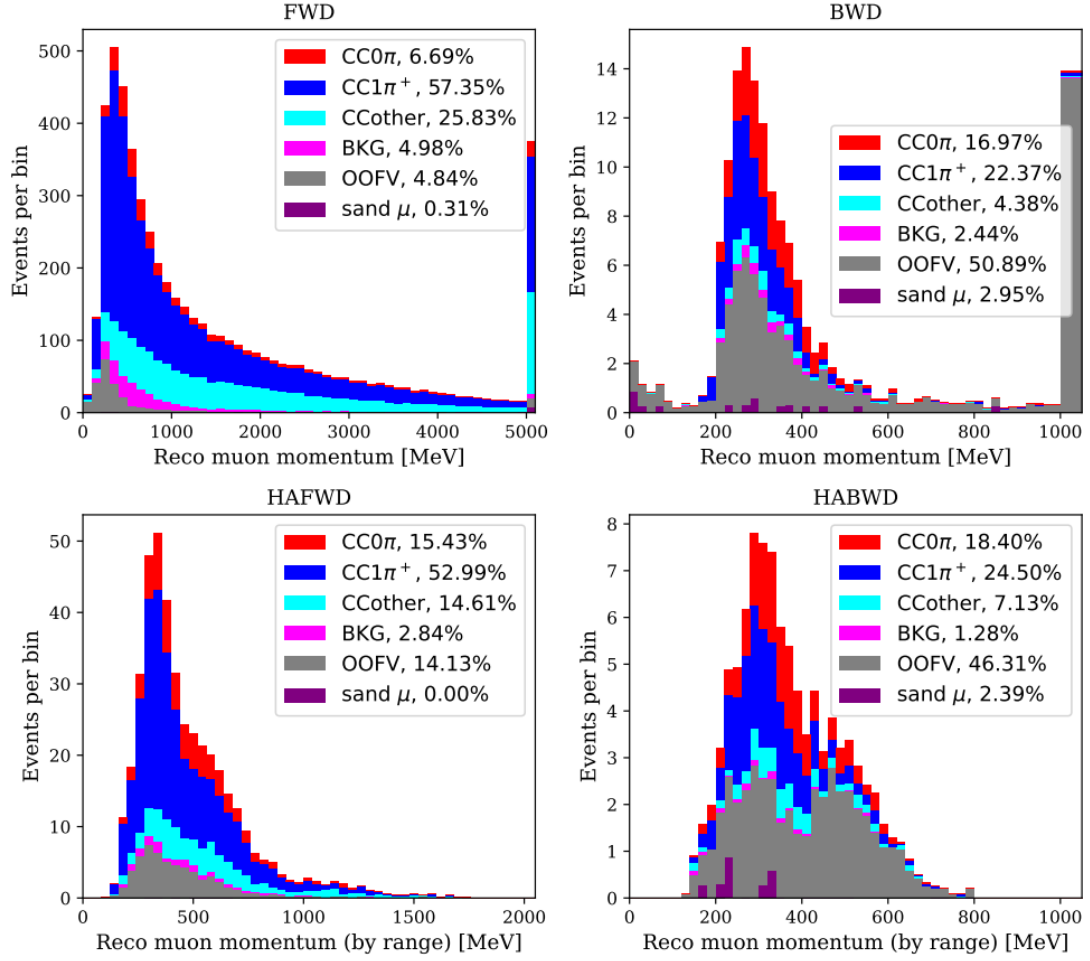


Figure 8.5: Muon momentum in the $CC1\pi^+$ sample separated in muon direction [189].

While this cut reduces the OOFV events, it does require a track for both the muon and pion in order to compare the starting positions. In total there are three pion identification methods of which only two require a pion track, namely the TPC-tagged and FGD-tagged ones. Whenever the Michel electron is used, the pion itself will not necessarily yield a track. For those cases, a new way to remove the out-of-fiducial-volume background is required.

ME-tagged pions cut

The momentum for ME-tagged pions is derived from the distance between the neutrino vertex (the muon starting point in the forward direction and the muon ending point in the backward direction) and the charge weighted position of the Michel electron. This makes the distance a proxy for the momentum. Upon studying momentum distributions for all four muon directions in figure 8.5, it was found that the OOFV contribution in the backward-going samples seems to have come from events with Michel electrons passing the selection (57% in BWD and 78% in HABWD, purities also represented in figure 8.7).

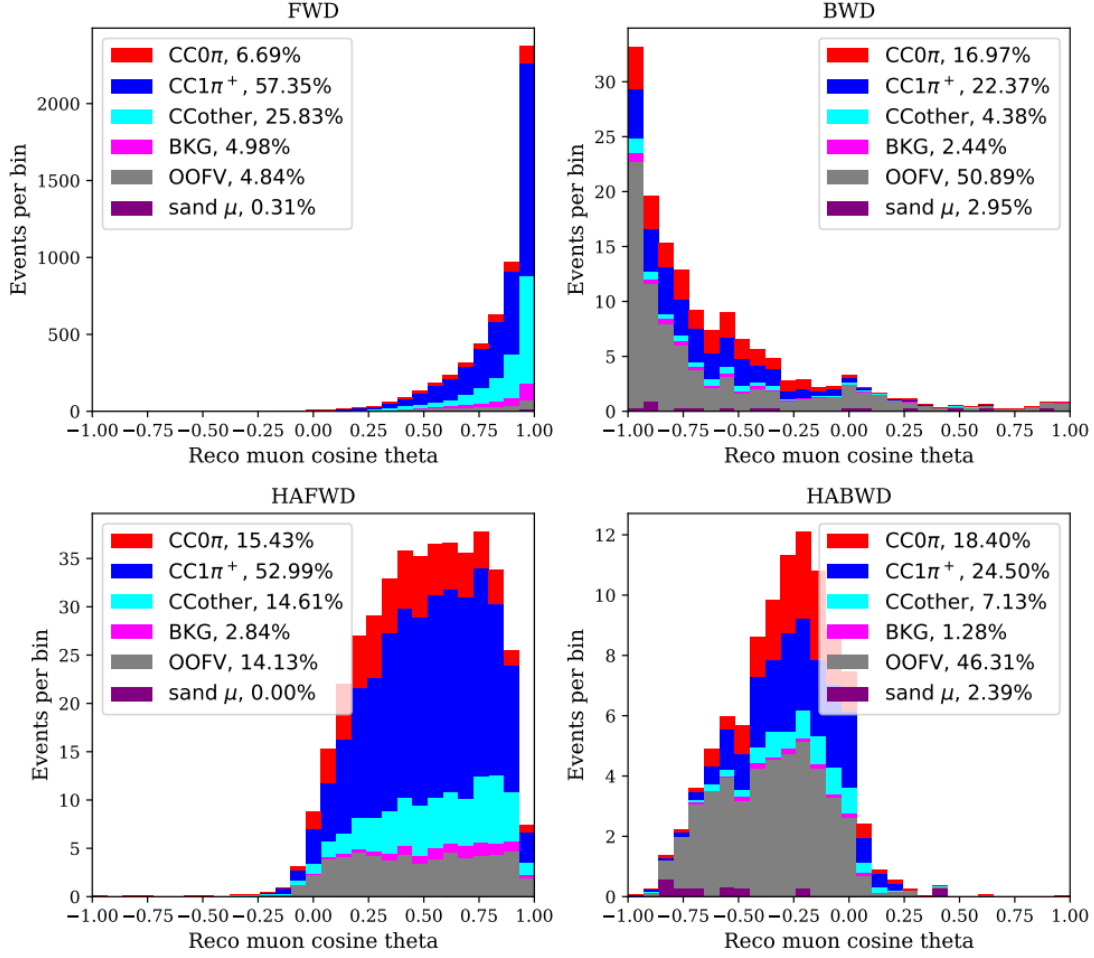


Figure 8.6: Cosine of the muon angle with respect to the incoming neutrino beam in the CC1 π^+ sample separated in muon direction [189].

With significant levels of OOFV events in the new ME-tagged pion sample, it is important to look for ways of reducing them.

ME distance cut

Going back to the separation between the Michel electron's position and the neutrino vertex yielded the results shown in figure 8.7. The OOFV contribution, where the true vertex is outside the FV, overlaps with the region in which the signal is most present. The Michel electron is expected to be relatively close to the neutrino interaction vertex as the parent particles will not be able to travel indefinitely in the FGD (i.e., before the signal is lost) due to decay rates and FGD size restrictions. There is only so much distance they can cover until they decay or exit the FGD.

One can understand this by considering the correction responsible for the time of flight that is applied to the Monte Carlo samples. When switching this correction on and off,

the OOFV contribution grows or shrinks. This correction smears the start and end time of a muon track, sometimes causing $t_{\text{start}} > t_{\text{end}}$ and thus forcing a track flip to retrieve the chronological order, resulting in a reconstructed direction that is rotated by 180° from the correct direction. Forward would become backward and vice-versa. The difference in statistics between those samples makes the track flips significant for the BWD direction.

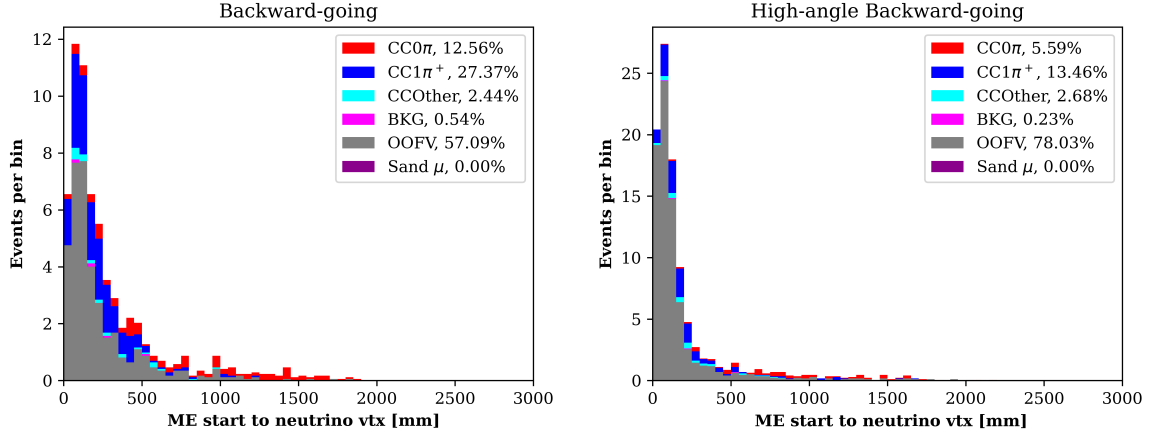


Figure 8.7: Distance between the neutrino interaction vertex and the muon decay vertex.

Forward-going muons could enter the FGD and produce a Michel electron through their decay. This type of event would not pass the $\text{CC1}\pi^+$ selection criteria, because the track's starting position is not inside the fiducial volume. In some scenarios, the aforementioned smearing might lead to the muon track being flipped (the starting and ending position are then swapped). Now it will appear as if the muon is going backward coming from the FGD. On top of that, the ME will make it seem as if a pion has decayed near the start of the muon track (also referred to as the neutrino interaction vertex). A muon and pion coming from this position allows the event to pass the entire selection. With the true vertex being outside the FV, it is classified as an OOFV event.

Distinguishing between these signatures is deemed to be very difficult and beyond the scope of this analysis. Hence the choice is made to reject the Michel-electron tagged pions from the high-angle backward-going sample. For the backward-going sample, a cut allowing distances below 500 mm in neutrino-to-ME separation to pass yields a slight improvement in the purity (27% to 34%). As this is slightly better than the 'TPC&FGD-only'-sample purity it is still considered a valuable addition to the selection.

The same study can be performed in the forward-going direction. The contribution at large distances is mainly from the $\text{CC0}\pi$ topology. As this is the largest background

in the forward-going direction, reducing it would be beneficial.

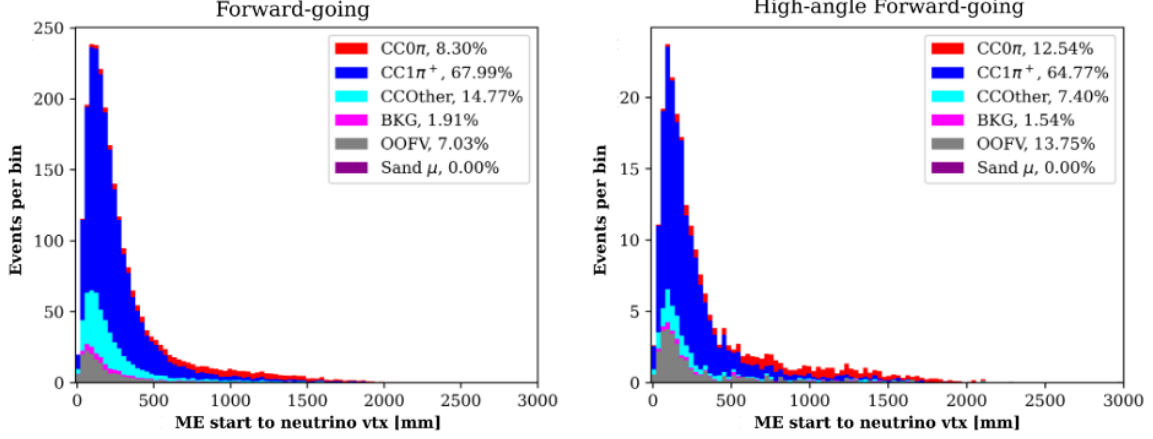


Figure 8.8: Distance between the neutrino interaction vertex and muon decay vertex

The region above 750 mm shows the worst signal to background ratio and thus the cut is placed precisely there (see figure 8.8). This improves the signal purity from 68% and 65% to 72% and 71% for the forward and high-angle forward-going direction, respectively. This concludes the final step in the selection procedure. What the phase space looks like and how the ME-tagged pions contribute to the overall kinematic distributions as well as the efficiencies and purities will be discussed in the next section.

8.4 SIGNAL AND CONTROL SAMPLES

The kinematic distributions for the $CC1\pi^+$ analysis on hydrocarbon in all muon directions with the inclusion of ME-tagged pion kinematics will be presented here. A topological breakdown will be given for the signal ($CC1\pi^+$) and control sample ($CC0\pi$, $CC1\pi^+1\pi^\pm$, $CC1\pi^+1\pi^0$) regions in the pion's momentum and angle in addition to the muon's momentum and angle. The evolution of the efficiency for the four kinematic properties will also be presented, highlighting the parts of the spectra where improvements can be made.

The statistics used to create the figures in the sections of this chapter can be expressed in terms of the number of protons on target (POT) for each of the data taking runs of the T2K experiment. The POT can be found in table 8.1 divided into three columns. The ratio between data and MC POT can be used to scale the Monte Carlo event numbers to the expected rates in data. This has been done for all figures in this chapter. ‘Sand’ refers to muons coming from neutrinos interacting with the material (sand/rock, etc.) in the cavern surrounding ND280 that make it into the detector in coincidence with a beam event.

Sample	MC POT	Data POT	MC Sand POT
Run 2a	1.68019×10^{21}	3.59885×10^{19}	11.1964×10^{20}
Run 2w	1.20375×10^{21}	4.33502×10^{19}	11.1964×10^{20}
Run 3	3.07804×10^{21}	1.59337×10^{20}	11.1964×10^{20}
Run 4a	3.61220×10^{21}	1.78927×10^{20}	11.1964×10^{20}
Run 4w	3.61215×10^{21}	1.69529×10^{20}	11.1964×10^{20}
Run 8a	3.64094×10^{21}	4.15013×10^{20}	11.1964×10^{20}
Run 8w	2.40863×10^{21}	1.58053×10^{20}	11.1964×10^{20}

Table 8.1: Summary of POT (Protons On Target) for various T2K runs.

8.4.1 Signal distributions

In figure 8.9, the selected candidate events are shown as a function of the reconstructed muon momentum for the four muon directions.

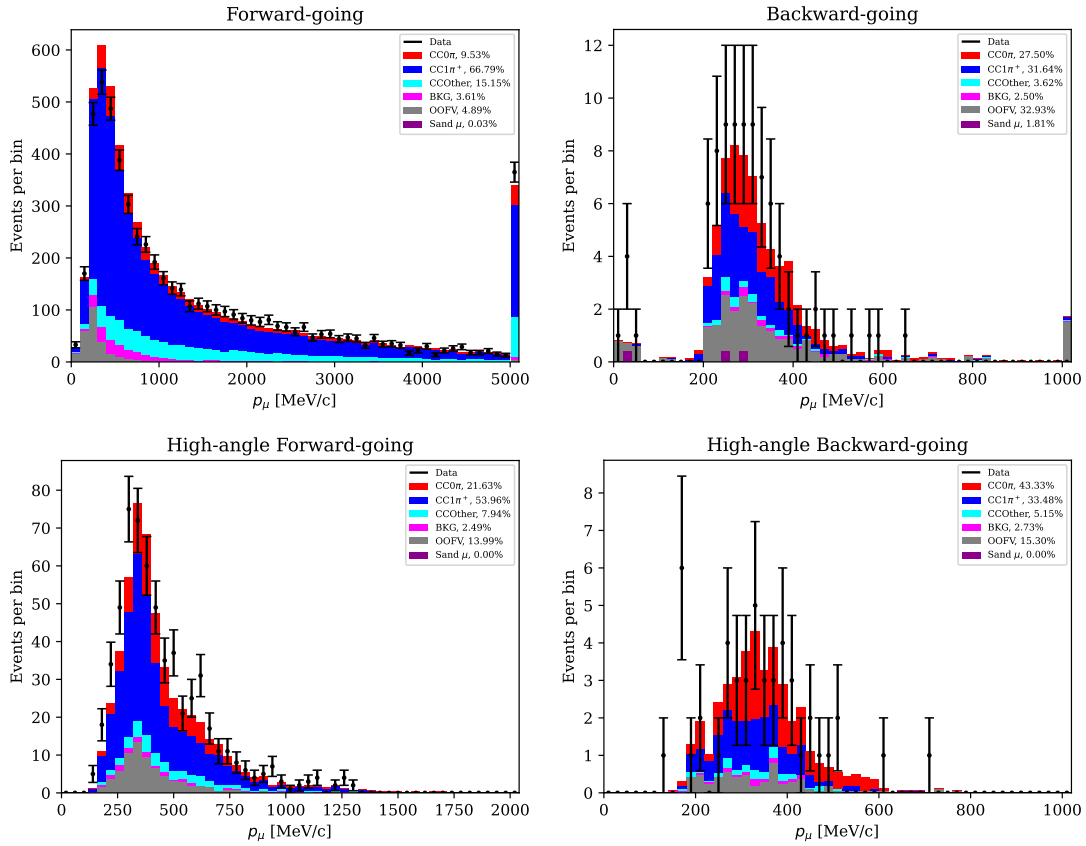


Figure 8.9: The final muon momentum in the $CC1\pi^+$ selection separated in muon direction in topological breakdown.

Figure 8.10 reflects the same muon direction configuration, but now binned in the cosine of the muon angle. It can be seen that the events are predominantly in the forward-going direction with a 67% signal purity. The remaining three regions sit at purities of 32%

for backward-going, 54% for HA forward-going and 33% for HA backward-going. These contain fewer statistics, but cover an interesting part of the phase space.

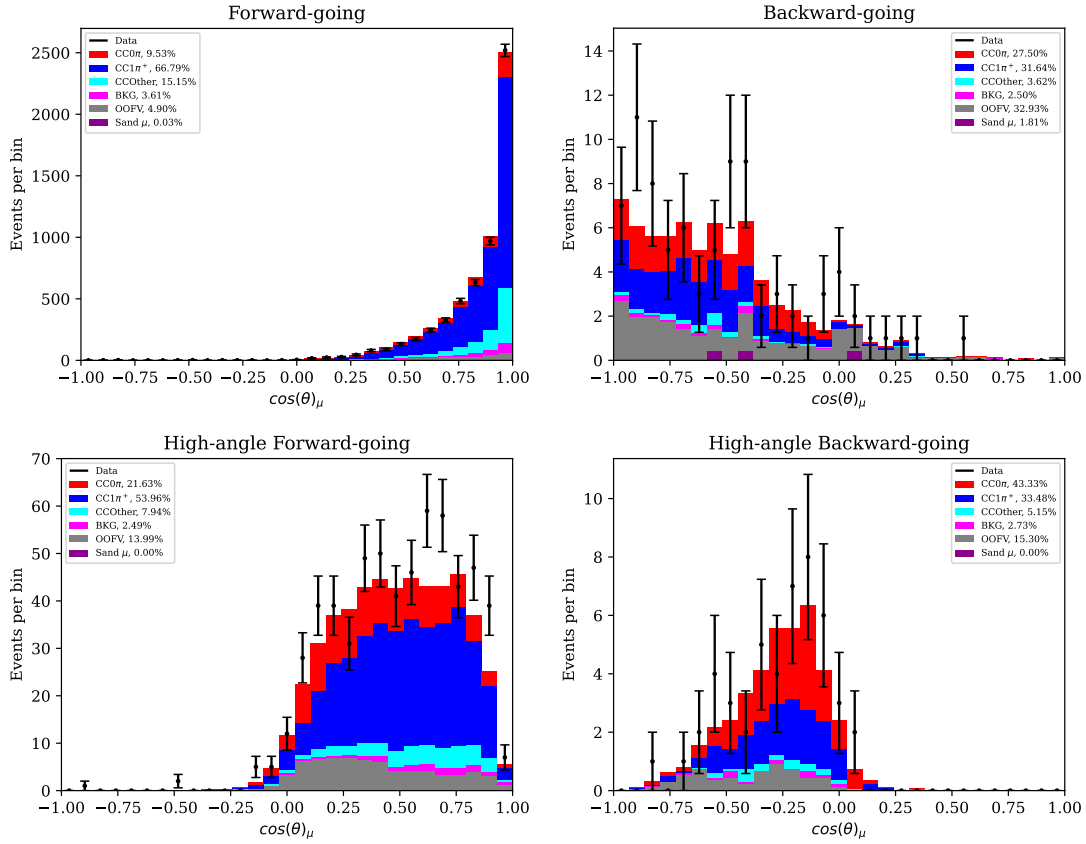


Figure 8.10: The final cosine of the muon angle in the $\text{CC}1\pi^+$ selection separated in muon direction in topological breakdown.

The reconstructed pion momentum and angle for the $\text{CC}1\pi^+$ signal selection are shown in figure 8.11. There is an overwhelming contribution to the background coming from the out-of-fiducial-volume and $\text{CC}0\pi$ events in all samples except in the forward-going direction. There, CCOther forms the dominant source of background. The control samples to estimate the background thus consist of alternative pion topologies, whereby CCOther is split into $\text{CC}1\pi^+ \& 1\pi^\pm$ and $\text{CC}1\pi^+ \& 1\pi^0$.

To illustrate how often the identified highest momentum track actually describes a muon, figure 8.12 contains the particle breakdown instead of the final state topology in terms of the muon kinematics. It can be seen that the selection performs with an accuracy of above 80%, reaching almost 92% in the forward-going samples. The positive pion selection results can be found in figures 8.13 and 8.14 divided into TPC&FGD identified pions and ME-tagged pions, revealing the importance of adding the latter by the high pion purity (around 95%). The majority of the contamination in the TPC&FGD sample

comes from protons with a smaller fraction of positive and negative muons. The mis-identification is especially visible for protons above 1200 MeV in the TPC and below 200 MeV in the FGD. For the Michel electron sample, the background comes from electrons that originate from the decay of the muon at the neutrino interaction vertex instead of the subsequent decay of the pion.

Figure 8.15 shows the efficiency as a function of the four true kinematic variables. Each row shows the efficiency with respect to the full available statistics on the left and with respect to the statistics after angular separation on the right.

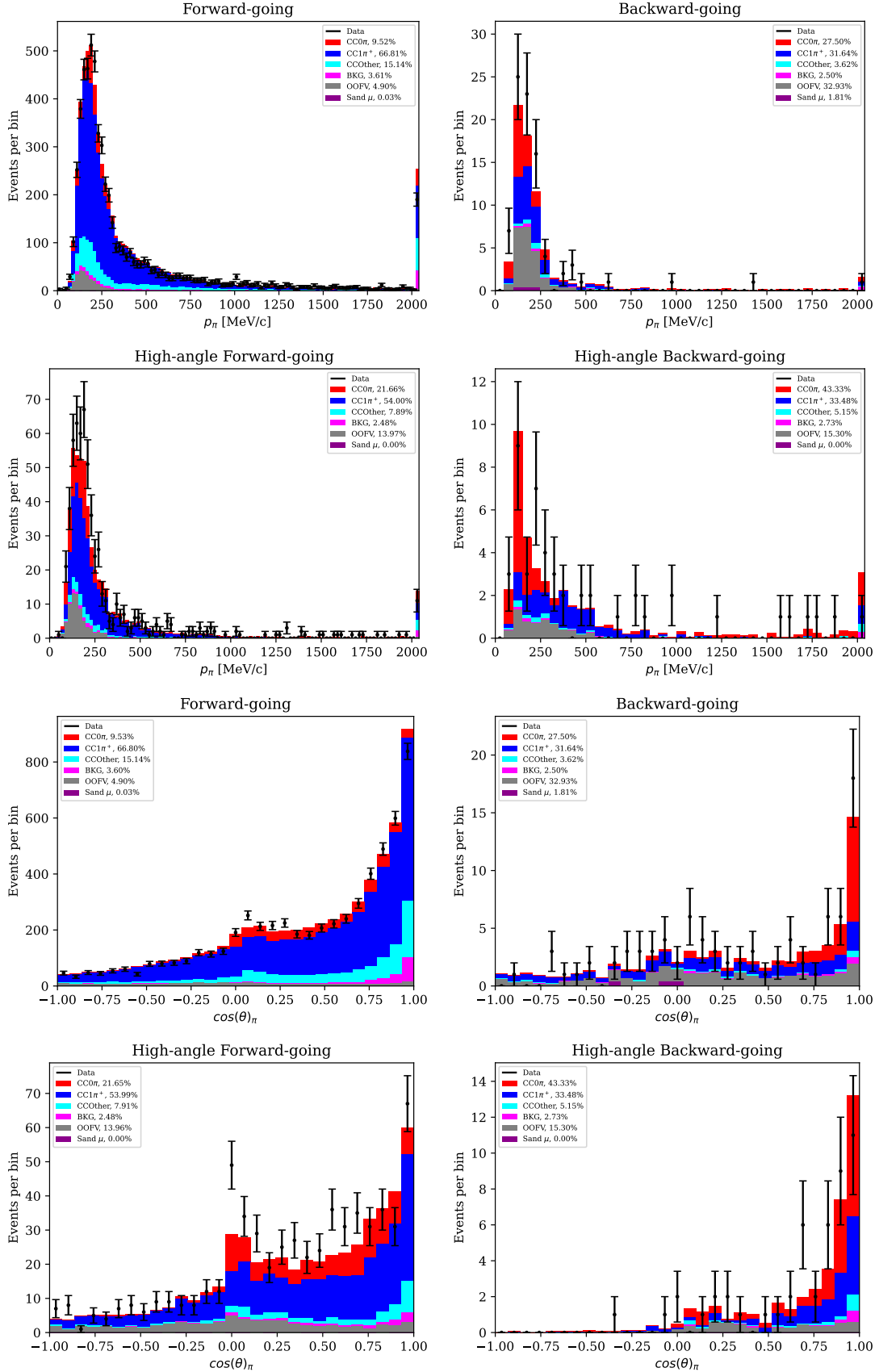


Figure 8.11: The final pion momentum (top four) and cosine of the angle (bottom four) in the $CC1\pi^+$ selection separated in muon direction: forward-going (top left), backward-going (top right), high-angle FWD and high-angle BWD (bottom right) in topological breakdown.

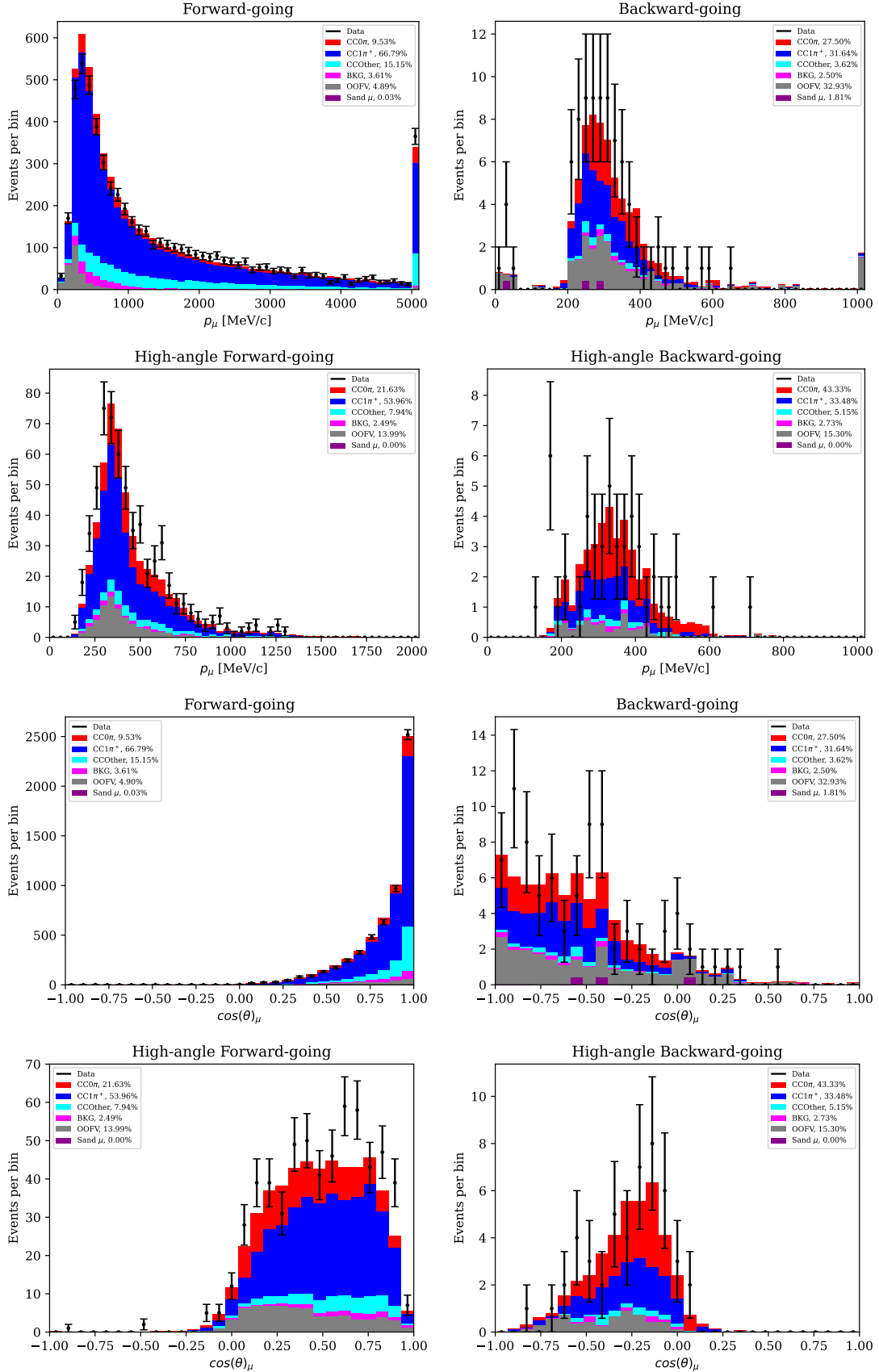


Figure 8.12: The muon momentum (top four) and cosine of the angle (bottom four) in the $CC1\pi^+$ selection separated in muon direction: forward-going (top left), backward-going (top right), high-angle FWD and high-angle BWD (bottom right) in true particle breakdown.

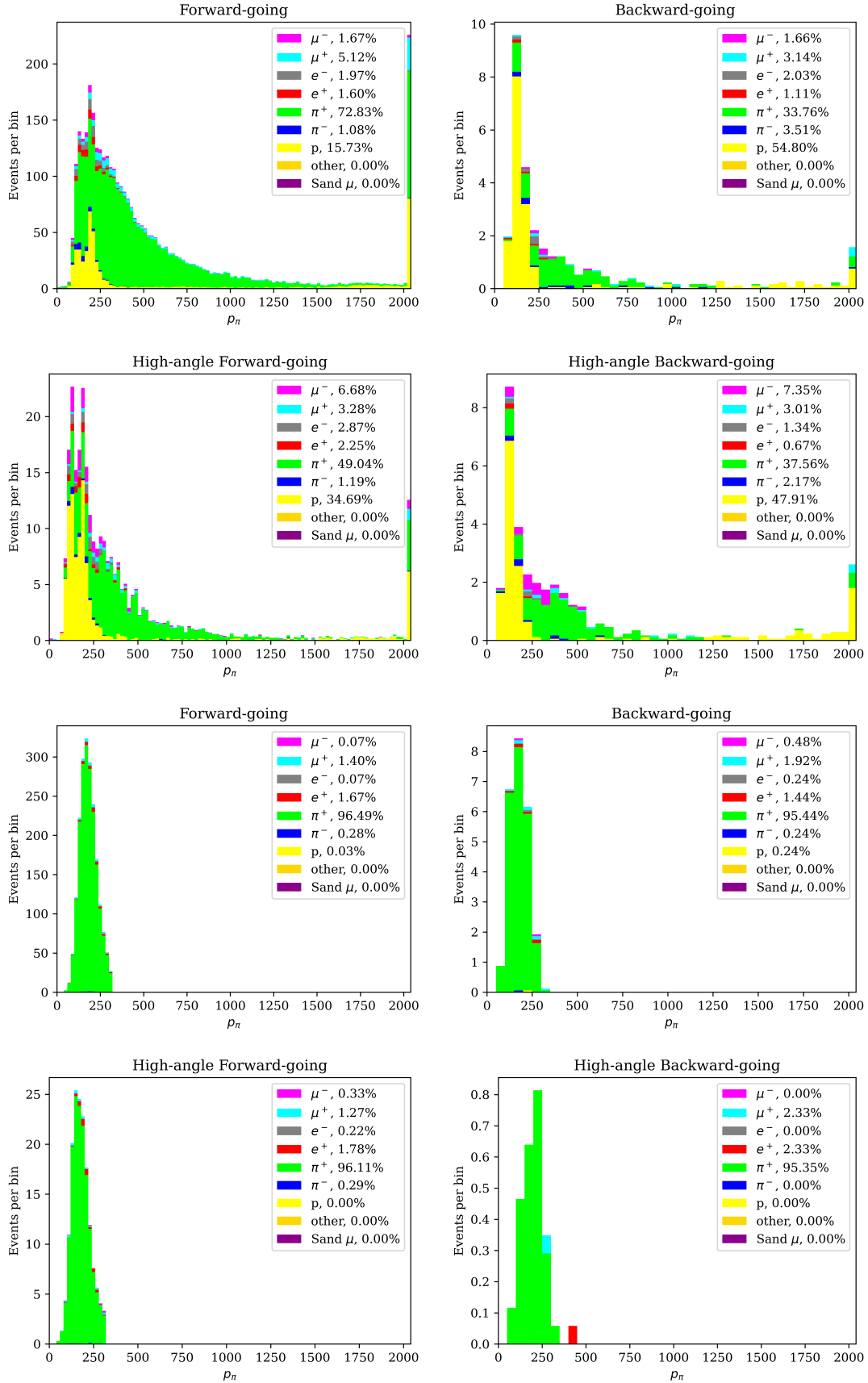


Figure 8.13: Momentum for TPC&FGD-tagged (top four) and ME-tagged pions (bottom four) in the CC1 π^+ selection by muon direction: forward-going (top left), backward-going (top right), high-angle FWD and high-angle BWD (bottom right) in true particle breakdown.

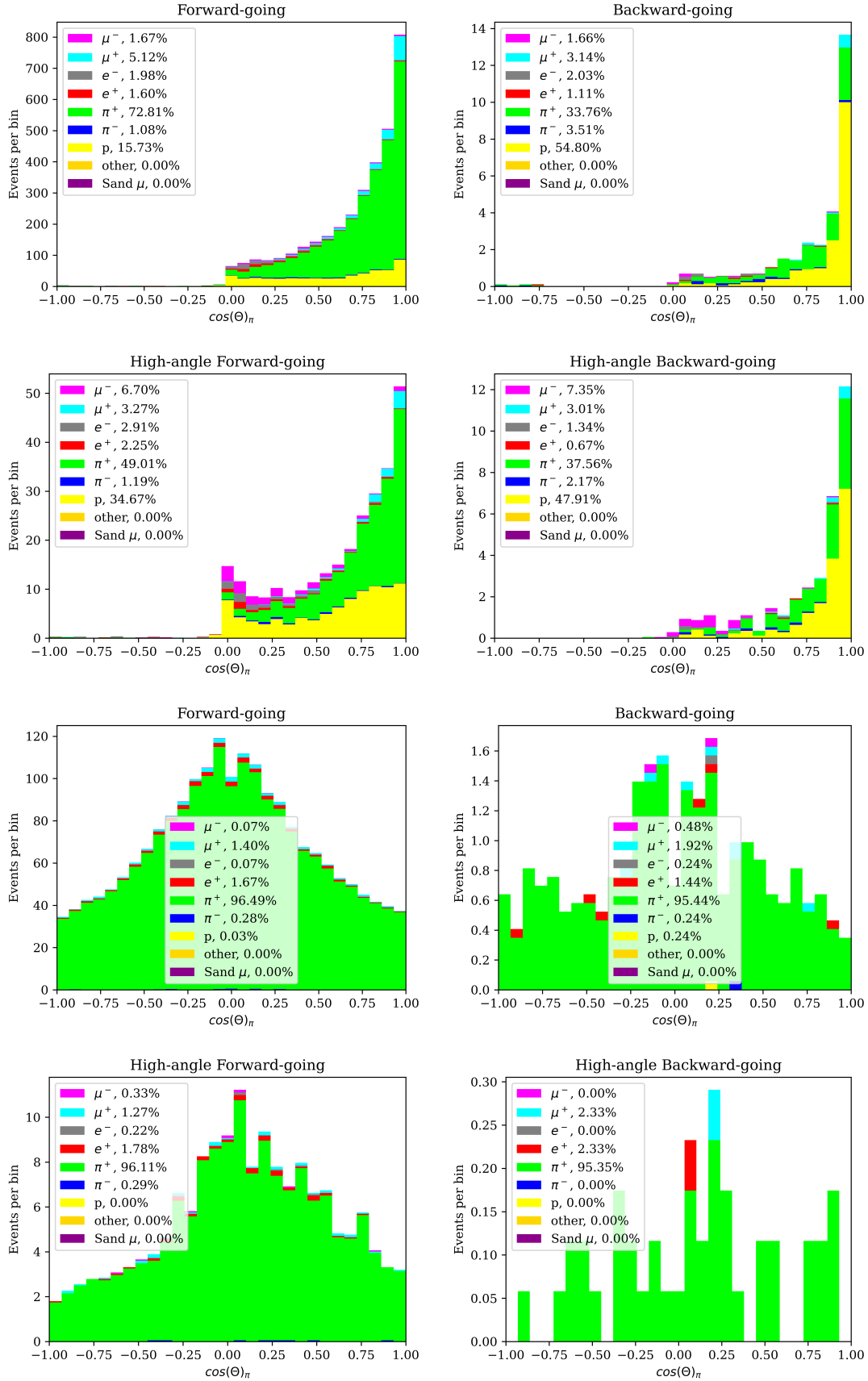


Figure 8.14: Cosine of the angle for TPC&FGD-tagged (top four) and ME-tagged pions (bottom four) in the CC1 π^+ selection by muon direction: forward-going (top left), backward-going (top right), high-angle FWD and high-angle BWD (bottom right) in true particle breakdown.

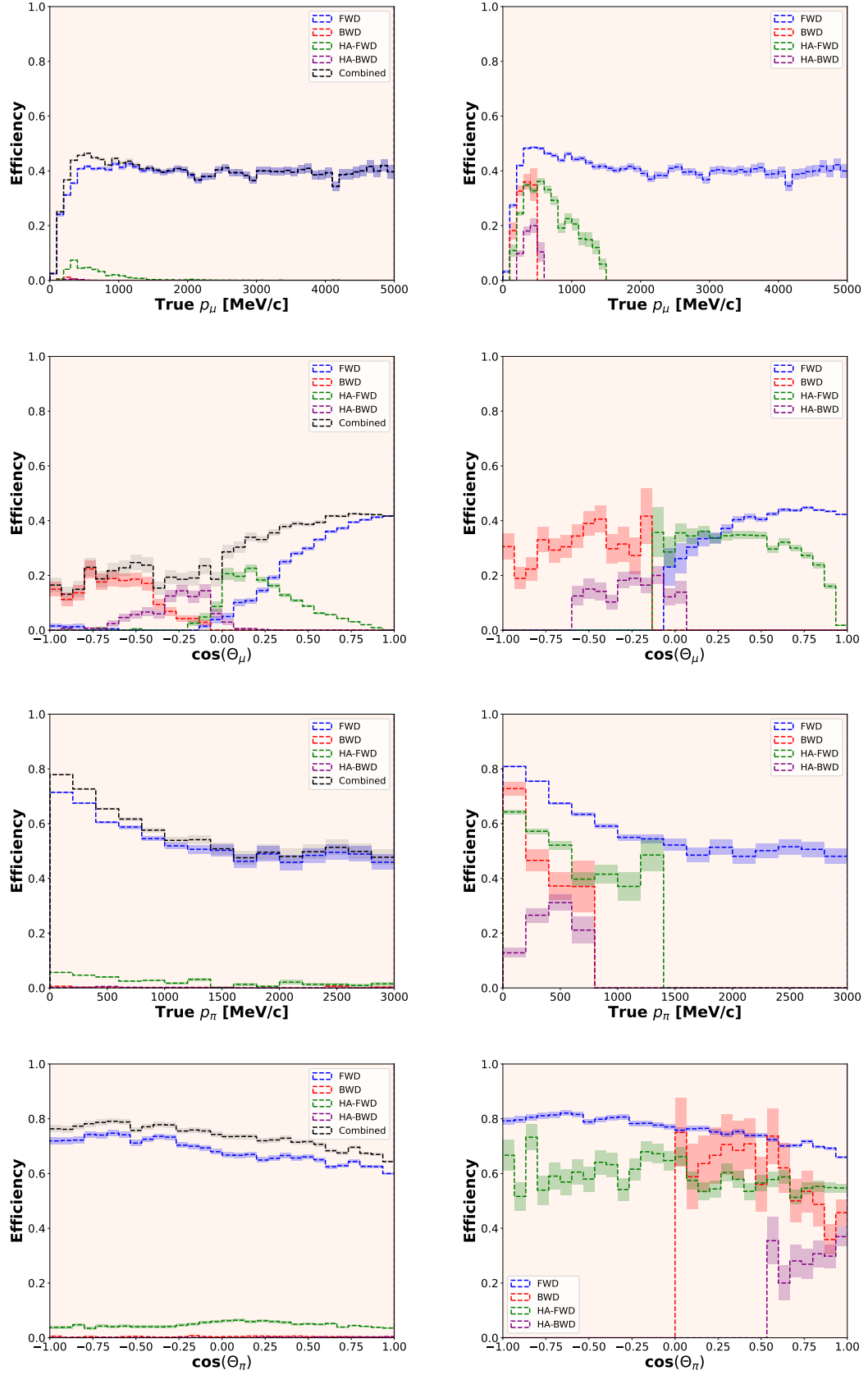


Figure 8.15: Efficiency as a function of muon momentum (top row), cosine of the muon angle (second row), positive pion momentum (third row) and cosine of the pion angle (bottom row) for the CC1 π^+ sample with respect to the full available statistics (left) and to the statistics after the angular separation (right).

8.4.2 Background samples: Quasi-Elastic like

The $\text{CC}0\pi$ events dominate the background in the high-angle forward-going sample, but also contribute significantly to the other three directions. Hence, an additional set of samples is added to represent a $\text{CC}0\pi$ sideband, which helps better understand its behavior in our $\text{CC}1\pi^+$ signal region. All selection steps leading up to the topology criteria described in section 8.3.1 are identical. Instead of looking for a single positively charged pion, the ‘Zero pions’ cut is applied, followed by the Zero ECal photons cut of section 8.3.2 to reduce the number of neutral pions.

Figure 8.17 illustrates the distribution of selected $\text{CC}0\pi$ events broken down in true topology plotted against muon kinematics. The particle categorization can be found in figure 8.18. Signal purity within these samples varies, with the HABWD branch exhibiting the lowest purity at 77%, and the HAFWD branch the highest at 83%. The $\text{CC}1\pi^+$ events constitute the primary background for the FWD branch, while OOFV contributions dominate the background for all other branches. Particularly for the BWD and HABWD branches, the out-of-fiducial volume background is substantial, comprising 14% and 20% of the total, respectively. The $\text{CC}0\pi$ sample shows the closest resemblance to charged-current quasi-elastic events out of all different pion multiplicity samples.

A comparison between the plots in figures 8.17 and 8.18 reveals that regions with a high presence of out-of-fiducial-volume events (e.g., tracks with $\cos(\theta_\mu) \approx -1$) coincide with areas where particles are often misidentified as muons. It can be concluded that positively forward-going (or backwards-going) particles, mistakenly identified as backward-going (or forward-going) muons, have minimal impact. Given the performance of the muon selection, correctly identifying 94% to 97% of muons, as depicted in figure 8.18, the OOFV background does not stem from misidentified particles. Instead, it primarily arises from events originating within the FGD but lying outside the fiducial volume, with a smaller contribution from events originating within the POD (figure 8.16).

The efficiency of the $\text{CC}0\pi$ selection, in terms of true muon kinematics, is shown in figure 8.19. The efficiency remains relatively constant for muons within the 4π acceptance range with momenta exceeding 500 MeV. However, it varies depending on the muon’s direction, being higher for forward-going muons compared to backward-going ones. The efficiency is lowest (at 5%) for muons traveling perpendicular to the neutrino direction. These muons typically bypass the TPC, moving up along singular FGD bars leaving only faint traces behind before reaching the ECal.

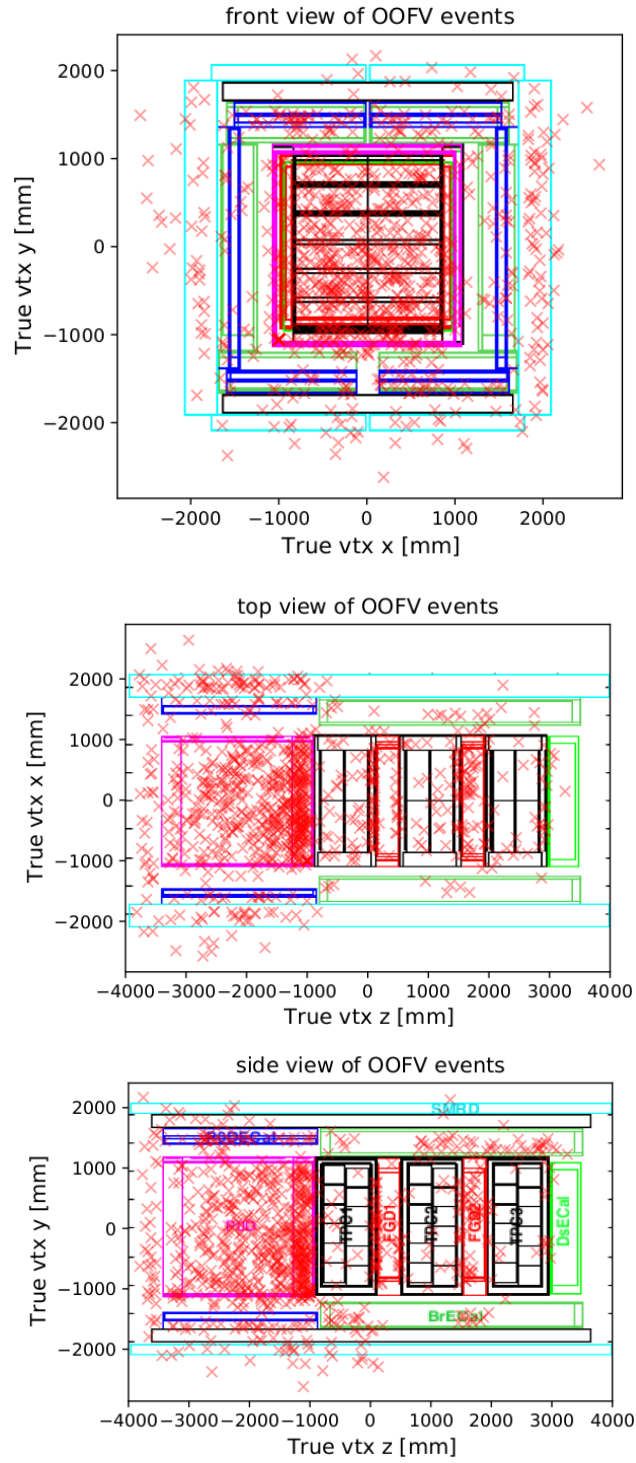


Figure 8.16: True vertex position in three projected views of ND280 for the out-of-fiducial volume events.

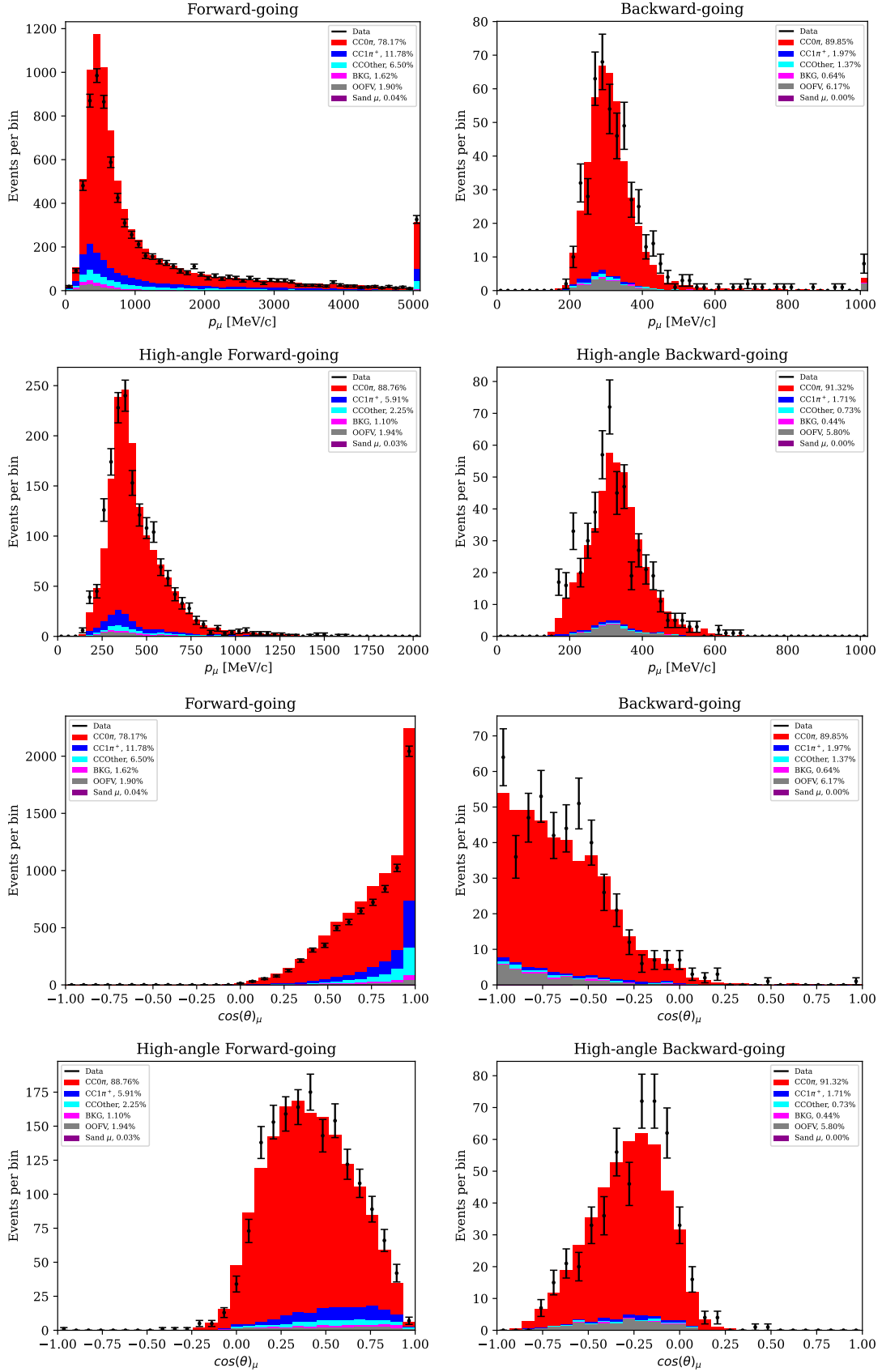


Figure 8.17: The muon momentum (top four) and cosine of the angle (bottom four) in the CC0 π selection separated in muon direction: forward-going (top left), backward-going (top right), high-angle FWD and high-angle BWD (bottom right) with the topological breakdown.

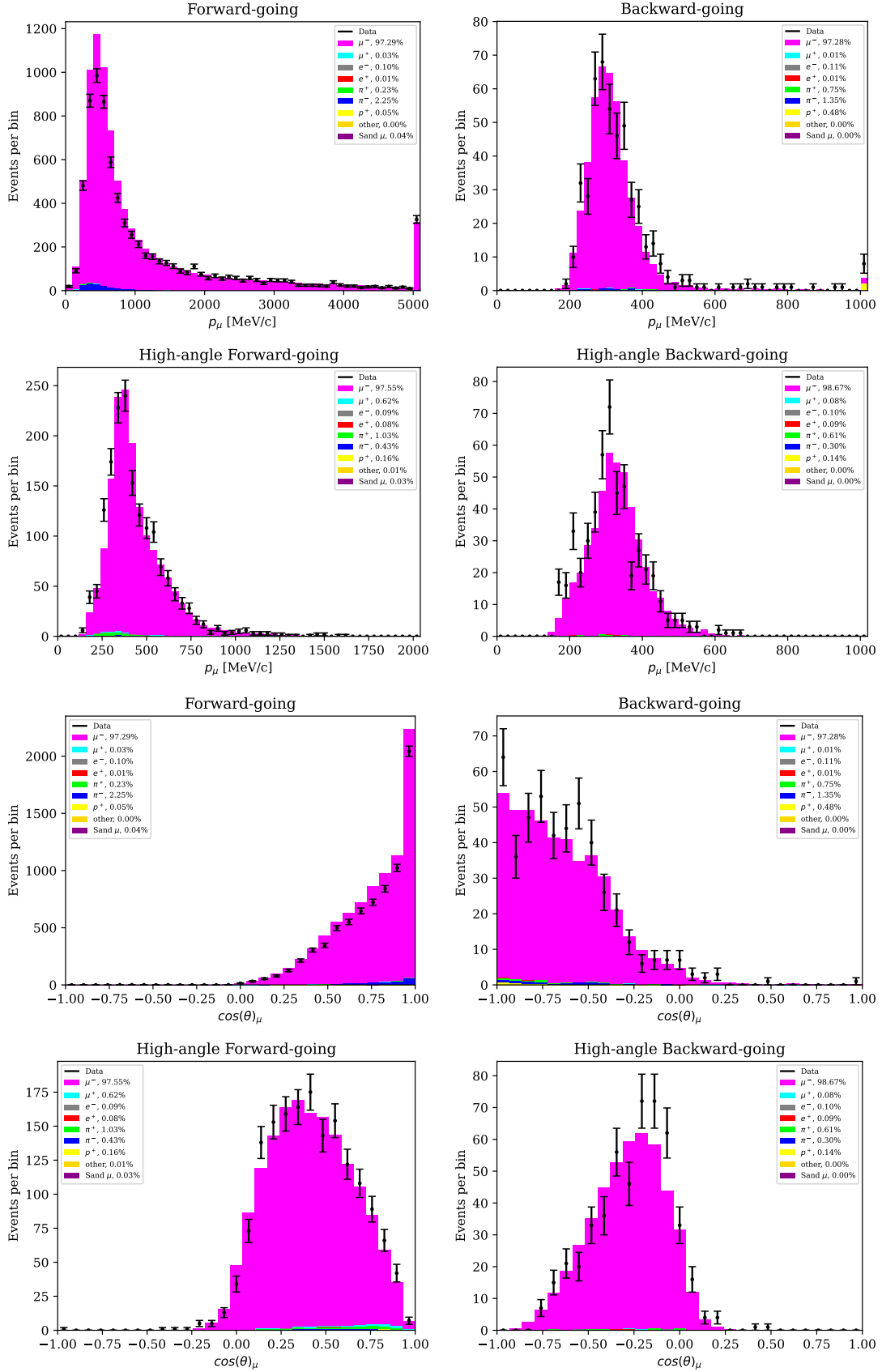


Figure 8.18: The muon momentum (top four) and cosine of the angle (bottom four) in the CC0 π selection separated in muon direction: forward-going (top left), backward-going (top right), high-angle FWD and high-angle BWD (bottom right) in true particle breakdown.

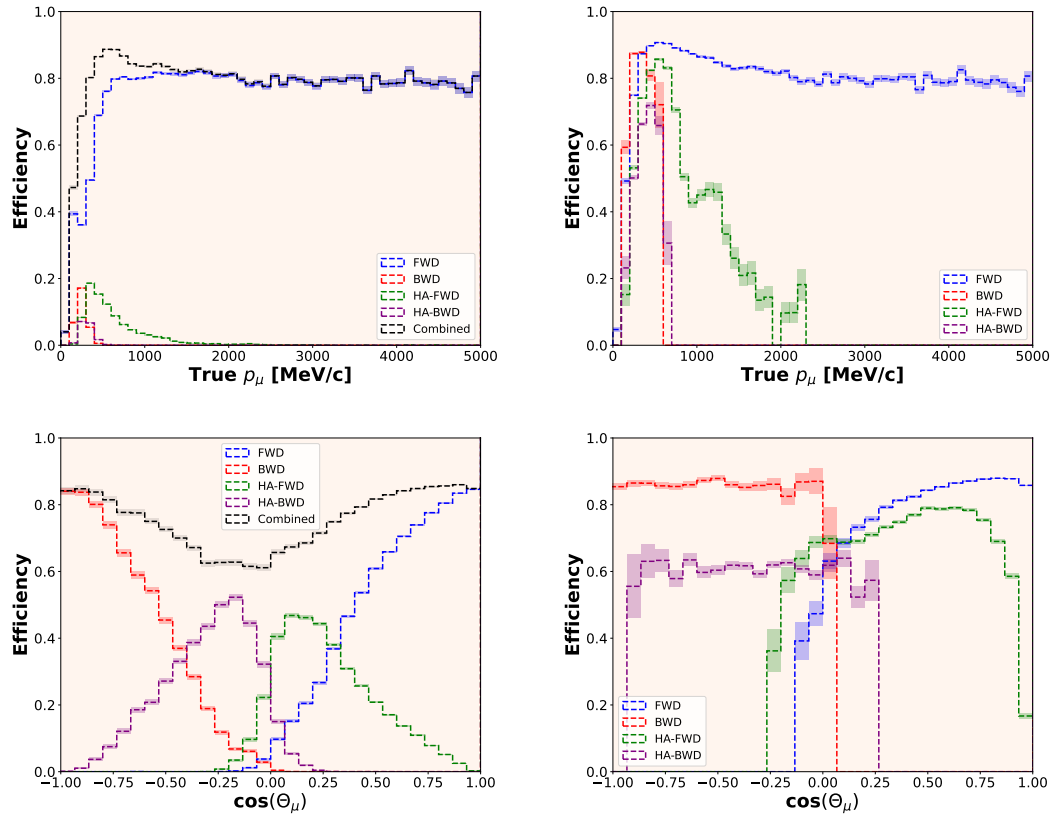


Figure 8.19: Efficiency as a function of muon momentum (top row) and cosine of the muon angle (second row) for the $CC0\pi$ sample with respect to the full available statistics (left) and to the statistics after the angular separation (right).

8.4.3 Background samples: Signal with an additional pion

The CCOther events encompass a combination of deep-inelastic scattering and resonant pion production, as well as lower fractions of shallow inelastic scattering and multi-pion production processes that all create additional pions. The results shown here are divided into cases where the extra pion is a charged pion and cases where it is a neutral pion. The selection procedure for both of these topologies is identical to the CC1 π^+ one, but uses the ‘Others’ cut described in section 8.3.1. To separate this topology further, the identification of an additional pion is required. In the case this refers to a charged pion, the Zero ECal photons cut is again applied to reduce the neutral pion contribution.

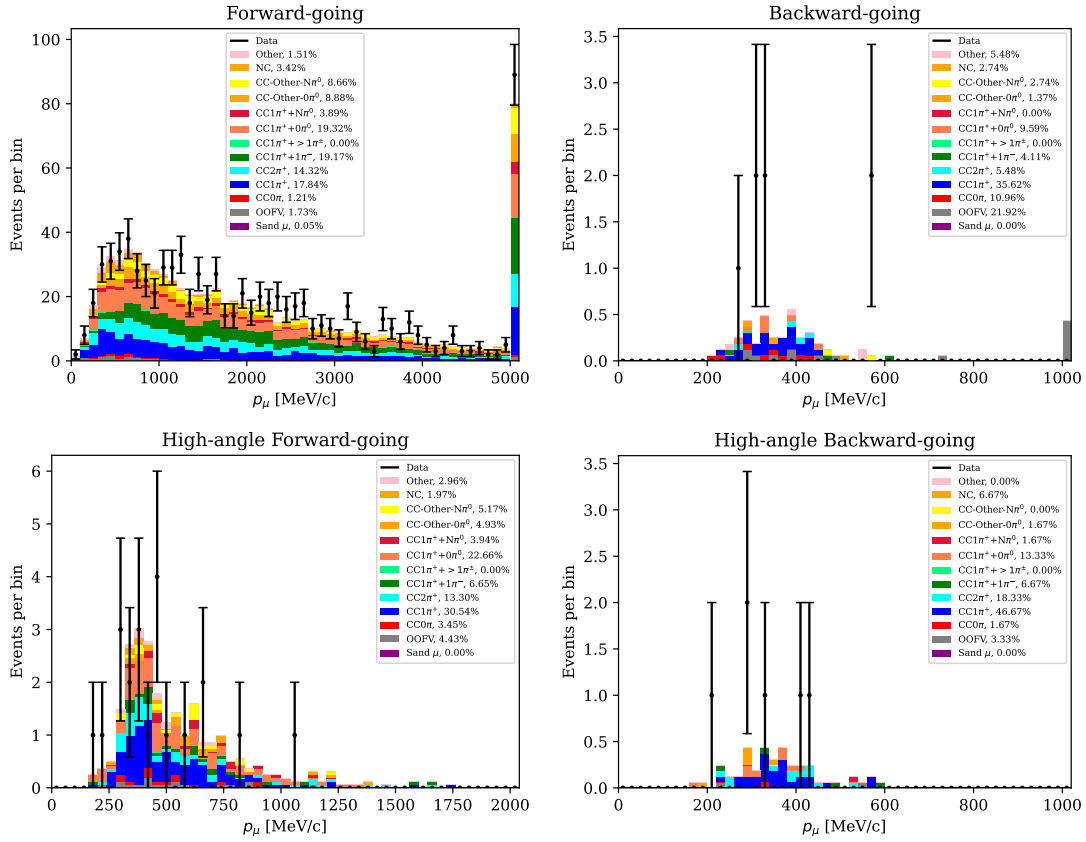


Figure 8.20: The muon momentum in the CC1 π^+ &1 $\pi^\pm$ selection separated in muon direction: forward-going (top left), backward-going (top right), High-angle Forward-going and High-angle Backward-going (bottom right) with the topological breakdown.

In figure 8.21, the muon kinematic distributions are shown for the selection with an additional charged pion, while figure 8.22 illustrates the momentum and angle for the most energetic charged pion found in the final state (this is only relevant for CC1 π^+ &1 $\pi^\pm$). All four are broken down in topology. For the particle identification, the reader is referred to figure 8.23 for the muon and figure 8.24 for the pion.

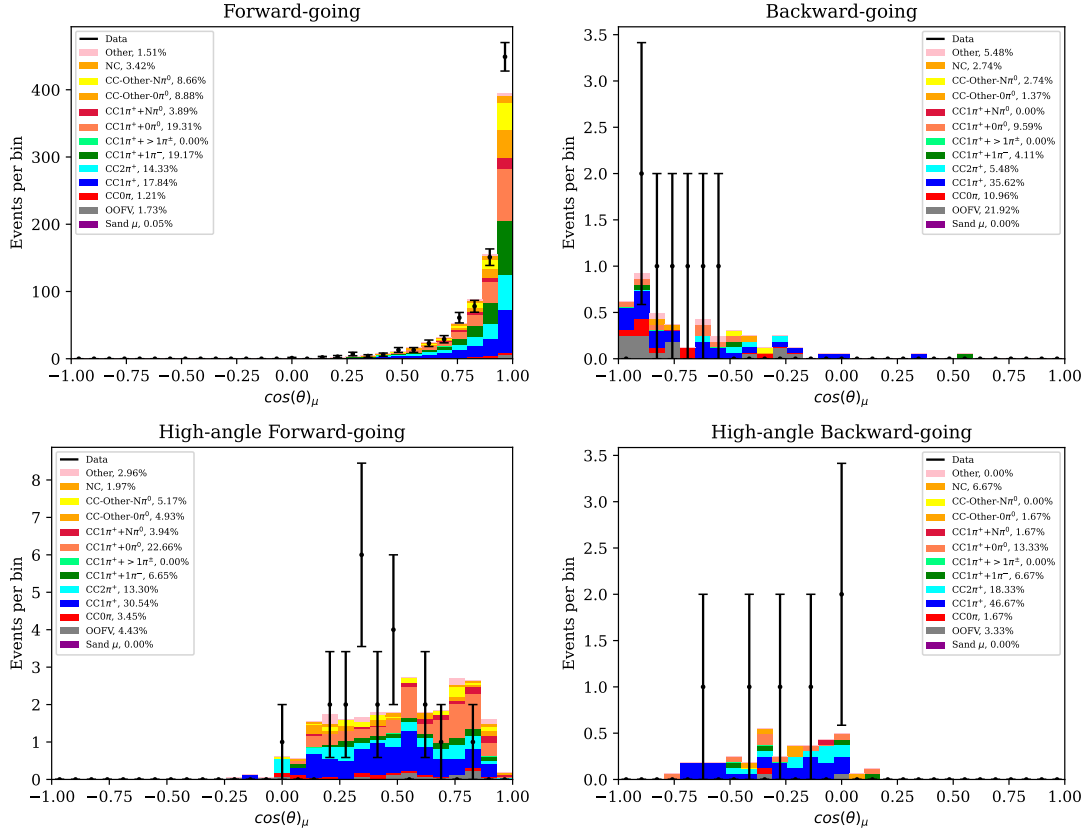


Figure 8.21: The cosine of the muon angle in the $CC1\pi^+ & 1\pi^\pm$ selection separated in muon direction: forward-going (top left), backward-going (top right), High-angle Forward-going and High-angle Backward-going (bottom right) with the topological breakdown.

Observing these figures reveals that the $CC1\pi^+ & 1\pi^\pm$ sample exhibits very low statistics in all muon directions except the forward-going one. The purity ranges from 9.5% for BWD to 33.5% for FWD, with all branches predominantly influenced by the $CC1\pi^+$ events. The particle content of OOFV events is characterized by highly backward-going, high-momentum positive particles, as can be derived from the top-right plot in figure 8.21. This strongly implies that these particles are actually forward-going but have been mistakenly flipped, thus appearing as negative particles. In the FWD branch, 13% of muons are incorrectly identified as negative pions, while it is mainly positive pions in the high-angle forward-going direction. The rate at which pions are correctly identified lies around 77% in the forward-going direction and 60% in the other directions. Pions are most often mistaken for protons (up to 15% in FWD and 18% in HAFWD) with momenta below 250 MeV/c and above 2 GeV/c mainly propagating in the beam's direction. The selection efficiency can be found in figure 8.25, which shows a stable 10% for muon momenta above 500 MeV/c and for the entire range of pion kinematics.

For the topologies associated with the additional neutral pion, the muon momentum and angle can be found in figure 8.26. The pion kinematic properties can be found in figure 8.27. The muon selection accuracy is showcased in figure 8.28 with the pion selection in figure 8.29.

The particle identification for the $CC1\pi^+1\pi^0$ sample exhibits even lower statistics. The purity ranges from 23% for HABWD to 45% for FWD, with all branches again being polluted by the $CC1\pi^+$ events. In the FWD branch, 11% of muons are incorrectly identified as negative pions, while the muons are misidentified as positive pions in the high-angle forward-going direction. For the charged pions, the identification is successful in 75% of the cases in the forward-going direction and down to 68% in the high-angle forward-going sample. The misidentification is mainly coming from electrons and protons resembling charged pions in these samples. The efficiency can be found in figure 8.30, which shows a stable 7% for muon momenta above 500 MeV and for the entire pion kinematic range.

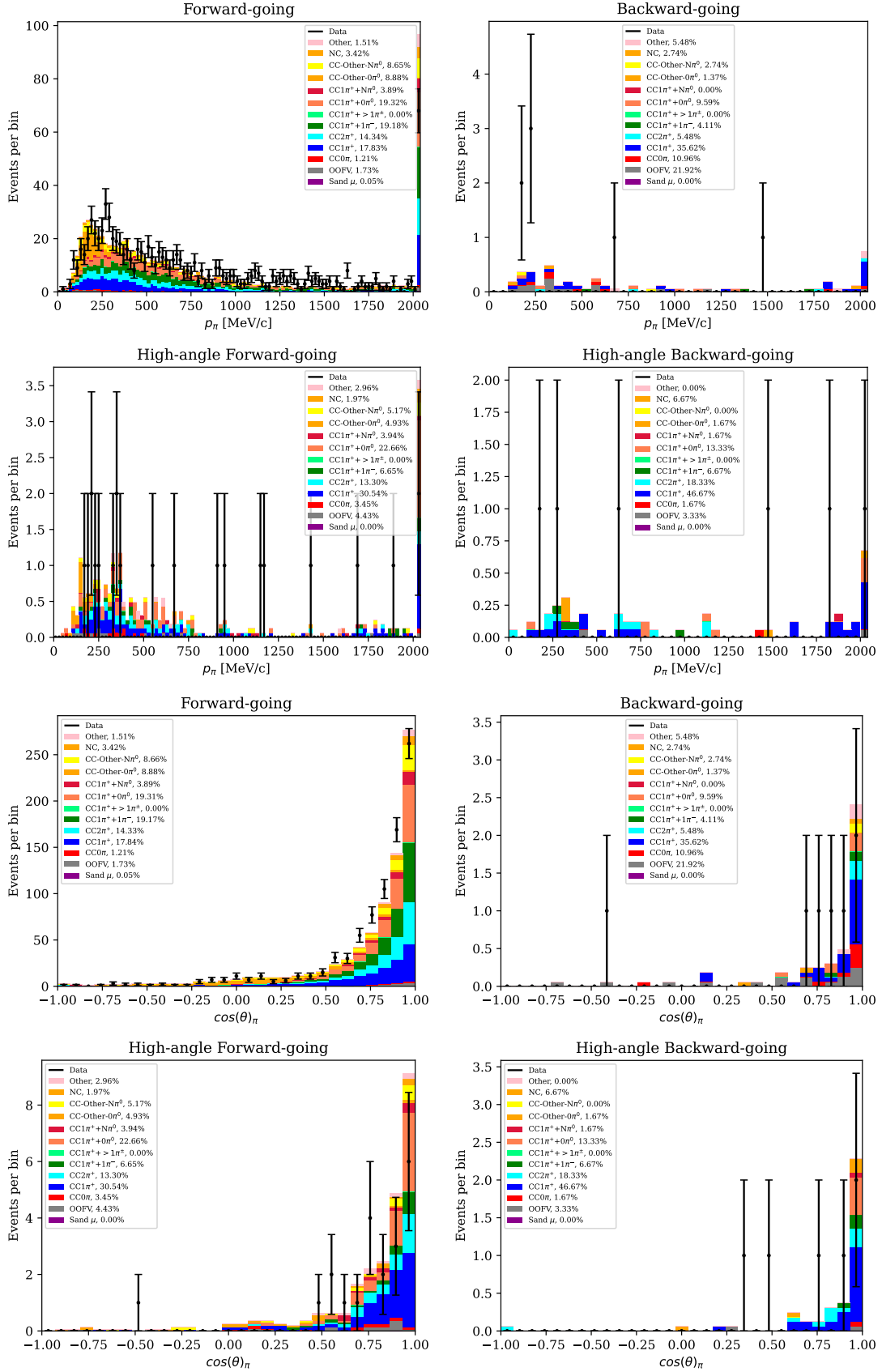


Figure 8.22: The pion momentum (top four) and cosine of the angle (bottom four) in the $CC1\pi^+ + 1\pi^\pm$ selection separated in muon direction: forward-going (top left), backward-going (top right), high-angle FWD and high-angle BWD (bottom right) with the topological breakdown.

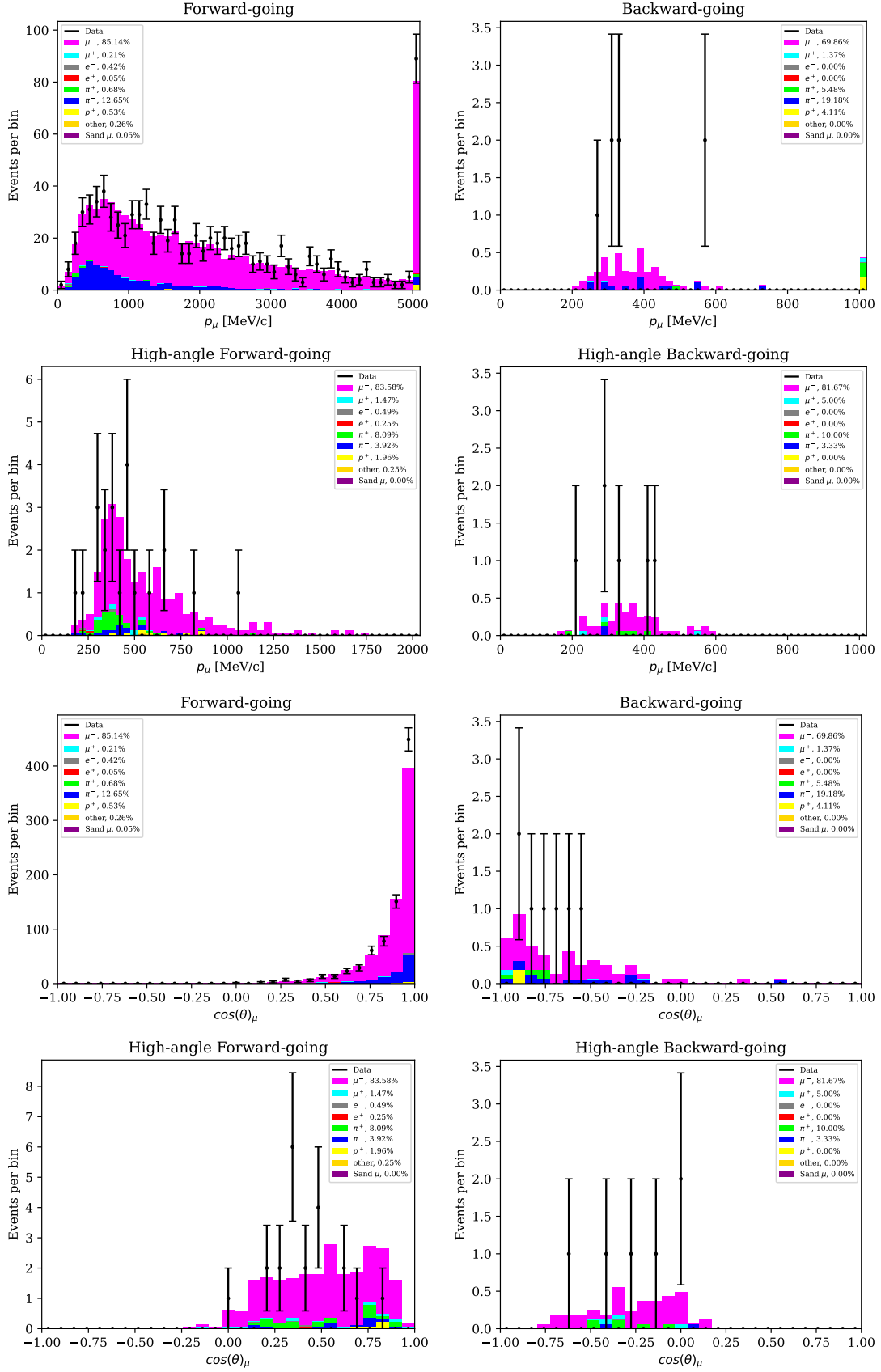


Figure 8.23: The muon momentum (top four) and cosine of the angle (bottom four) in the CC1 π^+ &1 $\pi^\pm$ selection separated in muon direction: forward-going (top left), backward-going (top right), high-angle FWD and high-angle BWD (bottom right) in true particle breakdown.

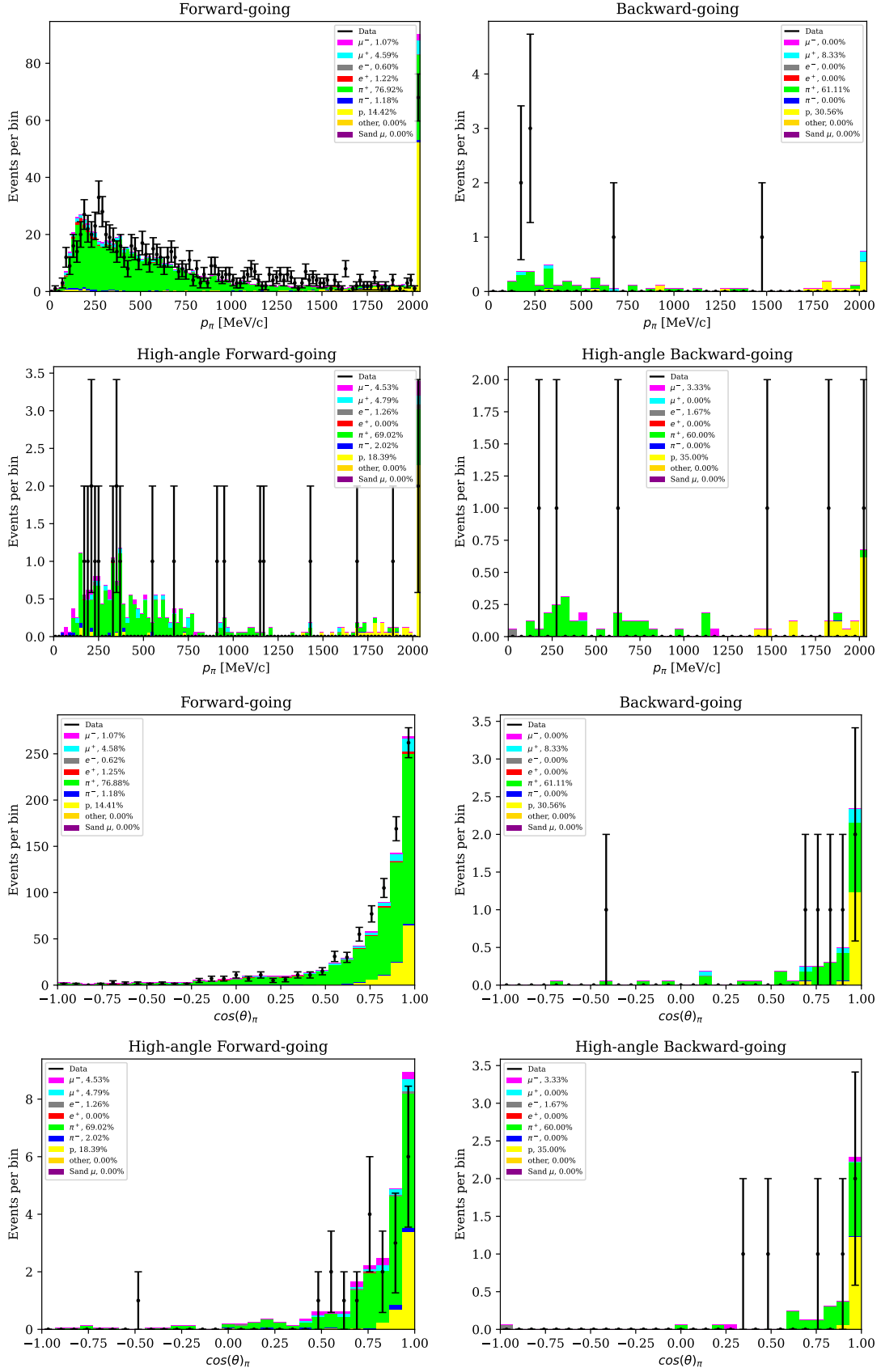


Figure 8.24: The momentum (top four) and cosine of the angle (bottom four) for the pion identified track in the CC1 π^+ &1 $\pi^\pm$ selection separated in muon direction: forward-going (top left), backward-going (top right), high-angle FWD and high-angle BWD (bottom right) in true particle breakdown.

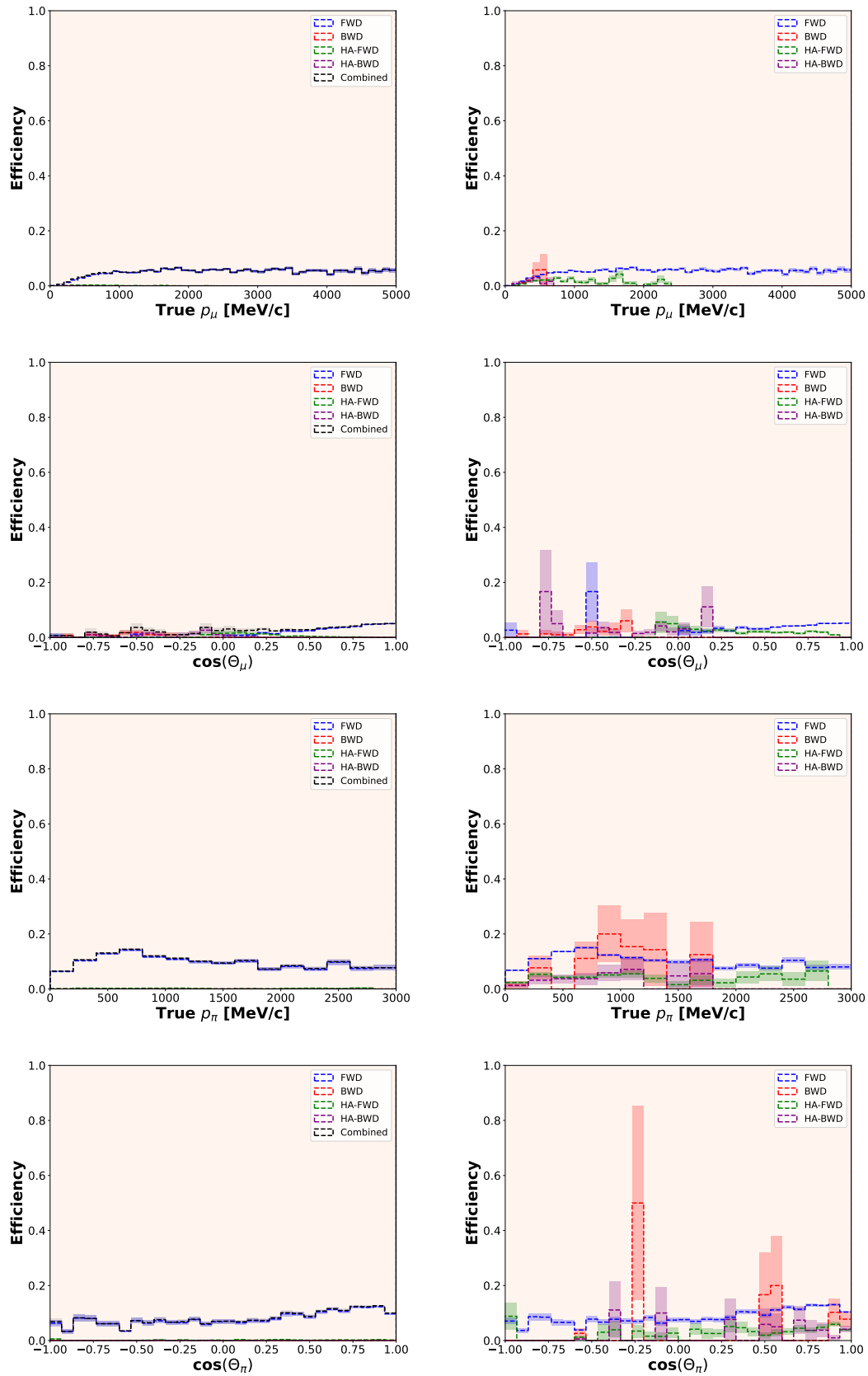


Figure 8.25: Efficiency as a function of muon momentum (top row), cosine of the muon angle (second row), positive pion momentum (third row) and cosine of the pion angle (bottom row) for the CC1 $\pi^+\&\pi^\pm$ sample with respect to the full available statistics (left) and to the statistics after the angular separation (right).

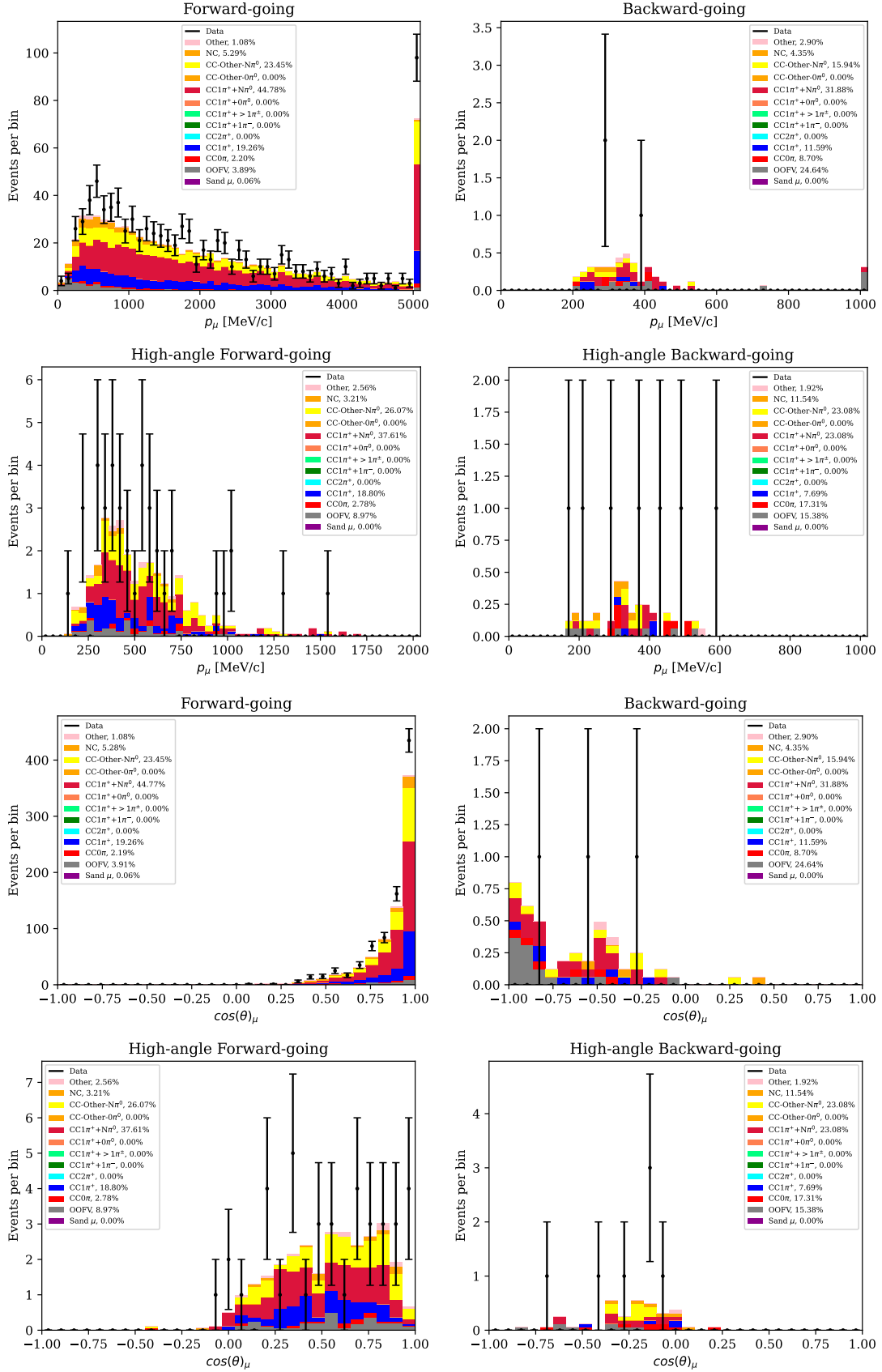


Figure 8.26: The muon momentum (top four) and cosine of the angle (bottom four) in the $CC1\pi^+ + 1\pi^0$ selection separated in muon direction: forward-going (top left), backward-going (top right), high-angle FWD and high-angle BWD (bottom right) with the topological breakdown.

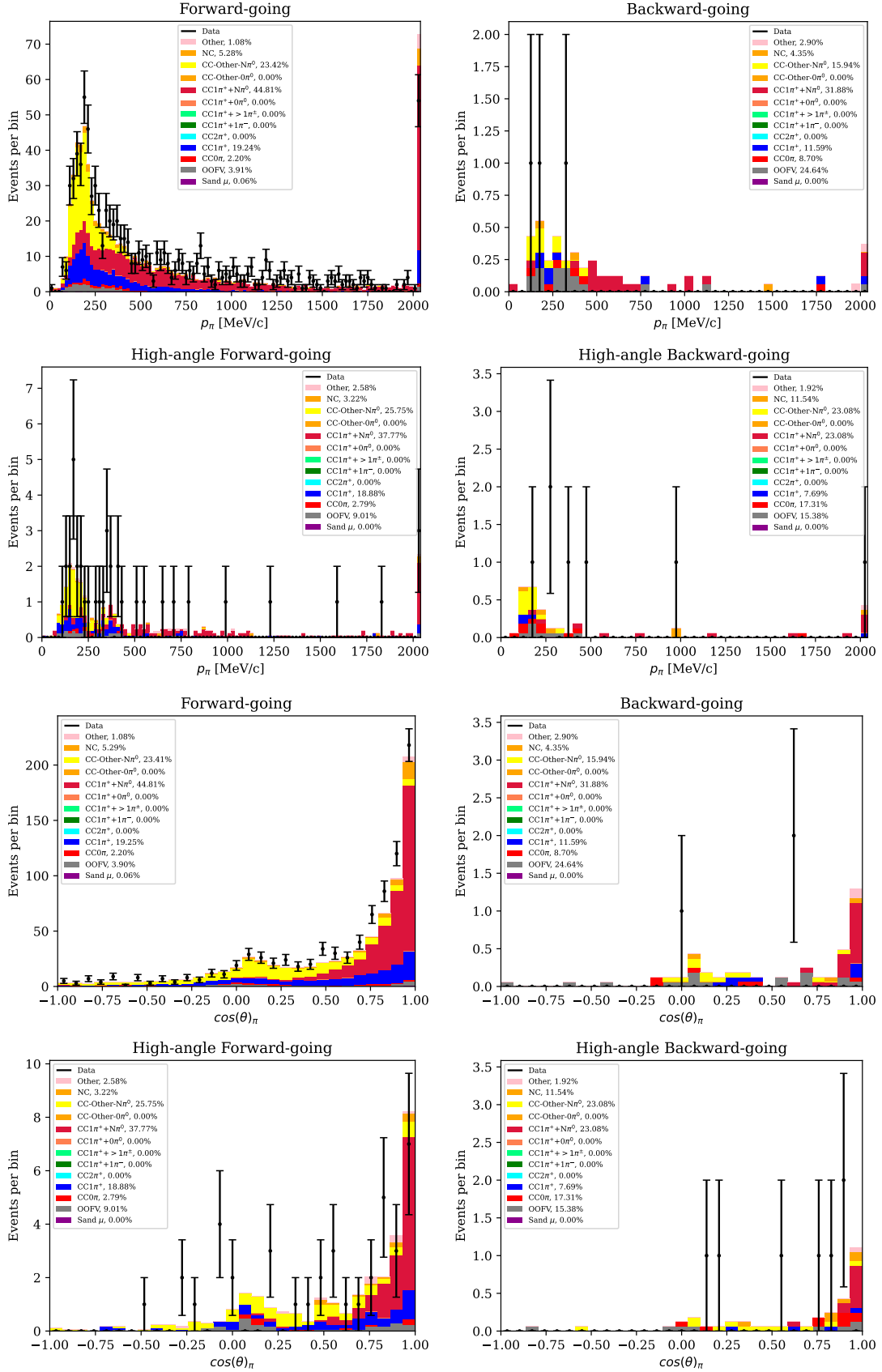


Figure 8.27: The pion momentum (top four) and cosine of the angle (bottom four) in the $CC1\pi^+1\pi^0$ selection separated in muon direction: forward-going (top left), backward-going (top right), high-angle FWD and high-angle BWD (bottom right) with the topological breakdown.

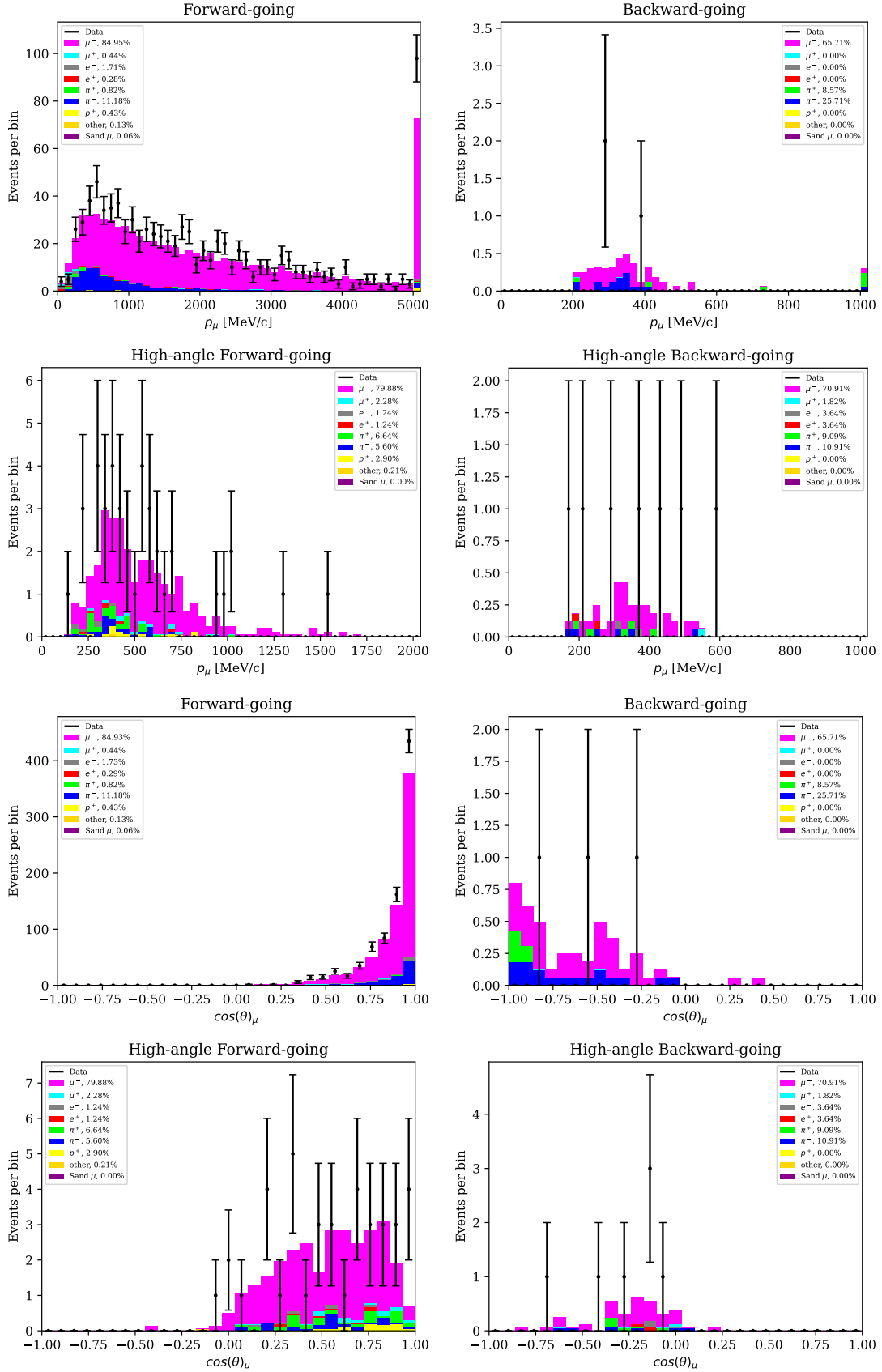


Figure 8.28: The muon momentum (top four) and cosine of the angle (bottom four) in the $CC1\pi^+\&1\pi^0$ selection by muon direction: forward-going (top left), backward-going (top right), high-angle FWD and high-angle BWD (bottom right) in true particle breakdown.

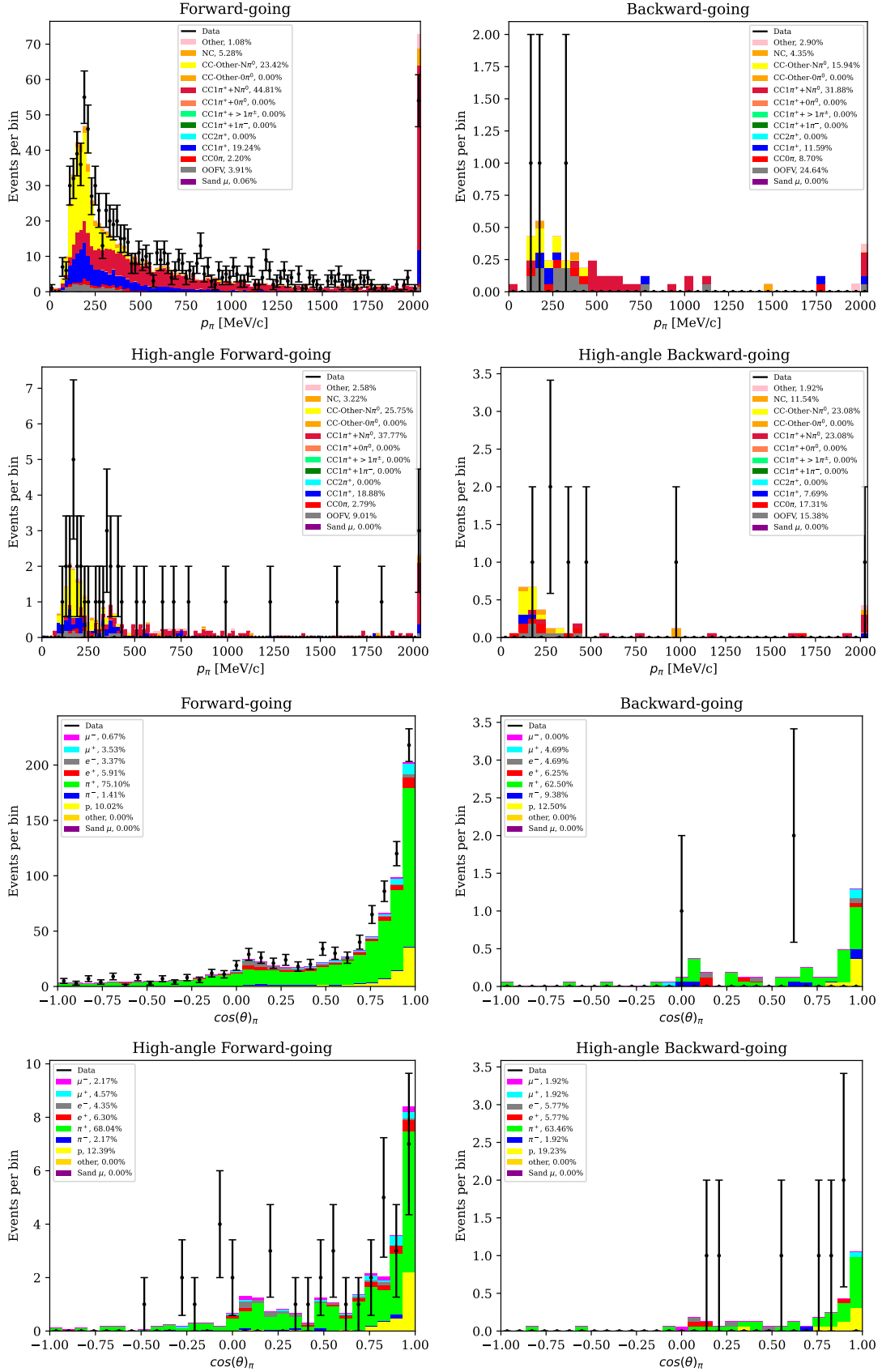


Figure 8.29: The momentum (top four) and cosine of the angle (bottom four) for the pion track in the CC1 π^+ &1 π^0 selection by muon direction: forward-going (top left), backward-going (top right), high-angle FWD and high-angle BWD (bottom right) in true particle breakdown.

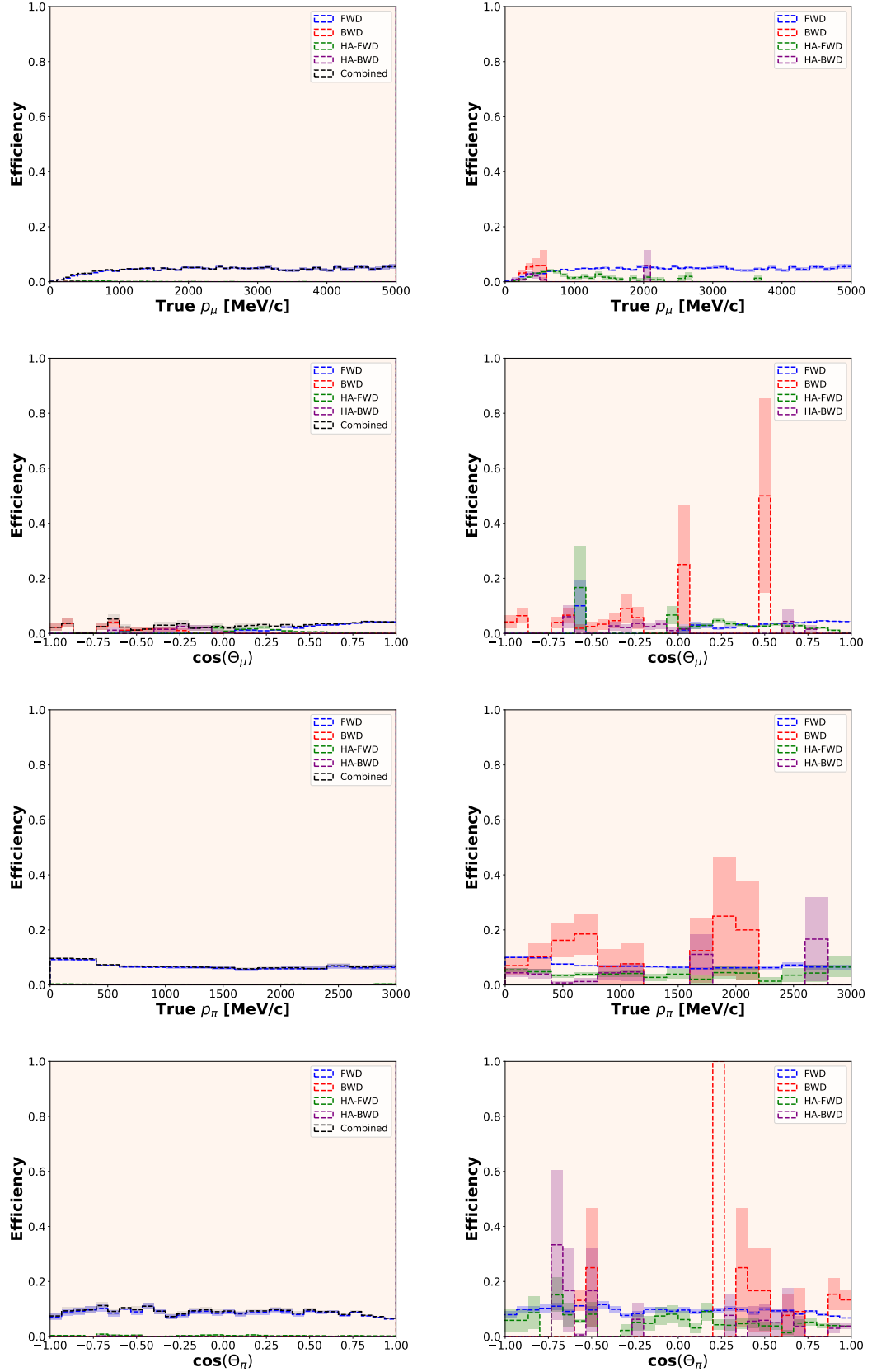


Figure 8.30: Efficiency as a function of muon momentum (top row), cosine of the muon angle (second row), positive pion momentum (third row) and cosine of the pion angle (bottom row) for the $CC1\pi^+\&\pi^0$ sample with respect to the full available statistics (left) and to the statistics after the angular separation (right).

SYSTEMATIC EVALUATION

9

In an ideal world with unquestionable accuracy and precision, a cross-section would be found straightforwardly through the number of signal events in relation to the total number of events. As our understandings of the world and our detectors are far from this almost unimaginable scenario, biases and distortions are incorporated into the observations we make and hence we have to allow our framework to capture those biases.

This is done through the introduction of systematic uncertainties, which describe the uncertainty in our models of the underlying truth. Careful assessment of the uncertainties provides not only a more reliable result, but also gives insight into the limitation of the experimental setup and the theoretical models. In this chapter, the relevant uncertainties to the $\nu_\mu\text{CC}1\pi^+$ in 4π cross-section measurement on hydrocarbon will be described, focusing on three main categories: those associated with the detector responses (section 9.1), the neutrino interaction models (section 9.2) and the neutrino flux (section 9.3).

The chapter will conclude with a discussion on the analysis binning (section 9.4) in both truth and reconstructed space. The former describes the bins in which the cross-section result will be expressed, while the latter describes the bins in which the muon and pion kinematics are measured.

9.1 DETECTOR SYSTEMATIC UNCERTAINTIES

Detector systematic uncertainties arise from the performance and characteristics of the detector, finding their origin in calibration, resolution, and efficiency. Variations in the detector response to different particle types or energy ranges can smear and bias the reconstructed event rate distributions and ultimately the measured cross sections. The incorrect modeling of detector components or parameters in the Monte Carlo simulation might lead to differences in reconstructed variables. This in turn causes the selection cuts to have a disparate effect on the data compared to the simulation, changing the number of events in the final selection and thus the efficiency. In addition, depending on the binning scheme and the magnitude of the discrepancy, events will migrate from one bin to another, causing the resulting distributions to be different.

There is a total of 31 sources of systematic uncertainties in this analysis. Here only the largest ones will be described in detail as these will impact the analysis the most. Two summary tables containing all sources (table 9.1) and total uncertainties (table 9.2) are provided at the end of this section. For more in-depth information on individual systematics, the reader is referred to appendix C.

Before the origin and construction of these uncertainties is discussed, the method of propagation should be explained. There are three types of systematics: Reconstruction, Normalization and Efficiency. The latter two can be summarized by the overarching weight systematic uncertainties category.

9.1.1 Reconstruction systematic uncertainties

This section covers uncertainties in the mean value (scale) and/or the resolution of a reconstructed observable (e.g., particle momentum, particle identity, time of flight). The propagation is accomplished by repeating the selection multiple times for different values of the observable. Each iteration of the selection is referred to as a toy experiment. The number of toys resembles the number of different sets of variations. Here, it is set to 500 as a higher number of toys did not improve the calculated covariance matrix significantly. This means that there is a total of 500 universes with different values for the underlying continuous observables.

Varying these values might affect the number of selected events or lead to the migration

of events between analysis bins. A distortion in the B-field could lead to a different value for the muon momentum, making it migrate from one bin to another, or a muon's momentum might be altered in such a way that it is outside of the desired cut range and is thus rejected.

To estimate this effect, the observable is varied according to the relevant uncertainty in two different ways:

1. The reconstructed observable x is varied according to the propagated uncertainty from the underlying parameter:

$$x_{\text{toy}} = x_{\text{rec}}^{\text{MC}} + \alpha \delta x \quad (9.1)$$

2. A small variation is added to the corrected observable x according to the uncertainty of the correction. We need to distinguish between variations of the mean or of the resolution. In the case of the mean we find

$$x_{\text{toy}} = x_{\text{corr}}^{\text{MC}} + \alpha \delta \Delta \bar{x}, \quad (9.2)$$

with

$$x_{\text{corr}}^{\text{MC}} = x_{\text{rec}}^{\text{MC}} + \Delta \bar{x} \text{ and } \Delta \bar{x} = x_{\text{dec}}^{\text{data}} - x_{\text{rec}}^{\text{MC}}. \quad (9.3)$$

If we need to vary the observable because of a difference in resolution between MC and data, we apply the following:

$$x_{\text{toy}} = x_{\text{true}} + (1 + \alpha \delta s)(x_{\text{corr}}^{\text{MC}} - x_{\text{true}}), \quad (9.4)$$

$$x_{\text{corr}}^{\text{MC}} = x_{\text{true}} + s(x_{\text{rec}}^{\text{MC}} - x_{\text{true}})s = \frac{\sigma_{\text{data}}}{\sigma_{\text{MC}}}, \quad (9.5)$$

where α is a random parameter, usually drawn from a Gaussian distribution centered at 0 with a width of 1 (except the B-field distortions, which have a uniform probability density function (PDF)).

9.1.1.1 B-Field distortions (Appendix C.1)

The ND280 tracker region, comprising the FGDs, the TPCs, the ECals and the P0D, is surrounded by a magnet. Distortions in the magnetic field therefore affect the capabilities of all of these components, but those of the TPC in particular, as the curvature in the tracks of crossing charged particles is used to determine their momentum.

9.1.1.2 TPC momentum resolution (Appendix C.2)

For particles that leave more than 18 separate clusters in the TPC, their momentum is reconstructed using the curvature in their tracks. The uncertainty in measuring is estimated by looking at tracks that cross multiple TPCs, so their individual measurements can be used as cross checks for the global momentum reconstruction.

9.1.1.3 TPC momentum scale (Appendix C.3)

This systematic uncertainty is the result of the uncertainty in the magnetic field measurements that were performed before the detector was operated, affecting the calculation of particle momentum.

9.1.1.4 TPC particle identification (Appendix C.4)

Particles are identified by their characteristic energy loss dE/dx curve in the material of the TPC by adhering a likelihood score to a certain track. These likelihood scores are altered by varying the measured energy loss in each TPC segment. Distinguishing between muons and pions for the TPC-identified highest momentum track is important as a misrepresentation of the particle in question will lead to an improper reconstruction of the initial energy and or interaction process. This can also happen in the case of protons and pions and to a lesser degree for electrons and pions or muons.

9.1.1.5 Momentum by range resolution (Appendix C.5)

For particles that never make it into the TPC or do not leave more than 18 clusters in it (high-angle tracks), the momentum can be estimated by range. The reconstruction for these isolated tracks is dependent on how well the track length can be determined and how well the energy deposition in the material of the FGD is understood.

9.1.1.6 Momentum bias by vertex migration (Appendix C.6)

The neutrino interaction vertex for events inside the FGDs is found by looking at the start position of the muon candidate. It follows from a matching sequence between the TPC and FGD reconstructed objects that lie within the same time window. The scintillator bars in the FGD dictate its reconstruction resolution. For events in which the outgoing lepton and hadron are produced back to back, their origin is hard to define. The same can be said for a lepton and a decay electron. These are the key factors in the backward-going direction. Furthermore, for events with high particle multiplicity, several of the hits produced by other particles might be associated with the candidate muon. This is mainly

caused by low momentum hadrons and is the dominant contribution for the mismatch in the forward-going region.

Both of these scenarios affect the precision by which vertex position can be determined, leading to a measured FGD segment length that might not be consistent with the true vertex. This will introduce a bias in the reconstructed momentum for the cases where this length is used. The migration distance is higher in the backward-going directions due to the fact that the matching algorithm was optimized for forward-going tracks. In addition, the number of migrations is higher as well. This combination leads to a more prominent bias in the backward-going direction, while it is almost negligible in the forward one.

9.1.1.7 FGD particle identification (Appendix [C.7](#))

Particles that are contained within the FGD lose all their kinetic energy through ionization without reinteracting. The relationship between the deposited energy and the traversed distance can be used to distinguish between different particle masses. As muons and pions are very close in mass, their energy depositions will look rather similar, leading to a single systematic, that covers both particle hypotheses. Hence, the FGD PID is primarily used to distinguish between positively charged pions and protons.

9.1.1.8 FGD pion momentum from Michel electron resolution (Appendix [C.8](#))

The Michel electron-tagged pion sample introduces a systematic uncertainty to cover the inaccuracies in reconstructing the pion momentum through its subsequent decay electron. As the pions at these energies generally do not leave a track, the Michel vertex is used as the end point of the pion's track. The difficulty resides in finding this vertex to be used in the momentum by range calculation.

9.1.1.9 ECal EM scale and ECal EM Resolution (Appendix [C.9](#))

Particles that make it through the FGDs and the TPCs meet electromagnetic calorimeters at either the downstream end or on the sides of the tracker region. The electromagnetic energy associated with clusters of hits triggered by these particles is calculated from three fundamental quantities: the total charge, the spread of the charge within the cluster and the asymmetry of the charge distribution.

9.1.1.10 Time-of-flight resolution (Appendix C.10)

Track orientation or particle direction is derived from the time-of-flight measurements between the subsystems of ND280. Any inaccuracies in measuring the time of arrival of an individual particle at a specific subdetector might result in an incorrect orientation by flipping a forward-going track to become a backward-going track or vice versa.

9.1.1.11 Neutrino parent decay vertex position (Appendix C.11)

The position from which the neutrinos originate lies somewhere in the decay pipe. As this value is used to derive several kinematic variables down the line, any uncertainty in determining it could result in inaccuracies in the description of the event (e.g., the transverse momentum for which one needs to project the daughter particles' directions on to the surface perpendicular to the neutrino direction).

9.1.2 Weight systematic uncertainties

These systematic uncertainties affect only discrete observables such as the number of reconstructed segments or the event topologies instead of particle properties. The selected number of events remains the same, but the weights on each event change such that the integral varies within each toy universe. This means that these weights can be applied without redoing the selection. There are two subcategories for this type:

1. Efficiency-related systematic uncertainties: weight is assigned to rescale a discrete observable (number of FGD clusters). Multiple weights can be assigned to a single event.
2. Normalization systematic uncertainties: weight is applied to inflate or deflate a certain event rate in order to estimate the effects (e.g., a rescaling of the number of OOFV events). Only a single weight is applied.

Efficiency-related systematic uncertainties concern the performance of the reconstruction and selection, which can differ between data and MC. By constructing dedicated control samples in which the underlying efficiency can be determined accurately, those differences can be understood and used to reweight the full Monte Carlo simulation to better reflect the data. This is done by assuming that the ratio of efficiencies in the control sample r^{CS} is the same as the ratio of efficiencies in the analysis sample:

$$\varepsilon_{data} = \frac{\varepsilon_{data}^{CS}}{\varepsilon_{MC}^{CS}} \varepsilon_{MC} = r^{CS} \varepsilon_{MC}. \quad (9.6)$$

We can assign an efficiency or inefficiency weight to the event as follows:

$$w_{\text{eff}} = \frac{\varepsilon_{\text{data}}}{\varepsilon_{\text{MC}}} \text{ or } w_{\text{ineff}} = \frac{1 - \varepsilon_{\text{data}}}{1 - \varepsilon_{\text{MC}}}. \quad (9.7)$$

For the error propagation we simply change these weights by varying the ratio r_{CS} and recalculating the efficiency in data $\varepsilon'_{\text{data}}$:

$$\varepsilon'_{\text{data}} = (r^{CS} + \alpha \delta r^{CS}) \varepsilon_{MC}. \quad (9.8)$$

The error δr^{CS} is a combination of the relative difference between the Monte Carlo and data ($1 - r^{CS}$) and statistical uncertainty (computed using Gaussian error propagation):

$$\delta r^{CS} = \sqrt{(1 - r^{CS})^2 + (r^{CS})^2 \left[\left(\frac{\delta \varepsilon_{\text{data}}}{\varepsilon_{\text{data}}} \right)^2 + \left(\frac{\delta \varepsilon_{MC}}{\varepsilon_{MC}} \right)^2 \right]} \quad (9.9)$$

Normalization-like systematic uncertainties describe uncertainties we have on the total event rate of CC-inclusive events. In that case we can immediately vary the event weight,

$$w_{\text{event}} = 1 + w_{\text{corr}} + \alpha \delta, \quad (9.10)$$

where w_{corr} is a potential correction, δ quantifies the rate uncertainty related to the systematic parameter and α is again a random parameter, drawn from a Gaussian distribution centered at 0 and with width 1.

9.1.2.1 TPC charge identification efficiency (Appendix C.12)

The particle's charge sign is determined from the orientation of the track's curvature. Highly energetic particles with high rigidity will have a near linear track, which reduces the accuracy of the charge determination. The charge identification relies on measurements from multiple subdetectors, leading to two different issues. On the one hand, there is the probability of swapping the charge identification on a cluster by cluster basis (local). On the other hand, the global track could be swapped based on the best local elements.

9.1.2.2 TPC cluster efficiency (Appendix C.13)

Charged particles crossing the TPCs ionize the argon gas mixture. To be considered a potential forward or backward-going muon candidate, the particle has to leave behind at least 19 clusters. Not reconstructing one or more clusters from the TPC hits might lead to a reduction in muon or other charged-particle candidates, which in turns causes

inaccuracies in determining the underlying process or the angular segmentation.

9.1.2.3 TPC tracking efficiency (Appendix C.14)

The TPC clusters in turn allow for the reconstruction of charged particle track segments. The track efficiency describes what the percentage is of doing so correctly in each of the three TPCs.

9.1.2.4 FGD hybrid tracking efficiency (Appendix C.15)

A considerable amount of the pions in the $CC1\pi$ signal sample are contained in the FGD and can thus only be reconstructed based on FGD information. This efficiency describes how well these particular tracks are reconstructed in the presence of a FGD-TPC-matched muon candidates, leading to additional deposits in the FGD.

9.1.2.5 ECal tracking efficiency (Appendix C.16)

There are different signatures that the particles can leave behind in the ECal. They can be through-going or contained and in the shape of showers or simple tracks. The accuracy by which the particular signature is reconstructed is captured by this efficiency.

9.1.2.6 ECal photon pile-up (Appendix C.17)

The electromagnetic calorimeter is utilized in several steps of this analysis to reduce backgrounds mainly coming from neutral pions. It also plays a key role in the high angle samples, as the ECals are located at the outer edges of the detector. The photon pile-up in the ECal coming from interactions unrelated to neutrinos could interfere with our understanding of the event's characteristics. Any isolated ECal object could be the result of a pile-up interaction and hence this systematic weight is applied to all events that contain such objects.

9.1.2.7 ECal PID and ECal EM highly ionizing PID (Appendix C.18)

The ECal is especially proficient in discriminating electrons and photons from muons through the MIP-EM variable and from stopping proton tracks via the EM-HIP variable. It is important to quantify the bias on these parameters as particle IDs could migrate from one type to another, redefining the topology of the entire interaction.

9.1.2.8 Michel electron efficiency (Appendix C.19)

Most of the low energy (50-400 MeV) pions in the signal region come from the identification of a Michel electron in the FGD. Both the detection of a suitable ME candidate and the level at which this is done correctly are taken into account in this systematic weight.

9.1.2.9 Pile-up (Appendix C.20)

‘Sand’ muons are those that come from neutrino interactions in the materials surrounding the detector hall, which is primarily sand. They can still make it into the detector and pollute the neutrino events that do happen in the fiducial volume by depositing energy overlapping in time and space. Using the activity in TPC1 as a veto for this type of event, it can be shown that the majority of rejected events are not charged-current interactions. This means that the coincidence of these muons with the magnet events can’t be used directly and thus a correction must be made. There is a 10% uncertainty in the sand muon simulation in addition to the differences between the actual and simulated beam intensity, so a systematic weight on this pile-up contribution is included.

9.1.2.10 Out of fiducial volume background (Appendix C.21)

One of the final steps in the selection procedure was dedicated towards reducing the contamination from events coming from outside the fiducial volume. Especially in the backward-going direction, this background was very prominent. The general tendency is for these tracks to have been improperly matched between the FGD and the TPC. In those categories where OOFV events are selected to be within the FGD fiducial volume, the reconstruction uncertainty reflects our misunderstanding of the probability to incorrectly reconstruct the vertex position.

9.1.2.11 Sand muon background (Appendix C.22)

This background finds its origin in the sand that surrounds the detector hall. Beam neutrinos can interact with the sand and the resulting muons could enter the detector. The total event rate is compared to data, through which a 10% discrepancy is observed.

9.1.2.12 Matching efficiencies

Tracing the charged particles back to their origin over multiple subdetectors helps to understand several of these particles’ properties. This does, however, require there to be a mechanism to match partial tracks that cross detector boundaries. As this mechanism is

not perfect, the efficiency for matches between every possible combination of subdetectors has to be evaluated. In total, there are five:

1. TPC-FGD (Appendix C.23): Tracing the track back to the origin to find the neutrino vertex.
2. TPC-ECal (Appendix C.24): Useful for additional particle identification.
3. TPC-P0D (Appendix C.25): Timing information is used to define the direction.
4. FGD-ECal (Appendix C.26): High-angle tracks do not cross the TPC; useful for ECal particle identification.
5. FGD-ECal-SMRD (Appendix C.27): Useful for singling out muons that make it into the SMRD.

9.1.2.13 Appendix Pion secondary interactions (C.28)

Pions originating from the neutrino interaction vertex that made their way out of the nucleus can re-interact with the detector material. This is referred to as pion secondary interactions. There is a wide variety of different processes possible, but the protagonists are: elastic scattering, quasi-elastic scattering, absorption and single Charge Exchange. Each of these can lead to either a change in the pion's momentum or its type, which could affect the reconstructed topology.

9.1.2.14 Appendix Proton secondary Interactions (C.29)

Protons can also have secondary interactions after they leave the neutrino vertex. By varying the proton interaction cross section as protons are stepped through the detector based on the introduced uncertainty, the final weight can be calculated.

9.1.3 All systematic uncertainties combined

In figures 9.1 and 9.2, the relative errors as a function of muon and positive pion kinematic variables when all systematic parameters are thrown together can be found. The higher relative errors in the backward-going directions are both the result of lower statistics and the different detector components required to do measurements in those areas (P0D for timing in the backward-going direction and the ECal and fine-grained detector instead of the time-projection chamber for high-angle orientations). The main contributors to the uncertainty in the muon momentum for the different muon directions are listed below.

- Forward-going direction: ECal HipPID, pion secondary interactions and the TPC PID (TPC momentum scale and resolution to a lesser extent).
- Backward-going direction: momentum bias due to vertex migration, the TPC PID, the TPC-P0D matching efficiency and the OOFV parameters (as well as TPC momentum scale and resolution).
- High-angle: ECal HipPID, the ECal scale and ECal track efficiency (momentum by range).

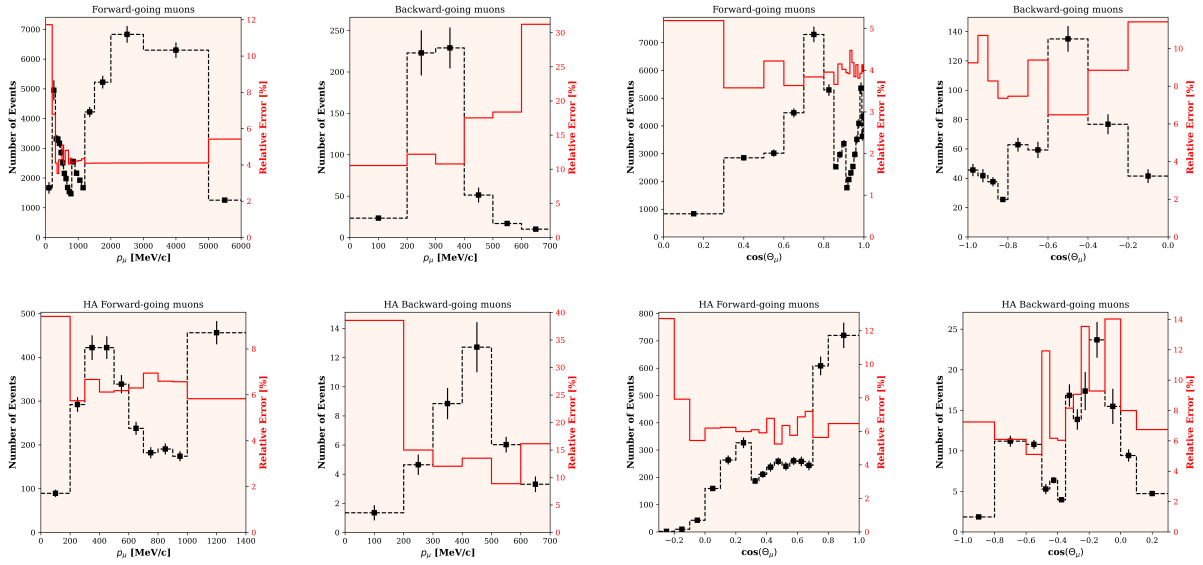


Figure 9.1: Relative errors as functions of muon momentum (left-hand set) and cosine of the muon angle (right-hand set) distributions for all systematic parameters combined.

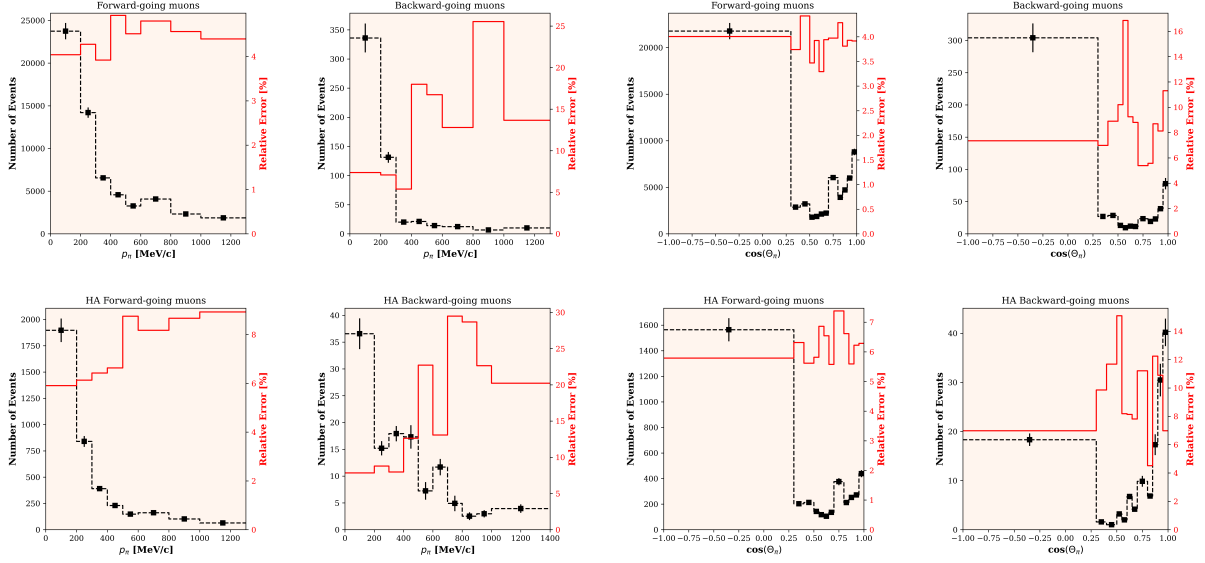


Figure 9.2: Relative errors as functions of positive pion momentum (left-hand set) and cosine of the positive pion angle (right-hand set) distributions for all systematic parameters combined.

For the angular distributions, the systematic parameters affecting momentum (e.g., TPC momentum scale/resolution) are not the dominant contributors. Here the neutrino parent decay uncertainty becomes more significant. The pion kinematic variables see the same factors contributing to the overall uncertainty with the Michel electron efficiency playing a larger role in the backward-going direction. In the appendix, the key contributions will be shown in a similar fashion to the ‘all systematics’ plots before.

The covariance matrix is evaluated in 4D binning for the reconstructed kinematic variables (muon momentum and angle and pion momentum and angle) described in subsection 9.4.2 using the aforementioned 500 toy universes for these 31 detector systematic parameters. The bins belonging to the two signal samples (TPC&FGD-identified pions and ME-identified pions) and the three background samples (signal + $\pi^{\pm}$, signal + π^0 and CC0 π + proton) are indicated on the top of figure 9.3.

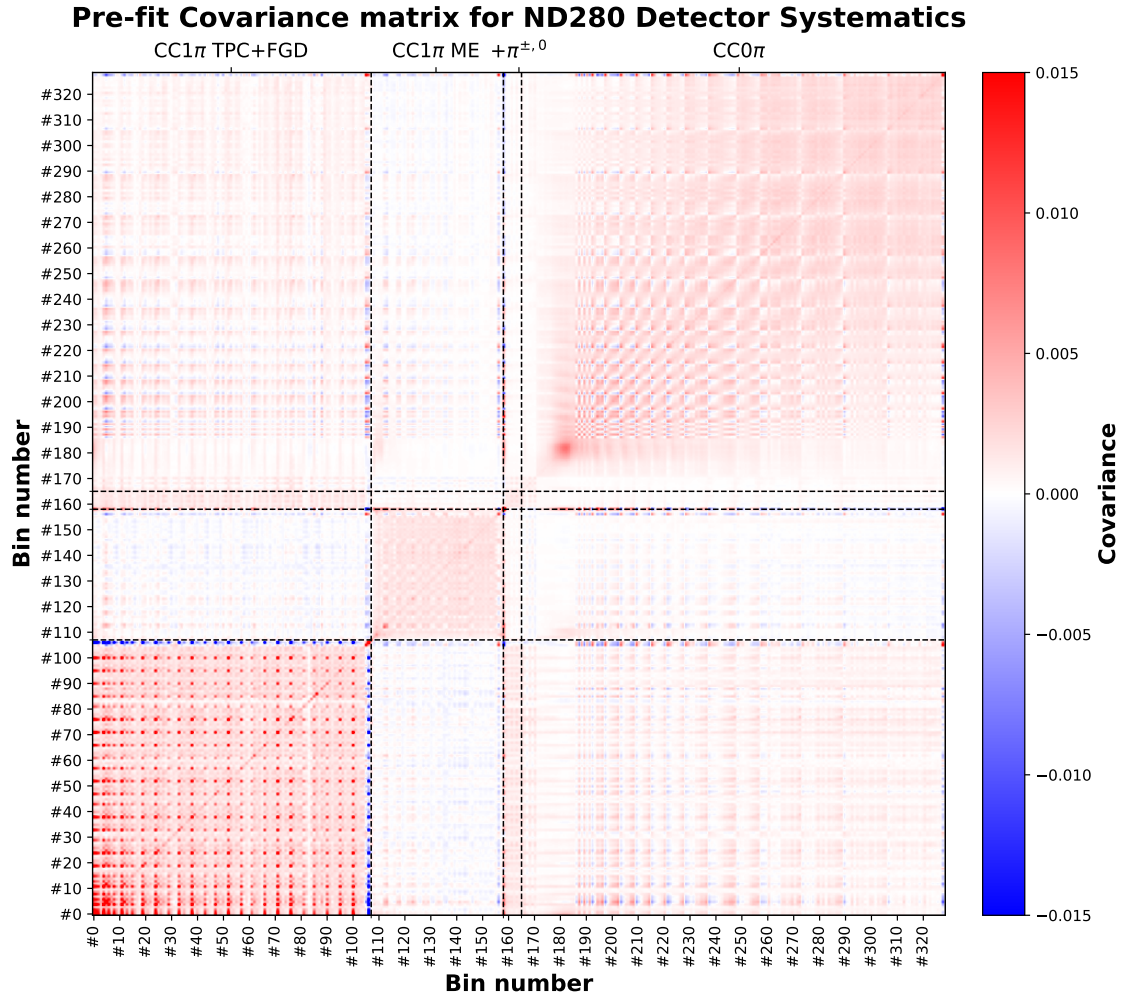


Figure 9.3: ND280 detector covariance matrix for signal + control sample binning.

Systematic	T2K TN Reference	Type
B-Field Distortions	TN-061 [190]	Reconstruction
TPC Mom Resolution	TN-222 [191]	Reconstruction
TPC Mom Scale	TN-081 [192]	Reconstruction
TPC PID	TN-221 [193]	Reconstruction
Mom Range Resolution.	TN-216 [194]	Reconstruction
Mom Bias Vtx Migration	TN-245 [187]	Reconstruction
FGD PID	TN-223 [195]	Reconstruction
FGD Pion Mom from ME Resol	TN-417 [188]	Reconstruction-like
ECal EM Scale	TN-279 [196]	Reconstruction
ECal EM Resolution	TN-279 [196]	Reconstruction
TOF Resolution	TN-245 [187]	Reconstruction
Neutrino Parent Decay Pos	TBD	Reconstruction-like
TPC Charge ID Eff.	TN-229 [197]	Efficiency
TPC Cluster Eff.	TN-234 [198]	Efficiency
TPC Tracking Eff.	TN-163 [199]	Efficiency
FGD Hybrid Tracking Eff.	TN-223 [195]	Efficiency
ECal Tracking Eff.	TN-279 [196]	Efficiency
ECal Photon Pile-up	TN-421 [196]	Efficiency
ECal PID	TN-279 [200]	Efficiency
ECal EM hip PID	TN-279 [200]	Efficiency
Michel Electron Eff.	TN-104 [200]	Efficiency
Pile-Up	TN-152 [201]	Normalization
OOFV Background	TN-098 [202]	Normalization
Sand Background	TN-077 [203]	Normalization
TPC-FGD Matching	TN-075 [204]	Efficiency
TPC-ECal Matching	TN-279 [196]	Efficiency
TPC-P0D Matching	TN-245 [187]	Efficiency
FGD-ECal Matching	TN-228 [205]	Efficiency
FGD-ECal-SMRD Matching	TN-245 [187]	Efficiency
Pion Secondary Interactions	TN-125 [206]	Normalization
Proton Secondary Interactions	TN-216 [194]	Normalization

Table 9.1: Summary of the relevant detector systematic uncertainties and their types

Systematics Uncertainty Source	Total uncertainty (in %) per kinematic variable			
	p_μ	$\cos \theta_\mu$	p_π	$\cos \theta_{\pi^+}$
B-Field Distortions	0.4371	0.0240	0.2903	0.0156
TPC Mom Resolution	0.5279	0.0749	0.3357	0.0291
TPC Mom Scale	0.6629	0.0213	0.5430	0.0137
TPC PID	1.1424	2.3012	2.2730	1.2127
Mom Range Resolution	0.0453	0.0	0.1230	0.0057
Mom Bias Vtx Migration	1.1842	0.0456	1.6458	0.0386
FGD PID	0.2055	0.2653	0.1303	0.2644
FGD Pion Mom from ME Resol	0.0	0.0	0.0	0.0
ECal EM Scale (HA)	1.8357	3.1346	2.0384	2.3525
ECal EM Resolution (HA)	0.4785	0.8146	0.5838	0.8075
TOF Resolution	0.0176	0.0168	0.0204	0.0182
Neutrino Parent Decay Pos	0.0	0.2821	0.0	0.0601
TPC Charge ID Eff. (LA)	0.1426	0.1132	0.1477	0.1370
TPC Cluster Eff.	0.0133	0.0126	0.0127	0.0137
TPC Tracking Eff. (LA)	0.6913	0.5808	0.6848	0.6643
FGD Hybrid Tracking Eff.	0.2047	0.1909	0.2042	0.1972
ECal Tracking Eff. (HA)	3.7247	3.8274	3.7639	3.5854
ECal Photon Pile-up	0.00092	0.00098	0.00097	0.00096
ECal PID (HA)	0.0085	0.0124	0.0102	0.0204
ECal EM hip PID	3.4037	3.4350	3.3472	3.3948
Michel Electron Eff.	0.2755	0.2557	0.2687	0.2631
Pile-Up	0.2314	0.2297	0.2387	0.2259
OOFV Background	0.3625	0.3766	0.3696	0.3481
Sand Background	0.0032	0.0029	0.0081	0.0026
TPC-FGD Matching	0.1369	0.1439	0.1436	0.1416
TPC-ECal Matching	0.6469	0.6548	0.6451	0.6384
TPC-P0D Matching (LA)	0.0062	0.0032	0.0027	0.0036
FGD-ECal Matching (HA)	0.9847	1.0351	1.0165	0.9924
FGD-ECal-SMRD Matching (HA)	1.7007	1.5588	1.7669	1.6498
Pion Secondary Interactions	1.3342	1.3838	1.2830	1.2382
Proton Secondary Interactions	0.5875	0.6059	0.5934	0.5915
All detector effects comb.	4.6004	4.2472	4.3153	3.9532

Table 9.2: Integrated relative errors (in %) for each source of detector systematic parameter split by kinematic variable

9.2 CROSS-SECTION SYSTEMATIC UNCERTAINTIES

The neutrino interaction generator NEUT produces the Monte Carlo distributions in the signal and background regions by utilizing tunable interaction models. Via these tunes or dials, the underlying model parameters are allowed to vary within a certain range and thus provide more freedom for the fit to explore the parameter space. The values prior to the fit are the result of external data fits. The relevant model parameters and their values are described in table 9.3. These dials represent the uncertainties in neutrino interaction modeling used to produce the MC samples by directly affecting the cross-section predictions.

Each cross-section dial corresponds to a particular parameter (e.g., M_A^{QE}) or reaction mechanism (e.g., DIS, CC Coherent on C) and can be used to tune the relevant number of events, while leaving unrelated event rates unchanged. The distinction is made between normalization and shape-type dials. The table also contains a column to indicate the affected reaction mode. The normalization-type dials affect the distributions as scale factors, whereas the shape-type dials influence the model through the underlying parameter and thus changes the shape of the respective distribution.

Instead of evaluating the effect of a change in any of these values to the event rate distributions by reproducing the entire Monte Carlo simulation for each individual set of parameters, a different approach is used. The T2KReweight tool calculates a weight to be assigned to each event based on response functions. These response functions are constructed by varying the model parameters around the nominal value for up to three standard deviations, as instructed in figure 9.4 (i.e. seven points in total) and studying the effect on each true analysis bin. This is then categorized by event sample and topology. The response is then interpolated between these seven points and the curve is stored as a spline. The spline can be referenced during the fitting stage to relate the value of a model parameter to the event weight, thereby reducing the computing time.

All systematic sources included here are derived from the T2K oscillation analysis and are the most significant out of all the implemented uncertainties. Prior constraints on these cross-section parameters are looser than those for detector and flux systematic parameters, which allows the steps in the fitting framework to explore a wider range of values for each individual cross-section parameter. This increased flexibility helps in adjusting the sample distributions to better match the data. To this end both signal- and background-cross-section-specific parameters have been added to the analysis.

Index	Parameter	Type	Mode	Prior $\pm$ Error
0	M_A^{QE}	shape	CCQE	1.03 ± 0.06
1	2p2h ν norm	norm	2p2h	1.0 ± 1.0
2	2p2h ν shape	shape	2p2h	0.0 ± 1.0
3	M_A^{RES}	shape	CCRES	0.91 ± 0.1
4	C_A^5	shape	CCRES	1.06 ± 0.1
5	Bkg Resonant	norm	CCRES	1.21 ± 0.27
6	CC1 π $E_\nu < 2.5$ GeV	norm	CCRES	1.0 ± 0.50
7	CC1 π $E_\nu > 2.5$ GeV	norm	CCRES	1.0 ± 0.50
8	DIS	shape	CCDIS	0.0 ± 1.0
9	CC DIS	norm	CCDIS	1.0 ± 0.035
10	CC Multi- π	norm	CCDIS	1.0 ± 0.50
11	CC Coherent on C	norm	CCRES	1.0 ± 0.3
12	NC Coherent	norm	CCRES	1.0 ± 0.3
13	NC Other	norm	CCRES	1.0 ± 0.3
14	FSI Inelastic < 0.5 GeV	shape	FSI	1.069 ± 0.313
15	FSI π absorption	shape	FSI	1.404 ± 0.432
16	FSI Charge exchange < 0.5 GeV	shape	FSI	0.697 ± 0.305
17	FSI Inelastic > 0.5 GeV	shape	FSI	1.824 ± 0.859
18	FSI π production	shape	FSI	1.002 ± 1.101
19	FSI Charge exchange > 0.5 GeV	shape	FSI	1.8 ± 0.288
20	MDLSPiEj	shape	CCRES	1.0 ± 1.0
21	Multi- π Shape	shape	CCDIS	0.0 ± 1.0
22	Multi- π X-Sec	shape	CCDIS	0.0 ± 1.0
23	$Q_1^2 : [0.25 - 0.5]\text{GeV}^2$	norm	CCQE	1.0 ± 0.11
24	$Q_2^2 : [0.5 - 1]\text{GeV}^2$	norm	CCQE	1.0 ± 0.18
25	$Q_3^2 : [> 1]\text{GeV}^2$	norm	CCQE	1.0 ± 0.40
25	Binding energy RES	shape	CCRES	25 ± 25
26	SF-P Mean Field	shape	CCQE	0.0 ± 0.2
27	SF-S Mean Field	shape	CCQE	0.0 ± 0.45
28	SF-SRC	norm	CCQE	1.0 ± 2.0
29	SPP π^0	norm	CCRES	1.0 ± 0.3
30	Nucleon FSI	shape	All	0.0 ± 0.3

Table 9.3: Overview of the relevant cross-section model parameters with type and prior values

Muon-neutrino-induced CC1 π^+ interactions are the primary contributor to the signal channel. The background mainly comes from CC0 π and CCOther topologies, which are the result of CCQE, 2p2h and FSI reactions on one hand and CCDISn on the other. These sources can thus be separated into five distinct reaction modes, CCRES, CCQE, 2p2h, CCDIS, and FSI, that are in some way, shape or form influenced by the cross-section parameters as further discussed below.

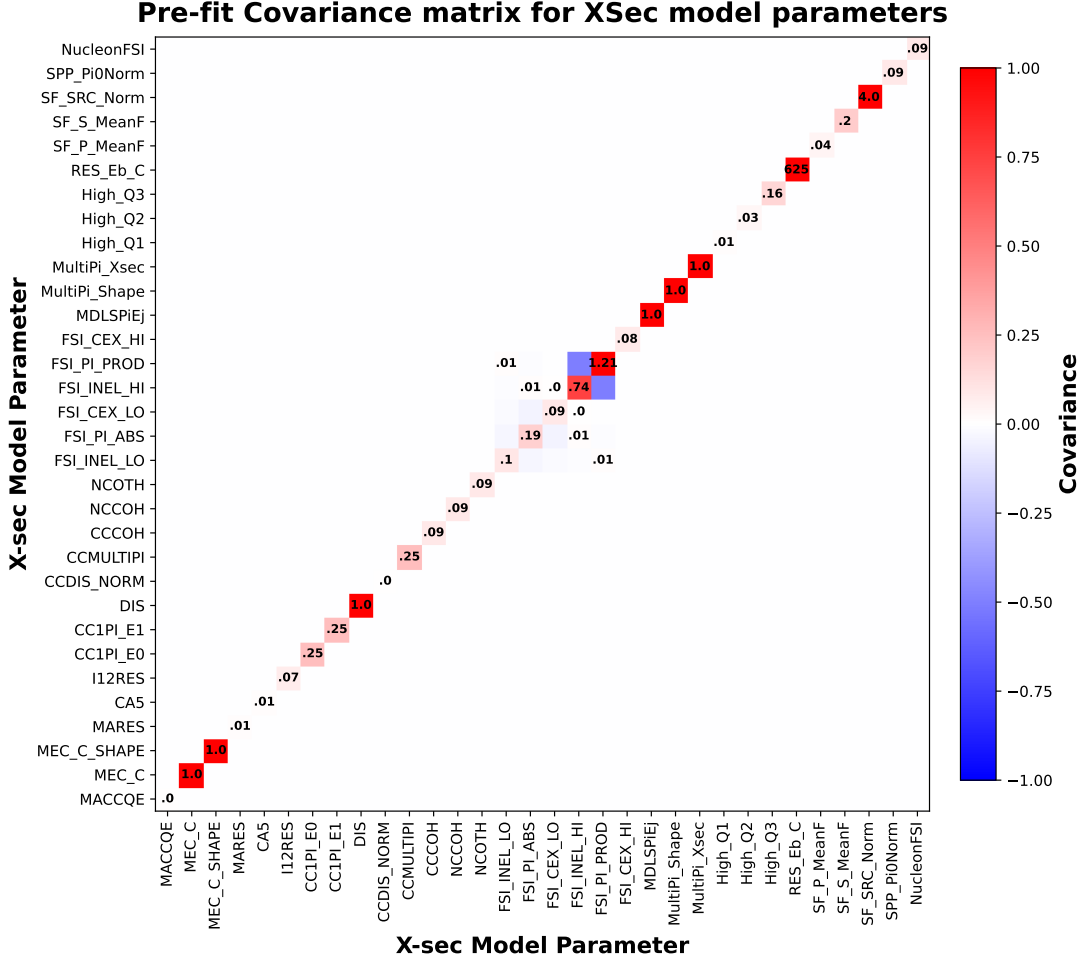


Figure 9.4: The cross-section covariance matrix describing the dependency of each systematic uncertainty on one another

Signal: Charged-current resonant pion production model parameters

As has been explained in chapter 3 on neutrino interactions, charged-current resonant pion production has been described by an array of different models with the Rein-Sehgal (RS) model being the default in the T2K NEUT neutrino event generator. The uncertainties associated with this reaction stem from the predictive power of the model. The parameters for this model comprise: M_A^{RES} (mass parameter in CCRES axial-vector form factor), C_A^5 (normalization of CCRES axial-vector form factor), and $I_{1/2}$ non-resonance background contribution.

Uncertainties in the RS Δ -resonance decay affects the kinematics of mesons and hadrons produced by the decay. The non-zero binding energy for constituents of the carbon atom

are also taken into account. Lastly, there is a set of four normalization dials that reweight specific topologies. The CC Coherent and NC Coherent parameters cover charged-current and neutral-current coherent events, respectively, whereby small amounts of energy are transferred to the nucleus. NC Other can scale the number of neutral current non-coherent instances. Lastly, the SPP π^0 dial alters the fraction of CC1 π^0 events.

Background: Charged-current quasi-elastic model parameters

One of the largest contributors to the background are events with the CC0 π topology, which consists almost entirely of the charged-current quasi-elastic reaction. Uncertainties in this mode are addressed by the CCQE dial category and revolve around modeling the interactions and the nucleon initial motion, which is represented by the Spectral Function.

Similarly to the resonant case, the mass parameter M_A^{QE} is responsible for shaping the axial-vector form factor. On top of that, three normalization parameters are introduced across different regions of Q^2 : 0.25–0.5 GeV², 0.5–1.0 GeV², and above 1.0 GeV². These parameters provide freedom to adjust the CCQE prediction specifically in the high Q^2 regions, where axial-vector form factors different from the standard dipole model may apply.

For the nucleon initial motion uncertainties, two types of parameters that affect the spectral function are incorporated. The Mean-Field (MF) approach defines the nucleon ground state in terms of the shell structures (S and P) and the uncertainties consider the normalization on each shell. For the short-range correlations (SRC), an overall normalization parameter is introduced to control the total contribution.

Background: 2p2h model parameters

Here, the uncertainties describe overall normalizations (i.e., the total cross section) of 2p2h interactions and the relative contributions from different interaction mechanisms and nucleon pairs to the 2p2h channel. In NEUT, two interaction mechanisms contribute to the 2p2h channel: meson exchange current (MEC) and nucleon-nucleon correlation (NN). Tunable parameters control the relative fraction of each source to the total 2p2h interaction.

Background: Charged-current deep inelastic scattering model parameters

The CCOther category is the second largest source of background events. This topology primarily consists of interactions in the deep-inelastic scattering regime, which is described by the Bodek-Yang model in the NEUT event generator. A correction parameter from the

Bodek-Yang (BY) model (DIS) and a normalization parameter for multi-pion production (CC Multi- π) are applied to account for these uncertainties. Additionally, two parameters specific to the multi-pion production aspect of the BY model are used to estimate the shape and total cross-section uncertainties associated with multi-pion production (Multi- π shape and x-sec). Finally, the CCDIS overall normalization parameter, which alters the total contribution from CCDIS interactions, is added.

Background: Final state interaction model parameters

There are two types of final state interaction model parameters. There are the ones that govern the pion FSI and those that affect the nucleon FSI.

The interaction channels for pion FSI are quasi-elastic (QE), charge exchange (CE), pion absorption, and inelastic (INEL) scattering. Parameters are introduced to control the probability of each interaction type occurring. Additionally, in the quasi-elastic scattering and charge exchange interaction, two parameters are applied for each channel: one for low pion momentum ($p_\pi < 0.5$ GeV/c) and one for high pion momentum ($p_\pi > 0.5$ GeV/c).

In the nucleon FSI case, the interaction channel under consideration is that in which a single pion is produced, meaning that the underlying parameter scales the probability for this process to occur. Since it affects the proton kinematics and the protons are one of the main reasons that the CC0 π topology ends up in the signal sample, it is important to include here.

9.3 FLUX SYSTEMATIC UNCERTAINTIES

Flux-related systematic parameters correspond to uncertainties in the beam composition and intensity. As described in chapter 6, the T2K neutrino beam is produced by a complex system of beamline elements. Any modeling or alignment inaccuracies within these elements will result in uncertainties on the flux. In figure 9.5, an overview is shown of these uncertainties with regard to the muon neutrino flux.

The main ingredients for the flux prediction at the near detector consist of: the primary proton beam profile and off-axis angle, alignment of the target and the focusing horns, the modeling of the magnetic field within the horns, and the hadronic interactions in the target. The largest contributor to the ν_μ flux uncertainty up to the peak neutrino energy is uncertainties in the pion spectra produced when 30 GeV protons hit the T2K target.

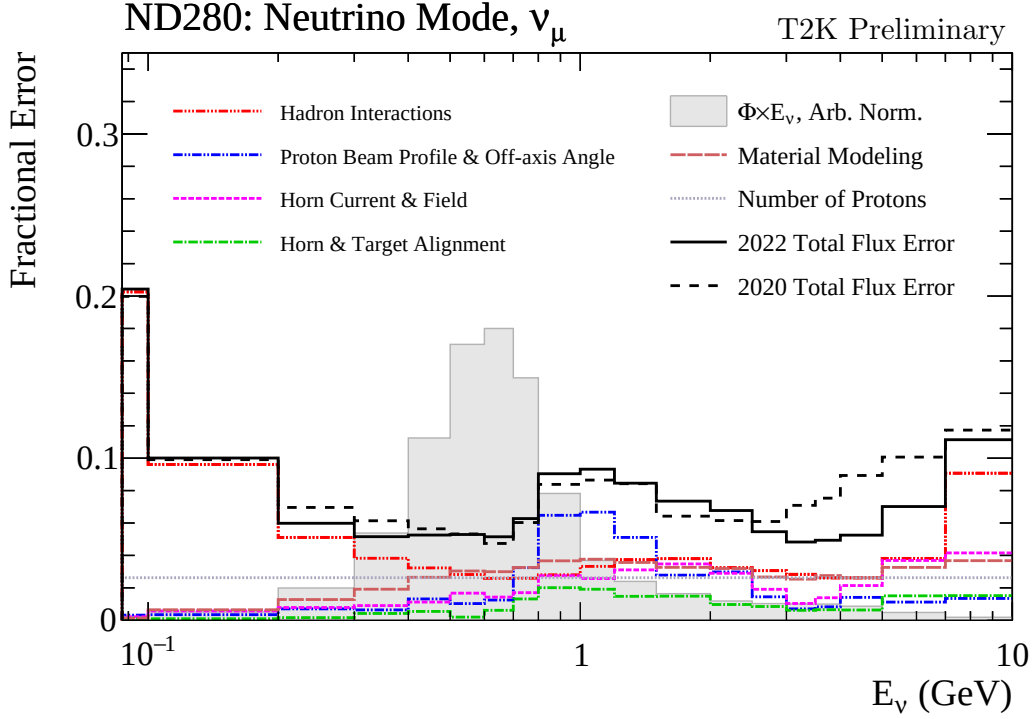


Figure 9.5: Systematic uncertainties on the ND280 flux prediction in neutrino mode

In figure 9.6 similar plots to figure 9.5 are shown, but are now broken down by hadron interactions on the left and non-hadron interactions on the right.

The meson rescatter is the result of subsequent interactions in the target or beamline material by pions and kaons that eventually decay into neutrinos. These interactions have been studied in NA61/SHINE, which is a hadron production experiment using a replica of the T2K target. The uncertainties in the proton beam profile and its off-axis

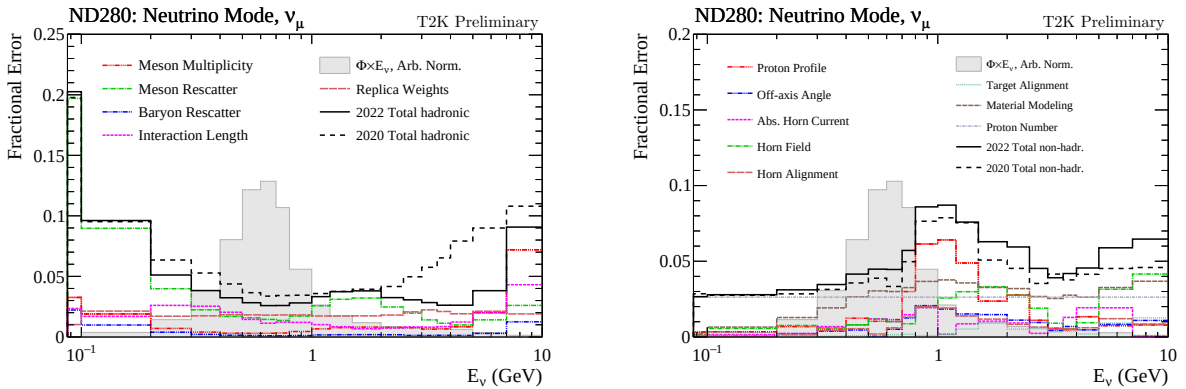


Figure 9.6: Hadron (left) and non-hadron (right) interaction model uncertainties evaluated on the ND280 flux prediction in neutrino mode.

angle shown in the right image of figure 9.6 are constrained by the beamline monitors, of which the optical transition radiation monitor described in section 6.2 is the final one before the protons reach the target.

The uncertainties are summarized in a flux covariance matrix. As the cross-section sought is for muon neutrinos on hydrocarbon, the matrix considers only the relevant bins for this horn current mode. The binning scheme is shown in table B.1, where the bins are smaller at lower energies as the T2K neutrino flux is larger there. The covariance matrix is constructed by taking a multitude of toy universes with toy throws around the nominal flux values for each systematic parameter listed in the figure legends above. These are then combined via equation 9.11:

$$V_{ij} = \frac{\sigma_i \sigma_j \rho_{ij}}{\Phi_i \Phi_j}. \quad (9.11)$$

Here, $\sigma_{i/j}$ denotes the systematic uncertainty in question and ρ_{ij} is the correlation between bins i and j . This quantity is then normalized by $\Phi_{i/j}$. The resulting covariance matrix is shown in figure 9.7.

9.4 ANALYSIS BINNING

The parameters discussed in the previous sections cover all of the relevant systematic uncertainties for the $\text{CC}1\pi^+$ signal and several background topologies. However as a binned likelihood fit will be used to ultimately do the cross-section extraction in the observable phase space, the template (truth), cross-section (truth) and detector (reconstructed) parameters as well as the samples themselves have to follow respective binning schemes. The bin edges should satisfy the following requirements to ensure the analysis' success.

The ideal approach is to make each bin as small as possible to accurately capture the event distribution and extract detailed cross-section information. However, statistical limitations and detector resolution constraints might require adjustments to the bin size for optimal results. The following factors are taken into account when determining the appropriate binning scheme:

1. A threshold on the number of events to limit the statistical uncertainty.
2. The efficiency of selecting signal events should be relatively consistent from one bin to the next. Since efficiency corrections are applied at the bin level, significant

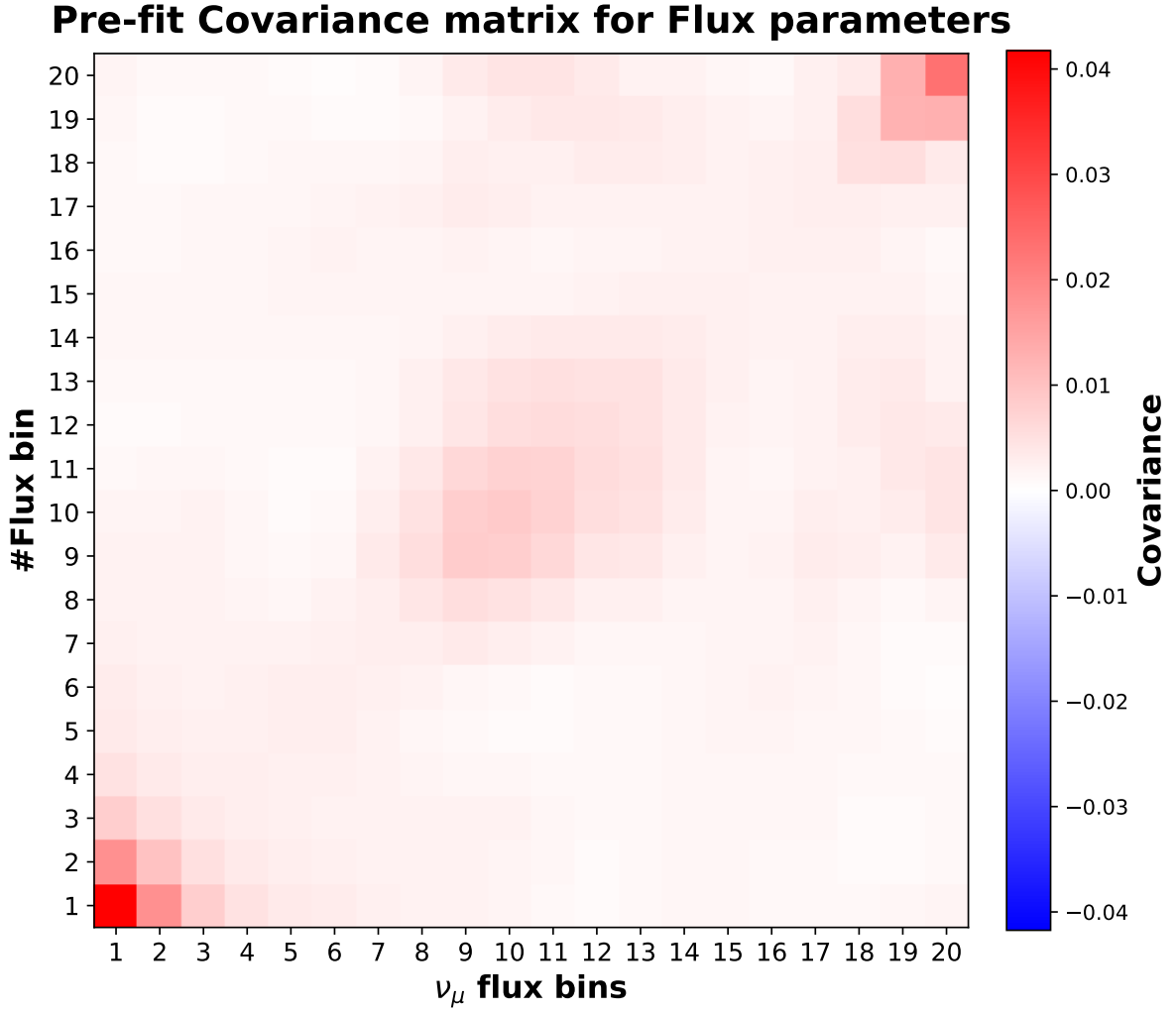


Figure 9.7: The flux covariance matrix binned in neutrino energy in neutrino mode

fluctuations in efficiency within a single bin can lead to strange interpolation issues in areas where the efficiency is lower than average.

3. When studying the reconstructed kinematics for events in a truth space bin, the smearing can be assessed. High levels of smearing indicate that there is large leakage of true events into neighboring bins in reconstructed space, which can lead to anti-correlations between neighboring bins. Hence, the binning is chosen so that the smearing is small.

Meeting all these requirements at the same time is challenging, so a compromise must be made to effectively capture the cross-section distribution's shape and differentiate between predictions from various neutrino-nucleus interaction models.

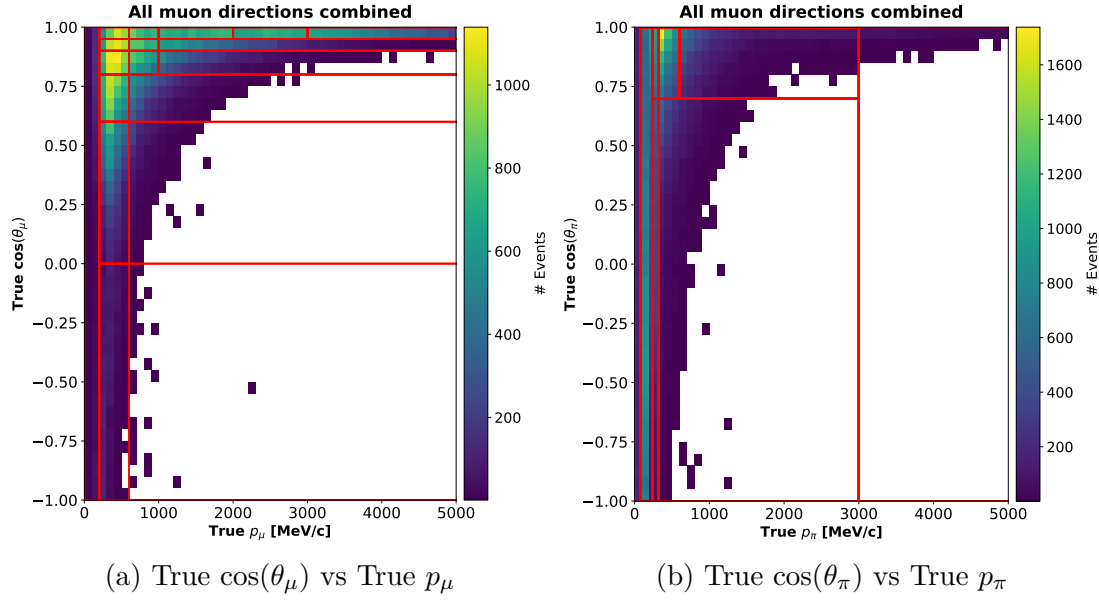


Figure 9.8: True event distributions for all $\text{CC}1\pi^+$ signal samples combined in 2D subsets of muon and pion kinematic variables. Cross-section bins are outlined in red.

9.4.1 Template binning

The template parameters are defined as bins in four-dimensional truth space regarding the muon and pion kinematic variables: momentum and angle. Figure 9.8 displays the distribution of signal events within a 2D subset of the analysis observable space, with the red lines marking the bin edges for the proposed template parameters. The histogram uses a finer binning to more clearly illustrate highly concentrated areas. Generally, regions with fewer events are binned more coarsely, while those with higher statistics feature finer binning. The singular bin on the far left in both plots represents a kinematic region that is out-of-phase-space (OOPS) (0-200 for p_μ and 0-80 for p_π). The bin in pion momentum $p_\pi > 3000$ MeV/c is also included in that regime.

Figure 9.9 illustrates the signal selection efficiencies across the observable space. As per point two in the list of requirements above, the bin edges here are selected to ensure that the efficiency distribution is somewhat flat within each bin. The selection purity is shown in the same binning scheme in figure 9.10. A clear distinction can be found in signal purity between the forward-going and backward-going region in the 2D muon kinematic space, something that was already noted in chapter 8 when studying the 1D signal sample distributions.

To assess the truth to reconstructed smearing, a two-dimensional smearing matrix is shown in figure 9.11. The x-axis indicates the truth bins ranging from 0 to 53. The y-axis represents the same binning scheme, but for reconstructed space (truth bin #0 thus

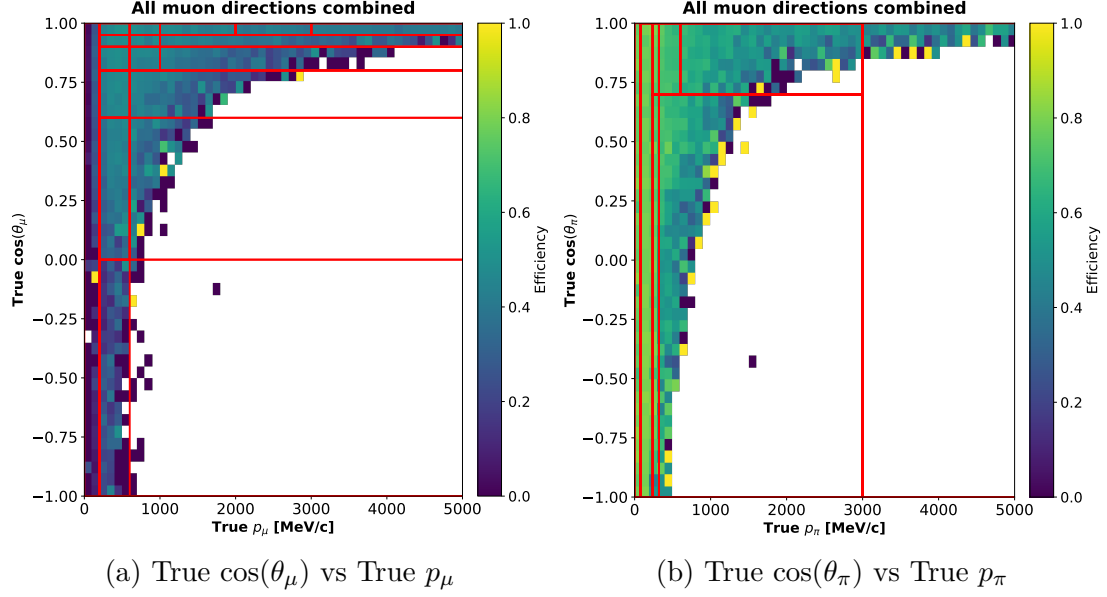


Figure 9.9: True selection efficiency distribution for all $\text{CC}1\pi^+$ signal samples combined in 2D subsets of muon and pion kinematic variables. Cross-section bins are outlined in red.

has identical bin edges to reco bin #0 etc.) The color bar shows the spillover to other bins from this center bin. An additional overview can be found in appendix B figures B.1 and B.2. Here the spillover is shown as a fraction of the number of events in the reconstructed bin, that corresponds to same bin in truth space.

Overall, the smearing is well-behaved with only the first bin, spanning the backward-going and high-angle backward-going muon distributions, and the final out-of-phase-space bin showing fractions above the average. As seen before, the number of events and efficiency are poor in the region for $-1 < \cos(\theta_\mu) < 0.0$, making this an expected result. By looking at the bin edges for the template binning summarized in table B.2 of appendix B, the smearing usually extends only to adjacent bins within the same angular range for the muon as a result of good reconstruction performance for this kinematic variable.

Bins #52, #53 and #54 shown in table B.2 are all out-of-phase-space bins added to estimate bin migration in the Monte Carlo simulation. This migration is the result of the detector smearing effect that reduces the accuracy of the particle kinematics reconstruction. The OOPS events are regarded as an another source of background but have very low impact based on signal purity checks. When extracting the cross-section, these bins are thus excluded. Finally with the template binning derived, the expected signal sample statistics and selection efficiency in each of the bins are shown in figures

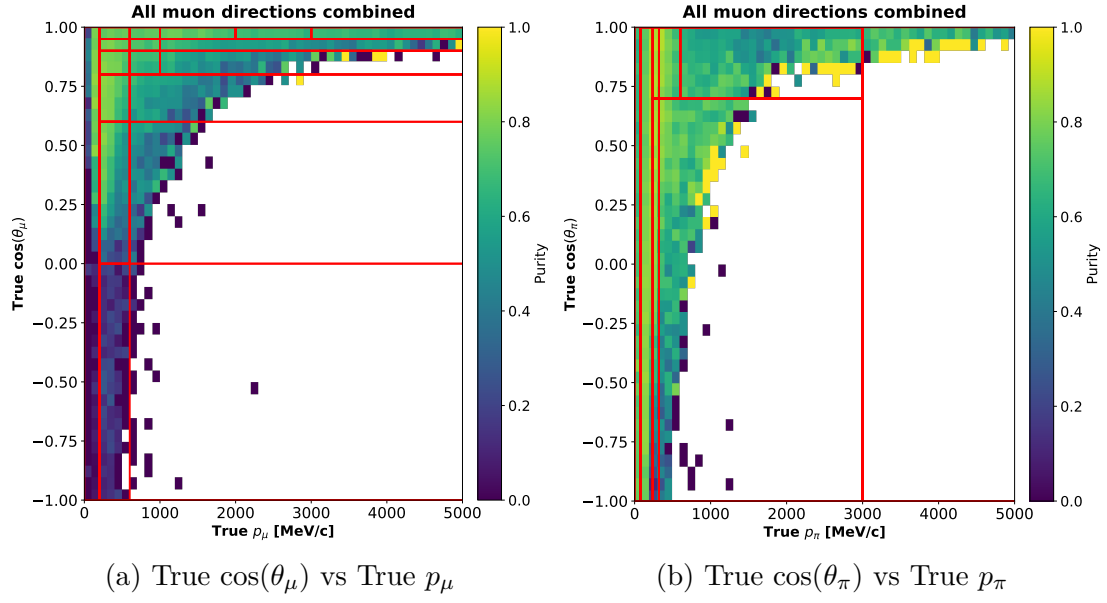


Figure 9.10: True selection purity distribution for all $\text{CC}1\pi^+$ signal samples combined in 2D subsets of muon and pion kinematic variables. Cross-section bins are outlined in red.

9.12 and 9.13, respectively. The MC statistics are normalized to have the same POT as data.

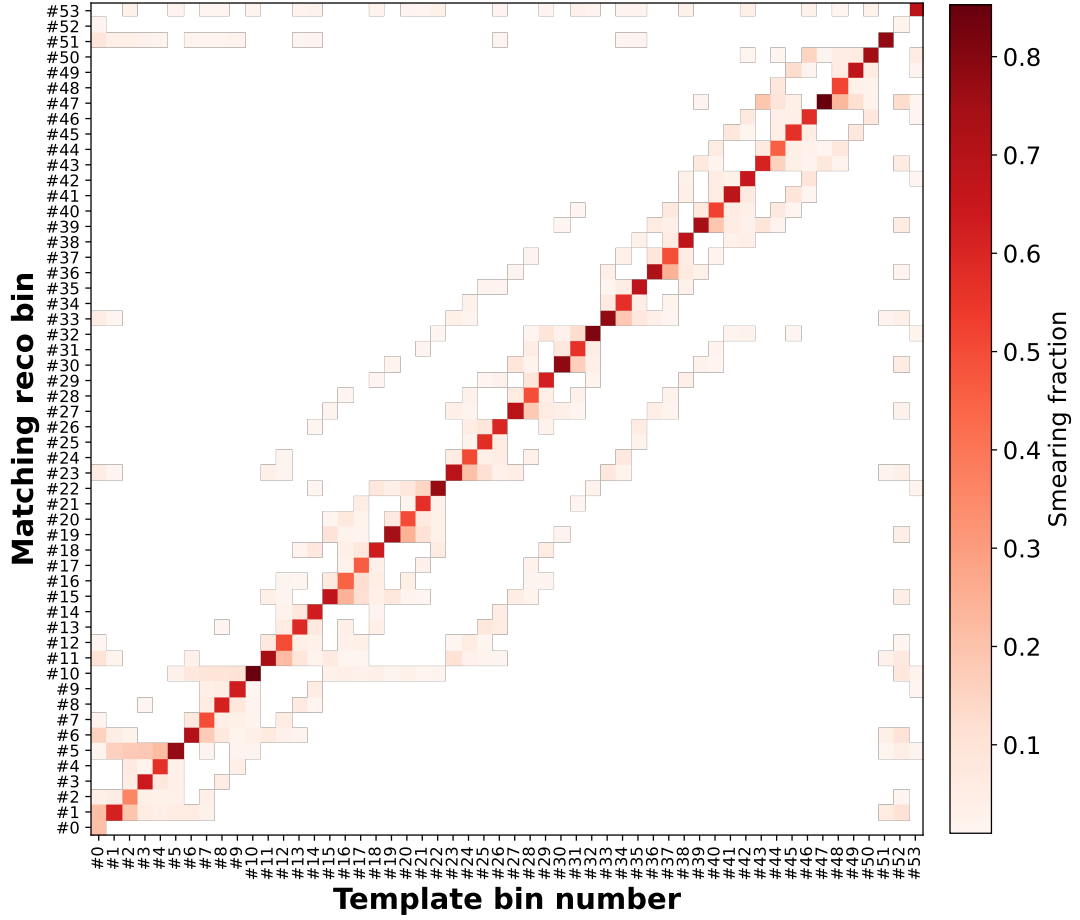


Figure 9.11: Smearing from truth to reconstructed space for the selected $\text{CC}1\pi^+$ signal sample.

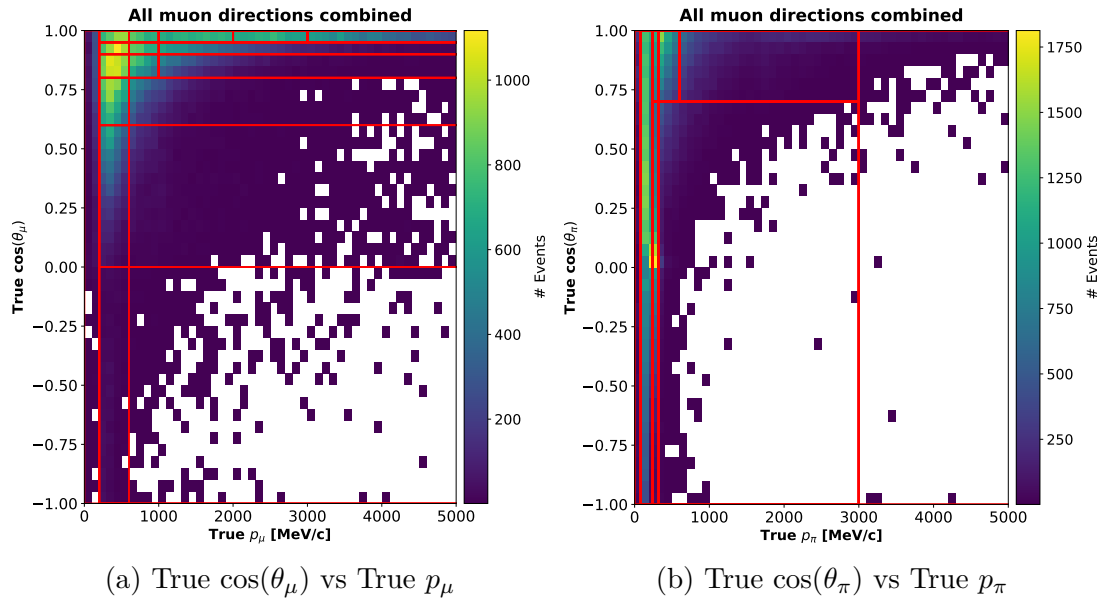


Figure 9.12: Expected event distribution for all $\text{CC}1\pi^+$ signal samples combined in 2D subsets of muon and pion kinematic variables. Cross-section binning in red.

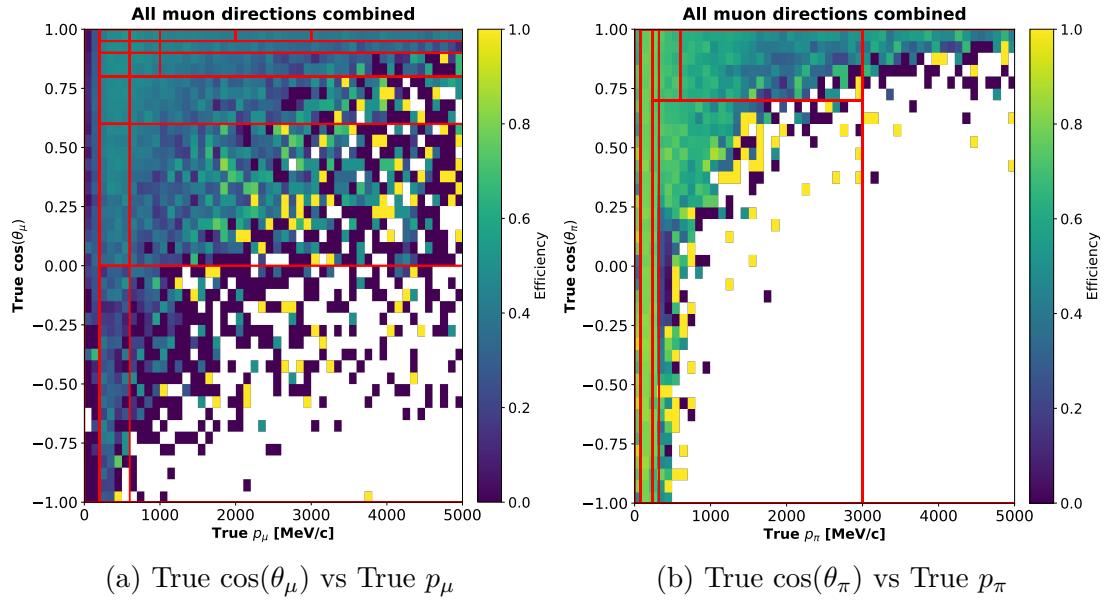


Figure 9.13: Expected selection efficiency distribution for all CC1 π^+ signal samples combined in 2D subsets of muon and pion kinematic variables. Cross-section binning in red.

9.4.2 Sample binning

There are two signal and three background samples supplied to the fitting framework in order to understand the rate of signal events in the data. Each of these comes with its own set of bin edges following a similar strategy as shown before but now in reconstructed space, where the selected MC and data samples are filled and compared. To be consistent with template parameter binning, an attempt is made to retain the same edges. Below, the number of events in each of the five samples' binning schemes is presented. The binning schemes themselves can be found in appendix B. Note that the signal is split in two based on the pion identification method. For FGD&TPC-tagged pions in table B.3, the range for $\cos(\theta_\pi)$ does vary bin-to-bin. This is not the case for pions identified by their subsequent Michel electron in table B.4. An overview for the number of events in both of the signal samples can be found in figures 9.14 and 9.15. The red dashed line indicates 100 events.

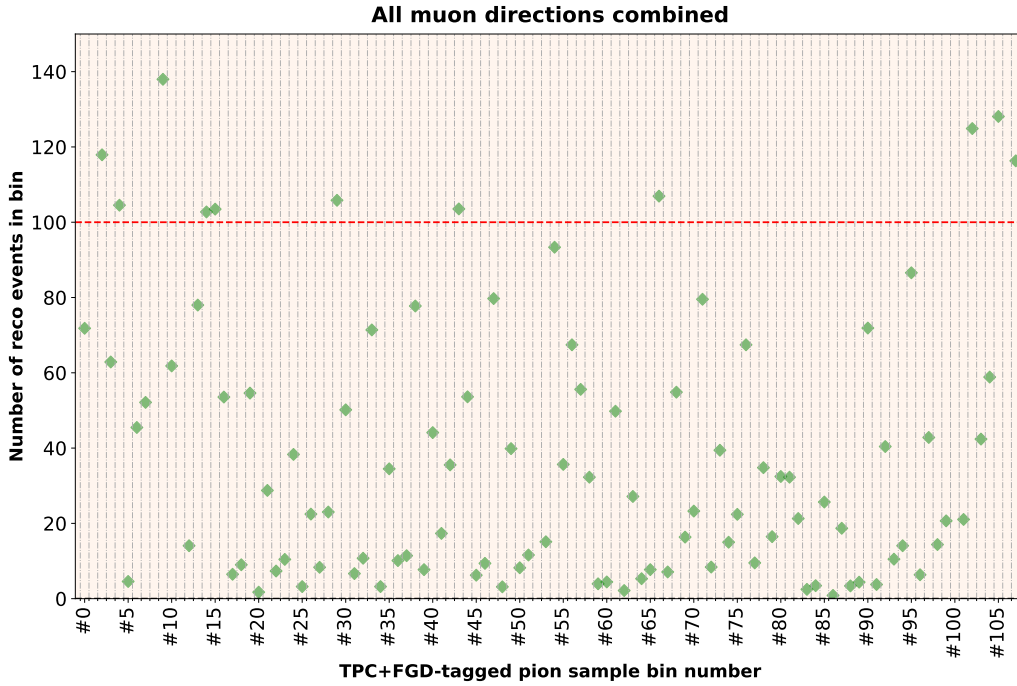


Figure 9.14: Expected event distribution for the $CC1\pi^+$ TPC and FGD-tagged pion signal samples with all muon directions combined in 4D kinematic variables.

The bin edges for background samples with an additional charged and neutral pion can be found in tables B.5 and B.6, respectively. Because the statistics for these topologies are very limited, the number of bins has been greatly reduced compared to the signal samples. A combined overview for the number of events in both of these samples can be found in figure 9.16. Notice that signal samples had an additional OOPS bin, similar

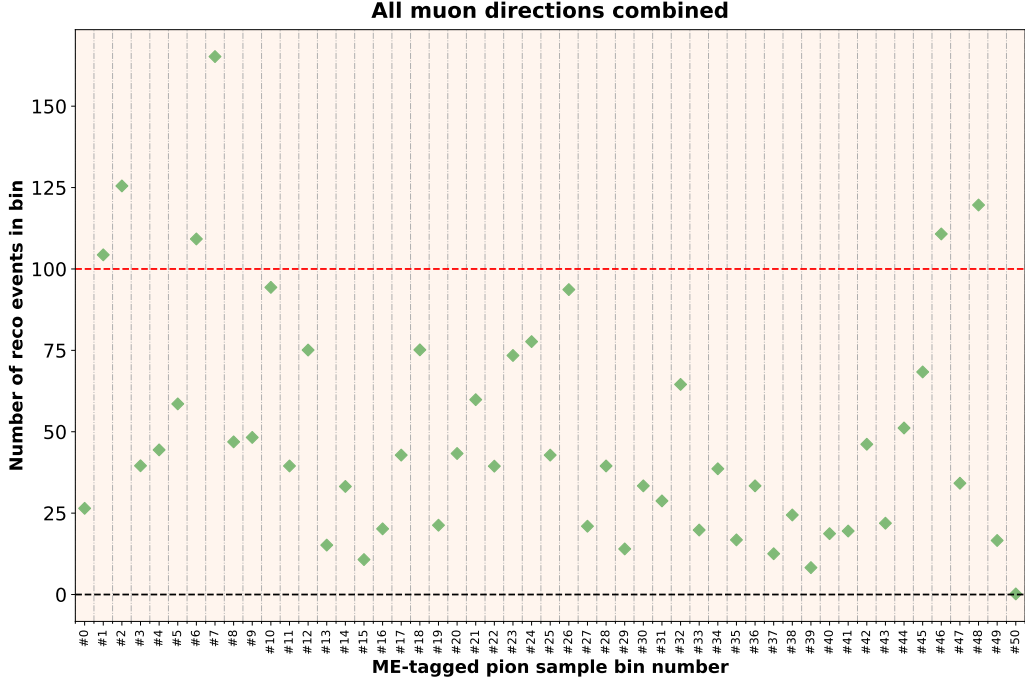


Figure 9.15: Expected event distribution for the $CC1\pi^+$ ME-tagged pion signal samples with all muon directions combined in 4D kinematic variables.

with template binning. While these control samples do not consider such bins as the IPS and OOPS only relate to the signal topology.

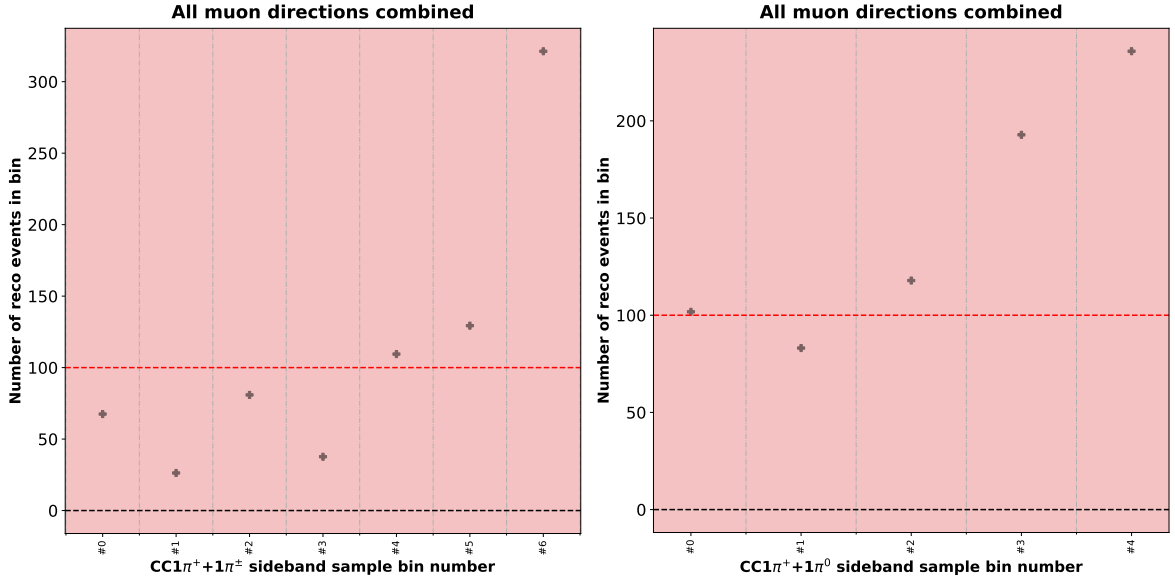


Figure 9.16: Expected event distribution for the $CC1\pi^++1\pi^\pm$ (left) and $CC1\pi^++1\pi^0$ (right) control samples with all muon directions combined in 4D kinematic variables.

The bin edges for the $CC0\pi$ background sample, in which the proton is identified as a pion can be found in table B.7. Because this event type is so prevalent, the number of

bins can be extended tremendously, yielding more accuracy for smaller sizes. OOPS bins are also included in this control sample and correspond to the latter two in the list. The number of events can be found in figure [9.17](#).

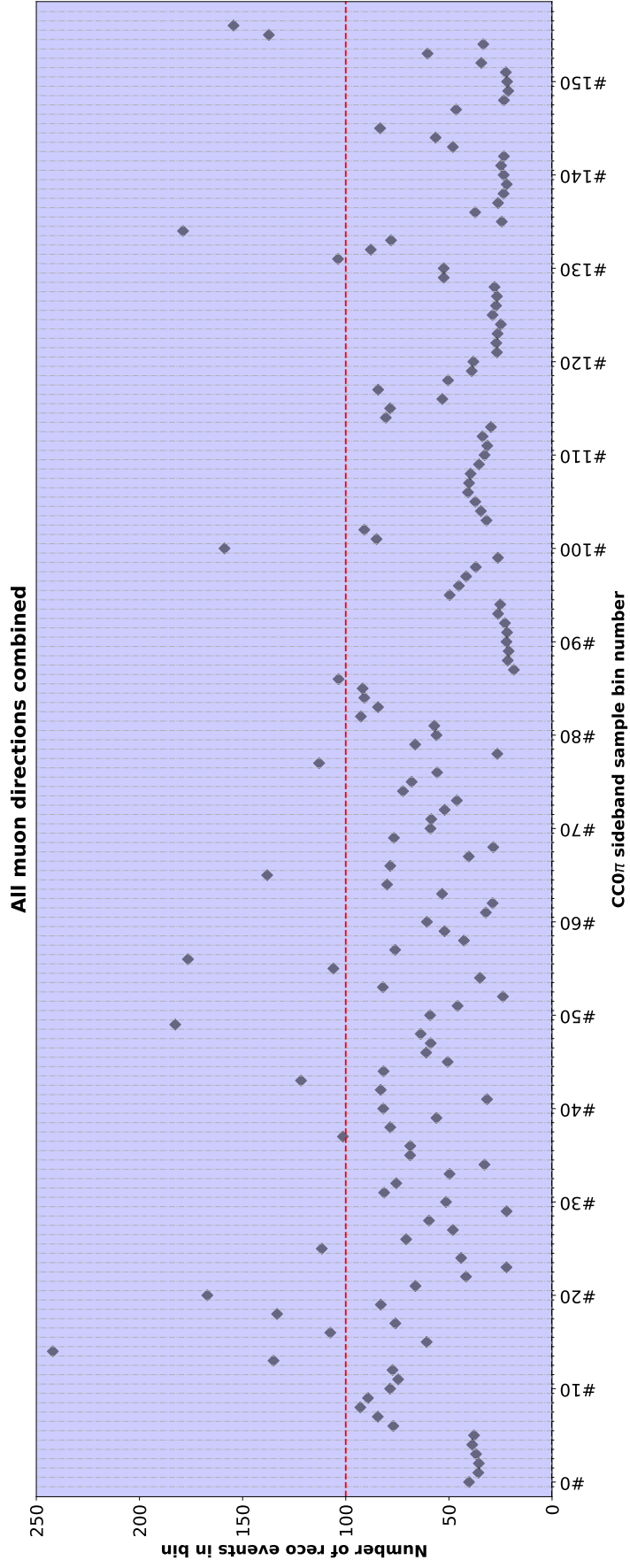


Figure 9.17: Expected event distribution for the CC0 π control sample with all muon directions combined in 4D kinematic variables.

VALIDATING THE FITTER

10

Before the cross-section can be extracted from the result of fitting the Monte Carlo simulation to the measured data events in FGD1 of ND280, the fitting procedure's robustness has to be evaluated under different circumstances. This is done to understand any biases in the final result that could be introduced by neutrino interaction models in the MC. Chapter 9 described the template, detector, flux and cross-section parameters that will be incorporated at different stages. The fit is allowed to alter each of these within certain bounds to minimize the χ^2 . As the fit uses a binned likelihood strategy, the binning schemes have been discussed at length. Together with the signal and background samples from chapter 8, this completes the input GUNDAM requires. The validation is then conducted in two parts.

Firstly, the general behavior of the fitter is put through the test. In table 10.1, these checks are outlined above the red line and all revolve around Asimov-like fits. The Asimov dataset is created by filling each bin with the expected mean number of events coming from the Monte Carlo simulation and assigning each model parameter its expected mean value. More details can be found in section 10.1. After proving that the framework does not misbehave and is capable of returning the truth values within the error bars every time, more complex tests can be performed. These will be referred to as 'Fake Data Studies', where signal or background events are increased or decreased artificially to represent the analysis' ignorance to the frequency of certain topologies or reaction modes. This will be covered in-depth in section 10.2.

Fit name	Description
Asimov fit	Data identical to MC simulation
Random Template priors D.1.1	Asimov fit: Truth bin prior values have been randomized
MC fluctuations	Asimov fit: Poisson varied reco sample bins
Altered out-of-fiducial-volume weights D.2.2	Data fit: to 10% decreased OOFV weights
Altered background (CCOther) weights D.2.3	Data fit: to 10% decreased control sample CCOther weights
Altered out-of-phase-space weights D.2.1	Data fit: to 10% increased event weight for events with $P_\mu < 200$ MeV or $P_{\pi^+} < 80$ MeV (out-of-phase-space)
Altered resonant weights	Data fit: to 30% increased CC1Pi signal event weights

Table 10.1: Description of the different validation fits

The fitting results will comprise the best post-fit values (e.g., χ^2), errors, covariance and correlation matrices for each of the four parameters sets (template, flux, cross section, and detector). These can then be utilized to obtain the four-dimensional neutrino cross sections in muon and pion kinematic variables, as will be shown in chapter 11. To assess the fitting stability and performance, several metrics will be used.

1. The fit's success rate (% converged)
2. Comparison of pre-fit and post-fit χ^2 reveals the improvements on the initial guess of the distributions
3. Comparison of pre-fit and post-fit signal and sideband binned event rates will provide an overview of what bins are responsible for misbehavior
4. Comparison of pre-fit and post-fit parameter values and associated errors will reveal the effect that altering the weights has on the fit's capabilities to find the nominal values
5. Comparison between the resulting and expected number of degrees of freedom

(#DoF) by visualizing all best-fit χ^2 values in case of multiple toy universes (repeated throws)

Each of these items can reveal misbehavior during the fitting stage. If the χ^2 does not improve significantly, the binning scheme could be too fine. If the #DoF returned by a χ^2 fit to the resulting distribution does not come close to the expected value, there could be parameters that are too heavily correlated. Another hint could be the impact that altering a certain weight has on an unrelated parameters (e.g., increase of signal events on a $CC0\pi$ model parameter). If any of these complications show up, they will be described in the sections below.

10.1 THE BASIC CHECKS

The entire validation procedure is based on attempting to fit different variations of the Monte Carlo distributions using the same set or subsets of parameters. The basic checks are a simplified version of these tests. They all consider Asimov-like fits with the first iteration described in section 10.1.1 considering the case in which the data and MC are completely identical. Afterwards, in section 10.1.2.1 the bins in reconstructed space will be statistically varied. The validation procedure for the random truth bin priors can be found in section D.1.1 of appendix D.

10.1.1 Asimov fit

In this case, the fit starts from the true best-fit point. This means that it should not find an improvement in the likelihood (i.e., a decrease in the value for χ^2) while exploring the parameter space and hence will return the same nominal parameters as were put in. As this is the simplest possible test, any deviation from these values indicates the fitter is misbehaving and is thus reason for concern. In order to fully test this framework and simultaneously ensure it is robust, it is run multiple times. Each iteration allows a different subset of the parameter set to float, introducing more freedom to the fitter (Template, Template + Flux, Template + Flux + Detector, Template + Flux + Detector + X-section). In figures 10.1, 10.2, 10.3 and 10.4, the result for the full space is provided which will ultimately help understand the range of the errors on the future calculated cross-section. Alongside with the pre and post-fit values for each of the individual parameters, the figure also shows the parameter's rate of change (ROC) and the error ratio (ER) described by equation 10.1:

$$\text{ROC} = \frac{\mu_{\text{postfit}} - \mu_{\text{prefit}}}{\mu_{\text{prefit}}} \quad \text{ER} = \frac{\sigma_{\text{postfit}}}{\sigma_{\text{prefit}}}. \quad (10.1)$$

10.1.1.1 Parameters

It can be seen that the nominal values are returned in every bin for every parameter (rate of change is exactly zero) and the errors are reduced in certain regions for the flux, detector and cross-section related ones (ratio below 1). In case of the template parameters, the uncertainty is related to the available statistics in a specific bin. With the exception of a few outliers, these uncertainties lie around the same value. This is to be expected from the binning scheme's design where the focus lay on keeping the true number of events consistent across all 4D bins. The same philosophy holds for the detector parameters, but revolving around the number of reconstructed events.

Lastly, there are the flux and cross-section model parameters. In both spaces, the most affected bins are the ones related to the $\text{CC1}\pi^+$ signal or the energy region where the signal is most pronounced. The former indicates that the sideband control samples indeed constrain the underlying parameters (CC1Pi_E0 , CC1Pi_E1 , DIS , CCMultiPi , Res_Eb_C).

The post-fit correlation and covariance between template and flux parameters can be found in figure 10.5, while the detector and cross-section ones can be seen in figure 10.6. In general, the covariance is orders of magnitude lower than the correlation and the color bar had to be adjusted to reveal the underlying structure. Bins 16, 20 and 25 in truth space (template parameters) show features of anti-correlation. These bins correspond to parts of phase space in which the pion momentum is split into 80 – 240 MeV and 240 – 320 MeV. For the cross-section model parameters, the anti-correlated pairs mainly come from the CCMultiPi dial on one hand and the final state interaction parameter on the other. Events that have a topology with multiple pions can't also be deep-inelastic scattering simultaneously, leading to the anti-correlation when the fit is performed. A similar statement can be made about the FSI dials. Boosting absorption will reduce the possibility of any other FSI process to zero as the pion is now gone.

10.1.1.2 Samples

In order to get an estimate on the goodness of fit and regions where the fitter might misbehave, the signal and sideband binned event rates are shown in figures 10.7 and 10.8, respectively. As this is an Asimov fit, the expectation is that the same points in parameter space will be returned post-fit (proven by $\chi^2 = 0$ in the post-fit case) as the nominal values that were put in pre-fit (also represented by $\chi^2 = 0$ in the pre-fit case). The χ^2 is calculated through equation 10.2 and will be of more importance in the second half of this discussion where the starting point for the fit will deviate from the nominal

position.

$$\chi^2 = \sum_i \frac{(N_{i,pred} - N_{i,data})^2}{N_{i,data}} \quad (10.2)$$

Here $N_{i,pred}$ and $N_{i,data}$ represent the nominal and fake data event rates in bin i for one of the signal or sideband samples, respectively.

10.1.1.3 Cross-section calculation

The final step in the validation sequence is extracting the cross-section from the altered MC distribution or (fake) data and comparing it to the predicted value. This prediction is derived from the nominal MC parameter position of an Asimov fit. The extraction is done by generating 2000 toys from the post-fit template parameters and using the mean and root-mean-squared (RMS) of the distribution to find the cross-section and its uncertainty in each individual truth bin.

To estimate the fitter's performance at this stage of the analysis, a new χ^2 calculation is introduced that relates the nominal cross-section to the one resulting from the fake data via equation 10.3.

$$\chi^2 = \sum_{i,j} \left(\frac{d\sigma}{dX_{i,pred}} - \frac{d\sigma}{dX_{i,meas}} \right) (V^{-1})_{ij} \left(\frac{d\sigma}{dX_{j,pred}} - \frac{d\sigma}{dX_{j,meas}} \right), \quad (10.3)$$

in which $\frac{d\sigma}{dX_{i,pred}}$ and $\frac{d\sigma}{dX_{i,meas}}$ are the extracted cross-section values within template bin i or j for the nominal MC and (fake) data, respectively. V_{ij} is the post-fit covariance matrix describing the covariance between these bins. It is provided by equation 10.4, which uses the mean over all toys for the values enclosed by $\langle \rangle$:

$$V_{ij} = \frac{1}{N_{toy}} \sum_t^{N_{toy}} \left(\frac{d\sigma}{dX_{i,t}} - \left\langle \frac{d\sigma}{dX_i} \right\rangle \right) \left(\frac{d\sigma}{dX_{j,t}} - \left\langle \frac{d\sigma}{dX_j} \right\rangle \right). \quad (10.4)$$

The values are supplied in the legends of figures related to the cross-section. In figure 10.9, it can be seen for the Asimov fitted results. As the pre-fit and post-fit parameters are identical, the cross-section results are as well and thus the χ^2 values are 0 as expected, proving the method's stability under these simplistic conditions.

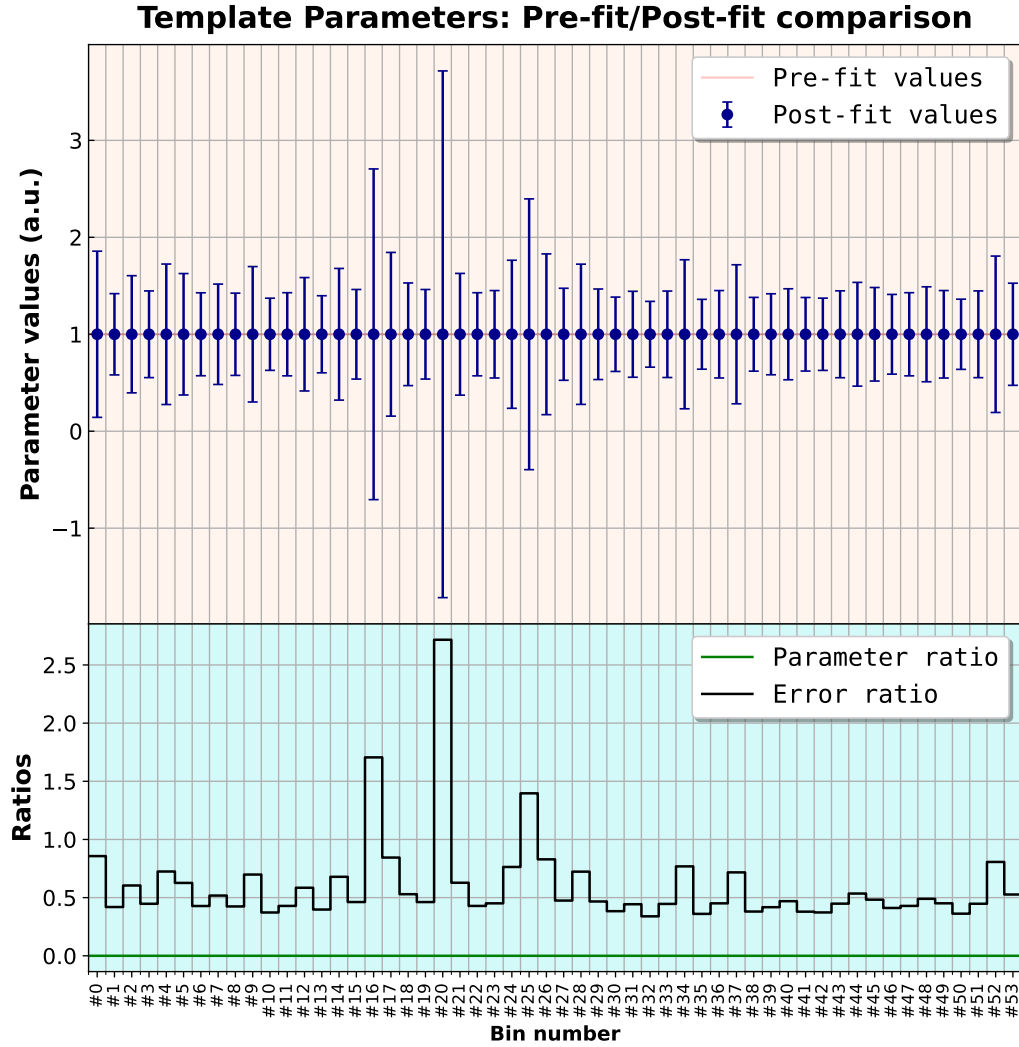


Figure 10.1: Comparisons between the pre-fit and post-fit values for truth bins in 4D true kinematics variables, where bins 52 through 54 indicate out-of-phase-space (i.e., overflow) bins for an Asimov fit. The red line in the top half of the figure represents the pre-fit nominal value, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

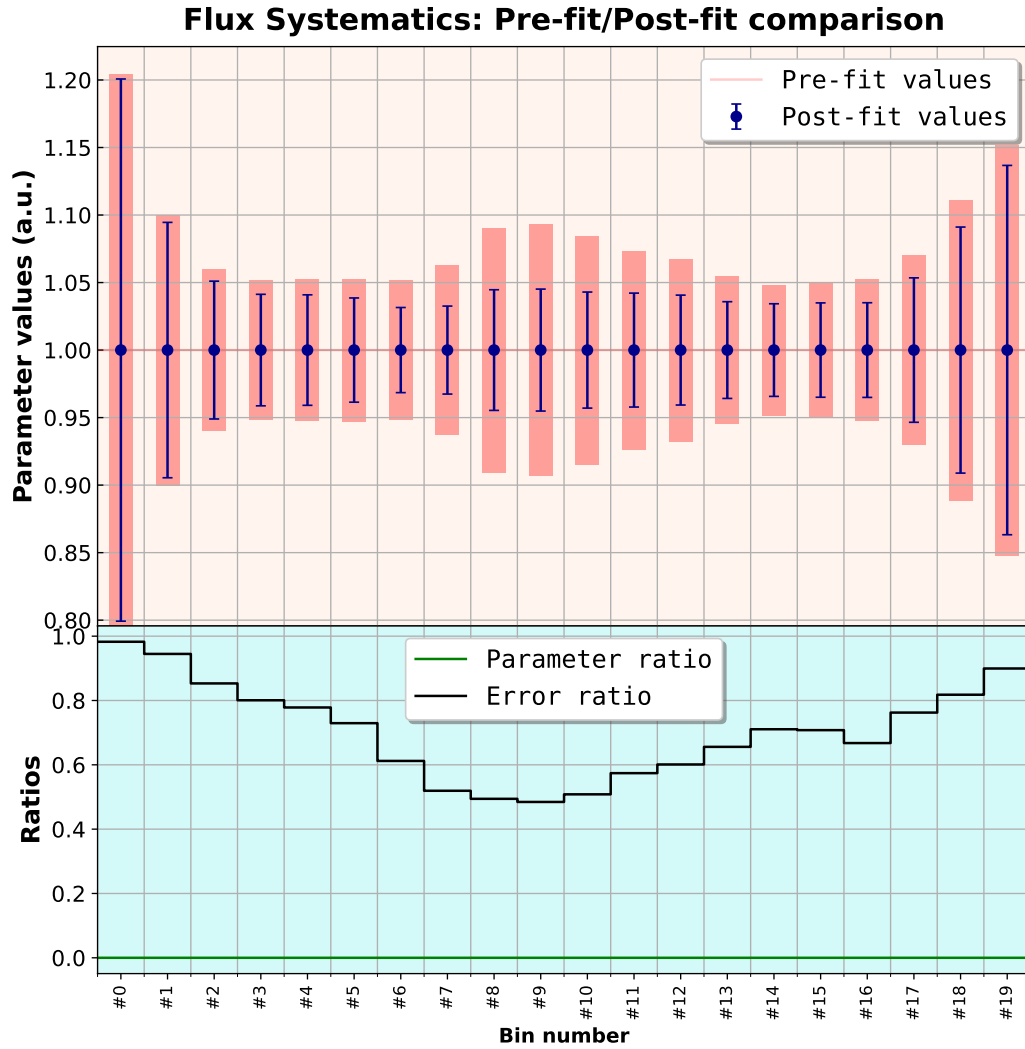


Figure 10.2: Comparisons between the pre-fit and post-fit values for the flux parameters binned in neutrino energy for an Asimov fit. The red line and red shaded region in the top half represent the pre-fit nominal value and associated uncertainty, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

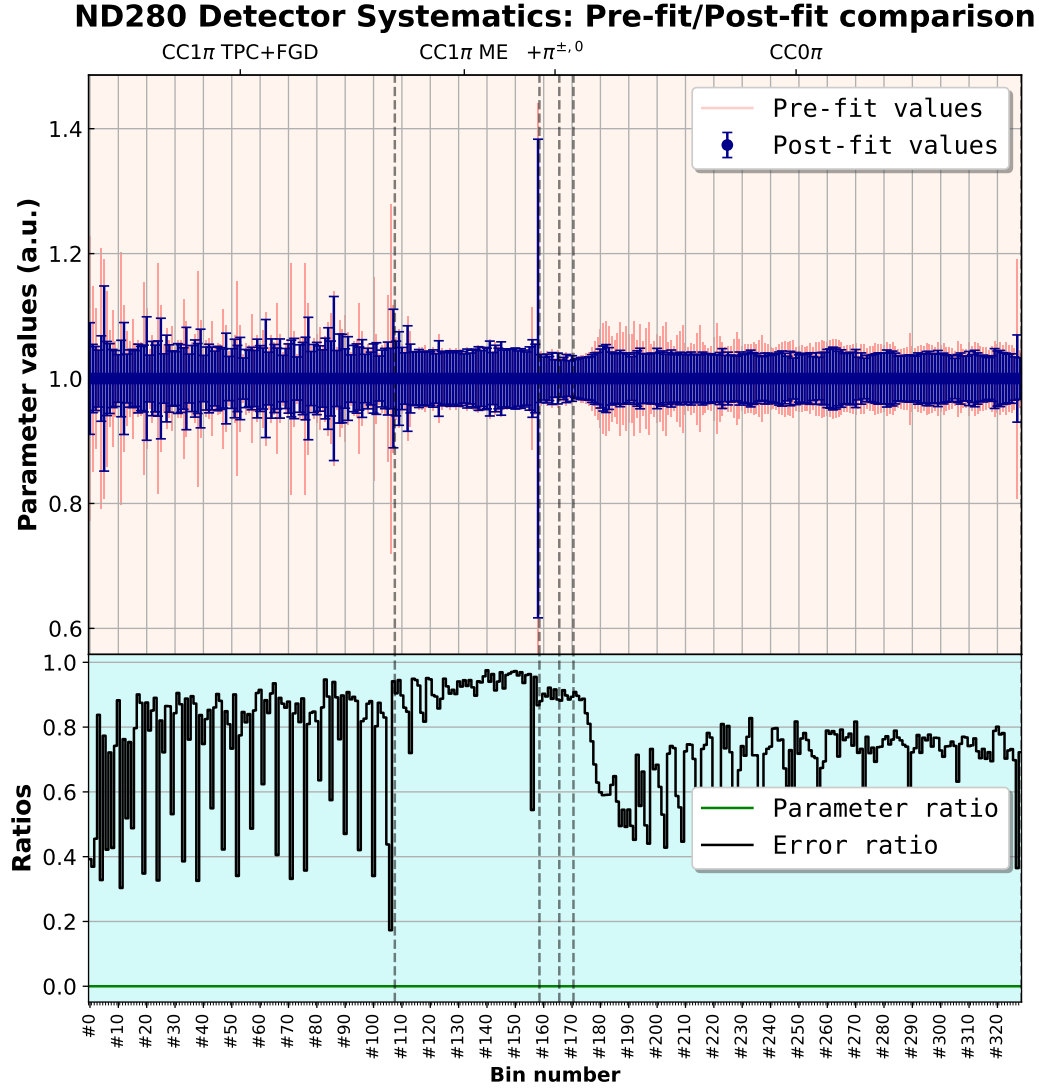


Figure 10.3: Comparisons between the pre-fit and post-fit values for the detector parameters binned in 4D reconstructed variables for each sample individually for an Asimov fit. The separation between samples can be found at the top and is marked by the vertical dashed black line. The red line and red shaded region in the top half represent the pre-fit nominal value and associated uncertainty, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

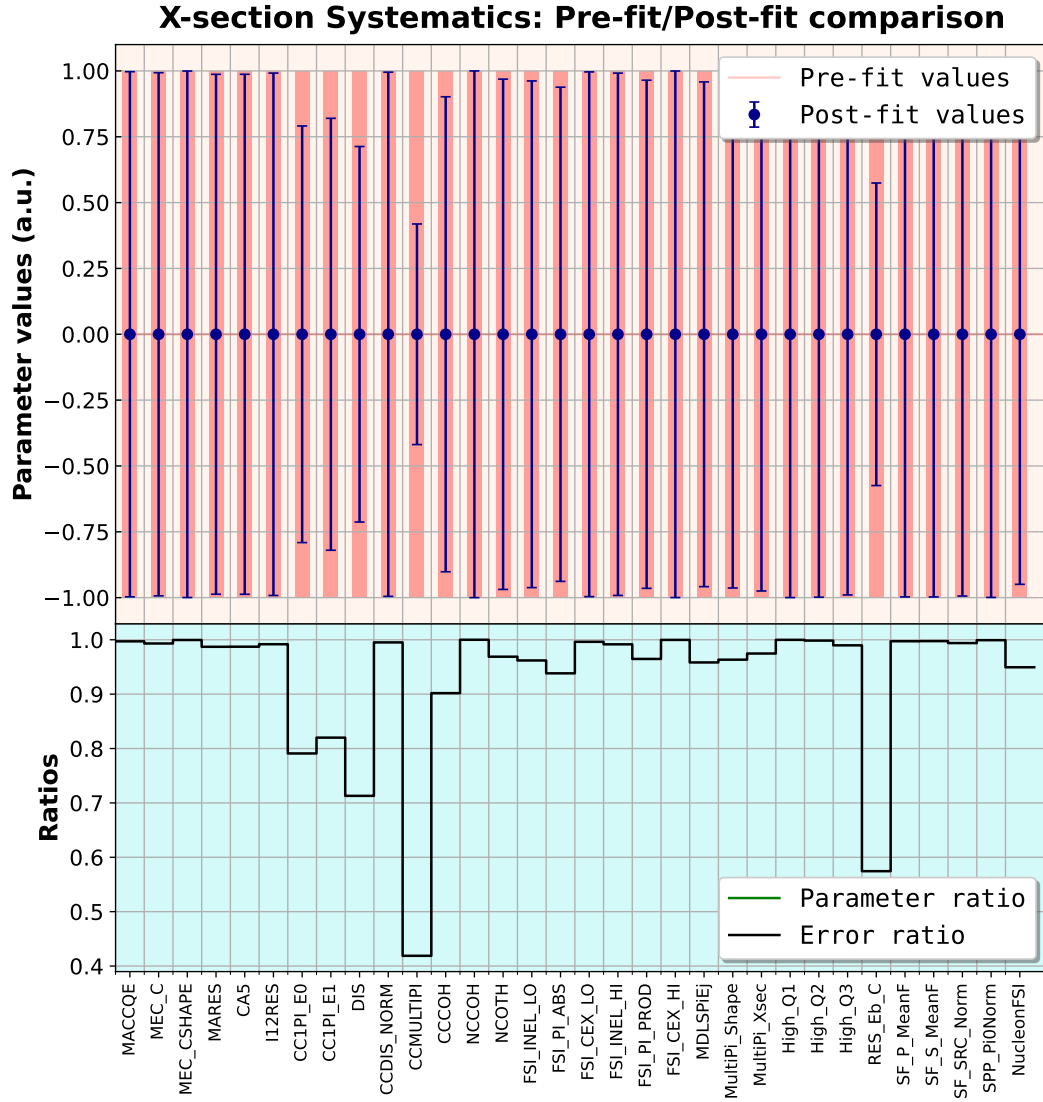


Figure 10.4: Comparisons between the pre-fit and post-fit values for the normalized cross-section model parameters for an Asimov fit. The red line and red shaded region in the top half represent the pre-fit nominal value and associated uncertainty, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

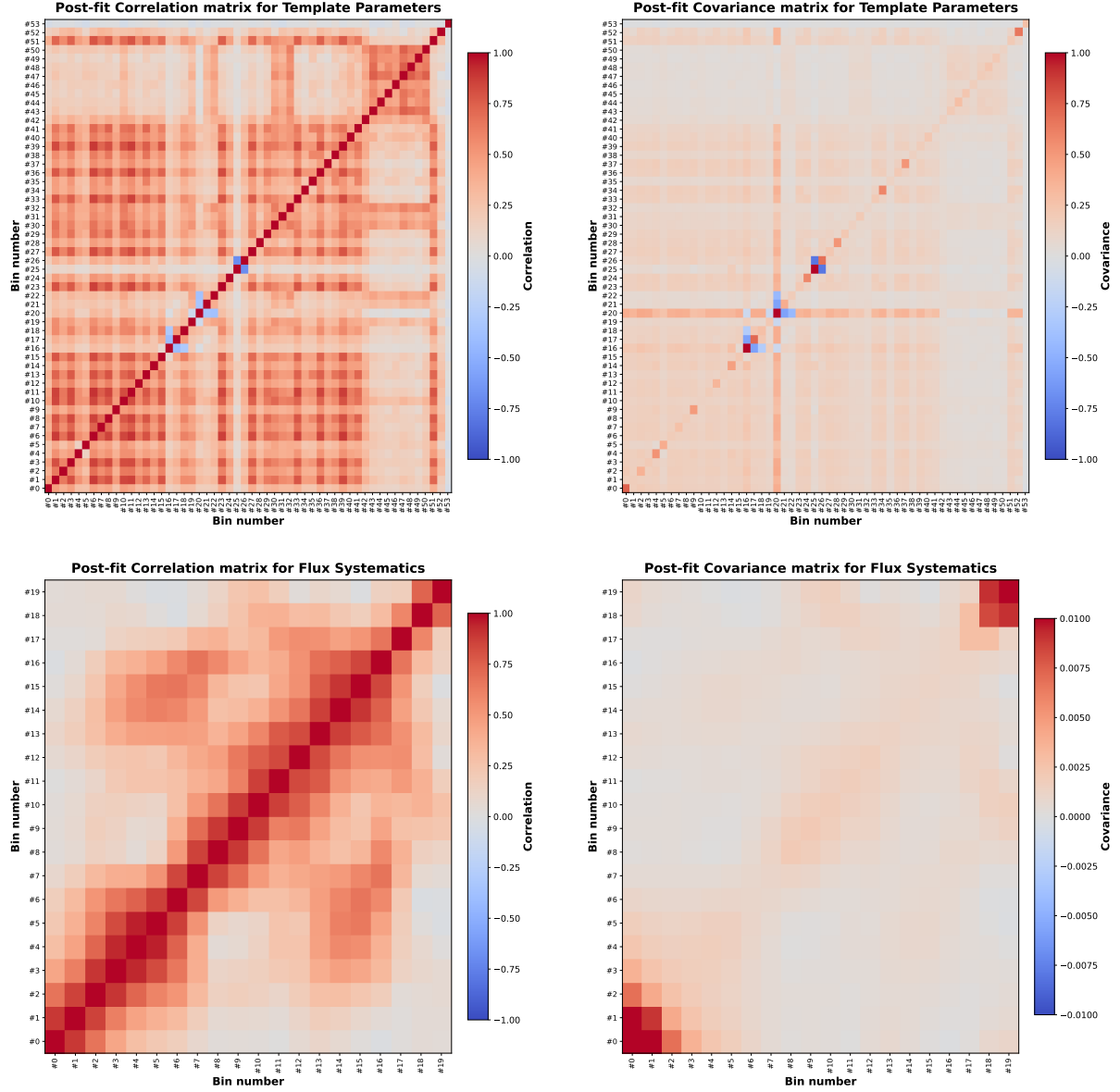


Figure 10.5: Asimov post-fit correlation (left column) and covariance (right column) matrices for the template (top) and flux parameters (bottom). The color bar for the covariance is set at a different (smaller) range to reveal the matrix' structure.

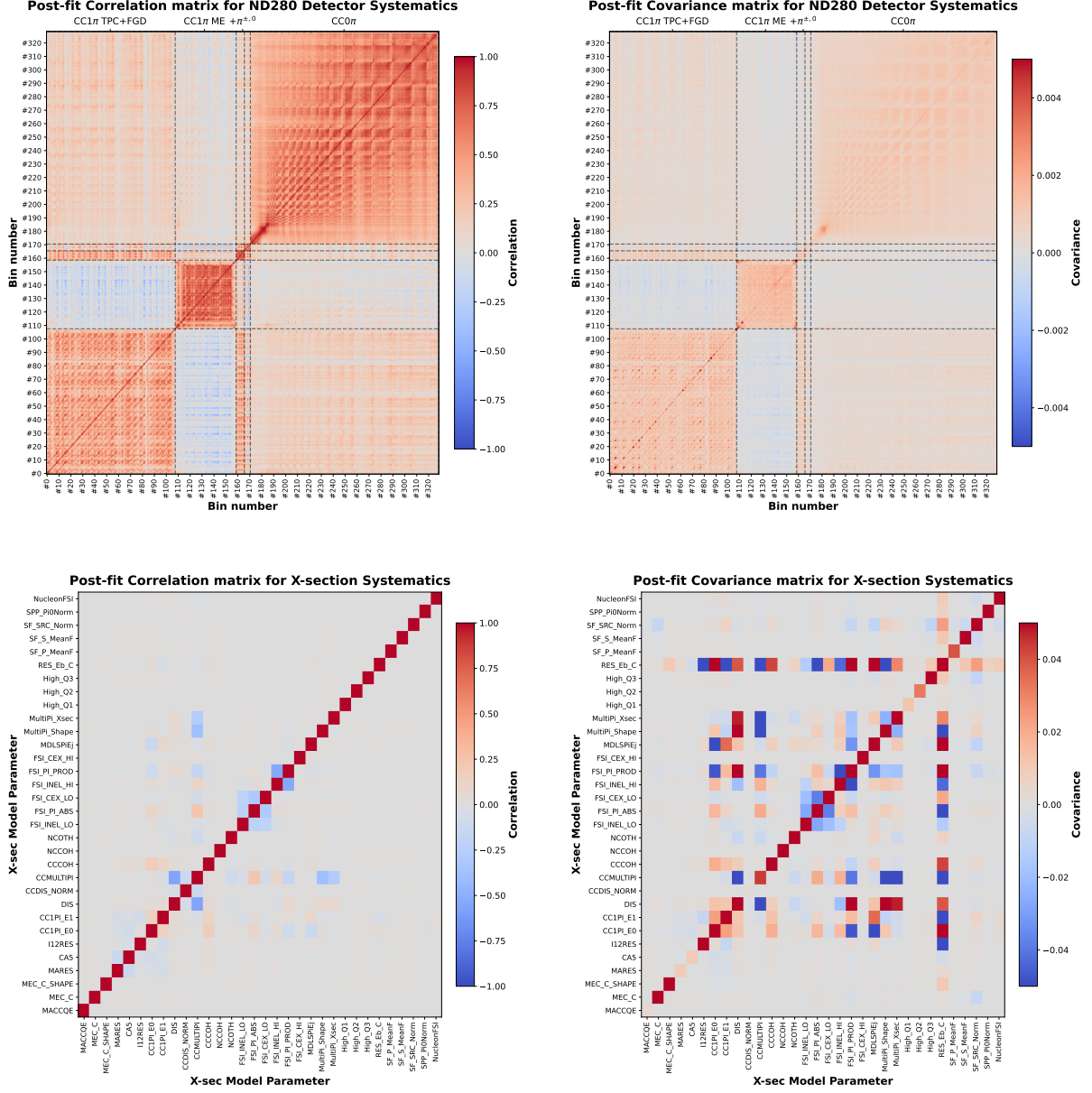


Figure 10.6: Asimov post-fit correlation (left column) and covariance (right column) matrices for the detector (top) and cross-section model parameters (bottom). The color bar for the covariance is set at a different (smaller) range to reveal the matrix' structure.

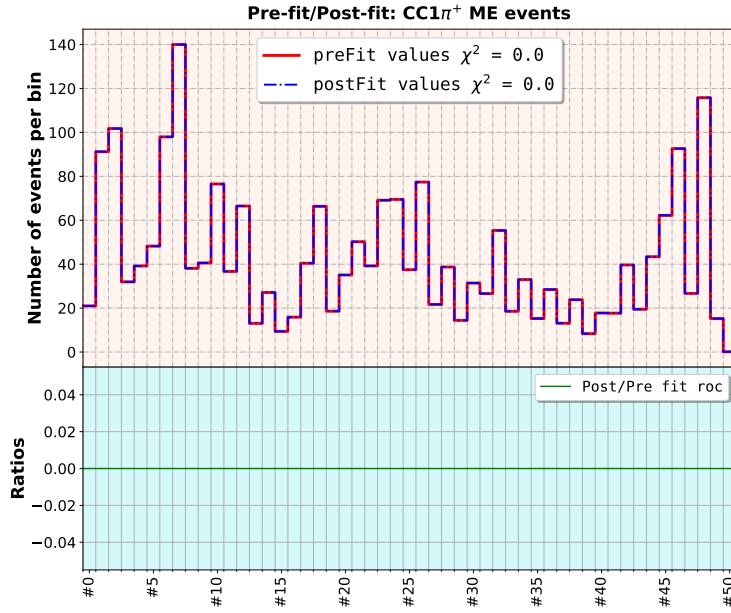
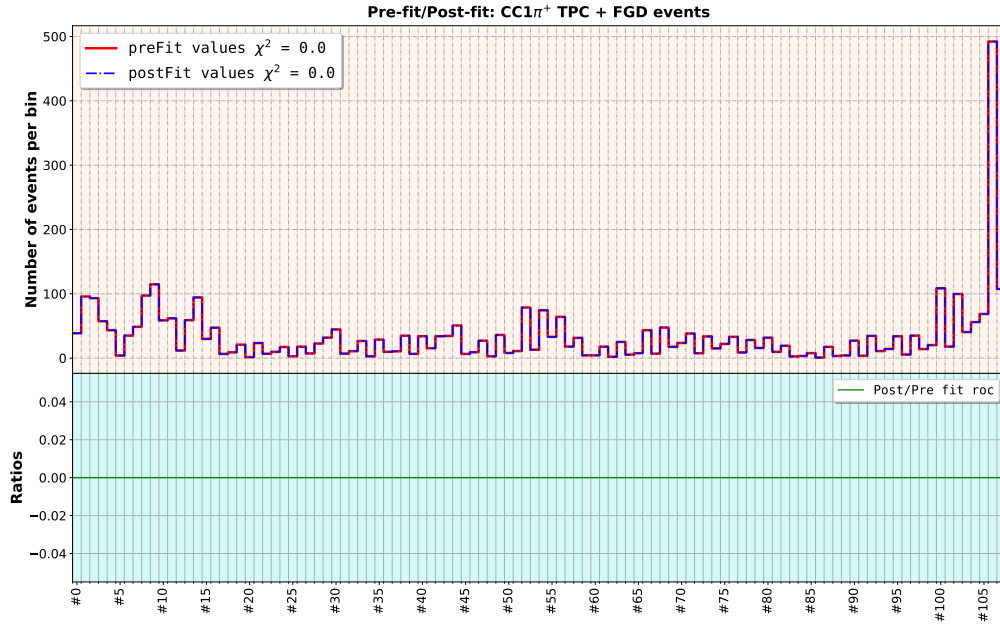


Figure 10.7: Comparisons between the pre-fit and post-fit signal event numbers with error bounds for an Asimov fit starting at the true best-fit points or nominal values. CC1 π^+ events identified through a pion candidate in the TPC or FGD are shown on the top. Events identified through the subsequent Michel electron on the bottom.

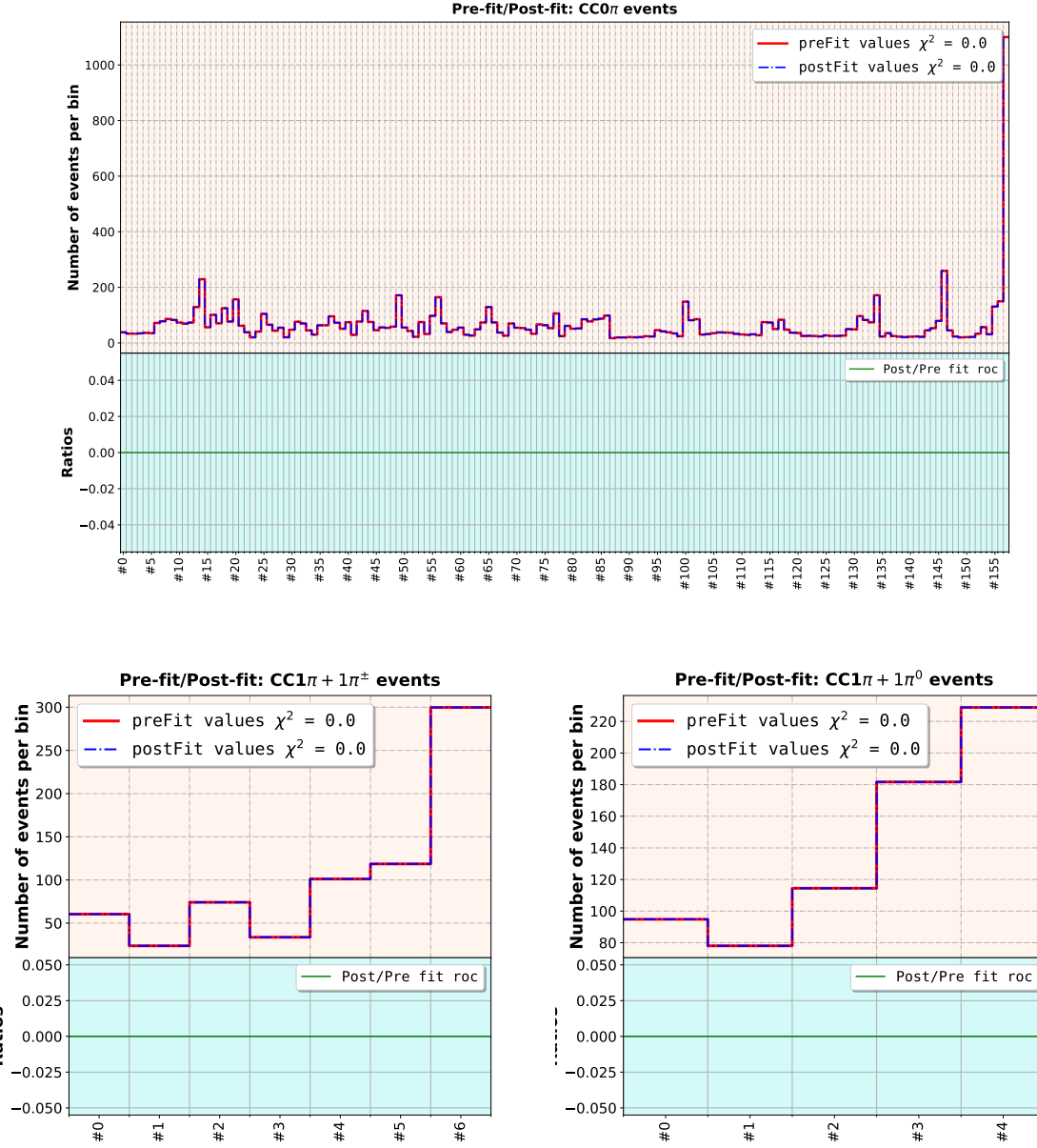


Figure 10.8: Comparisons between the pre-fit and post-fit sideband event numbers with error bounds for an Asimov fit starting at the true best-fit points or nominal values. Three sidebands in total are shown, with the top image representing the CC0 π samples and the bottom row displaying the CC1 π^+ signal with an additional pion

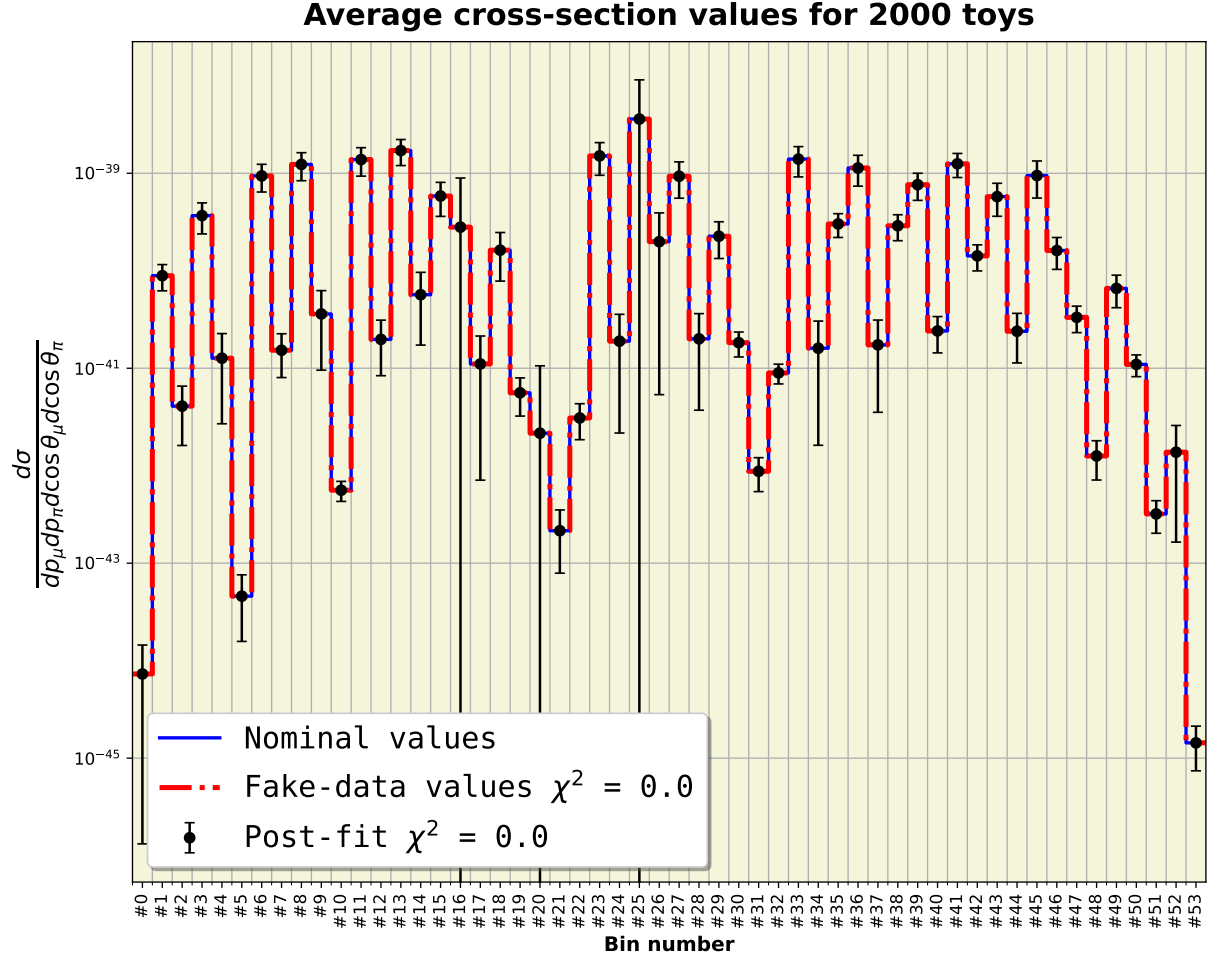


Figure 10.9: Calculated cross-section for template binning in true 4D kinematic variables. Each data point refers to a specific region in phase space determined by a range in muon momentum and angle and pion momentum and angle. Blue represents the cross-section based on the nominal MC parameters. The dashed red line refers to cross-section values based on the inserted fake data set used as ‘data’, which is identical to the nominal MC in an Asimov fit. The black scatter points with error bars are the cross-section values derived from the post-fit template parameters.

10.1.2 Monte Carlo fluctuations

It has now been shown that the nominal values of all parameters can be recovered independently of the prior constraints on the template parameters in Asimov and Asimov-like fits. This proves that the fitter’s foundation is well-behaved and allows for the next step in which the input is a statistically fluctuated version of the nominal Monte Carlo. This is done by randomly drawing the number of true and reconstructed events from a Poisson distribution of which the mean is equal to the number of MC events in that specific bin. In more concrete terms, only the Template Parameters are thrown and hence the study is referred to as ‘Statistical Fluctuations’. The results are shown in section [10.1.2.1](#).

For the ‘Systematic Fluctuations’ in section [10.1.2.2](#), all parameters are thrown based on their pre-fit covariance matrix. These include the ones related to the flux, detector and cross-section models. The resulting values are used to reweight the sample distribution and therefore alter the number of events in each sample bin.

Since the fit does not start at the best-fit points for any of the two studies laid out here, the capability to find the correct minimum when it does not start from there is tested. The χ^2 is no longer expected to be zero. By running 2000 toys, whereby each has its own set of modified parameter values, a distribution of the post-fit goodness of fit can be produced. The mean should represent the number of degrees of freedom available. This equates to the total number of sample bins, which is 329 for all signal and sideband samples, minus the number of free (or unbound) parameters described by the 54 bins in truth space (template parameters). The expected value is thus 275.

If the fit returns a value for χ^2 that exceeds 275, some of the assumed free parameters might be bound through correlation. If the fit shows a lower χ^2 value, some of the sample bins might be heavily correlated. In either scenario, it would be worthwhile to also inspect the post-fit correlation matrix. Hence, it is provided below. As with the previous two studies, the systematic variations are introduced in steps of parameter sets (Flux, Flux + Detector, Flux + Detector + Cross-section). However, only the results for all parameters thrown at once are shown here.

10.1.2.1 Statistical fluctuations

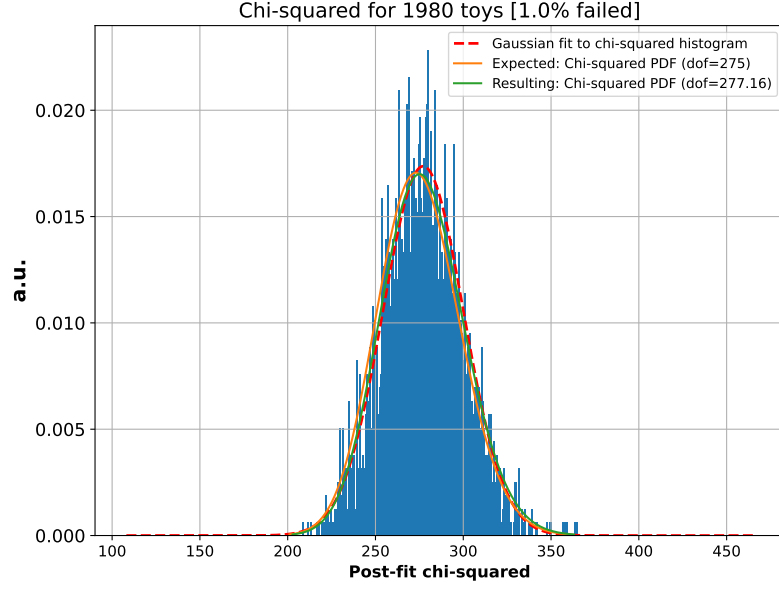


Figure 10.10: Post-fit χ^2 for 2000 parallel fits to statistically varied toy distributions found by equation 10.2. The Gaussian fit to the histogram is shown by the dashed red line. The theoretical χ^2 PDF with 275 degrees of freedom ($\#$ sample - $\#$ template bins) is shown orange, while the χ^2 PDF for the histogram's mean is shown in green.

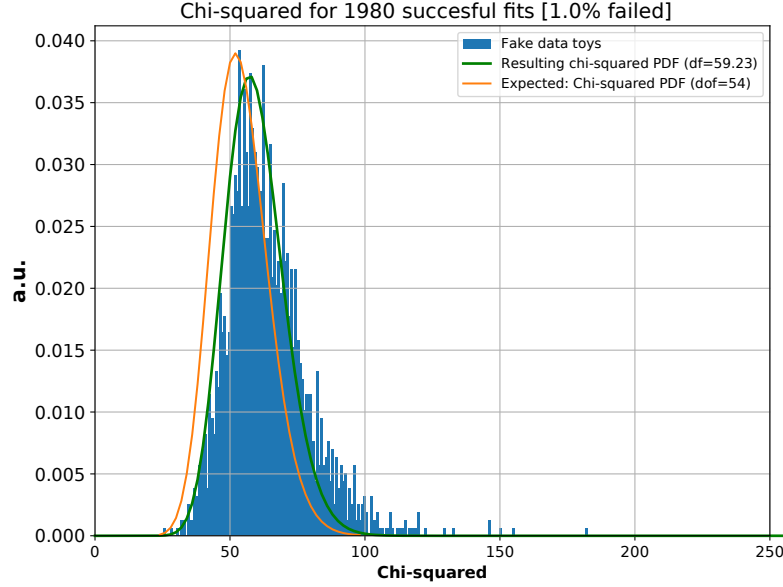


Figure 10.11: Histogram of the extracted cross-section χ^2 (equation 10.3) for 2000 toy throws on the best fit values for the results described in figure 10.10. The theoretical χ^2 PDF with 54 degrees of freedom ($\#$ template bins) is shown in orange, while the χ^2 PDF for the histogram's mean is shown in green.

10.1.2.2 Systematic fluctuations

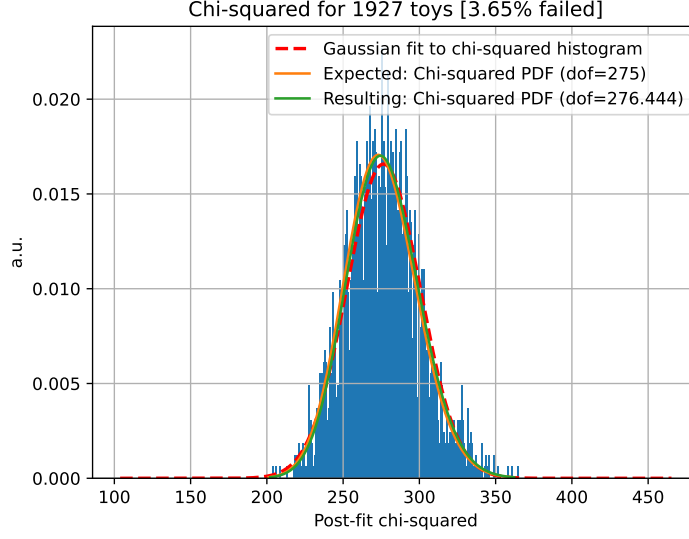


Figure 10.12: Post-fit χ^2 (equation 10.2) for 2000 parallel fits to statistically and systematically varied toy distributions. The Gaussian fit to the histogram is shown by the dashed red line. The theoretical χ^2 PDF with 275 degrees of freedom ($\#$ sample - $\#$ template bins) in is shown orange, while the χ^2 PDF for the histogram's mean is shown in green.

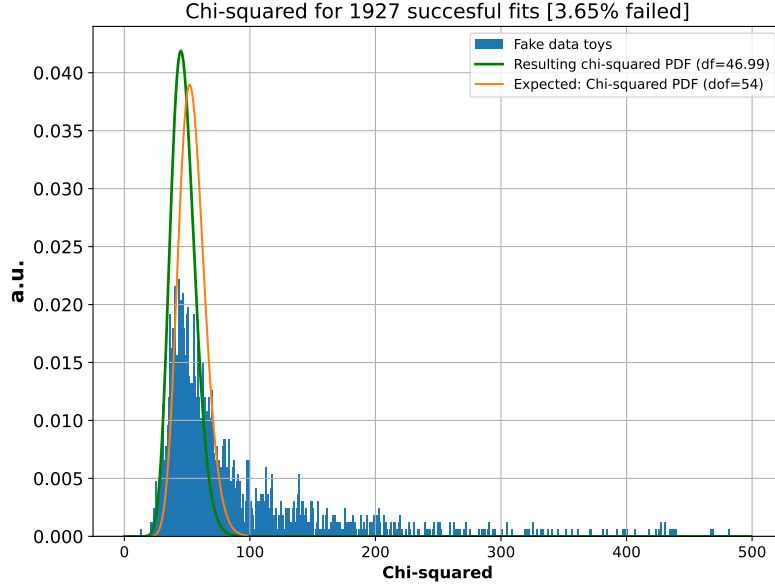


Figure 10.13: Histogram of the extracted cross-section χ^2 (equation 10.3) for 2000 toy throws on the best fit values for the results described in figure 10.12. The theoretical χ^2 PDF with 54 degrees of freedom ($\#$ template bins) is shown in orange, while the χ^2 PDF for the histogram's mean is shown in green.

10.2 FAKE DATA STUDIES

With the studies involving statistical fluctuations in the rear-view mirror, the basic checks on the nominal Monte Carlo simulations have concluded. In the following section, certain signal or background topologies will be enhanced or diminished in a way that replicates the assumed discrepancies between Monte Carlo and actual detector data (e.g., $CC1\pi^+$ signal enhancement of 30%, $CC0\pi$ diminution and OOFV diminution of 10%). Regions in phase space where the detector does not operate accurately will see their event weights raised or lowered in order to assess the fitter’s performance by testing if it can recover the changes correctly (e.g., OOPS enhancement of 10%). The fake data sets are produced by re-weighting events that belong to the region under consideration. In this section only the signal enhancement for the $CC1\pi^+$ topology will be described. Others can be found in appendix [D](#).

10.2.1 Signal enhancement

For the signal enhancement study, the weights for each and every $CC1\pi^+$ event are multiplied by 1.3, a factor that is expected to be returned solely by a normalization in the template parameters since they are not subject to any initial error or to a penalty for moving, which ensures that none of the flux, detector or cross-section related parameters undergo any changes.

10.2.1.1 Parameters

The results of the all-parameter fit with increased signal event weights can be seen in figures [10.14](#), [10.15](#), [10.16](#), [10.17](#) for the truth bins, the flux parameters, the detector parameters and the cross-section model parameters, respectively. With the exception of the out-of-fiducial-volume bins 52 through 54 and the low statistics first bin, the normalization of 1.3 is returned everywhere for the truth bins in the first figure. Moreover, the flux and detector parameters experience a change below the 5% level across the entire kinematic space, with a slight rising wedge in the $CC0\pi$ section of the bottom left graph. The affected model parameters are limited to the single-pion and multi-pion regimes.

The post-fit correlation and covariance matrices in figures [10.18](#) and [10.19](#) display similar behavior to the pure Asimov fit of section [10.1.1](#) with added anti-correlating bins for the $CC1\pi$.E0 and $CC1\pi$.E1 dials (i.e., the two energy regimes for $CC1\pi$ production).

10.2.1.2 Samples

The signal samples showcased in figure [10.20](#) are more heavily influenced by the increase in the event weights than the background samples of figure [10.21](#), as expected. The χ^2 value is significantly reduced for all samples, bringing the post-fit values to ranges below 1 across the board, proving the fit’s capability of retrieving the changes made to the MC.

10.2.1.3 Cross-section calculation

Finally, upon inspecting the extracted cross-section in figure 10.22, a clear difference can be found between the nominal and the fake-data calculation with the latter being around 30% higher in all bins. The fit is in fact able to recover the change. A comparison of the post-fit and fake-data values yield a χ^2 of zero.

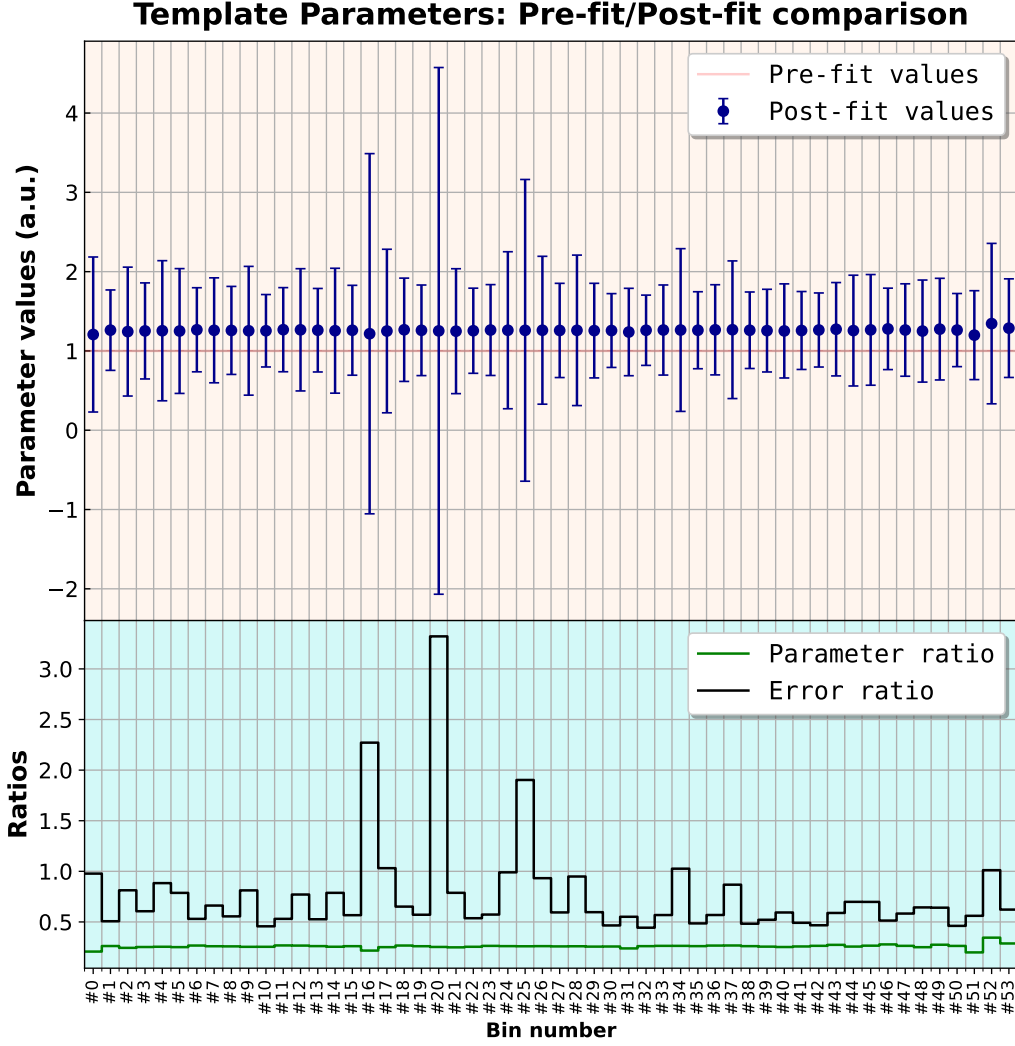


Figure 10.14: Comparisons between the pre-fit and post-fit values for truth bins in 4D true kinematics variables for a fake data fit with the $\text{CC1}\pi^+$ signal event rate increased by 30%.

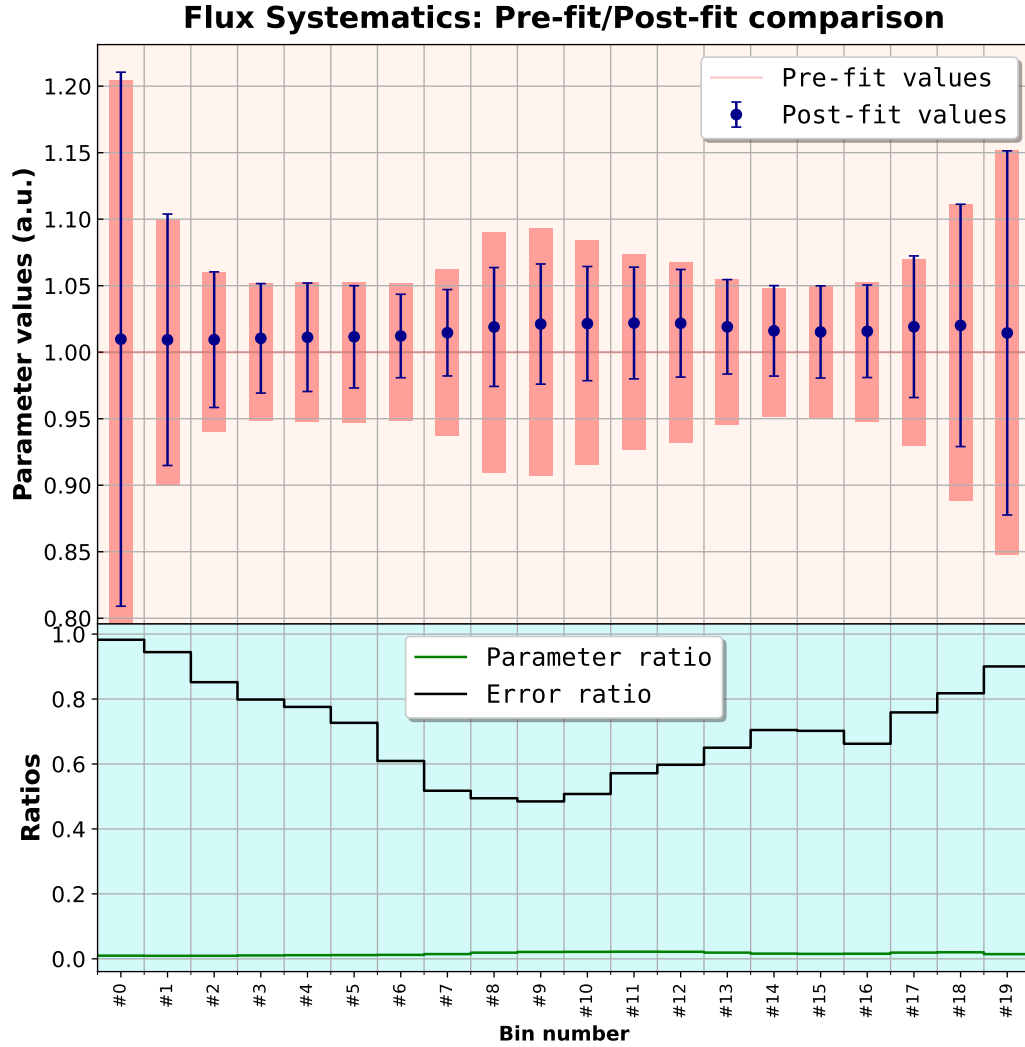


Figure 10.15: Comparisons between the pre-fit and post-fit values for the flux parameters binned in neutrino energy for a fake data fit with the $\text{CC1}\pi^+$ signal event rate increased by 30%. The red line and red shaded region in the top half represent the pre-fit nominal value and associated uncertainty, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

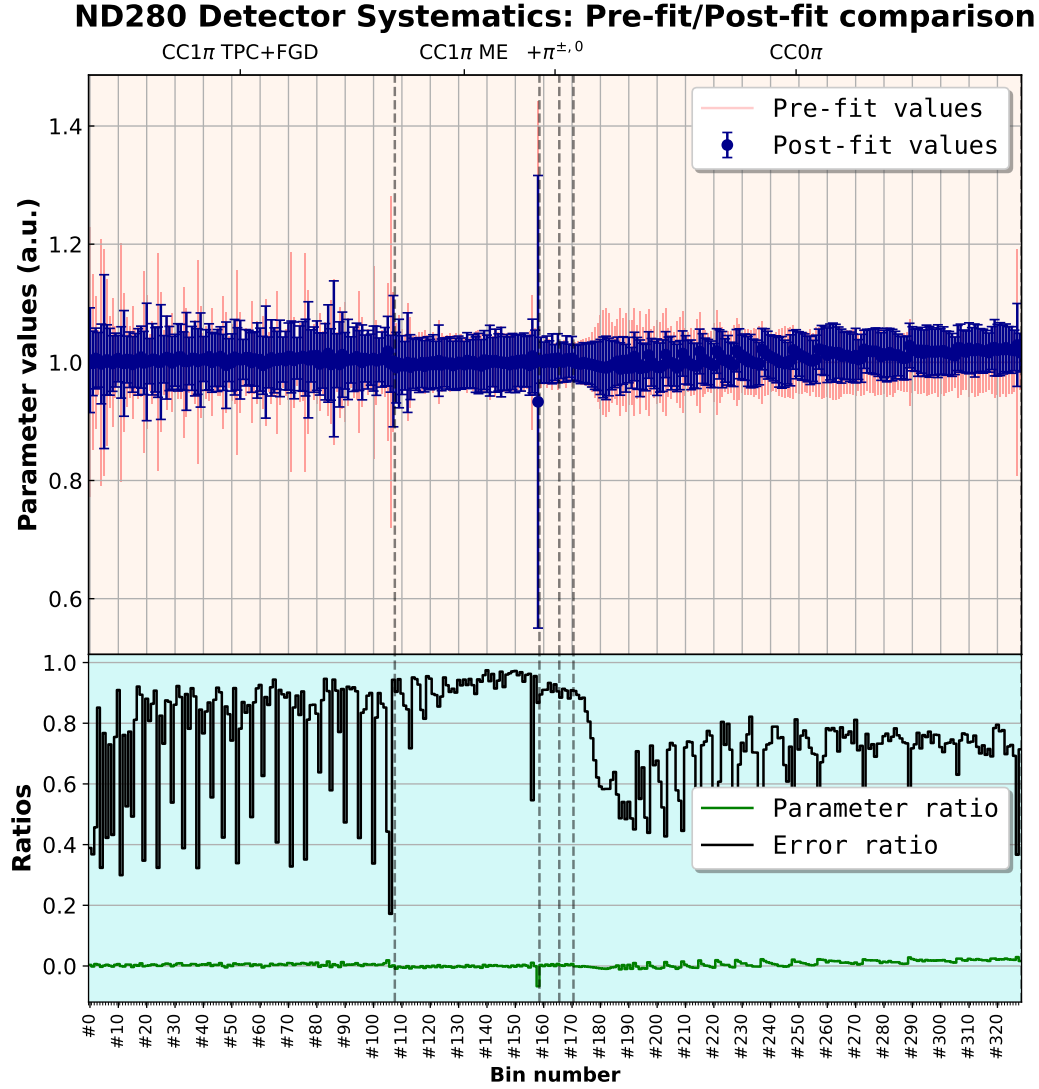


Figure 10.16: Comparisons between the pre-fit and post-fit values for the detector parameters binned in 4D reconstructed variables for each sample individually for a fake data fit with the $CC1\pi^+$ signal event rate increased by 30%. The separation between samples can be found at the top and is marked by the vertical dashed black line. The red line and red shaded region in the top half represent the pre-fit nominal value and associated uncertainty, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

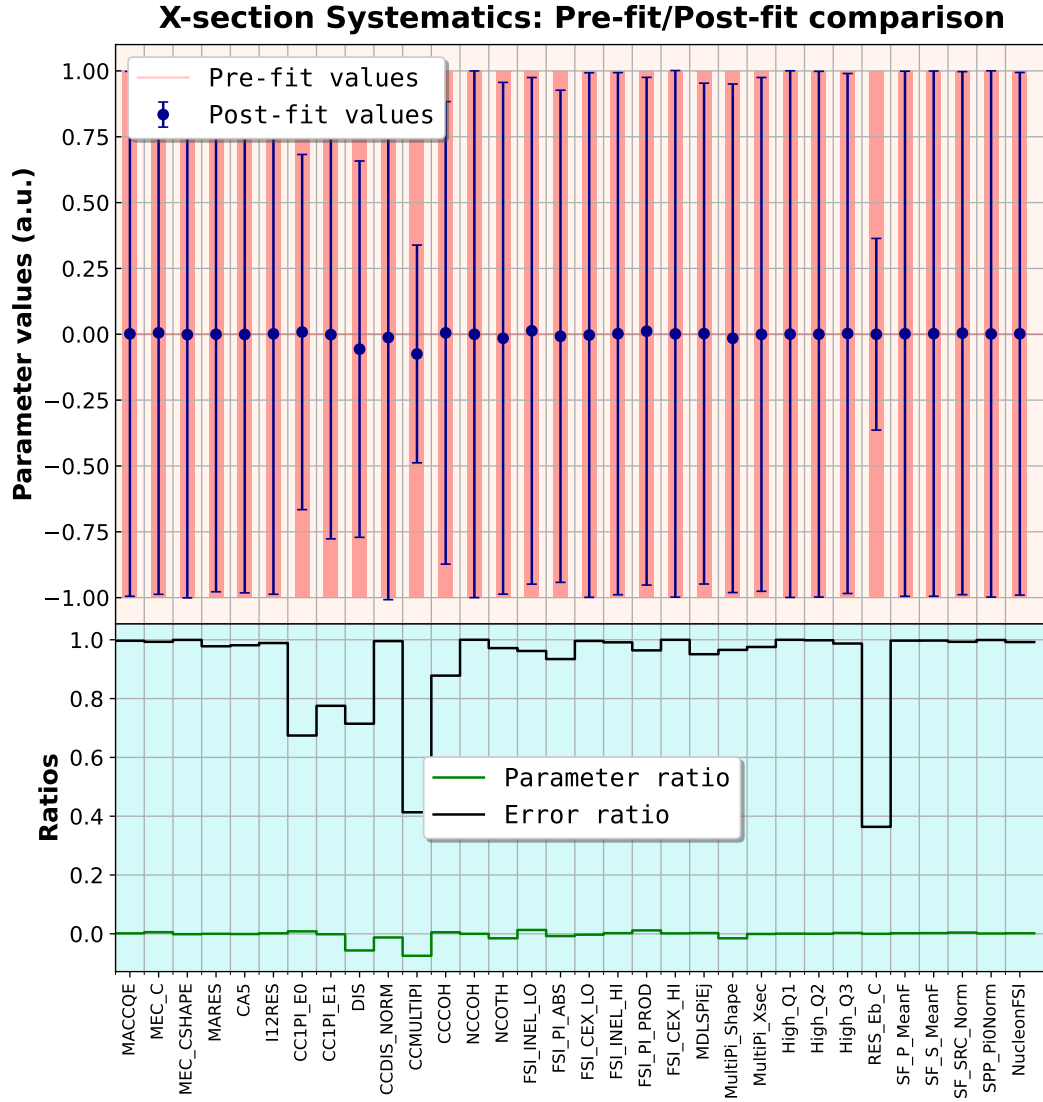


Figure 10.17: Comparisons between the pre-fit and post-fit values for the normalized cross-section model parameters for a fake data fit with the $\text{CC}1\pi^+$ signal event rate increased by 30%. The red line and red shaded region in the top half represent the pre-fit nominal value and associated uncertainty, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

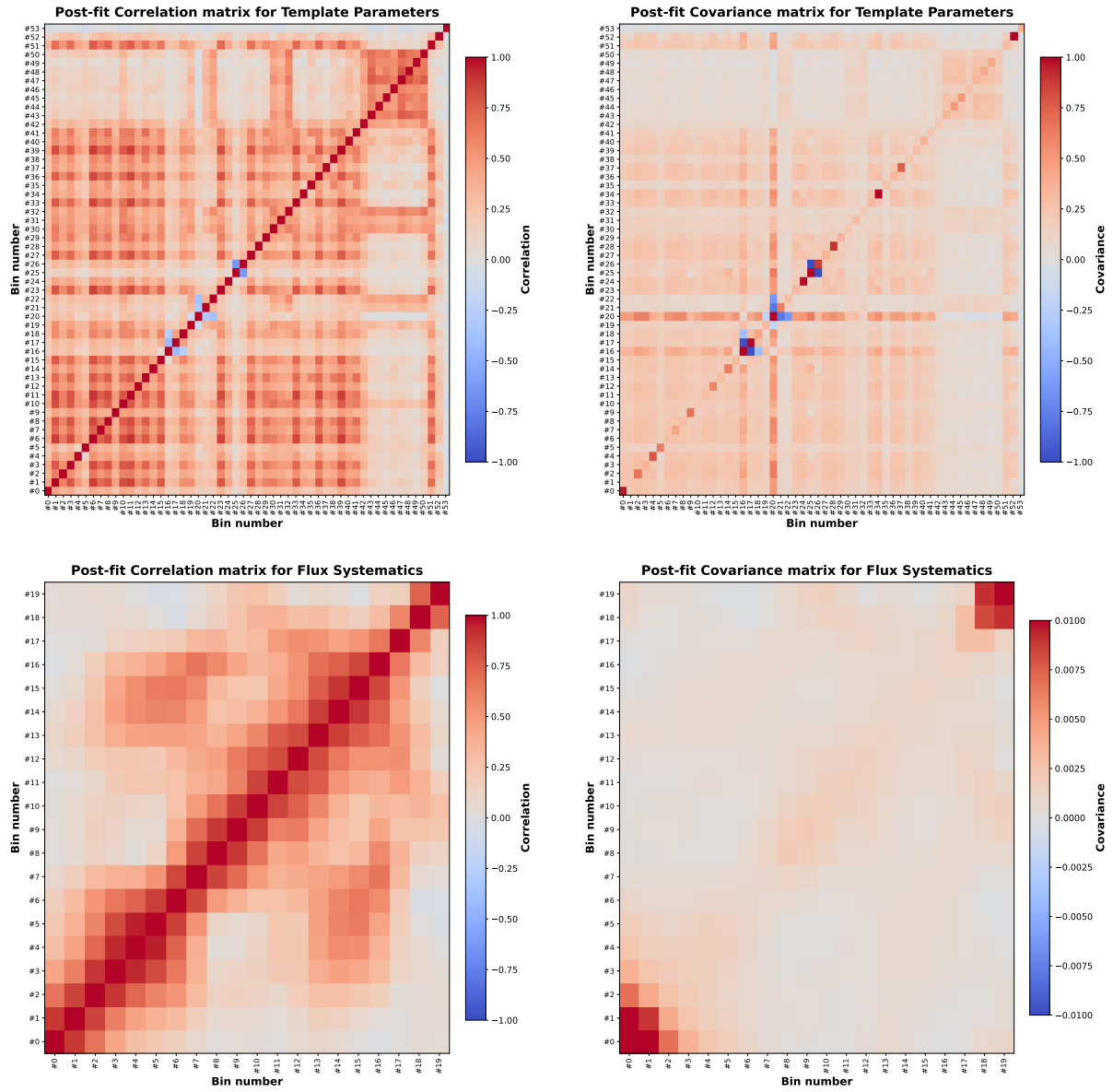


Figure 10.18: Signal enhanced post-fit correlation (left column) and covariance (right column) matrices for the template (top) and flux parameters (bottom). The color bar for the covariance is set at a different (smaller) range to reveal the matrix' structure.

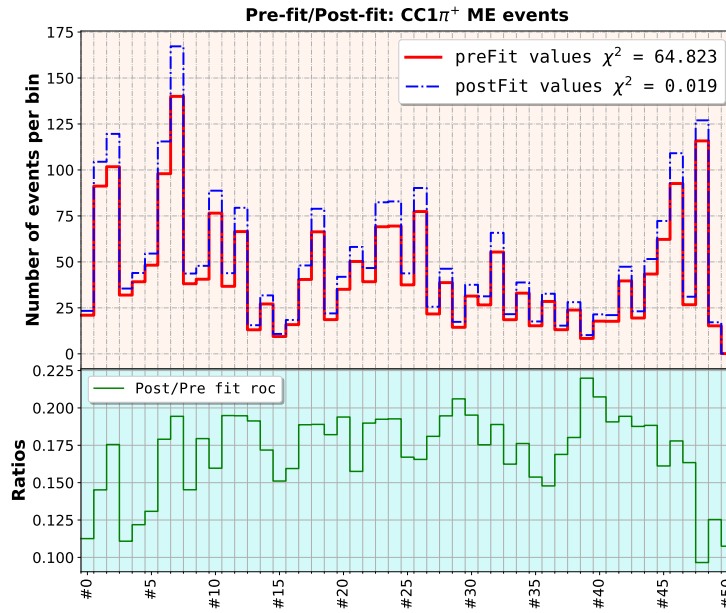
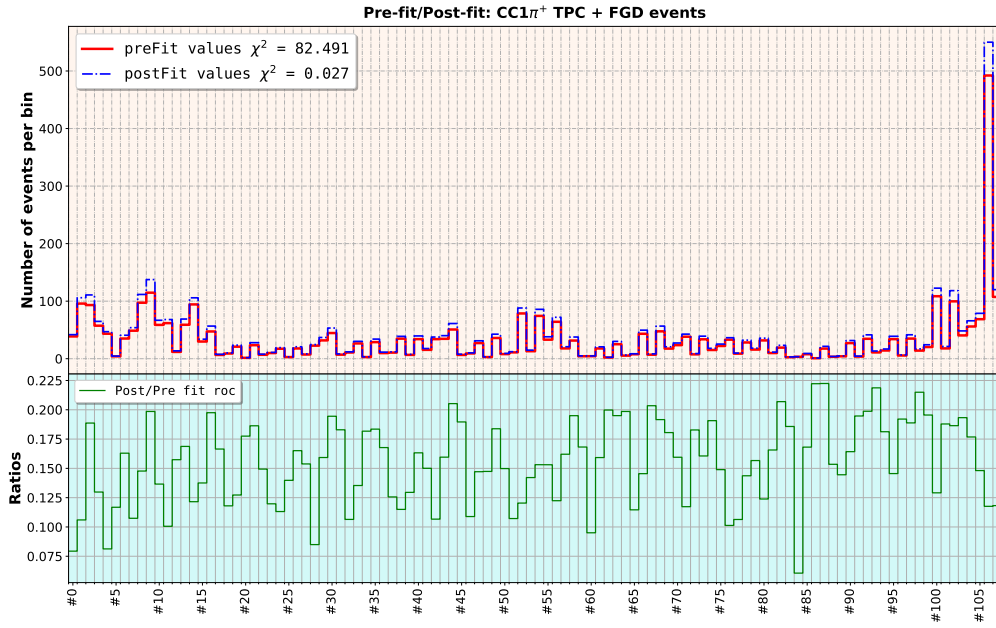


Figure 10.20: Comparisons between the pre-fit and post-fit signal event numbers with error bounds for a signal enhanced fit. CC1 π^+ events identified through a pion candidate in the TPC or FGD are shown on the top. Events identified through the subsequent Michel electron are shown on the bottom.

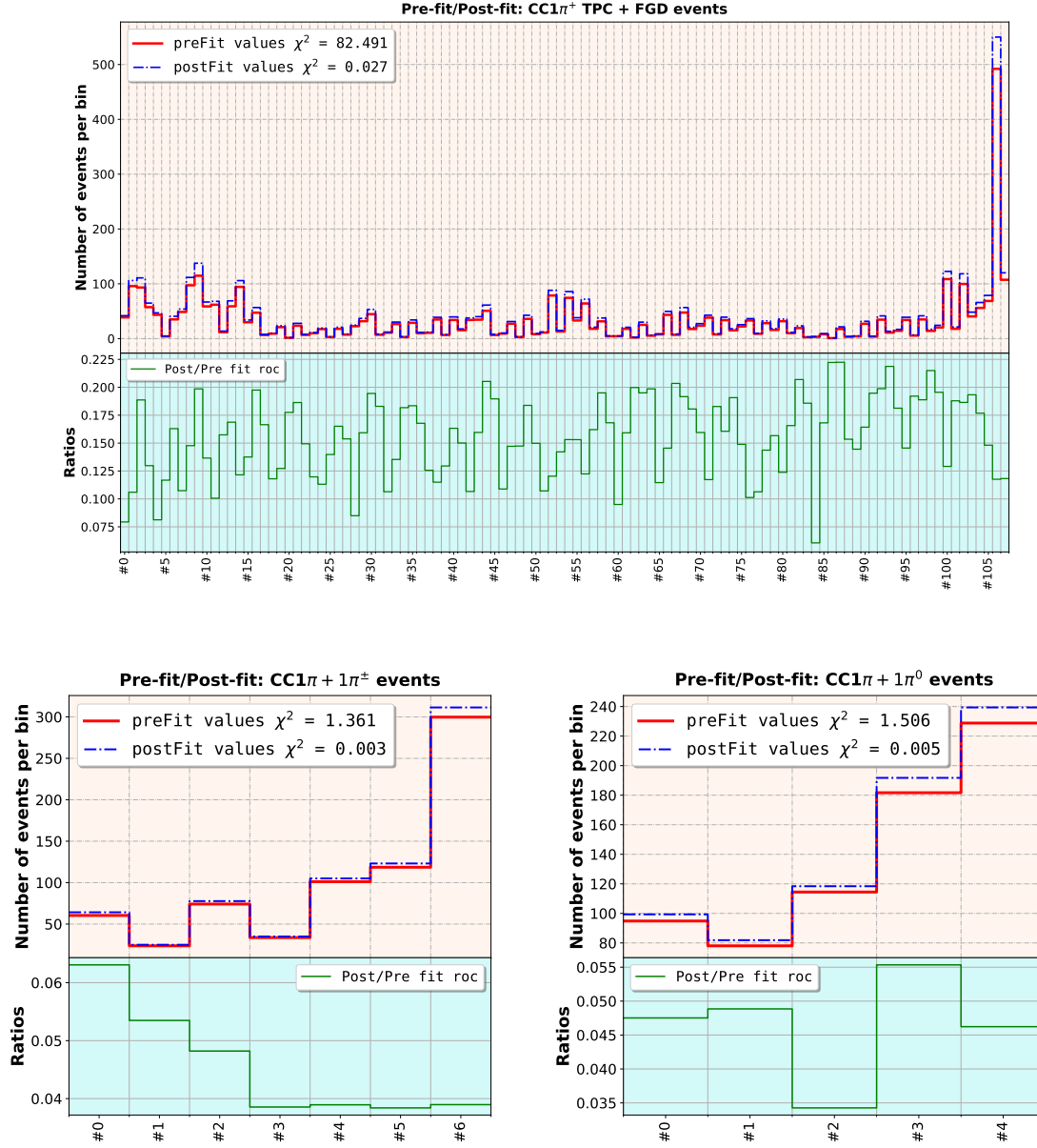


Figure 10.21: Comparisons between the pre-fit and post-fit sideband event numbers with error bounds for a signal enhanced fit. Three sidebands in total are shown, with the top image representing the CC0 π samples and the bottom row displaying the CC1 π^+ signal with an additional pion

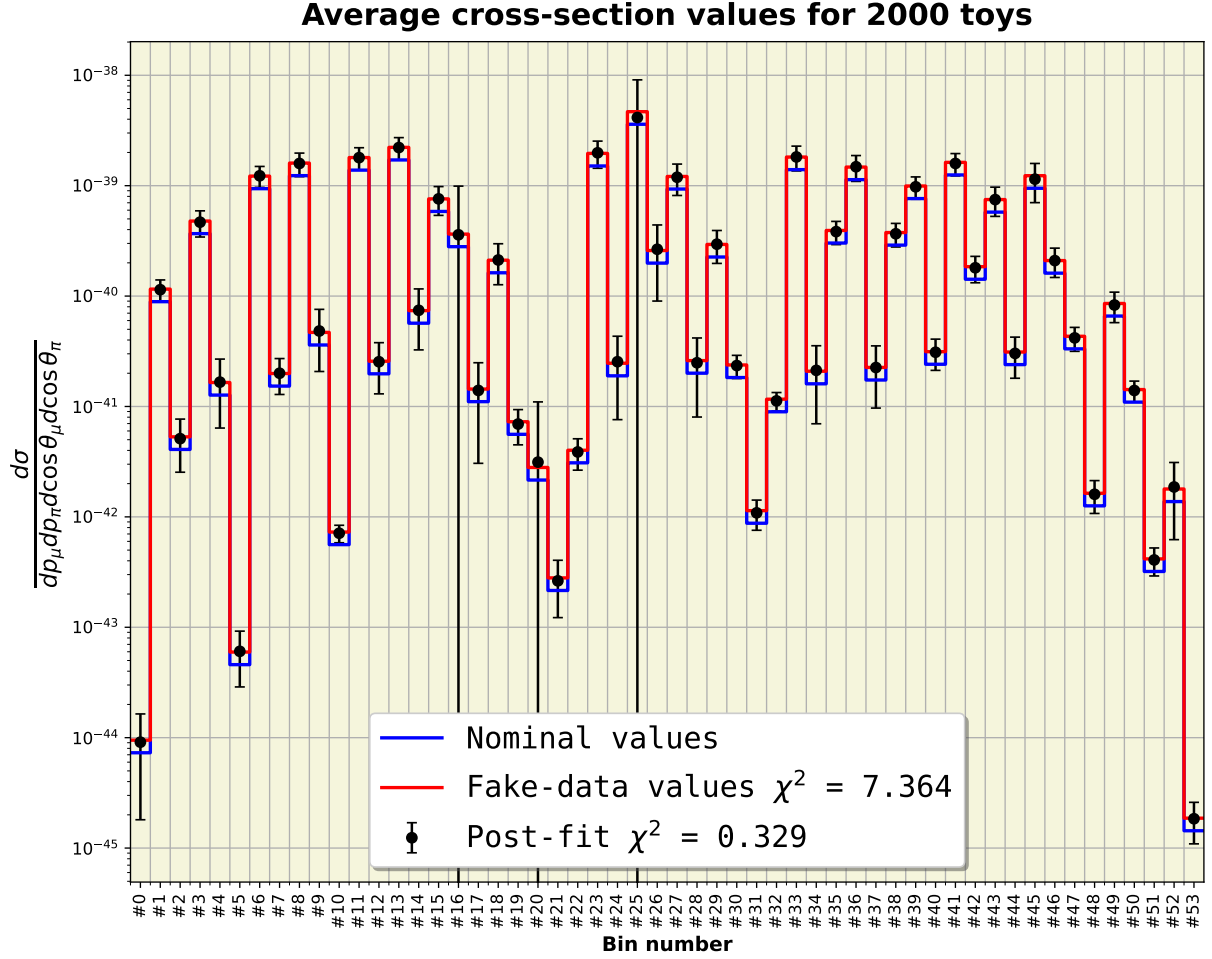


Figure 10.22: Signal enhanced calculated cross-section for template binning in true 4D kinematic variables. Each data point refers to a specific region in phase space determined by a range in muon momentum and angle and pion momentum and angle. Blue represents the cross-section based on the nominal MC parameters. The dashed red line refers to cross-section values based on the inserted fake data set used as ‘data’, which is identical to the nominal MC in an Asimov fit. The black scatter points with error bars are the cross-section values derived from the post-fit template parameters.

DISCUSSION

The validation procedure has been thoroughly tested with the fake data studies elaborated upon in the previous chapter. Signal and background enhancement studies did not induce any significant bias in the post-fit results with most of the fits returning original input Monte Carlo values. With this level of confidence, it is now safe to perform the data fit. In this chapter, the best fit result will be presented along with the extracted $\nu_\mu\text{CC}1\pi^+$ cross-section on hydrocarbon true 4D parameter binning, as described in section 7.

The reconstructed number of events in data can be found in black for the TPC+FGD (top) and ME (bottom) signal samples in figure 11.1 and for the sidebands in figure 11.2. Also shown are the nominal MC, or pre-fit, and the post-fit values in the same binning. All distributions show clear improvement as a result of the binned likelihood fit, which is represented by the decrease in χ^2 with respect to the data across the board.

On the bottom of these figures, the post-fit over pre-fit rate of change is shown, displaying which bins were affected the most. Specifically in the $\text{CC}0\pi$ sideband, there seems to be a recurring pattern in the ROC showing that there is part of the 4D space that is uniquely affected. This indicates that the resolution for a specific parameter or set of parameters is poor in that region, which allows the migration between neighboring bins to cause more fluctuation than expected.

The other component of the minimization consisted of the template, flux, detector and cross-section parameters. In figures 11.3, 11.4, 11.5 and 11.6, the post-fit values from each of these four sources are shown. With a few exceptions, most of the template parameters find the nominal value within their error bounds. For the template parameters that lie outside the nominal values, different statements can be made. For the two OOPS bins on the far right, this is not a problem as they are not included in the final result. For the others in bin #24 and #34, this might cause issues down the line and a different binning

scheme will be proposed for future efforts. The flux parameters all fluctuate around the nominal value, with a more significant dip on the order of 10% in the central region for neutrino energies corresponding to the range between 600 MeV and 1200 MeV, where resonant pion production starts becoming the dominant process, as well as the three last bins above 5000 MeV where deep-inelastic scattering is most probable (see table B.1 in chapter 9).

The cross-section dials are mostly found to have central values within 20% of their priors. A few outliers show larger deviations. These include the CC1Pi_E1 and FSI_PI_PROD (negative) and DIS dials (positive), as well as to a lesser extent the CCCOH, NCOTH and FSI_INEL_HI dials. The positive increase of the DIS, NCOTH and higher energy inelastic FSI dials is to be expected as a result of the higher energy flux parameters, which are where these interactions are more likely to occur. The decrease in pion production dials follows a similar explanation for the dip in post-fit neutrino energy around the medium energies. Coherent pion production seems to be underestimated by the current model, which is in accordance with earlier results.

The detector parameters show similar behavior to the sample distributions, where a specific pattern is repeated while stepping through the muon angle with the error being reduced in each of the 329 bins post-fit. There are two regions that stand out. One represents the maximum error ratio found in the initial bin of the CC1 π^+ +1 $\pi^\pm$ sideband. The other can be observed in the first few bins of the CC0 π region. There seems to be a steady increase followed by a decrease in the post-fit parameter value with respect to the prior for muons in the backward region, hinting at an underestimation of the event rate in those bins.

The relative sizes of the uncertainty categories can be derived from the information provided to the fitting sequence and the results mentioned before. In table 9.2, the combined uncertainty for all detector effects is found to be slightly above 4%. The flux systematic parameters described in section 9.3 are introduced with an overall uncertainty between 9-10% and reduced to around 6% post-fit, which can also be seen in figure 11.4. The relative sizes of the uncertainties on the model systematic parameters is more difficult to assess as they do not affect the cross-section result linearly. The CCQE normalization dial has a prior uncertainty of 11% for instance, but it only affects the CCQE topology and not the entirety of the selected sample. The overview of the reconstructed events in the signal and background samples shows that the total uncertainty is dominated by the statistical uncertainty. This is an artifact of the four-dimensional binning scheme and the fine bin width that was chosen to do this analysis in.

A summary of the data fit results for all samples and parameter sets can be found in table 10.1. The first column lists the post-fit χ^2 values. As the numbers of degrees of freedom in the second column vary, the first alone does not provide insight into which category is most responsible for the disagreement between MC and data. The pre- and post-fit discrepancy for the systematic parameters only induces a χ^2 of 18.3, which makes up less than 10% of the total. From this it can be concluded that the largest tension

between MC and data has a statistical basis. Taking the effective number of degrees of freedom (276.4) found in the coverage studies shown in figure 10.12 of section 10.1.2.1, the reduced chi-squared, χ^2/Ndf , for the entire fit can be found to be $346.3/276.4 = 1.25$.

The largest tension between data and post-fit values in the ME signal sample are found in the following bins:

- Overestimation (post-fit > data): pion momentum $80 < p_\pi < 160$ MeV/c
- Underestimation (post-fit < data): muon momentum ($p_\mu > 600$ MeV/c) and pion momentum ($160\text{MeV/c} < p_\pi < 600$ MeV/c)

In the FGD&TPC signal sample, the pion momentum binning does not extend below 160 MeV/c. However, the same underestimation can be observed at higher muon momentum above 600 MeV/c.

Table 11.1: Contributions from the signal samples, sideband samples and parameter sets to the total χ^2 value for the data fit

Source	χ^2	Ndf	χ^2/Ndf
SS1: CC1 π^+ (TPC+FGD)	92.025	108	0.85
SS2: CC1 π^+ (ME)	59.648	51	1.17
CS1: CC1 π^+ + 1 $\pi^\pm$	8.824	7	1.26
CS2: CC1 π^+ + 1 π^0	5.899	5	1.18
CS3: CC0 π	180.899	158	1.14
Flux Parameters	4.01	20	0.20
Detector Parameters	12.60	329	0.04
Cross-section Parameters	1.70	32	0.053
Statistical	328	–	–
Systematic	18.3	–	–
Total	346.3	–	–

With the post-fit distributions described, the cross-section can now be extracted. Similarly to the fake-data studies, the measurement is first presented in terms of 4-dimensional muon and pion kinematics, where the x-axis represents each individual bin in this space. These results can be found in figure 11.7 and exhibit several features that have to be further elaborated on. First of all, it is important to note once again that bins #51, #52 and #53 corresponds to out-of-phase-space regions and their returned value can thus be disregarded. Aside from these three, a negative value is found in bin #34.

These four bins in combination with a few others that show disagreement between the nominal MC and data cross-section are the main contributors to the χ^2 value of 64.68. Normalising this by the effective number of degrees of freedom (59.23), gives a reduced chi-squared χ^2/Ndf of 1.09. As the method of expressing the cross-section in terms of bin number does not easily reveal any structures in the distribution, figures 11.8 and 11.9 have been produced in an attempt to improve that. Each individual subplot covers a

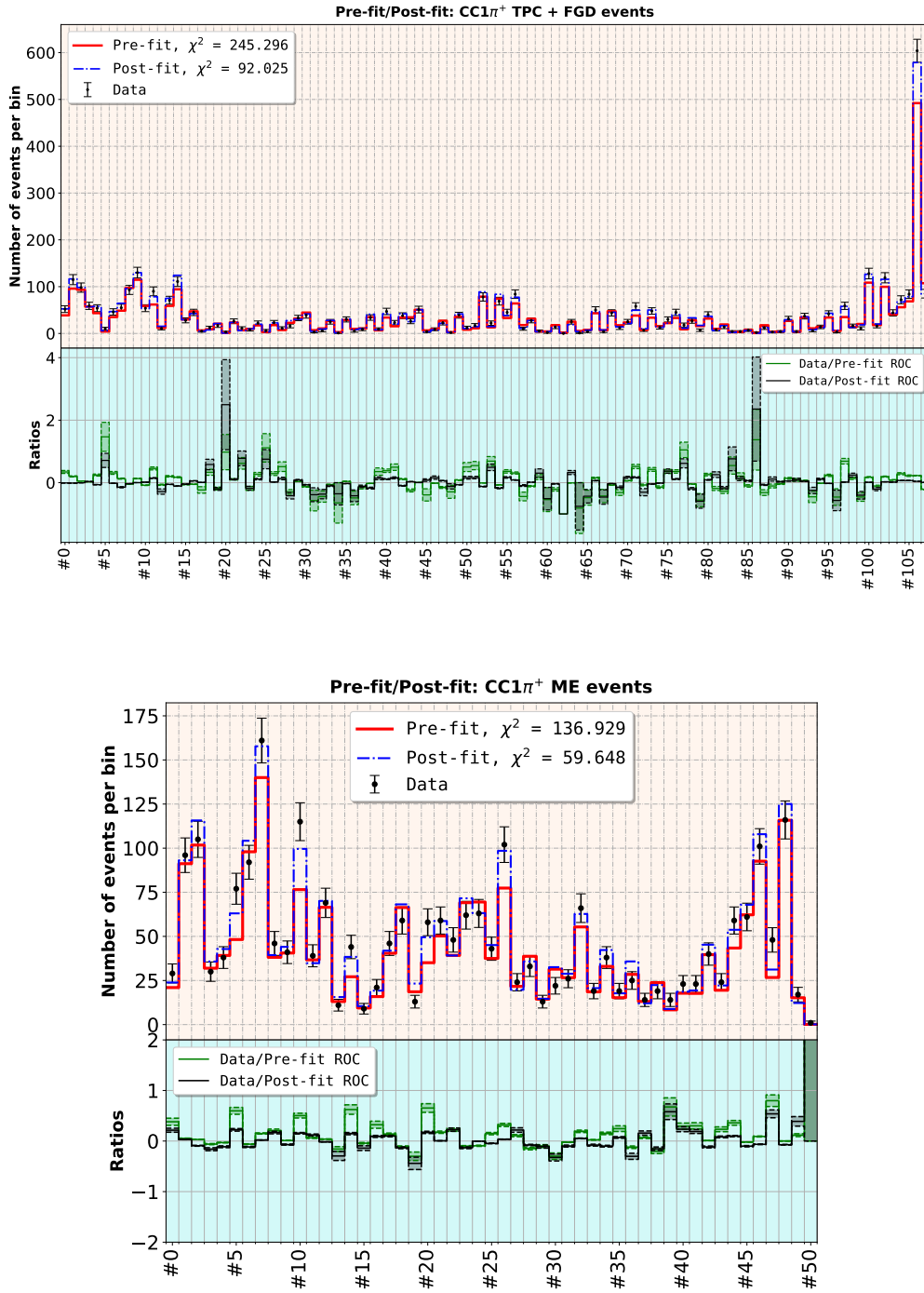


Figure 11.1: Comparisons between pre-fit, post-fit and data signal sample yields. CC1 π^+ events identified through a pion candidate in the TPC or FGD are shown on the top. Events identified through the subsequent Michel electron are shown on the bottom.

certain range in p_μ , $\cos(\theta_\mu)$ and $\cos(\theta_\pi)$ so that the cross-section can be shown in terms of p_π .

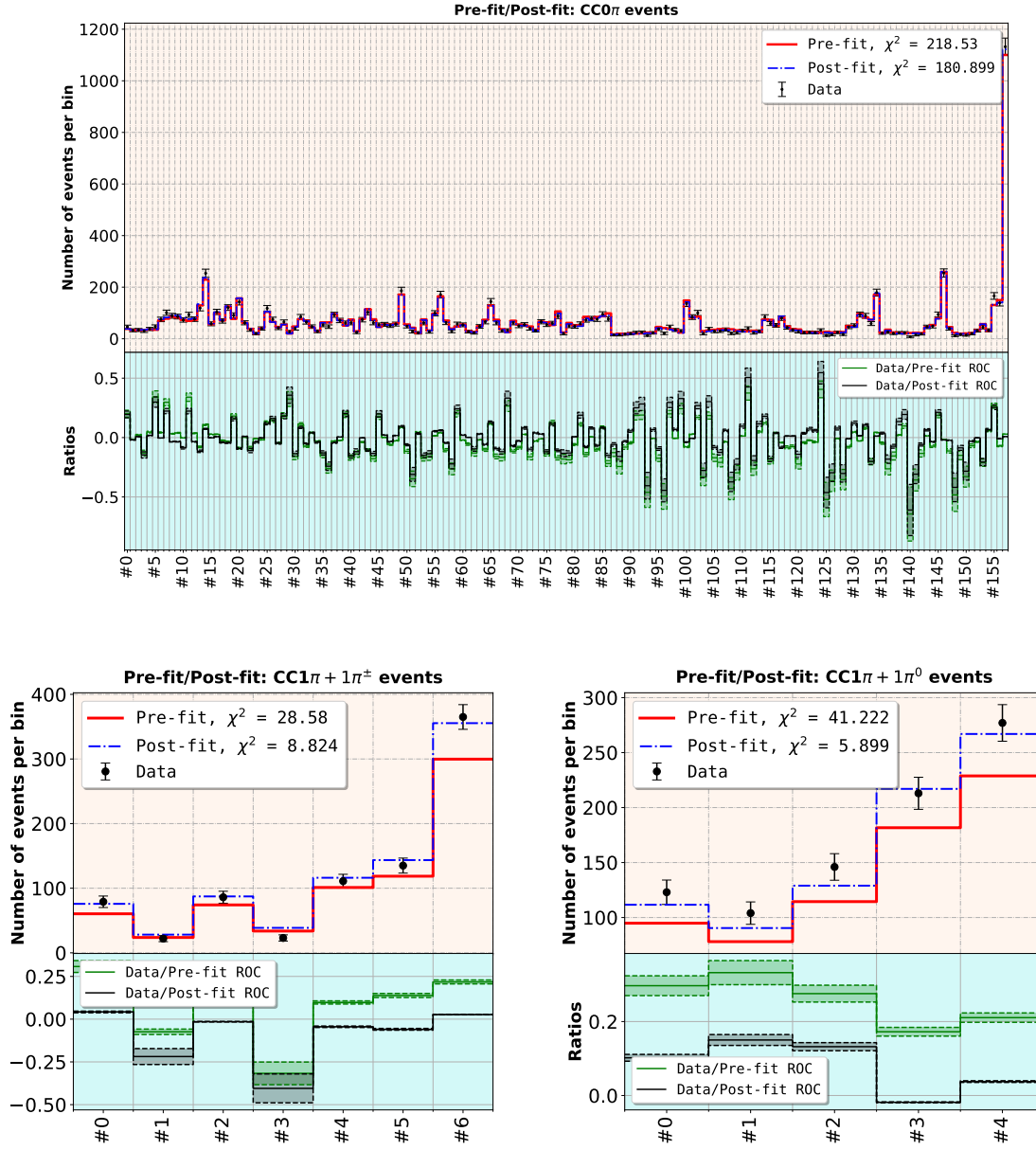


Figure 11.2: Comparisons between pre-fit, post-fit and data sideband sample yields. The top image represents the CC0 π samples and the bottom row displays the CC1 π^+ signal with an additional pion.

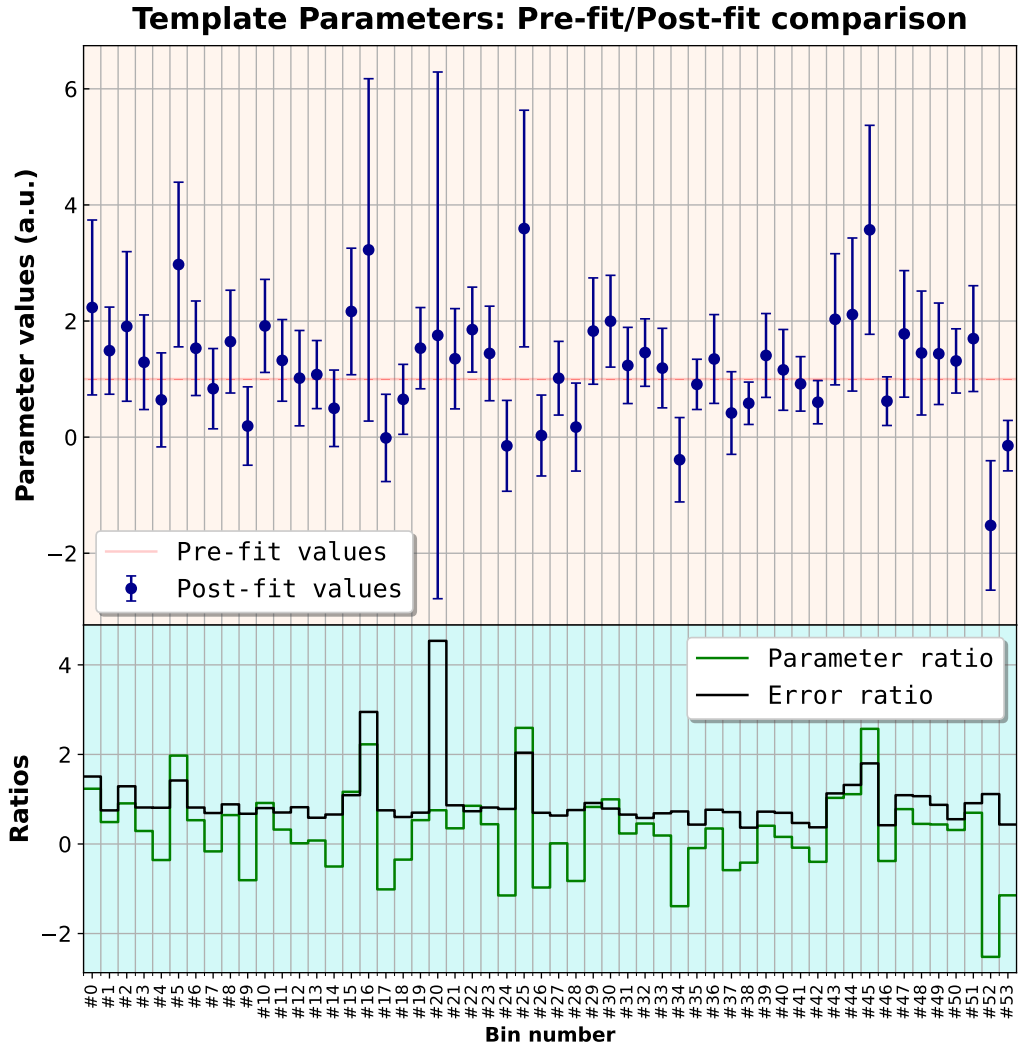


Figure 11.3: Comparisons between the pre-fit and post-fit number of events for each truth bin in 4D kinematic properties for the data fit.

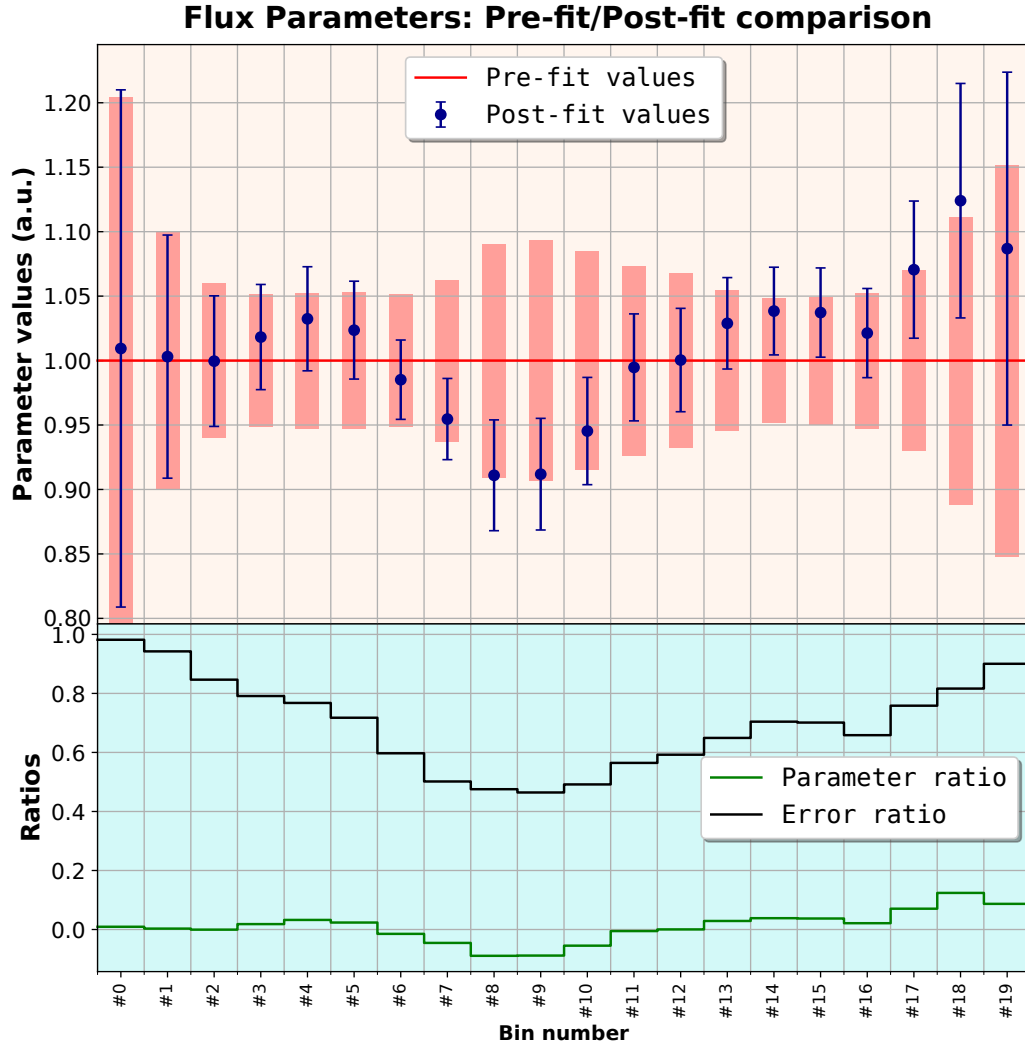


Figure 11.4: Comparisons between the pre-fit and post-fit flux parameters binned in neutrino energy for the data fit. The red line and red shaded region in the top half represent the pre-fit nominal value and associated uncertainty, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

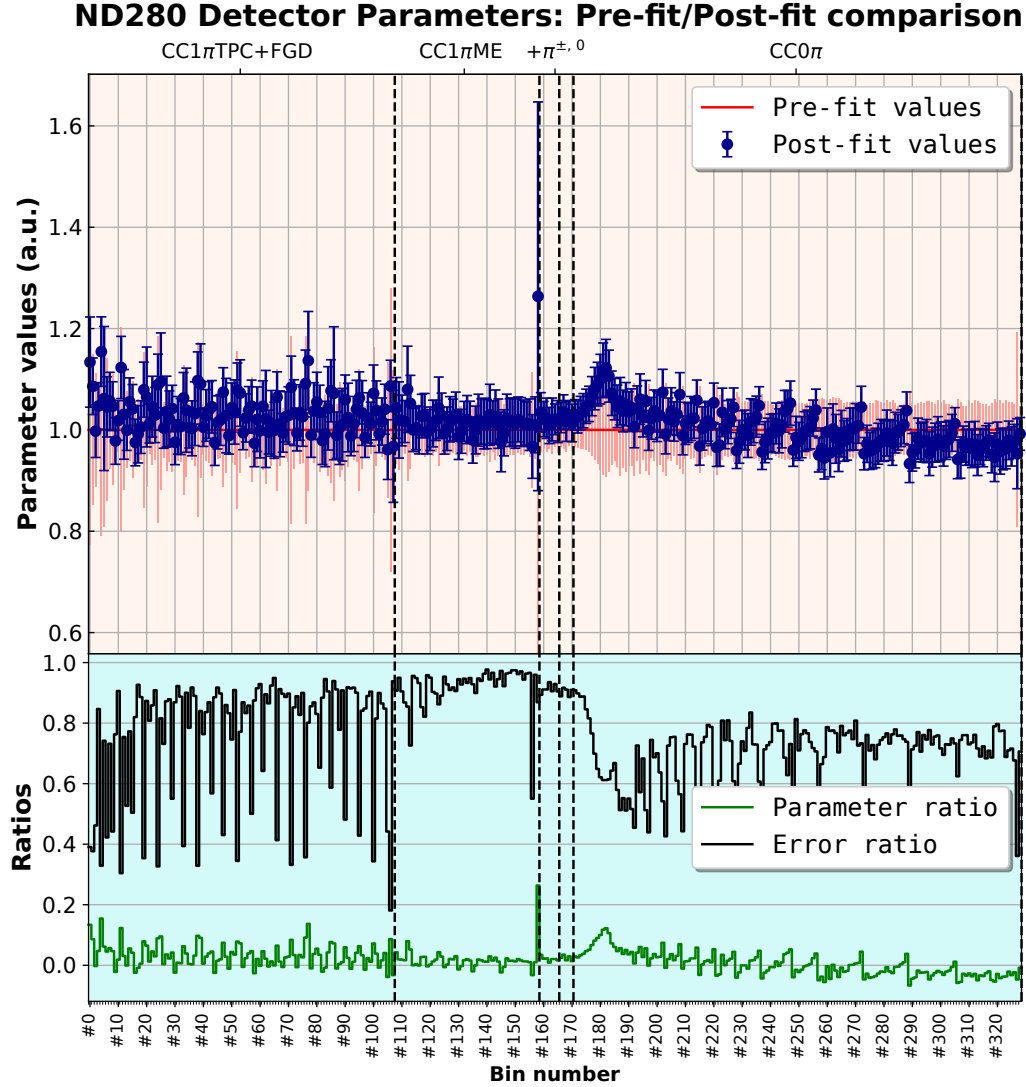


Figure 11.5: Comparisons between the pre-fit and post-fit reconstructed number of events in each 4D detector parameter bin for each sample in the data fit. The separation between samples can be found at the top and is marked by the vertical dashed black line. The red line and red shaded region in the top half represent the pre-fit nominal value and associated uncertainty, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

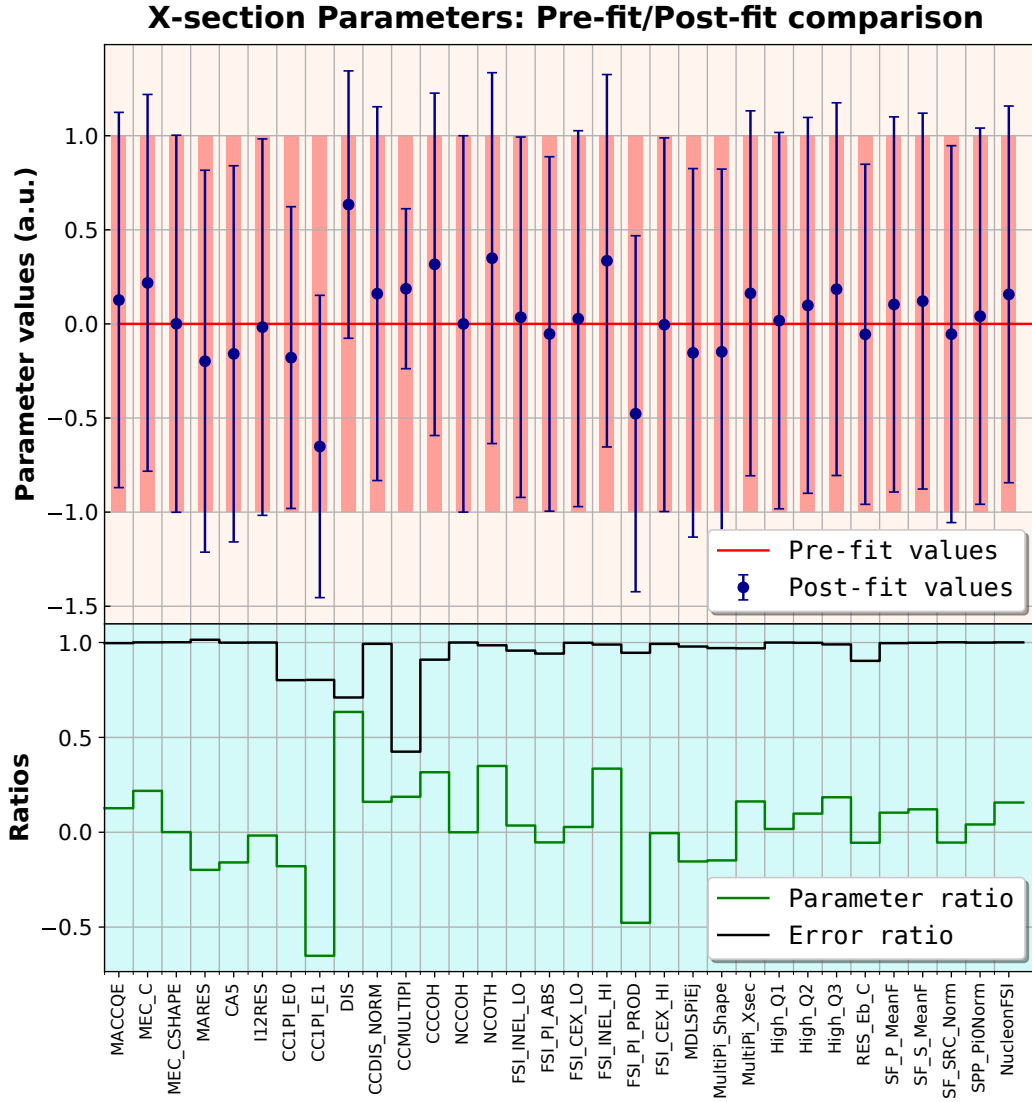


Figure 11.6: Comparisons between the pre-fit and post-fit normalized cross-section model parameters for the data fit. The red line and red shaded region in the top half represent the pre-fit nominal value and associated uncertainty, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

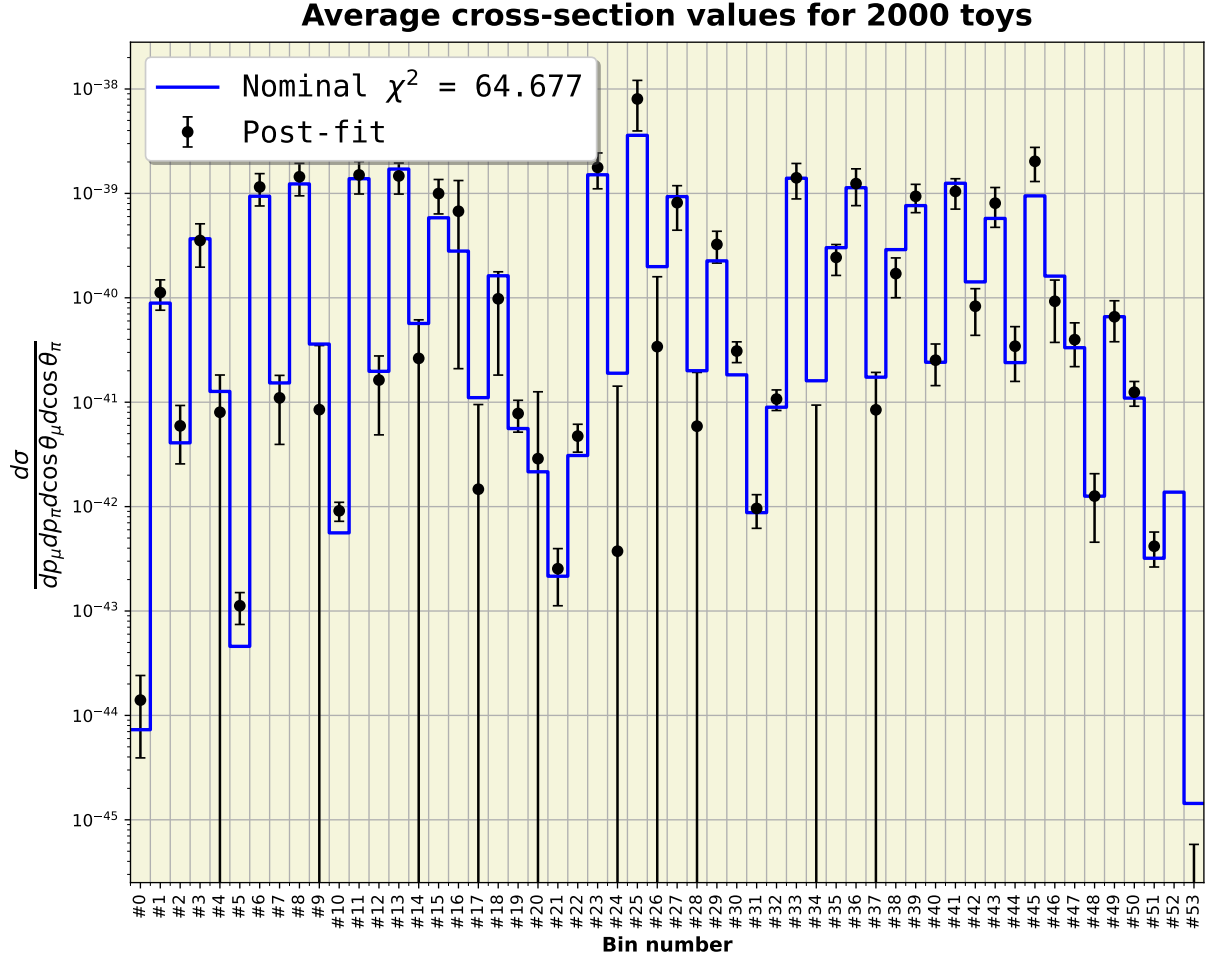


Figure 11.7: Cross-section result from ND280 data fit. Each data point refers to a specific region in phase space spanned by a range in muon momentum and angle and pion momentum and angle. Blue represents the cross-section based on the nominal MC parameters. The black scatter points with error bars are the cross-section values derived from the post-fit template parameters.

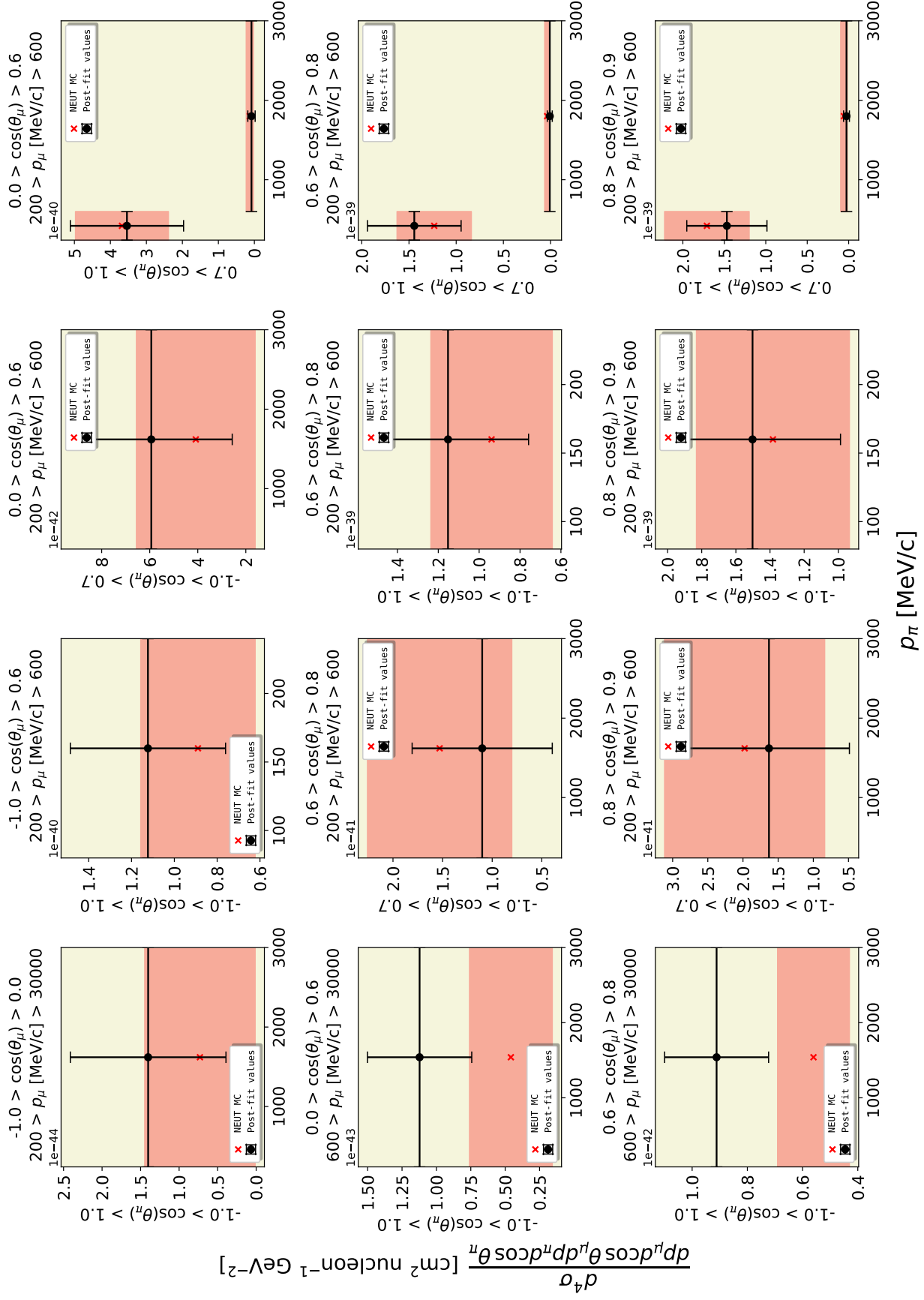


Figure 11.8: Extracted cross-section in 4D template binning for bins 1 through 12 (top left to bottom right). Muon momentum and angle bin displayed on the top of each figure, while the region in pion angular space is shown on the y-axis.

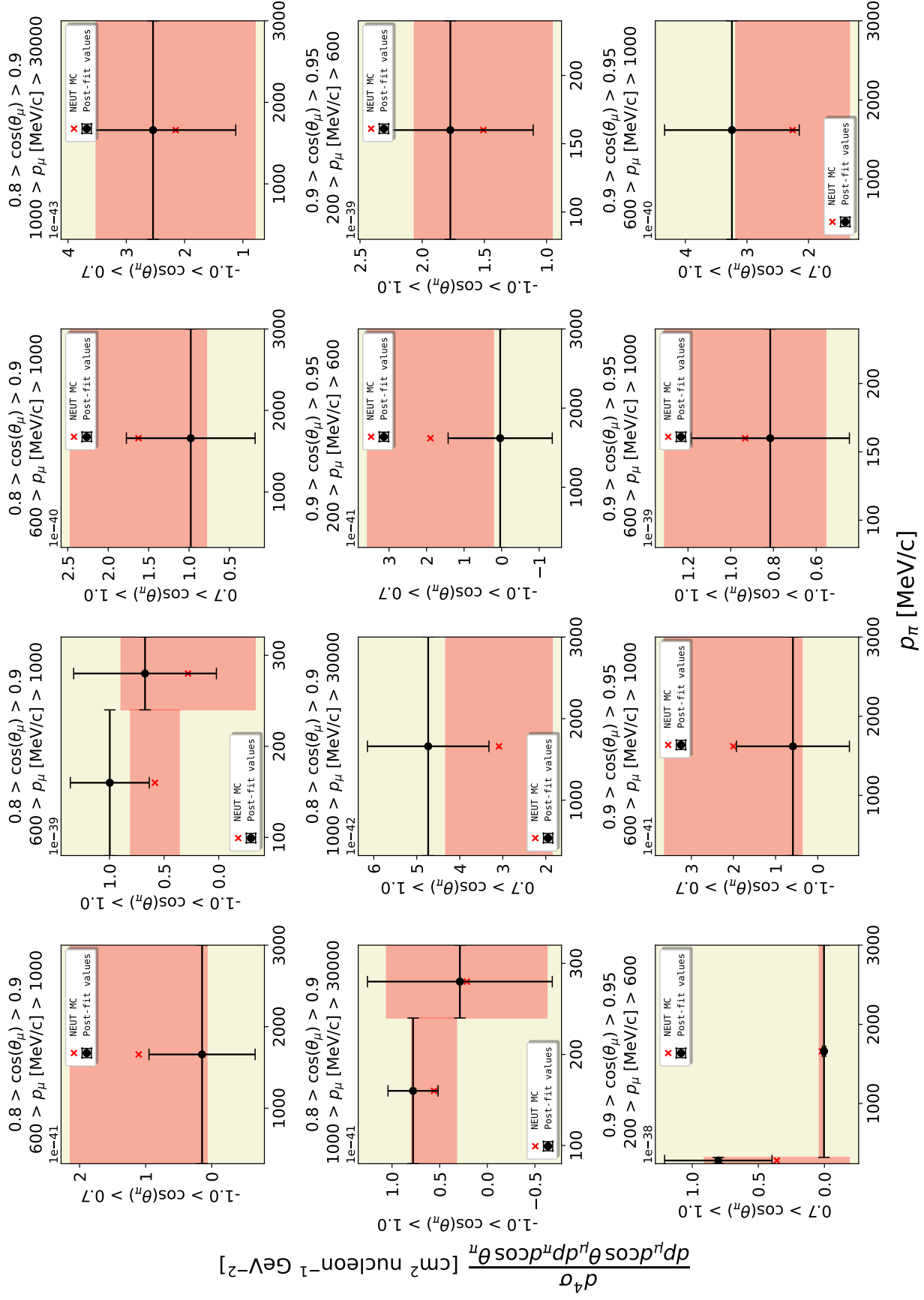


Figure 11.9: Extracted cross-section in 4D template binning for bins 13 through 24 (top left to bottom right). Muon momentum and angle bin displayed on the top of each figure, while the region in pion angular space is shown on the y-axis.

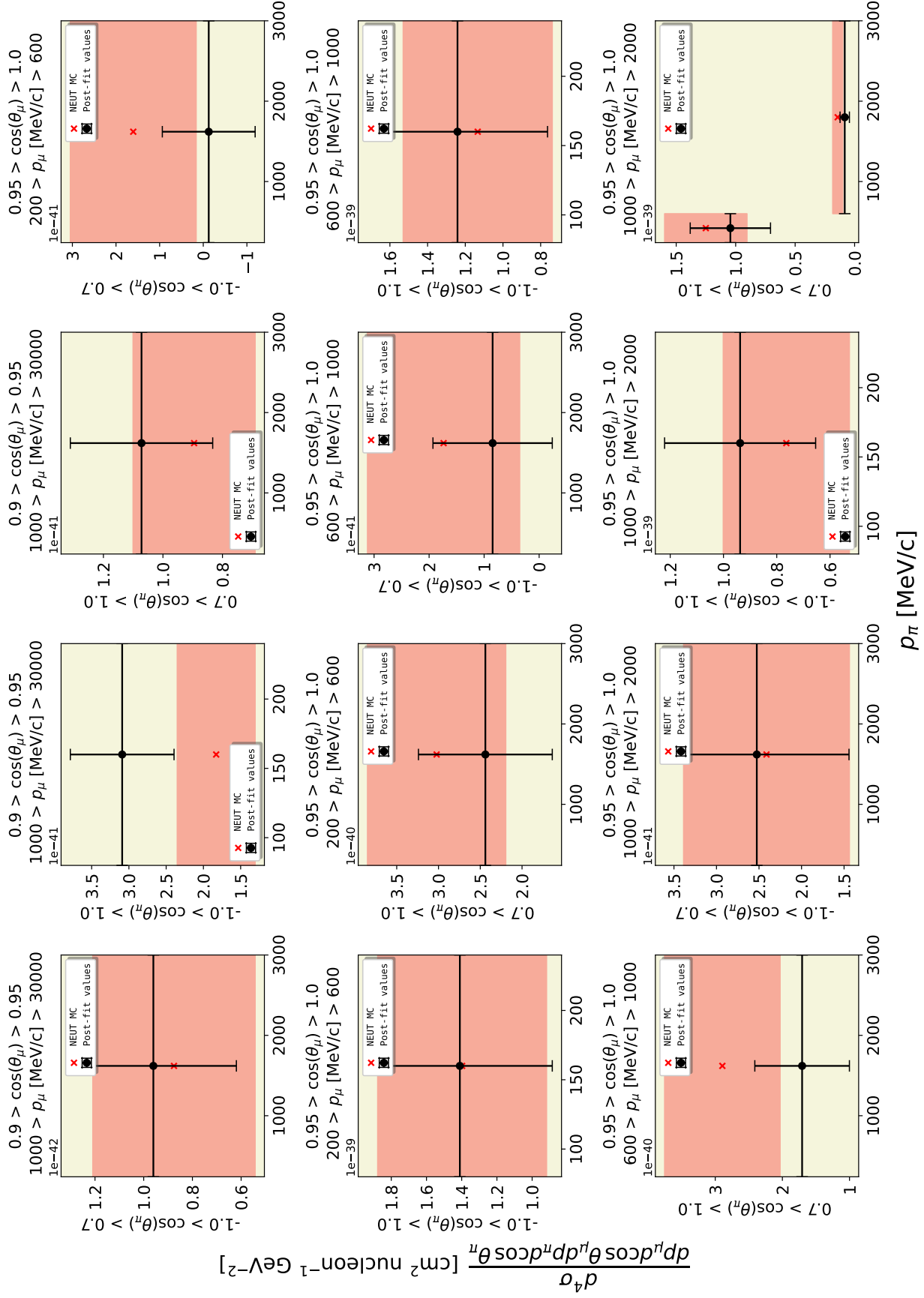


Figure 11.10: Extracted cross-section in 4D template binning for bins 25 through 36 (top left to bottom right). Muon momentum and angle bin displayed on the top of each figure, while the region in pion angular space is shown on the y-axis.

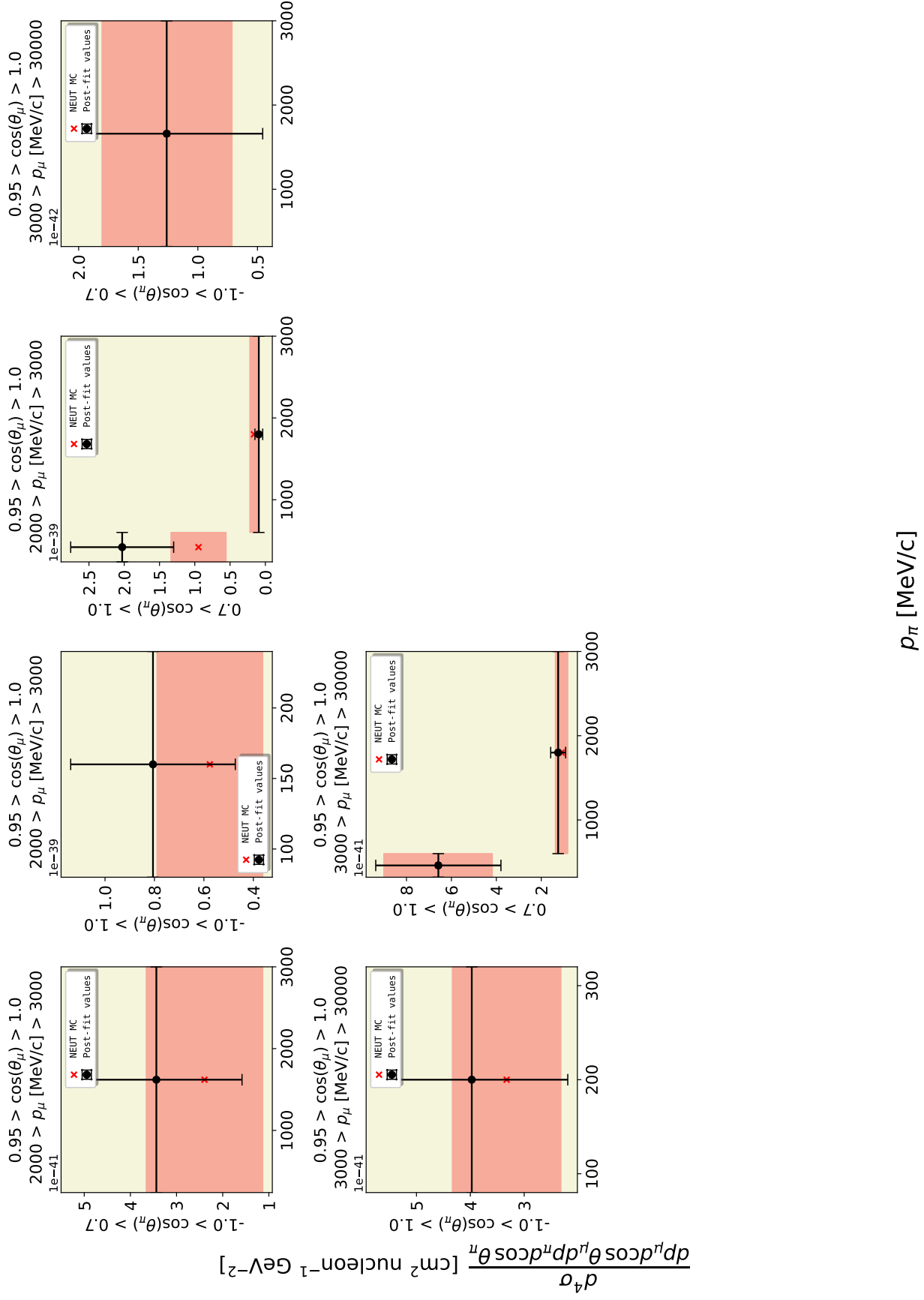


Figure 11.11: Extracted cross-section in 4D template binning for bins 37 through 42 (top left to bottom right). Muon momentum and angle bin displayed on the top of each figure, while the region in pion angular space is shown on the y-axis.

In the ideal case, this four-dimensional differential cross-section would be collapsed onto several subsets of the muon and pion kinematic variables. However, due to irregular widths chosen to optimize the number of events, the selection efficiency and the resolution in each individual bin, this is impossible. It can only be done for the cosine of the angle for the muon. This can be seen in figure 11.12.

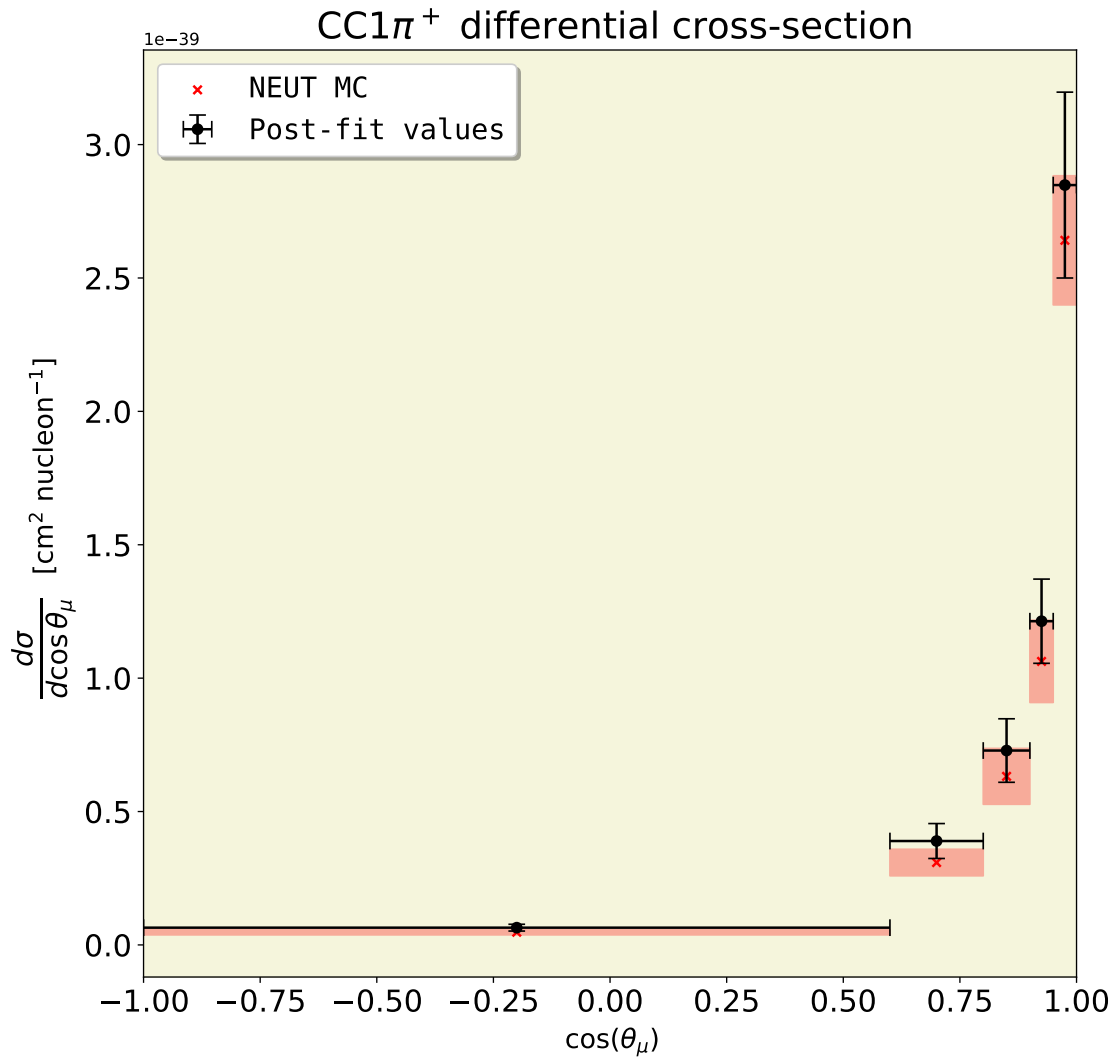


Figure 11.12: Integrated cross-section in 1D binning for muon angle.

11.1 CONCLUSION AND FUTURE IMPROVEMENTS

Ultimately, the goal of any accelerator-based neutrino experiment's near detector is to reduce the systematic uncertainties on the oscillation measurement. By placing the ND in a high-rate environment close to the neutrino source, the increased statistics can help with a better understanding of particle interactions at the far detector, which currently are the leading systematic uncertainties on the oscillation parameters.

Studying interactions at T2K's ND280 can thus provide more insights into how nuclear effects are contributing to the observations made at Super-Kamiokande. Cross-sections at the nucleon level are not perfectly known as the nuclear medium modifies them through affecting the observed final-state topology. With the addition of higher order ring samples to the oscillation analysis, interactions producing multiple particles above the Cherenkov threshold become more important.

In neutrino interaction models, especially those describing neutrino-nucleus scattering, there are many uncertainties related to the hadronic final state, nuclear effects, and pion production mechanisms. The $\text{CC}1\pi^+$ channel provides a test case for these models, helping to constrain nuclear and hadronic physics. A precise measurement of this cross-section allows T2K to validate and improve models of neutrino interactions in nuclei, which is crucial for accurate oscillation parameter extraction. T2K is designed to measure neutrino oscillations, particularly the mixing angle $\sin\theta_{23}$, the neutrino mass hierarchy, and CP violation in the lepton sector. Since the final state of neutrino interactions (like the produced pion in π^+ events) can affect the reconstruction of neutrino energy and the detection of oscillation signals, accurately measuring events with this topology helps reduce systematic uncertainties in energy reconstruction. This, in turn, improves the sensitivity of T2K to the oscillation parameters, especially in the low-energy regime.

A measurement of the muon neutrino charged-current single-pion production cross section was performed in four kinematic dimensions: muon momentum and angle and pion momentum and angle. This sample includes pions and muons going both forward and backward compared to the incoming neutrino direction, extending previous work that was limited to muons going in the forward direction. Moreover, the addition of the pure ME-tagged pion sample increased the overall statistics by 50% for pion momenta between 80 MeV and 320 MeV thus allowing for finer binning within that region. In this regime there are pions with momenta below the Cherenkov threshold of Super-Kamiokande, which makes this a particularly important region to understand as it affects the final state topology that is being observed. The dataset used comprises all of the T2K neutrino mode runs: 2, 3, 4 and 8 and the extraction was done by a simultaneous log-likelihood fit to data in the four kinematic dimensions for the outgoing muons and pions.

The log-likelihood fit and subsequent unfolded cross-section results show reasonable agreement between the data and input Monte Carlo models. The fit returned a post-fit reduced χ^2/Ndf of 1.25 and after extraction, the cross-section χ^2/Ndf is around 1.09. At

the individual bin level, the data and NEUT MC distributions agree within 1σ uncertainty bands for all 54 template bins with the exception of bin #30 found in sub figure 26 of figure 11.9, which shows a slight discrepancy. Furthermore, bin #34 showcases a negative value meaning that the cross-section here is just too low to be measured with the current statistics. These correspond to the following 4D ranges:

- Bin #30: $0.9 < \cos(\theta_\mu) < 0.95$, $1000 < p_\mu < 30000$ MeV/c, $-1.0 < \cos(\theta_\pi) < 1.0$, $80 < p_\pi < 240$ MeV/c
- Bin #34: $0.95 < \cos(\theta_\mu) < 1.0$, $200 < p_\mu < 600$ MeV/c, $-1.0 < \cos(\theta_\pi) < 0.7$, $320 < p_\pi < 3000$ MeV/c

Even though bin #34 considers a region with lower statistics (high angle, low momentum for the muon), it is not particularly low compared to others. Bin #30 shows no lack of statistics at all. This might indicate that background events in these regimes might not have been identified accurately indicating that some of the models in the generator are not fully representative of the effects in nature. The post-fit value for the deep-inelastic scattering dial did reveal that the reaction mode is underestimated, while the value for the high energy CC1Pi dial showed an overestimation of the CC1 π topology.

When projecting the four-dimensional cross-section onto the cosine of the angle for the muon in figure 11.12, similar levels of agreement between data and Monte Carlo can be observed. This shows that the models used in the T2K framework describe even the backward-going region where the cosine of the muon angle with respect to the neutrino beam is between -1 and 0.6 to within 36%, while the measurement itself only has an 18% uncertainty. The results from this analysis can then be used in the future to reduce the prior uncertainty on the pion production dials in this region.

The accuracy of the 4-dimensional differential cross-section in muon and pion kinematic distributions should not hold back any further development. Both at the analysis level as well as the data taking (detector architecture) level, major improvements can and will be made. The template binning scheme of this analysis ensures near uniform efficiency and an event rate above threshold for each individual bin, but not without cost. In the future, an attempt should be made at redefining the bins in a consistent manner for each combination of muon momentum, muon angle and pion angle so that the result can be made more visually intuitive. Negative value bin #34 could also be eliminated in this way by means of merging. Finally, the CC0 π background sample introduces the largest χ^2 value of the entire analysis and could therefore also be investigated.

In terms of detector development, the ND280 Upgrade has been finalized and future analyses can include better quality low momentum data due to higher levels of detector segmentation [207]. The additional statistics coming from the ME-tagged pions already provided insights into this regime, but had to be added in a separate signal sample with no bins in pion angle due to the poor angular information coming from the inaccurate reconstruction of the ME vertex in the FGDs. In the new SuperFGD, which is part of the upgrade, tracking is done by hydrocarbon scintillating cubes (i.e., directly in 3D). This provides far better resolution on the point of origin of the Michel electron than before

and should thus allow for more accurate reconstruction of the kinematic variables.

Moreover, a significant part of the out-of-fiducial volume contribution in the backward and high-angle backward regions came from ME events where the muon track was flipped (i.e., exiting FGD1 rather than entering it and passing the $CC1\pi^+$ selection through the Michel electron). While this will remain a problem, with the upgrade the time of flight capabilities of the detector might improve and the directionality of the muon understood to a better degree. This would limit the amount of background in those samples and allow for a better assessment of the cross-section in a region that is now only captured by a single bin.

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Appendices

PACKAGE IMPLEMENTATION A

This section serves as a supplement in describing the addition of a few functionalities to the NDLAr flow framework with the idea of being able to run efficiency studies in-situ when the ArgonCube-2x2 is operational in the NUMI beam at Fermilab. Leading up to this effort has been an extended investigation of the individual liquid argon time projection chamber modules that are part of this 2x2 assembly. Their characteristics in both the charge and light domain have been thoroughly studied. Here the focus will lie only on the charge component and more specifically on the overall pixel efficiency, the (individual) pixel pad efficiency and the dependency on charge deposit location in both time and space. What these terms describe exactly will be discussed alongside the manual for utilizing this code in future studies or analyses.

The flow framework is capable of simulating the response in a variety of detector configurations respecting the ultimate goal of the 35-module NDLAr near detector. In addition, it is used to reconstruct and process light and charge signals as recorded by the modular prototypes as tested in Bern. As detector geometry and pixel position in 2D space are key components of the studies at hand, the code described here currently accepts only singular modules (Module 0 through 3) and the 2x2. Compatibility with the full NDLAr near detector will be provided at a later stage.

There are two branches within the flow system named `module0_flow` & `proto_nd_flow` to be used with single module and 2x2 operation respectively. `Module0_flow` takes in reconstructed data from module 0, 1, 2 or 3 and runs it through a set of three stages to get to a file that can generate the efficiency map. `Proto_nd_flow` does the same for a reconstructed 2x2 data, but skips the first stage as can be seen in figure [A.1](#).

The stages are labeled **`z_convert`**, **`line_finder`** and **`eff_map`** in the processing sequence.

As the name suggests, `z_convert` transforms the drift temporal coordinate to a spatial one. This step will become obsolete in future versions of the reconstructed files once the reprocessing is done, but as it is still necessary at the moment it can be run in the following manner. The goal of this `z_convert` step is to have a uniform input file for the

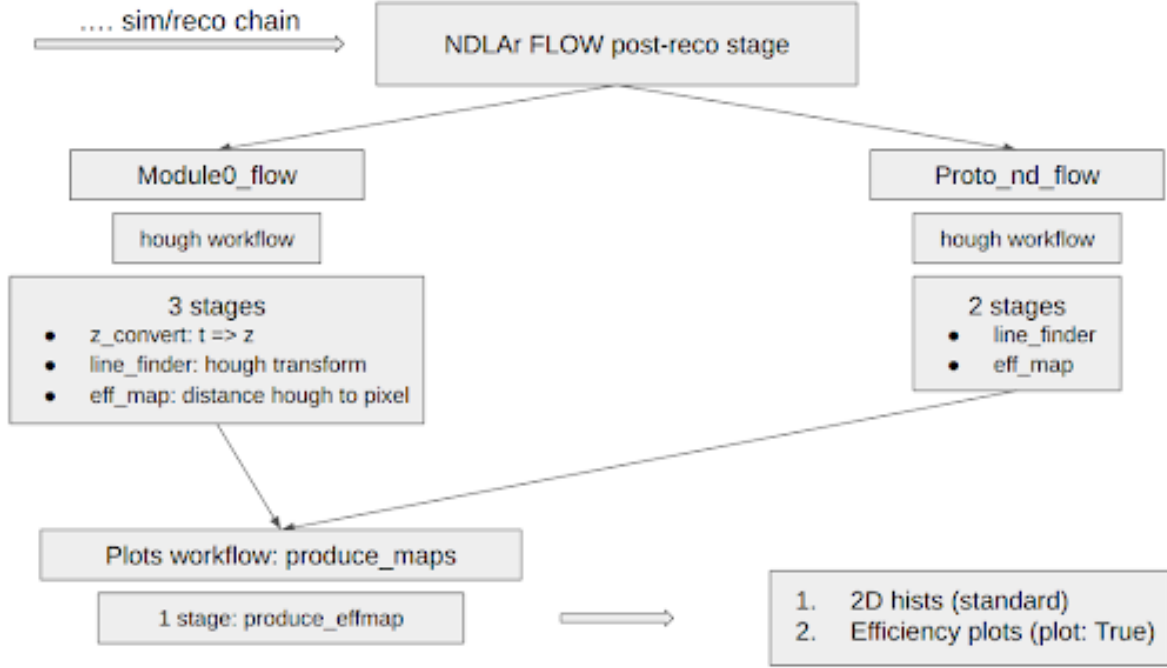


Figure A.1: Overview of the processing steps to form an efficiency map in-site

hough transform shared by each individual module. The time to position conversion is not shared between module 0&2 and module 1&3. For module 0 and 2, we take the time the hit arrives and subtract the event start time before multiplying by the drift velocity. For module 1 and 3, the reconstructed files already contain the converted coordinate albeit stored in a different array. The values are simply copied. Finally the number of external triggers is collected and stored so it can later be used as a mask to reject unwanted hits.

The output is an array called `hough_i` as in “hough input” and will contain all the necessary information to run a hough transform. The second stage is the `line_finder` and this incorporates the actual hough transform algorithm (HTA). It is similar for both the single module and the 2x2 in terms of its functionality.

Now we specify the hough transform properties `max_peaks` & `min_pixels` as well as the mode. `Max_peaks` describes the maximum number of hough lines to be found in the hit cloud and `min_pixels` describes the minimum number of hits to be considered a line. Mode separates between the self-built hough transform and the external C++ HTA package. For the external one, mode should be set to ‘external’. This is the default.

In the case of the external mode, the `line_finder` stage consists of three functions. Before any calculations are done, any event that has fewer than 125 hits is rejected by setting

the `hit_pass` variable to 0. This is done to keep all the referencing between events and hits, while also making sure that the events are still removed later.

1. Finding the hough line with `HoughOnArray`:

- `HoughOnArray` takes in the hits for a certain event and calls the external HTA package. As this external package reads in csv files, the x, y and z positions stored in the input array are saved in a csv file. A mask is applied at the start to reject unwanted hits before saving. The function returns the line center, angles, the start and end positions of the line in 3D. It also returns the number of votes.

If the line could not be found due to lack of hits or poor hit quality, the `hit_pass` is again set to zero.

2. Calculate the distance from the hits to the hough line with `d_pnt2line`

- Uses the previously calculated hough line to find the distance between this line and all hits that were used to reconstruct this line. The output is a list of distances called `dist` that will be stored in the output.

If the distance could not be found or if the number of events within a chosen radius around the line is below 25, we reject the event and set `hit_pass` to 0. This is to prevent erroneous lines from entering the analysis.

3. Get new line center by excluding far away hits with `trackLengthHoughCenter`

- Recalculate the hough line center by excluding all hits outside the chosen radius and performing a shift from the initial position. The track length is also put out along with the mask describing which hits were outside the defined radius.

The script puts out two arrays. On the one hand we have the `hough_o` array describing the lines that were found per event along with a useful column that stores the `hit_pass` value and can be used to mask the events in the efficiency calculation. On the other hand we have the `hough_hits_o` array, which contains all the hits per event and a `keep` column describing if the hits are supposed to be kept at a later stage.

The third stage is the `eff_map` and this is what ultimately constructs the array used by the plotting script to generate the efficiency maps. In the single module case, the module number is specified here (`mod0`, `mod1` etc). In the 2x2 case, the module parameter is simply not set at all. Furthermore, there is an option to activate the hit mask with `within_rad`: True or False. The default size of the pixel pad study is 5 by 5. There is also an option to extend or limit this overview by setting `num_pixels_plot`. Finally there is the `grid_size` parameter that is used to ensure none of the pixels are counted twice, so in the case of a 5x5 overview it would need to be set to at least $(\sqrt{2}) * 5 * \text{pixel_size}$ for the diagonal extremes). The default is 40 mm.

The script itself then loads in the `hough_o` and `hough_hits_o` arrays along with the working

pixel map of the respective detector. Firstly the line is separated in a number of segments. This number is determined by dividing the track length by the set value for grid size as mentioned before. Afterwards the algorithm described in the previous section is utilized to generate an output array named `effs` containing the distances for each of those points to the surrounding pixels, the pixel positions, the hit boolean, the drift position of the track segment and the track angle.

The final stage simply consists of generating 2D histograms and plots from the `effs` array. A new workflow has been created: `produce_maps.yaml` to distinguish between calculation steps and plot generation steps. Within the workflow, one sets the stage to be `produce_effmap`.

Aside from the options we described in the previous section in `within_rad`, `mode` and `module`, there are some additional ones. For the individual pixel map, the `axis_bound` option is used to define the number of bins per pixel (default is 20). The output directory name “`output_dir`” can be set and if the user would like to generate plots immediately they can set `plot` to `True` and define the directory “`plot_dir`” as well.

The output is two `.npy` files stored in the `output_dir` directory. One file contains all hits irrespective of whether they were hit (independent of the hit boolean) and the other contains only the hits that pass the hit boolean.

The plotting function takes the ratio of the hit histogram to the all histogram and shows it in a 5by5 pixel overview, where the x-axis is the distance to the point on the hough line in x (horizontal pixel plane coordinate) and the y-axis is the distance to that point in y (vertical pixel plane coordinate). These plots are then allowed to be viewed during operating to inform the experimenter on the detector’s performance.

ANALYSIS BINNING

B

B.1 FLUX BINNING

The table below outlines the ranges in neutrino energy chosen for the neutrino flux binning.

E_ν [MeV]			E_ν [MeV]		
BinNo.	begin	end	BinNo.	begin	end
1	0	100	10	1200	1500
2	100	200	11	1500	2000
3	200	300	12	2000	2500
4	300	400	13	2500	3000
5	400	500	14	3000	3500
6	500	600	15	3500	4000
7	600	700	16	4000	5000
8	700	800	17	5000	7000
9	800	1000	18	7000	10000
10	1000	1200	19	10000	30000

Table B.1: Flux binning in neutrino energy.

B.2 TEMPLATE BINNING

The bin edges for the template parameters (‘truth space’) are summarized in table [B.2](#).

Table B.2: 4D template parameter bin edges

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	$\cos(\theta_\pi)$ [$^\circ$]	p_π [MeV]
#1	-1.0 - 0.0	200 - 30000	-1.0 - 1.0	240 - 3000
#2	-1.0 - 0.6	200 - 600	-1.0 - 1.0	80 - 240
#3	0.0 - 0.6	200 - 600	-1.0 - 0.7	240 - 3000
#4	0.0 - 0.6	200 - 600	0.7 - 1.0	240 - 600
#5	0.0 - 0.6	200 - 600	0.7 - 1.0	600 - 3000
#6	0.0 - 0.6	600 - 30000	-1.0 - 1.0	80 - 3000
#7	0.6 - 0.8	200 - 600	-1.0 - 1.0	80 - 240
#8	0.6 - 0.8	200 - 600	-1.0 - 0.7	240 - 3000
#9	0.6 - 0.8	200 - 600	0.7 - 1.0	240 - 600
#10	0.6 - 0.8	200 - 600	0.7 - 1.0	600 - 3000
#11	0.6 - 0.8	600 - 30000	-1.0 - 1.0	80 - 3000
#12	0.8 - 0.9	200 - 600	-1.0 - 1.0	80 - 240
#13	0.8 - 0.9	200 - 600	-1.0 - 0.7	240 - 3000
#14	0.8 - 0.9	200 - 600	0.7 - 1.0	240 - 600
#15	0.8 - 0.9	200 - 600	0.7 - 1.0	600 - 3000
#16	0.8 - 0.9	600 - 1000	-1.0 - 1.0	80 - 240
#17	0.8 - 0.9	600 - 1000	-1.0 - 1.0	240 - 320
#18	0.8 - 0.9	600 - 1000	-1.0 - 0.7	320 - 3000
#19	0.8 - 0.9	600 - 1000	0.7 - 1.0	320 - 3000
#20	0.8 - 0.9	1000 - 30000	-1.0 - 1.0	80 - 240
#21	0.8 - 0.9	1000 - 30000	-1.0 - 1.0	240 - 320
#22	0.8 - 0.9	1000 - 30000	-1.0 - 0.7	320 - 3000
#23	0.8 - 0.9	1000 - 30000	0.7 - 1.0	320 - 3000
#24	0.9 - 0.95	200 - 600	-1.0 - 1.0	80 - 240
#25	0.9 - 0.95	200 - 600	-1.0 - 0.7	240 - 3000

Table B.2: 4D template parameter bin edges (*continued*)

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	$\cos(\theta_\pi)$ [$^\circ$]	p_π [MeV]
#26	0.9 - 0.95	200 - 600	0.7 - 1.0	240 - 320
#27	0.9 - 0.95	200 - 600	0.7 - 1.0	320 - 3000
#28	0.9 - 0.95	600 - 1000	-1.0 - 1.0	80 - 240
#29	0.9 - 0.95	600 - 1000	-1.0 - 0.7	240 - 3000
#30	0.9 - 0.95	600 - 1000	0.7 - 1.0	240 - 3000
#31	0.9 - 0.95	1000 - 30000	-1.0 - 1.0	80 - 240
#32	0.9 - 0.95	1000 - 30000	-1.0 - 0.7	240 - 3000
#33	0.9 - 0.95	1000 - 30000	0.7 - 1.0	240 - 3000
#34	0.95 - 1.0	200 - 600	-1.0 - 1.0	80 - 240
#35	0.95 - 1.0	200 - 600	-1.0 - 0.7	240 - 3000
#36	0.95 - 1.0	200 - 600	0.7 - 1.0	240 - 3000
#37	0.95 - 1.0	600 - 1000	-1.0 - 1.0	80 - 240
#38	0.95 - 1.0	600 - 1000	-1.0 - 0.7	240 - 3000
#39	0.95 - 1.0	600 - 1000	0.7 - 1.0	240 - 3000
#40	0.95 - 1.0	1000 - 2000	-1.0 - 1.0	80 - 240
#41	0.95 - 1.0	1000 - 2000	-1.0 - 0.7	240 - 3000
#42	0.95 - 1.0	1000 - 2000	0.7 - 1.0	240 - 600
#43	0.95 - 1.0	1000 - 2000	0.7 - 1.0	600 - 3000
#44	0.95 - 1.0	2000 - 3000	-1.0 - 1.0	80 - 240
#45	0.95 - 1.0	2000 - 3000	-1.0 - 0.7	240 - 3000
#46	0.95 - 1.0	2000 - 3000	0.7 - 1.0	240 - 600
#47	0.95 - 1.0	2000 - 3000	0.7 - 1.0	600 - 3000
#48	.95 - 1.0	3000 - 30000	-1.0 - 1.0	80 - 320
#49	0.95 - 1.0	3000 - 30000	-1.0 - 0.7	320 - 3000
#50	0.95 - 1.0	3000 - 30000	0.7 - 1.0	320 - 600

Table B.2: 4D template parameter bin edges (*continued*)

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	$\cos(\theta_\pi)$ [$^\circ$]	p_π [MeV]
#51	0.95 - 1.0	3000 - 30000	0.7 - 1.0	600 - 3000
#52	-1.0 - 1.0	0 - 200	-1.0 - 1.0	0 - 30000
#53	-1.0 - 1.0	200 - 30000	-1.0 - 1.0	0 - 80
#54	-1.0 - 1.0	200 - 30000	-1.0 - 1.0	3000 - 30000

B.3 SIGNAL SAMPLES BINNING

The bin edges for the signal samples (‘reconstructed space’) are summarized in tables [B.3](#) and [B.4](#) for the TPC&FGD sample and ME sample respectively.

B.3.1 The TPC&FGD sample

Table B.3: TPC & FGD identified pion sample bin edges

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	$\cos(\theta_\pi)$ [$^\circ$]	p_π [MeV]
#1	-1.0 - 0.0	200 - 30000	-1.0 - 1.0	160 - 3000
#2	0.0 - 0.6	200 - 600	-1.0 - 0.7	160 - 3000
#3	0.0 - 0.6	200 - 600	0.7 - 1.0	160 - 500
#4	0.0 - 0.6	200 - 600	0.7 - 1.0	500 - 3000
#5	0.0 - 0.6	600 - 30000	-1.0 - 0.7	160 - 500
#6	0.0 - 0.6	600 - 30000	-1.0 - 0.7	500 - 3000
#7	0.0 - 0.6	600 - 30000	0.7 - 1.0	160 - 500
#8	0.0 - 0.6	600 - 30000	0.7 - 1.0	500 - 3000
#9	0.6 - 0.8	200 - 600	-1.0 - 0.7	160 - 3000
#10	0.6 - 0.8	200 - 600	0.7 - 1.0	160 - 500
#11	0.6 - 0.8	200 - 600	0.7 - 1.0	500 - 3000
#12	0.6 - 0.8	600 - 30000	-1.0 - 0.7	160 - 500
#13	0.6 - 0.8	600 - 30000	-1.0 - 0.7	500 - 3000

Table B.3: TPC & FGD identified pion sample bin edges (*continued*)

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	$\cos(\theta_\pi)$ [$^\circ$]	p_π [MeV]
#14	0.6 - 0.8	600 - 30000	0.7 - 1.0	160 - 500
#15	0.6 - 0.8	600 - 30000	0.7 - 1.0	500 - 3000
#16	0.8 - 0.85	200 - 600	-1.0 - 0.7	160 - 3000
#17	0.8 - 0.85	200 - 600	0.7 - 1.0	160 - 600
#18	0.8 - 0.85	200 - 600	0.7 - 1.0	600 - 900
#19	0.8 - 0.85	200 - 600	0.7 - 1.0	900 - 3000
#20	0.8 - 0.85	600 - 1000	-1.0 - 0.7	160 - 600
#21	0.8 - 0.85	600 - 1000	-1.0 - 0.7	600 - 3000
#22	0.8 - 0.85	600 - 1000	0.7 - 1.0	160 - 600
#23	0.8 - 0.85	600 - 1000	0.7 - 1.0	600 - 900
#24	0.8 - 0.85	600 - 1000	0.7 - 1.0	900 - 3000
#25	0.8 - 0.85	1000 - 30000	-1.0 - 0.7	160 - 600
#26	0.8 - 0.85	1000 - 30000	-1.0 - 0.7	600 - 3000
#27	0.8 - 0.85	1000 - 30000	0.7 - 1.0	160 - 600
#28	0.8 - 0.85	1000 - 30000	0.7 - 1.0	600 - 900
#29	0.8 - 0.85	1000 - 30000	0.7 - 1.0	900 - 3000
#30	0.85 - 0.9	200 - 600	-1.0 - 0.7	160 - 3000
#31	0.85 - 0.9	200 - 600	0.7 - 1.0	160 - 600
#32	0.85 - 0.9	200 - 600	0.7 - 1.0	600 - 900
#33	0.85 - 0.9	200 - 600	0.7 - 1.0	900 - 3000
#34	0.85 - 0.9	600 - 1000	-1.0 - 0.7	160 - 600
#35	0.85 - 0.9	600 - 1000	-1.0 - 0.7	600 - 3000
#36	0.85 - 0.9	600 - 1000	0.7 - 1.0	160 - 600
#37	0.85 - 0.9	600 - 1000	0.7 - 1.0	600 - 900
#38	0.85 - 0.9	600 - 1000	0.7 - 1.0	900 - 3000

Table B.3: TPC & FGD identified pion sample bin edges (*continued*)

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	$\cos(\theta_\pi)$ [$^\circ$]	p_π [MeV]
#39	0.85 - 0.9	1000 - 30000	-1.0 - 0.7	160 - 600
#40	0.85 - 0.9	1000 - 30000	-1.0 - 0.7	600 - 3000
#41	0.85 - 0.9	1000 - 30000	0.7 - 1.0	160 - 600
#42	0.85 - 0.9	1000 - 30000	0.7 - 1.0	600 - 900
#43	0.85 - 0.9	1000 - 30000	0.7 - 1.0	900 - 3000
#44	0.9 - 0.95	200 - 600	-1.0 - 0.7	160 - 3000
#45	0.9 - 0.95	200 - 600	0.7 - 1.0	160 - 600
#46	0.9 - 0.95	200 - 600	0.7 - 1.0	600 - 900
#47	0.9 - 0.95	200 - 600	0.7 - 1.0	900 - 3000
#48	0.9 - 0.95	600 - 1000	-1.0 - 0.7	160 - 600
#49	0.9 - 0.95	600 - 1000	-1.0 - 0.7	600 - 3000
#50	0.9 - 0.95	600 - 1000	0.7 - 1.0	160 - 600
#51	0.9 - 0.95	600 - 1000	0.7 - 1.0	600 - 900
#52	0.9 - 0.95	600 - 1000	0.7 - 1.0	900 - 3000
#53	0.9 - 0.95	1000 - 30000	-1.0 - 0.7	160 - 600
#54	0.9 - 0.95	1000 - 30000	-1.0 - 0.7	600 - 3000
#55	0.9 - 0.95	1000 - 30000	0.7 - 1.0	160 - 600
#56	0.9 - 0.95	1000 - 30000	0.7 - 1.0	600 - 900
#57	0.9 - 0.95	1000 - 30000	0.7 - 1.0	900 - 3000
#58	0.95 - 0.98	200 - 600	-1.0 - 0.7	160 - 3000
#59	0.95 - 0.98	200 - 600	0.7 - 1.0	160 - 600
#60	0.95 - 0.98	200 - 600	0.7 - 1.0	600 - 900
#61	0.95 - 0.98	200 - 600	0.7 - 1.0	900 - 3000
#62	0.95 - 0.98	600 - 1000	-1.0 - 0.7	160 - 600
#63	0.95 - 0.98	600 - 1000	-1.0 - 0.7	600 - 3000

Table B.3: TPC & FGD identified pion sample bin edges (*continued*)

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	$\cos(\theta_\pi)$ [$^\circ$]	p_π [MeV]
#64	0.95 - 0.98	600 - 1000	0.7 - 1.0	160 - 600
#65	0.95 - 0.98	600 - 1000	0.7 - 1.0	600 - 900
#66	0.95 - 0.98	600 - 1000	0.7 - 1.0	900 - 3000
#67	0.95 - 0.98	1000 - 2000	-1.0 - 0.7	160 - 600
#68	0.95 - 0.98	1000 - 2000	-1.0 - 0.7	600 - 3000
#69	0.95 - 0.98	1000 - 2000	0.7 - 1.0	160 - 600
#70	0.95 - 0.98	1000 - 2000	0.7 - 1.0	600 - 900
#71	0.95 - 0.98	1000 - 2000	0.7 - 1.0	900 - 3000
#72	0.95 - 0.98	2000 - 3000	-1.0 - 0.7	160 - 600
#73	0.95 - 0.98	2000 - 3000	-1.0 - 0.7	600 - 3000
#74	0.95 - 0.98	2000 - 3000	0.7 - 1.0	160 - 600
#75	0.95 - 0.98	2000 - 3000	0.7 - 1.0	600 - 900
#76	0.95 - 0.98	2000 - 3000	0.7 - 1.0	900 - 3000
#77	0.95 - 0.98	3000 - 30000	-1.0 - 0.7	160 - 600
#78	0.95 - 0.98	3000 - 30000	-1.0 - 0.7	600 - 3000
#79	0.95 - 0.98	3000 - 30000	0.7 - 1.0	160 - 600
#80	0.95 - 0.98	3000 - 30000	0.7 - 1.0	600 - 900
#81	0.95 - 0.98	3000 - 30000	0.7 - 1.0	900 - 3000
#82	0.95 - 0.98	200 - 600	-1.0 - 0.7	160 - 3000
#83	0.95 - 0.98	200 - 600	0.7 - 1.0	160 - 600
#84	0.95 - 0.98	200 - 600	0.7 - 1.0	600 - 900
#85	0.95 - 0.98	200 - 600	0.7 - 1.0	900 - 3000
#86	0.95 - 0.98	600 - 1000	-1.0 - 0.7	160 - 600
#87	0.95 - 0.98	600 - 1000	-1.0 - 0.7	600 - 3000
#88	0.95 - 0.98	600 - 1000	0.7 - 1.0	160 - 600

Table B.3: TPC & FGD identified pion sample bin edges (*continued*)

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	$\cos(\theta_\pi)$ [$^\circ$]	p_π [MeV]
#89	0.95 - 0.98	600 - 1000	0.7 - 1.0	600 - 900
#90	0.95 - 0.98	600 - 1000	0.7 - 1.0	900 - 3000
#91	0.95 - 0.98	1000 - 2000	-1.0 - 0.7	160 - 600
#92	0.95 - 0.98	1000 - 2000	-1.0 - 0.7	600 - 3000
#93	0.95 - 0.98	1000 - 2000	0.7 - 1.0	160 - 600
#94	0.95 - 0.98	1000 - 2000	0.7 - 1.0	600 - 900
#95	0.95 - 0.98	1000 - 2000	0.7 - 1.0	900 - 3000
#96	0.95 - 0.98	2000 - 3000	-1.0 - 0.7	160 - 600
#97	0.95 - 0.98	2000 - 3000	-1.0 - 0.7	600 - 3000
#98	0.95 - 0.98	2000 - 3000	0.7 - 1.0	160 - 600
#99	0.95 - 0.98	2000 - 3000	0.7 - 1.0	600 - 900
#100	0.95 - 0.98	2000 - 3000	0.7 - 1.0	900 - 3000
#101	0.95 - 0.98	3000 - 30000	-1.0 - 0.7	160 - 600
#102	0.95 - 0.98	3000 - 30000	-1.0 - 0.7	600 - 3000
#103	0.95 - 0.98	3000 - 30000	0.7 - 1.0	160 - 600
#104	0.95 - 0.98	3000 - 30000	0.7 - 1.0	600 - 900
#105	0.95 - 0.98	3000 - 30000	0.7 - 1.0	900 - 3000
#106	0.98 - 1.0	0 - 200	-1.0 - 1.0	160 - 30000
#107	0.98 - 1.0	200 - 30000	-1.0 - 1.0	0 - 160
#108	0.98 - 1.0	200 - 30000	-1.0 - 1.0	3000 - 30000

B.3.2 The ME sample

Table B.4: ME-tagged pion sample bin edges

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	$\cos(\theta_\pi)$ [$^\circ$]	p_π [MeV]
#1	-1.0 - 0.0	200 - 30000	-1.0 - 1.0	160 - 320
#2	0.0 - 0.6	200 - 600	-1.0 - 1.0	80 - 160
#3	0.0 - 0.6	200 - 600	-1.0 - 1.0	160 - 240
#4	0.0 - 0.6	200 - 600	-1.0 - 1.0	240 - 320
#5	0.0 - 0.6	600 - 30000	-1.0 - 1.0	80 - 160
#6	0.0 - 0.6	600 - 30000	-1.0 - 1.0	160 - 320
#7	0.6 - 0.8	200 - 600	-1.0 - 1.0	80 - 160
#8	0.6 - 0.8	200 - 600	-1.0 - 1.0	160 - 240
#9	0.6 - 0.8	200 - 600	-1.0 - 1.0	240 - 320
#10	0.6 - 0.8	600 - 30000	-1.0 - 1.0	80 - 160
#11	0.6 - 0.8	600 - 30000	-1.0 - 1.0	160 - 320
#12	0.8 - 0.85	200 - 600	-1.0 - 1.0	80 - 160
#13	0.8 - 0.85	200 - 600	-1.0 - 1.0	160 - 320
#14	0.8 - 0.85	600 - 1000	-1.0 - 1.0	80 - 160
#15	0.8 - 0.85	600 - 1000	-1.0 - 1.0	160 - 320
#16	0.8 - 0.85	1000 - 30000	-1.0 - 1.0	80 - 160
#17	0.8 - 0.85	1000 - 30000	-1.0 - 1.0	160 - 320
#18	0.85 - 0.9	200 - 600	-1.0 - 1.0	80 - 160
#19	0.85 - 0.9	200 - 600	-1.0 - 1.0	160 - 320
#20	0.85 - 0.9	600 - 1000	-1.0 - 1.0	80 - 160
#21	0.85 - 0.9	600 - 1000	-1.0 - 1.0	160 - 320
#22	0.85 - 0.9	1000 - 30000	-1.0 - 1.0	80 - 320
#23	0.9 - 0.95	200 - 600	-1.0 - 1.0	80 - 160
#24	0.9 - 0.95	200 - 600	-1.0 - 1.0	160 - 320
#25	0.9 - 0.95	600 - 1000	-1.0 - 1.0	80 - 320

Table B.4: ME-tagged pion sample bin edges (*continued*)

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	$\cos(\theta_\pi)$ [$^\circ$]	p_π [MeV]
#26	0.9 - 0.95	1000 - 30000	-1.0 - 1.0	80 - 160
#27	0.9 - 0.95	1000 - 30000	-1.0 - 1.0	160 - 320
#28	0.95 - 0.98	200 - 600	-1.0 - 1.0	80 - 160
#29	0.95 - 0.98	200 - 600	-1.0 - 1.0	160 - 320
#30	0.95 - 0.98	600 - 1000	-1.0 - 1.0	80 - 160
#31	0.95 - 0.98	600 - 1000	-1.0 - 1.0	160 - 320
#32	0.95 - 0.98	1000 - 2000	-1.0 - 1.0	80 - 160
#33	0.95 - 0.98	1000 - 2000	-1.0 - 1.0	160 - 320
#34	0.95 - 0.98	2000 - 3000	-1.0 - 1.0	80 - 160
#35	0.95 - 0.98	2000 - 3000	-1.0 - 1.0	160 - 320
#36	0.95 - 0.98	3000 - 30000	-1.0 - 1.0	80 - 160
#37	0.95 - 0.98	3000 - 30000	-1.0 - 1.0	160 - 320
#38	0.98 - 1.0	200 - 600	-1.0 - 1.0	80 - 160
#39	0.98 - 1.0	200 - 600	-1.0 - 1.0	160 - 320
#40	0.98 - 1.0	600 - 1000	-1.0 - 1.0	80 - 160
#41	0.98 - 1.0	600 - 1000	-1.0 - 1.0	160 - 320
#42	0.98 - 1.0	1000 - 2000	-1.0 - 1.0	80 - 160
#43	0.98 - 1.0	1000 - 2000	-1.0 - 1.0	160 - 320
#44	0.98 - 1.0	2000 - 3000	-1.0 - 1.0	80 - 160
#45	0.98 - 1.0	2000 - 3000	-1.0 - 1.0	160 - 320
#46	0.98 - 1.0	3000 - 30000	-1.0 - 1.0	80 - 160
#47	0.98 - 1.0	3000 - 30000	-1.0 - 1.0	160 - 240
#48	0.98 - 1.0	3000 - 30000	-1.0 - 1.0	240 - 320
#49	-1.0 - 1.0	0 - 200	-1.0 - 1.0	80 - 30000
#50	-1.0 - 1.0	200 - 30000	-1.0 - 1.0	0 - 80

#51		-1.0 - 1.0		200 - 30000		-1.0 - 1.0		320 - 30000
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B.4 SIDEBAND SAMPLES BINNING

The bin edges for the sideband samples (‘reconstructed space’) are summarized in tables B.5, B.6 and B.7 for the signal and an additional charged pion, the signal and an additional neutral pion and events with no pions in the final state respectively.

B.4.1 The signal + $\pi^\pm$ sample

Table B.5: CC1 π^+ +1 $\pi^\pm$ sideband sample bin edges

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	$\cos(\theta_\pi)$ [$^\circ$]	p_π [MeV]
#1	-1.0 - 0.6	200.0 - 30000.0	-1.0 - 1.0	80.0 - 3000.0
#2	0.6 - 0.8	200.0 - 30000.0	-1.0 - 0.7	80.0 - 3000.0
#3	0.6 - 0.8	200.0 - 30000.0	0.7 - 1.0	80.0 - 3000.0
#4	0.8 - 0.9	200.0 - 30000.0	-1.0 - 0.7	80.0 - 3000.0
#5	0.8 - 0.9	200.0 - 30000.0	0.7 - 1.0	80.0 - 3000.0
#6	0.9 - 1.0	200.0 - 30000.0	-1.0 - 0.7	80.0 - 3000.0
#7	0.9 - 1.0	200.0 - 30000.0	0.7 - 1.0	80.0 - 3000.0

B.4.2 The signal + π^0 sample

Table B.6: CC1 π^+ +1 π^0 sideband sample bin edges

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	$\cos(\theta_\pi)$ [$^\circ$]	p_π [MeV]
#1	-1.0 - 0.7	200.0 - 30000.0	-1.0 - 1.0	80.0 - 3000.0
#2	0.7 - 0.9	200.0 - 30000.0	-1.0 - 0.7	80.0 - 3000.0
#3	0.7 - 0.9	200.0 - 30000.0	0.7 - 1.0	80.0 - 3000.0
#4	0.9 - 1.0	200.0 - 30000.0	-1.0 - 0.7	80.0 - 3000.0
#5	0.9 - 1.0	200.0 - 30000.0	0.7 - 1.0	80.0 - 3000.0

B.4.3 The CC0 π sample

Table B.7: CC0 π sideband sample bin edges

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]
#1	-1.0 - -0.95	200 - 3000	#80	0.75 - 0.8	430 - 500
#2	-0.95 - -0.9	200 - 3000	#81	0.75 - 0.8	500 - 550
#3	-0.9 - -0.85	200 - 3000	#82	0.75 - 0.8	550 - 600
#4	-0.85 - -0.8	200 - 3000	#83	0.75 - 0.8	600 - 690
#5	-0.8 - -0.75	200 - 3000	#84	0.75 - 0.8	690 - 800
#6	-0.75 - -0.7	200 - 3000	#85	0.75 - 0.8	800 - 1000
#7	-0.7 - -0.6	200 - 3000	#86	0.75 - 0.8	1000 - 3000
#8	-0.6 - -0.5	200 - 3000	#87	0.8 - 0.85	200 - 400
#9	-0.5 - -0.4	200 - 3000	#88	0.8 - 0.85	400 - 425
#10	-0.4 - -0.3	200 - 3000	#89	0.8 - 0.85	425 - 450
#11	-0.3 - -0.2	200 - 3000	#90	0.8 - 0.85	450 - 475
#12	-0.2 - -0.1	200 - 3000	#91	0.8 - 0.85	475 - 500
#13	-0.1 - 0.0	200 - 3000	#92	0.8 - 0.85	500 - 525
#14	0.0 - 0.1	200 - 3000	#93	0.8 - 0.85	525 - 550
#15	0.1 - 0.2	200 - 3000	#94	0.8 - 0.85	550 - 575
#16	0.2 - 0.25	200 - 400	#95	0.8 - 0.85	575 - 600
#17	0.2 - 0.25	400 - 3000	#96	0.8 - 0.85	600 - 650
#18	0.25 - 0.3	200 - 400	#97	0.8 - 0.85	650 - 700
#19	0.25 - 0.3	400 - 3000	#98	0.8 - 0.85	700 - 750
#20	0.3 - 0.35	200 - 400	#99	0.8 - 0.85	750 - 800
#21	0.3 - 0.35	400 - 3000	#100	0.8 - 0.85	800 - 840
#22	0.35 - 0.4	200 - 350	#101	0.8 - 0.85	840 - 1200
#23	0.35 - 0.4	350 - 400	#102	0.8 - 0.85	1200 - 3000

Table B.7: CC0 π sideband sample bin edges (*continued*)

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]
#24	0.35 - 0.4	400 - 430	#103	0.85 - 0.9	200 - 400
#25	0.35 - 0.4	430 - 500	#104	0.85 - 0.9	400 - 450
#26	0.35 - 0.4	500 - 3000	#105	0.85 - 0.9	450 - 500
#27	0.4 - 0.45	200 - 350	#106	0.85 - 0.9	500 - 550
#28	0.4 - 0.45	350 - 400	#107	0.85 - 0.9	550 - 600
#29	0.4 - 0.45	400 - 470	#108	0.85 - 0.9	600 - 650
#30	0.4 - 0.45	470 - 500	#109	0.85 - 0.9	650 - 700
#31	0.4 - 0.45	500 - 600	#110	0.85 - 0.9	700 - 750
#32	0.4 - 0.45	600 - 3000	#111	0.85 - 0.9	750 - 800
#33	0.45 - 0.5	200 - 350	#112	0.85 - 0.9	800 - 850
#34	0.45 - 0.5	350 - 400	#113	0.85 - 0.9	850 - 900
#35	0.45 - 0.5	400 - 430	#114	0.85 - 0.9	900 - 950
#36	0.45 - 0.5	430 - 500	#115	0.85 - 0.9	950 - 1100
#37	0.45 - 0.5	500 - 600	#116	0.85 - 0.9	1100 - 1300
#38	0.45 - 0.5	600 - 3000	#117	0.85 - 0.9	1300 - 1500
#39	0.5 - 0.55	200 - 350	#118	0.85 - 0.9	1500 - 3000
#40	0.5 - 0.55	350 - 400	#119	0.9 - 0.95	200 - 350
#41	0.5 - 0.55	400 - 470	#120	0.9 - 0.95	350 - 430
#42	0.5 - 0.55	470 - 500	#121	0.9 - 0.95	430 - 500
#43	0.5 - 0.55	500 - 600	#122	0.9 - 0.95	500 - 550
#44	0.5 - 0.55	600 - 3000	#123	0.9 - 0.95	550 - 600
#45	0.55 - 0.6	200 - 350	#124	0.9 - 0.95	600 - 650
#46	0.55 - 0.6	350 - 400	#125	0.9 - 0.95	650 - 700
#47	0.55 - 0.6	400 - 450	#126	0.9 - 0.95	700 - 750
#48	0.55 - 0.6	450 - 500	#127	0.9 - 0.95	750 - 800

Table B.7: CC0 π sideband sample bin edges (*continued*)

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]
#49	0.55 - 0.6	500 - 560	#128	0.9 - 0.95	800 - 850
#50	0.55 - 0.6	560 - 3000	#129	0.9 - 0.95	850 - 900
#51	0.6 - 0.65	200 - 325	#130	0.9 - 0.95	900 - 1000
#52	0.6 - 0.65	325 - 375	#131	0.9 - 0.95	1000 - 1100
#53	0.6 - 0.65	375 - 400	#132	0.9 - 0.95	1100 - 1300
#54	0.6 - 0.65	400 - 470	#133	0.9 - 0.95	1300 - 1500
#55	0.6 - 0.65	470 - 500	#134	0.9 - 0.95	1500 - 1700
#56	0.6 - 0.65	500 - 600	#135	0.9 - 0.95	1700 - 3000
#57	0.6 - 0.65	600 - 3000	#136	0.95 - 0.98	200 - 350
#58	0.65 - 0.7	200 - 350	#137	0.95 - 0.98	350 - 500
#59	0.65 - 0.7	350 - 400	#138	0.95 - 0.98	500 - 600
#60	0.65 - 0.7	400 - 450	#139	0.95 - 0.98	600 - 700
#61	0.65 - 0.7	450 - 500	#140	0.95 - 0.98	700 - 800
#62	0.65 - 0.7	500 - 525	#141	0.95 - 0.98	800 - 900
#63	0.65 - 0.7	525 - 550	#142	0.95 - 0.98	900 - 1000
#64	0.65 - 0.7	550 - 600	#143	0.95 - 0.98	1000 - 1100
#65	0.65 - 0.7	600 - 700	#144	0.95 - 0.98	1100 - 1300
#66	0.65 - 0.7	700 - 3000	#145	0.95 - 0.98	1300 - 1500
#67	0.7 - 0.75	200 - 350	#146	0.95 - 0.98	1500 - 1800
#68	0.7 - 0.75	350 - 400	#147	0.95 - 0.98	1800 - 3000
#69	0.7 - 0.75	400 - 430	#148	0.98 - 1	200 - 600
#70	0.7 - 0.75	430 - 500	#149	0.98 - 1	600 - 800
#71	0.7 - 0.75	500 - 550	#150	0.98 - 1	800 - 1000
#72	0.7 - 0.75	550 - 600	#151	0.98 - 1	1000 - 1200
#73	0.7 - 0.75	600 - 650	#152	0.98 - 1	1200 - 1420

Table B.7: CC0 π sideband sample bin edges (*continued*)

Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]	Bin index	$\cos(\theta_\mu)$ [$^\circ$]	p_μ [MeV]
#74	0.7 - 0.75	640 - 690	#153	0.98 - 1	1420 - 1700
#75	0.7 - 0.75	690 - 800	#154	0.98 - 1	1700 - 2100
#76	0.7 - 0.75	800 - 1000	#155	0.98 - 1	2100 - 2300
#77	0.7 - 0.75	1000 - 3000	#156	0.98 - 1	2300 - 3000
#78	0.75 - 0.8	200 - 400	#157	-1 - 1	0 - 200
#79	0.75 - 0.8	400 - 430	#158	-1 - 1	3000 - 30000

B.5 TRUTH TO RECONSTRUCTION SMEARING

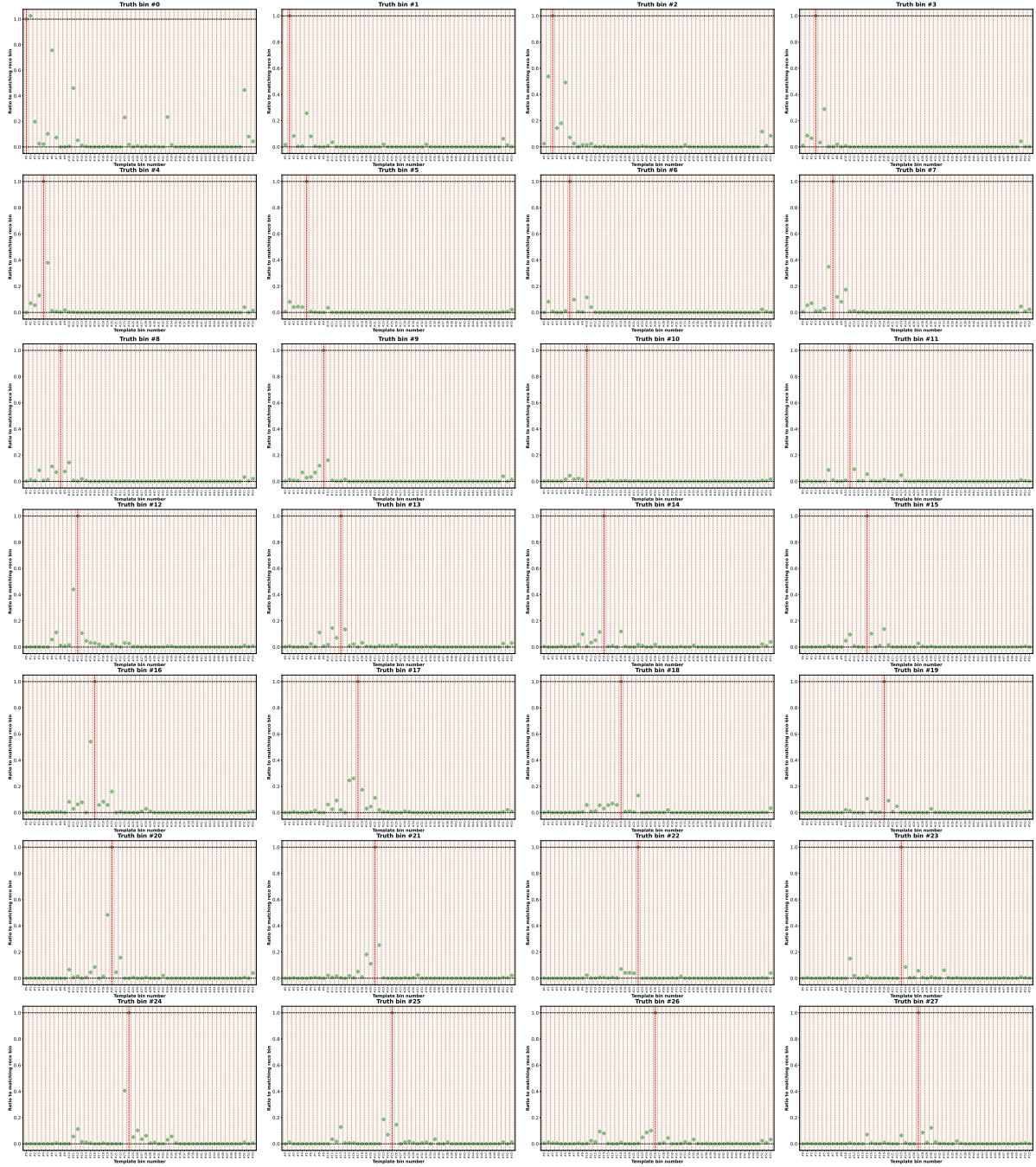


Figure B.1: Smearing from truth to reconstructed space for the selected $\text{CC}1\pi^+$ signal sample. Truth bin is highlighted by the red dashed line. Events in other bins are expressed as fractions of the normalized event rate in the same reconstructed bin (First 28 bins). Final three bins represent out-of-phase-space kinematic regions.

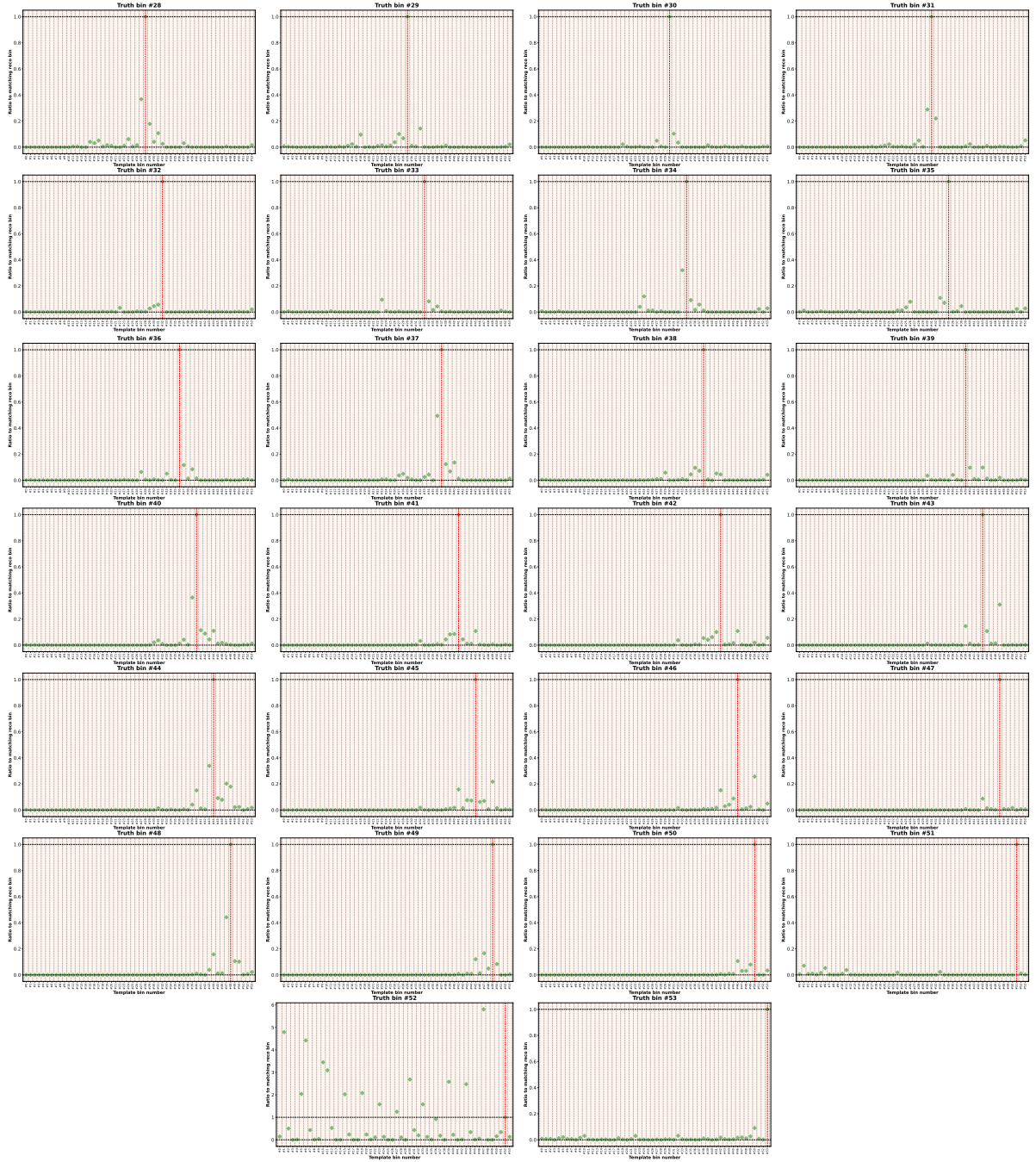


Figure B.2: Smearing from truth to reconstructed space for the selected $\text{CC1}\pi^+$ signal sample. Truth bin is highlighted by the red dashed line. Events in other bins are expressed as fractions of the normalized event rate in the same reconstructed bin (Last 26 bins). Final three bins represent out-of-phase-space kinematic regions.

DETECTOR SYSTEMATIC UNCERTAINTIES

C

This appendix contains in-depth discussions on the different systematic uncertainties associated with the detector's response. If more information is required, the reader is referred to the technotes as listed in these paragraphs or in table [9.1](#).

C.1 B-FIELD DISTORTIONS

The entire ND280 tracker region comprising the FGDs, the TPCs, the ECals and the POD is housed in the UA1 magnet. Distortions in the field produced by this magnet thus affects each of these components. In particular, it affects the TPC field which is used to determine the momentum of crossing particles through the curvature of their tracks. These distortions are treated by two separate corrections: The empirical correction and the B-field correction [[190](#)].

The first is constructed by shining a laser on aluminum dots on the cathode and thereby releasing photo-electrons. These electrons drift towards the anode where they are detected. This is done with both the magnetic field on and off to distinguish between the distortions induced by the B-field and those inherent to the TPC E-field. Finally, the expected recorded position is compared to the actual recorded position to find the map as a function of drift distance.

The second correction incorporates the magnetic field map from measurements within the tracker to reverse the drifting operation. The hit cluster on the anode is now drifted back

to its point of ionization and the field map is used to correct the positions of the clusters. Combined these two corrections give the B-field distortion systematic uncertainty.

C.2 TPC MOMENTUM RESOLUTION

For particles that leave more than 18 separate clusters in the TPC, the momentum is reconstructed using their tracks' curvature as a result of the magnetic field. The uncertainty in measuring this curvature is captured by the TPC momentum resolution systematic. It is derived by looking at tracks that have several measurements points, i.e. cross multiple TPCs so their individual measurements can be used as cross checks for the global momentum reconstruction [191].

By comparing the resolution in both data and Monte Carlo, a smearing factor can be found that covers the discrepancy. As the reconstructed momentum depends on the propagation direction of the particle (forward or backward), the track is characterised by the transverse momentum with respect to the magnetic field lines. The inverse of this kinematic variable is evaluated in each TPC segment and compared to the value in neighbouring TPCs. A correction is applied to account for the energy loss in the encompassed FGD.

The resulting distribution shows gaussian behavior centered around zero, where the shape is the result of the resolution inherent to the TPC. The systematic is then found by first smearing the Monte Carlo tracks to have better agreement between the two inverse transverse momentum distributions and then varying the inverse transverse momentum to recalculate the global reconstructed particle's momentum and the momentum assigned to each TPC segment.

The relative errors for the TPC momentum resolution as a function of muon and positive pion kinematic variables can be found in figures C.1 and C.2.

C.3 TPC MOMENTUM SCALE

This systematic comes from the uncertainty of the magnetic field measurements that were performed in ND280 before its operation. The systematic is propagated with a relative error of 0.57% and returns in the momenta of the particle tracks[192].

The relative errors for the TPC momentum scale as a function of muon and positive pion kinematic variables can be found in figures C.3 and C.4.

C.4 TPC PARTICLE IDENTIFICATION

Particles are identified by their characteristic energy loss dE/dx curve in the material of the TPC. This is done through adhering a likelihood score to a certain track. Distinguishing between muons and pions for the TPC identified leading momentum track is important

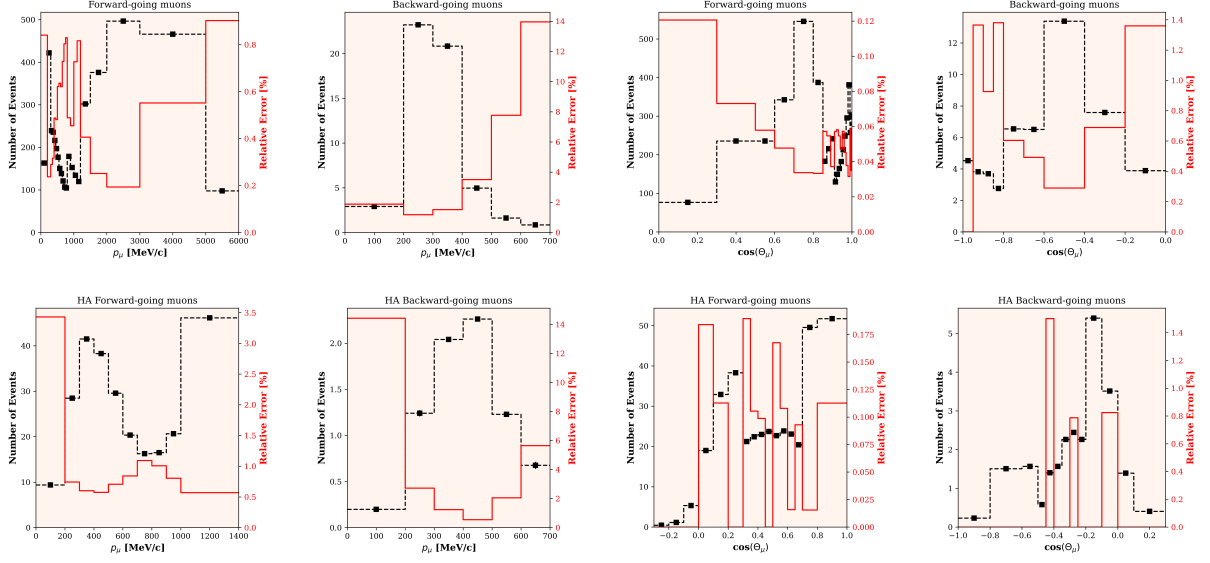


Figure C.1: Relative errors (using NEUT) as function of muon momentum (left-hand set) and muon cosine of theta (right-hand set) distributions for the TPC momentum resolution systematic for the $\text{CC}1\pi^+$ sample.

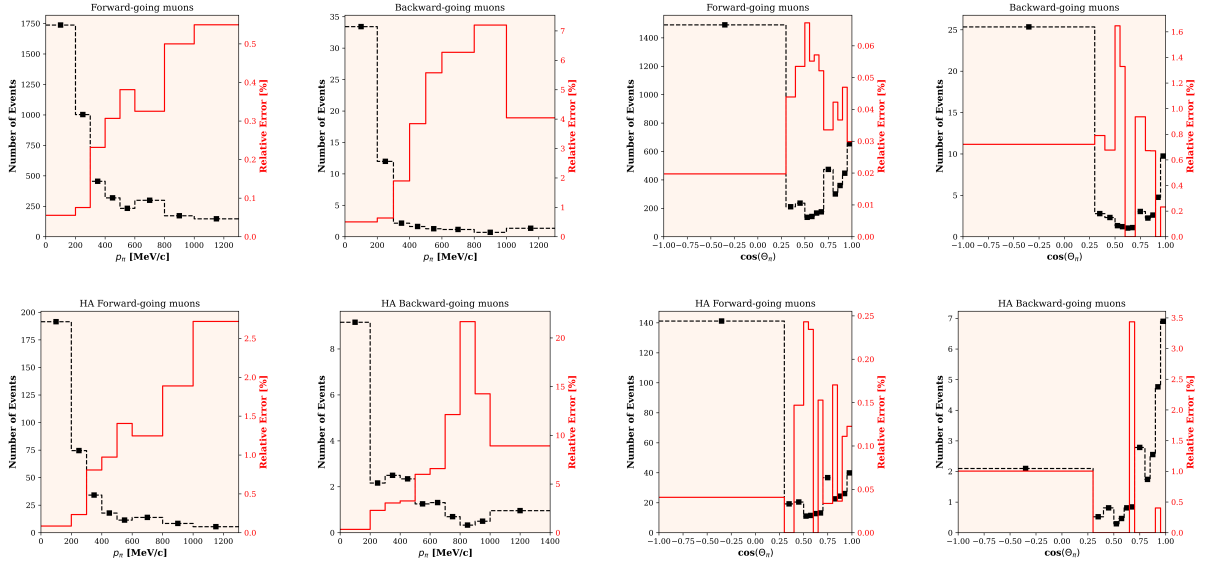


Figure C.2: Relative errors (using NEUT) as function of positive pion momentum (left-hand set) and positive pion cosine of theta (right-hand set) distributions for the TPC momentum resolution systematic for the $\text{CC}1\pi^+$ sample.

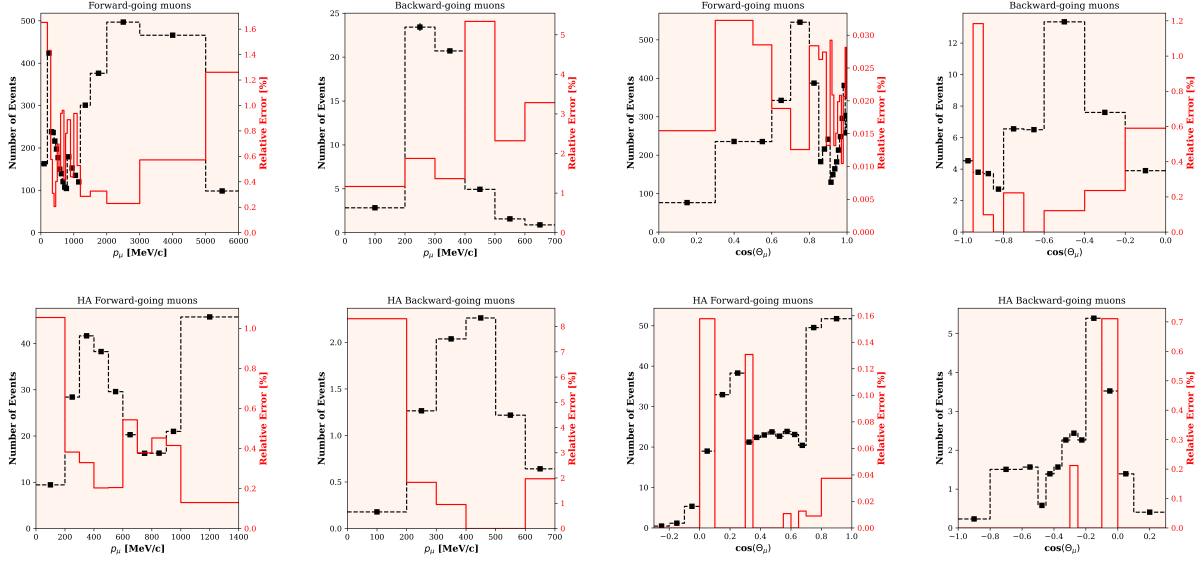


Figure C.3: Relative errors (using NEUT) as function of muon momentum (left-hand set) and muon cosine of theta (right-hand set) distributions for the TPC momentum scale systematic for the $\text{CC}1\pi^+$ sample.

as a misrepresentation of the particle in question will lead to an improper reconstruction of the initial energy and or interaction process. A similar thing can happen in the case of protons and pions and to a lesser degree for electron and pions or muons.

The systematic is evaluated by studying the pull variables in MC and data control samples for protons, muons and electrons. The proton sample is obtained from beam events in the forward horn current mode. As the energy deposition for muons and pions is relatively similar, the sand muon sample (muons coming from the surrounding cavern) can be used for both.

For the propagation, two quantities are needed from the MC and data pull distributions after fitting the distributions to a Gaussian. Firstly, the difference between the mean values which provides an idea of the bias between MC and data and secondly the data over MC ratio of the standard deviations which is then used to understand the necessary smearing to be applied in the toy universes. A complete overview of the evaluation and propagation of the TPC-PID systematic is found in TN-221 [193]. Here, it is necessary to understand that the pull and likelihood variables are altered by varying the measured energy loss in each TPC segment in each toy universe.

The relative errors for the TPC PID as a function of muon and positive pion kinematic variables can be found in figures C.5 and C.6.

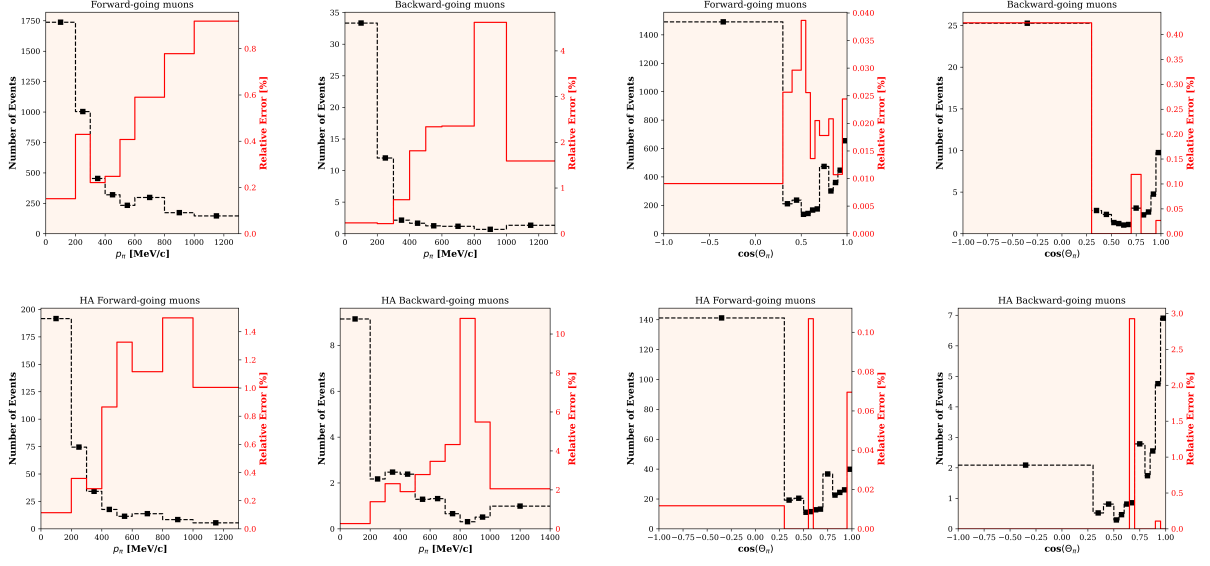


Figure C.4: Relative errors (using NEUT) as function of positive pion momentum (left-hand set) and positive pion cosine of theta (right-hand set) distributions for the TPC momentum scale systematic for the $\text{CC}1\pi^+$ sample.

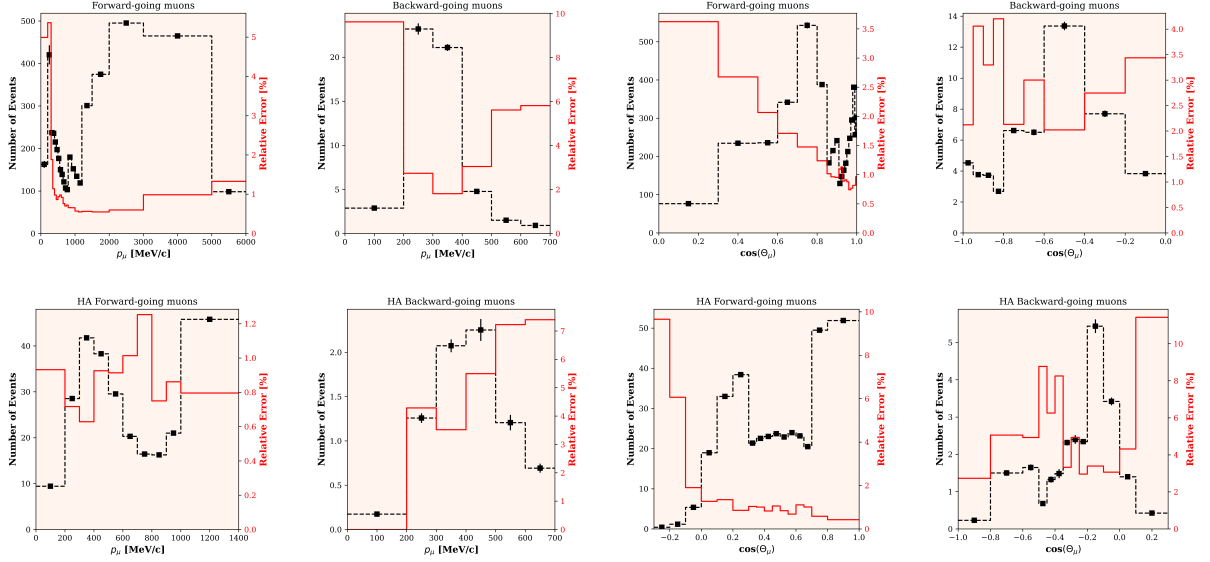


Figure C.5: Relative errors (using NEUT) as function of muon momentum (left-hand set) and muon cosine of theta (right-hand set) distributions for the TPC particle ID systematic for the $\text{CC}1\pi^+$ sample.

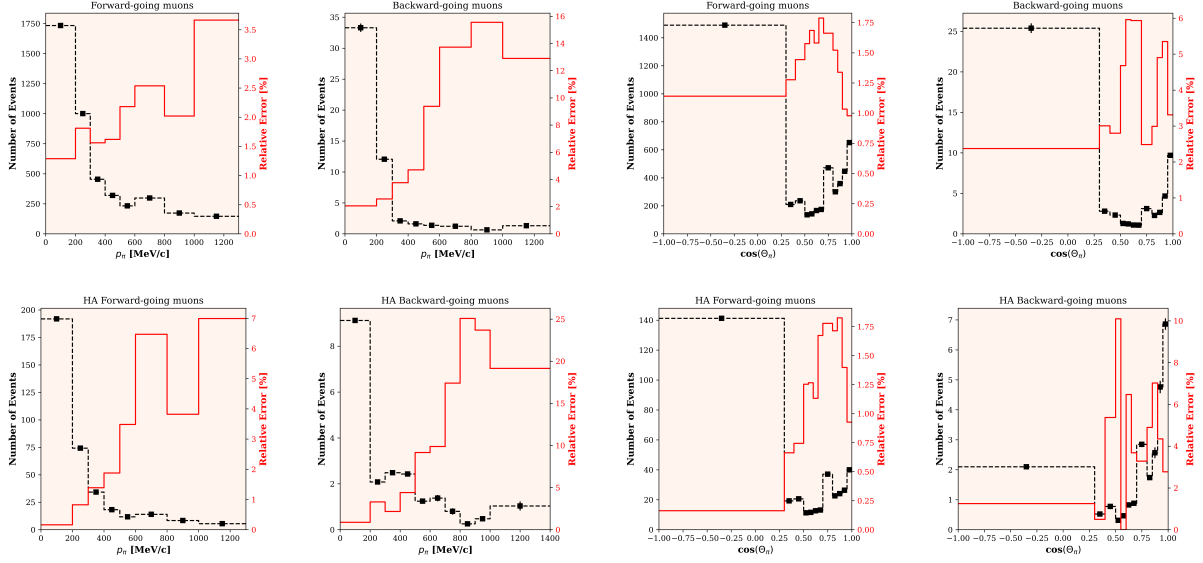


Figure C.6: Relative errors (using NEUT) as function of positive pion momentum (left-hand set) and positive pion cosine of theta (right-hand set) distributions for the TPC particle ID systematic for the CC1 π^+ sample.

C.5 MOMENTUM BY RANGE RESOLUTION

For particles that never make it into the TPC or do not leave significant number of clusters in it, and are thus classified as high-angle, the momentum can be estimated from the range of their trajectories. The reconstruction for these isolated tracks is dependent on how well the track length can be determined and how well the energy deposition is understood.

Here, the TPC measurement, provided the discrepancies between data and MC are now understood due to the momentum resolution studies, can actually be used to compare to the momentum found by the range calculation. The idea is that the control samples contain tracks that cross the TPC and stop in one of the other detectors. The momentum is then calculated in the two described ways in both MC and data. Any remaining discrepancies are the result of the error in the new method. How to move from this error to the systematic uncertainty itself is detailed in TN-216 [194].

C.6 MOMENTUM BIAS BY VERTEX MIGRATION

The neutrino interaction vertex for events inside the FGDs is found by looking at the start position of the muon candidate. It follows from a matching sequence between the TPC and FGD reconstructed objects that lie within the same time window. For the discussion here, it is only necessary to understand the consequences of inaccuracies in determining the vertex position. The scintillator bars in the FGD dictate its reconstruction resolution. For events in which the outgoing lepton and hadron are produced back to back, their

origin is hard to define. The same can be said for a lepton and a decay electron. These are the key factors in the backward-going direction. Furthermore, for events with high multiplicity several of the hits produced by other particles might be associated with the candidate muon. This is mainly caused by low momentum hadrons and is the dominant contribution for the mismatch in the forward going region.

Both of these scenarios affect the precision by which the position of the vertex can be determined leading to a measured FGD segment length that might not be consistent with the true vertex. This will introduce a bias in the reconstructed momentum for the cases where this length is used. The migration distance is higher in the backward-going directions due to the fact that the matching algorithm was optimized for forward-going tracks. In addition, the number of migrations is higher as well. This combination leads to a more prominent bias in the backward-going direction, while it is almost negligible in the forward one. To quantify the discrepancy between Monte Carlo and data the reconstructed momenta for TPC and FGD are compared. The energy loss is then inflated up until the point data and MC start to disagree and that becomes the smearing factor. Here it is set to 7MeV/c corresponding to three FGD layers for muons depositing around 2 MeV per centimeter.

The relative errors for the momentum bias by vertex migration as a function of muon and positive pion kinematic variables can be found in figures C.7 and C.8.

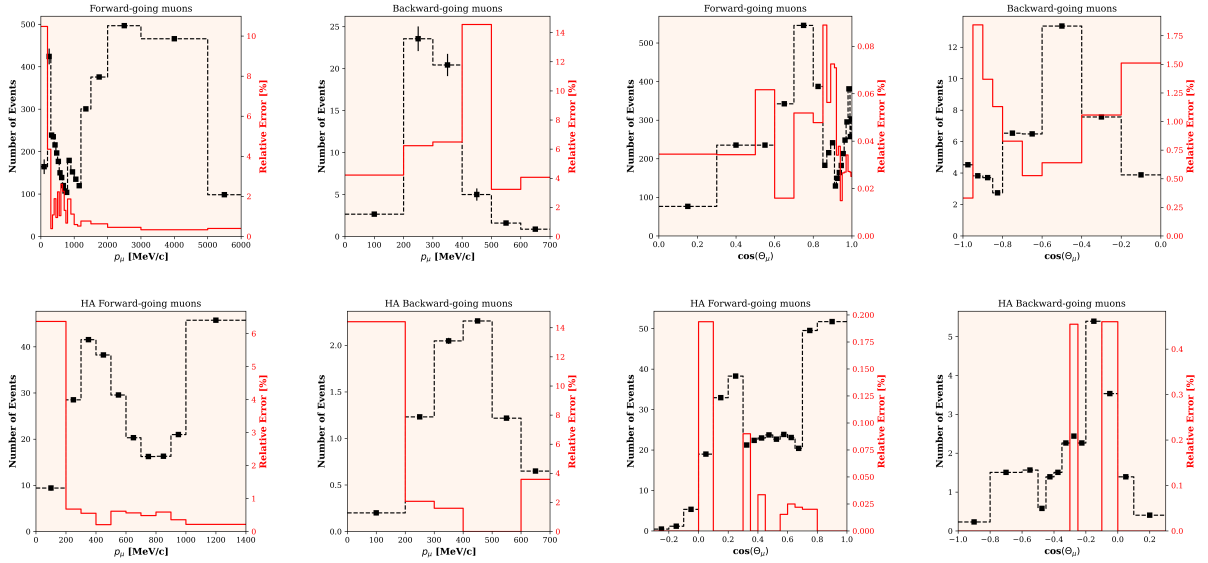


Figure C.7: Relative errors (using NEUT) as function of muon momentum (left-hand set) and muon cosine of theta (right-hand set) distributions for the momentum bias from vtx migration systematic for the CC1 π^+ sample.

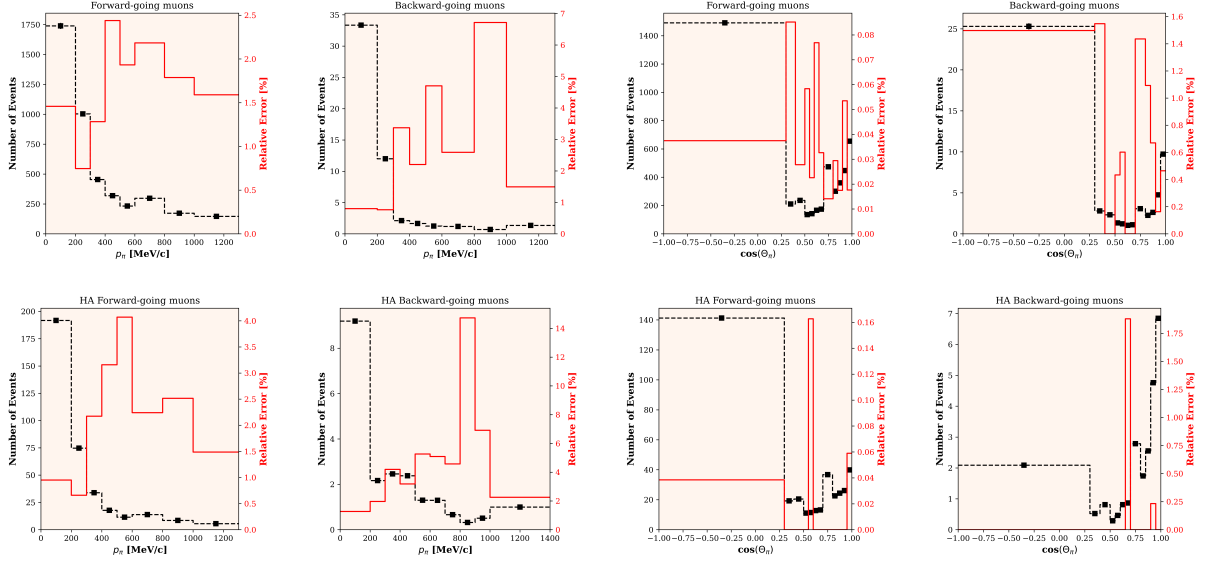


Figure C.8: Relative errors (using NEUT) as function of positive pion momentum (left-hand set) and positive pion cosine of theta (right-hand set) distributions for the momentum bias from vtx migration systematic for the CC1 π^+ sample.

C.7 FGD PARTICLE IDENTIFICATION

A similar strategy is employed for particles that are contained within the FGD detailed in TN-223 [195]. These particles lose all their kinetic energy through ionization without reinteracting. The structure of the FGD allows for a distance measurement through identifying the bars that were hit. The relationship between the deposited energy and this range can be used to distinguish between different particle masses.

This particle identification is done through the pull variable, which is the energy spread normalized difference between the expected and measured energy depositions at a certain range. These pull distributions can be fit to a Gaussian and then studied with control samples. To distinguish between muons or pions and protons in these samples, the TPC is used for particle identification. This means that only those events with tracks that partially cross the TPC can be used.

Ultimately, a set of toy universes is created in which the FGD PID measurement is varied in order to produce the systematic uncertainty. As muons and pions are very close in mass, their energy depositions will look rather similar leading to a single systematic that covers both particle hypotheses. Hence the FGD PID is primarily used to distinguish between positively charged pions and protons.

C.8 FGD PION MOMENTUM FROM ME RESOLUTION

The addition of the Michel electron-tagged pion sample to this analysis is accompanied by a systematic uncertainty to cover the inaccuracies in reconstructing the pion momentum

through its subsequent decay electron. It is evaluated in a similar way to the method used in the momentum by range case as this too relies on such a conversion. It then straightforwardly follows that the pion momentum resulting from the ME calculation should be compared to the momentum coming from a different source, namely the TPC.

To compare the two and arrive at an estimate of how well or poorly the method works, one control sample per FGD is constructed. The overarching requirement is that a pion travels through the TPC and stops in the first ten layers of the FGD, where a Michel electron is found as well. In these situations the event vertex lies outside the fiducial volume of the FGD meaning that the distance to the vertex can not be used. Instead the first observable hit in one of the FGD bars marks the starting point of the pion track. Now the distance between that point and the Michel vertex can be used to calculate the pion momentum. The TPC momentum is then used as reference. The distributions are not expected to be identical as the pion loses some energy in the TPC and the estimation through MEs is not perfect.

These methods are applied both in Monte Carlo and in data to quantify the differences between the two. It turns out that there is a 25% discrepancy across the entire momentum spectrum for both methods and both FGDs, which also returns in the residual distribution. To that end, an asymmetric Lorentzian was used as the fitting function. The uncertainty is then found by comparing the fit parameters of this function for the simulation and data.

C.9 ECAL EM SCALE & ECAL EM RESOLUTION

Particles that extend beyond the tracker region and make it through the FGDs and the TPCs meet the electromagnetic calorimeter at both the downstream end as well as the side regions as depicted in section 6.4.3.5. The electromagnetic energy associated with the clusters of hits triggered by these particles is calculated from three fundamental quantities; The total charge, the spread of the charge within the cluster and the asymmetry of the charge distribution. Out of the three, the EM energy seems to be most highly correlated with the first.

First, the distributions of these 3 quantities for a given input energy are created. Then, those distributions are fit to Gaussian functions for known constant energies allowing for the likelihood of any energy to be the true energy for any configuration of values for these three parameters to be calculated. Through-going or uncontained energy depositions will not be representative of the true energy of the incident particle. To combine all of this into a systematic uncertainty, the reconstructed energy can again be compared to what was found by the TPC. By looking at the TPC normalized difference between the ECal and the TPC found energies for Monte Carlo and data, discrepancies can be observed in both the scale and the resolution. These discrepancies are covered by the ECal EM Scale & ECal EM Resolution systematics [196].

C.10 TIME OF FLIGHT RESOLUTION

Track orientation or particle direction is derived from the time of flight measurements in several of the subsystems within ND280. The muon direction segmentation in the forward, backward, high-angle forward and high-angle backward regions is also a result of these measurements and the subsequent corrections [187].

The timing resolution provided by the different detector elements is not in agreement between data and Monte Carlo. The ToF distributions can be modeled by a sum of two Gaussian distributions for the forward and backward-going peaks respectively. Similarly to the discussion on the ECal EM energy, the difference between the data and MC is then fit to a Gaussian. This Gaussian is ultimately used to transform the MC to better mimic the data.

Due to the error-prone calculation of the ToF, the uncertainty is set to the maximum resolution correction for run 2, 3 and 4. For run 8, the uncertainty has to be inflated. In this run, the timing information from the inner detector became significantly worse. An independent study in TN-277 showed that the resolution for data with bad timing quality was three times wider than for data with good timing quality [208]. Hence the above-mentioned MC smearing to better match the data was increased by a factor of three for run 8 alone.

C.11 NEUTRINO PARENT DECAY VERTEX POSITION

The position from which the neutrinos originate lies somewhere in the decay pipe. As this value is used to derive several kinematic variables down the line, any uncertainty in determining it could result in inaccuracies in the description of the event. One example of this is the transverse momentum for which one needs to project the daughter particles' directions on to the surface perpendicular to the neutrino direction. For a particular interaction vertex, the mean is taken over a distribution of neutrino parent decay points to find the decay vertex. From those two points the neutrino direction can be estimated. In its current state this parameter varies the decay vertex position to resemble the effect of our ignorance.

The relative errors for the neutrino parent decay vertex position as a function of muon and positive pion kinematic variables can be found in figures C.9 and C.10.

C.12 TPC CHARGE IDENTIFICATION EFFICIENCY

Deducing whether the particle in question is positively or negatively charged is done with the curvature of its track in the TPC. The curvature is a convolution of the track length, the number of hits and the spatial resolution at every cluster or segment. Highly energetic particles with high rigidity will have a near linear track, which reduces the accuracy of the

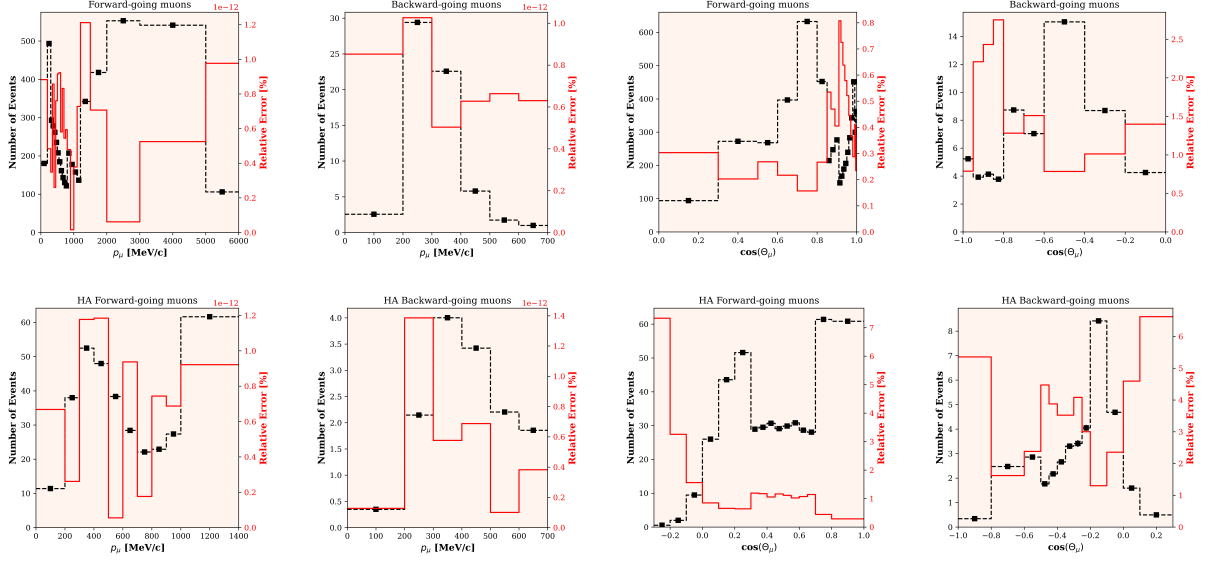


Figure C.9: Relative errors (using NEUT) as function of muon momentum (left-hand set) and muon cosine of theta (right-hand set) distributions for the neutrino parent decay position systematic for the $\text{CC}1\pi^+$ sample.

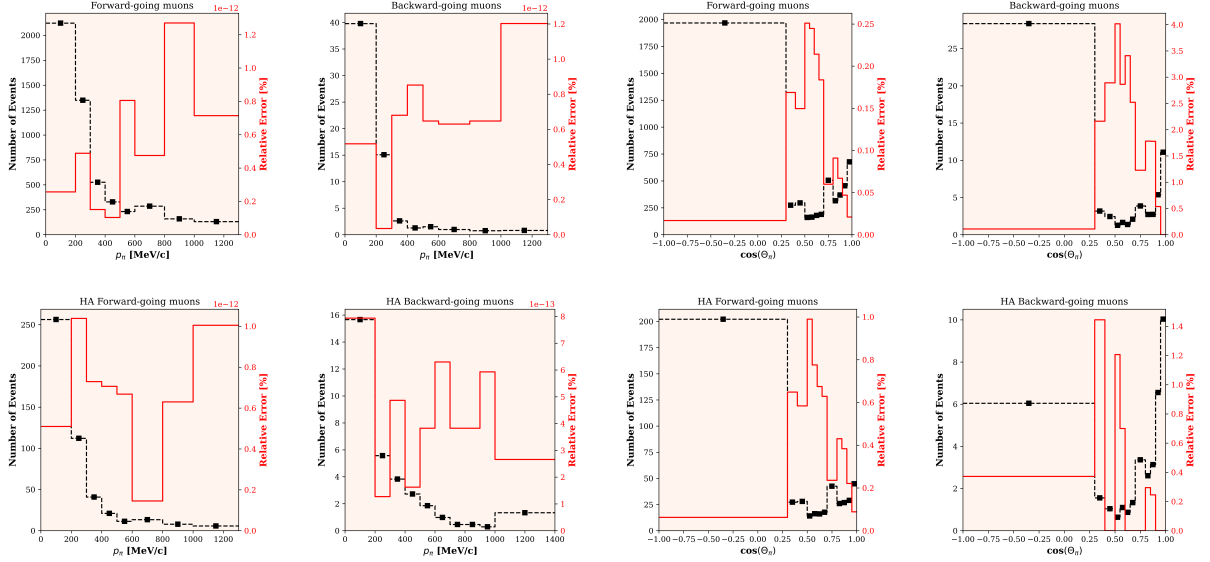


Figure C.10: Relative errors (using NEUT) as function of positive pion momentum (left-hand set) and positive pion cosine of theta (right-hand set) distributions for the neutrino parent decay position systematic for the $\text{CC}1\pi^+$ sample.

charge determination. The charge identification relies on the measurements from multiple subdetectors leading to two different systematic errors. On the one hand, there is the probability of swapping the charge identification on a cluster by cluster basis (local). On the other hand, the global track could be swapped based on the best local elements.

The control sample consists of particles crossing all three TPCs. The efficiency for the charge identification is then calculated by subtracting the probability of misidentifying the charge from 1 in both data and Monte Carlo and binned in track momentum. The error on the track momentum is then used to parameterise the disagreement [197].

C.13 TPC CLUSTER EFFICIENCY

Charged particles crossing the TPCs ionize the Argon gas mixture. To be considered a potential muon candidate, the particle has to leave behind at least 19 clusters. The TPC cluster efficiency describes the capability of the detector to reconstruct those clusters from the hits in the adjacent TPC pads. Missing one or more might lead to a reduction in muon or other charged particle candidates leading to inaccuracies in determining the underlying process[198].

The clustering is done in different dimensions based on the track angle with respect to the beam direction. For angles above 55 degrees horizontal hits are used and vice versa. The same strategy is used when trying to resolve the differences between the Monte Carlo and the data. In the control sample, muon-like tracks crossing the entire length of the width of the detector are used to benchmark the efficiency ϵ . At an $\epsilon = 100\%$, every horizontal and vertical cluster should be included. In reality, the efficiency lies around 99.5%. To rescale the MC to better match the data, the following factor is determined in both directions:

$$\alpha = \frac{\epsilon_{MC} - \epsilon_{data}}{\epsilon_{MC}} \quad (C.1)$$

The weighting as a result of the α factor will be applied to the track that only just passed the TPC quality cut as these situations are most affected.

C.14 TPC TRACKING EFFICIENCY

The goal of finding this set of clusters is to reconstruct the TPC track segment corresponding to a propagating charged particle. The track efficiency describes what the percentage is of doing so correctly in each of the three TPCs. To estimate the efficiency a control sample is constructed from muon tracks that pass through the TPC under investigation and have at least partial tracks in two of the adjacent detectors excluding the FGDs. This means that for TPC1, the P0D and TPC2 would be used [199].

In table C.1, a summary of the study can be found. Surprisingly enough none of the values depend on the momentum, the angle or the length of the considered track.

	TPC1	TPC2	TPC3
ε_{Data}	$99.9^{+0.1\%}_{-0.1\%}$	$99.7^{+0.2\%}_{-0.7\%}$	$99.3^{+0.5\%}_{-0.9\%}$
ε_{MC}	$99.6^{+0.2\%}_{-0.3\%}$	$99.5^{+0.3\%}_{-0.4\%}$	$99.8^{+0.1\%}_{-0.2\%}$

Table C.1: TPC tracking efficiencies

C.15 FGD HYBRID TRACKING EFFICIENCY

As the name suggests, this systematic uncertainty covers the reconstruction of FGD contained or isolated tracks, which constitute a considerable amount of the pions in the CC1 π signal sample [195]. The efficiency describes how well these particular tracks are reconstructed in the presence of a FGD-TPC matched muon candidates. It is called hybrid, because the test samples contain additional simulated FGD-isolated tracks on top of the CC0 π selection in both data and Monte Carlo. For around a thousand vertices, a Geant particle gun was used to produce pions and protons originating from the muon vertex before the entire data set was run through the FGD only reconstruction again.

Knowing both the apparent CC0 π and the truth of the added simulation allows to study the ability for the detector to find the pions and protons. The efficiency is calculated as the fraction of events with a least one correctly reconstructed track to the total number of events. In the scenario where the pion and proton propagated in the same direction as the muon, the efficiency was significantly lower as more of the FGD hits were assigned to the muon. The systematic uncertainty is designed by the difference between the data-hybrid and MC-hybrid samples.

C.16 ECAL TRACKING EFFICIENCY

There are different signatures that the particles can leave behind in the ECal. They can be through-going or contained and in the shape of showers or simple tracks. It is also beneficial to separate between the downstream and barrel ECals. This is exactly how the 4 control samples were constructed; DSECal shower-like, DSECal track-like, BarrelECal shower-like and BarrelECal track-like. Only high quality TPC tracks pointing in the direction of the ECal under investigation were used.

Showers were isolated from tracks by taking an enhanced e⁺/e⁻ sample and requiring the candidate track to not be the highest momentum negative track. This rejected the muons. To reject the protons at the higher energy end of the spectrum, a momentum cut was placed at 700 MeV. For the tracks, a muon PID cut was used. These cuts yielded around 80% and 76% showers and 91% and 85% tracks for the downstream and barrel ECal samples. After some additional manipulation listed in TN-279, the data is compared to the Monte Carlo to extract the systematic uncertainty [196].

C.17 ECAL PHOTON PILE-UP

The electromagnetic calorimeter is utilized in several steps of this analysis to reduce backgrounds mainly coming from π^0 's. It also plays a key role in the high angle samples as the ECals are located at the outer edges of the detector. The photon pile-up in the ECal coming from interactions unrelated to neutrinos could interfere with our understanding of the event's characteristics. Any isolated ECal object could be the result of a pile-up interaction and hence this systematic is applied to all events that contain such objects.

$$\text{Eff}_{\text{pile-up}} = \frac{\#(\text{events with ECal photons} \cap \text{no FGD activity})}{\#(\text{events with no FGD activity})} \quad (\text{C.2})$$

It is evaluated by introducing a control sample that has no FGD activity after the standard set of quality cuts. All activity outside the fiducial volume is then regarded as pile-up. Using equation C.2 to calculate the efficiency of selecting isolated photons in the electromagnetic calorimeter in both the simulation and in data allows for the difference to be used as the systematic uncertainty. In table C.2, these efficiencies are summarized. The number of isolated objects scale with the protons on target. The total integrated relative error for this systematic is 0.08% for CC1 π^+ [209].

Run	POT/spill in MC / 10^{13}	MC Efficiency (%)		Data Efficiency (%)	
		FGD1	FGD2	FGD1	FGD2
2	7.9891	1.779%	1.787%	2.163%	2.176%
3	9.463	2.103%	2.112%	2.494%	2.507%
4	9.463	2.103%	2.113%	2.999%	3.011%
8	22.7024	4.947%	4.962%	5.799%	5.819%

Table C.2: Table highlighting the effect of the protons on target on the ECal pile-up efficiencies for each FGD in each of the used run periods.

C.18 ECAL PID & ECAL EM HIP PID

Particle identification can be attempted in each of the subdetectors in ND280, but the ECal is especially proficient in discriminating electrons and photons from muons through the MIP-EM variable and from stopping proton tracks via the EM-HIP variable. It is important to quantify the bias on these parameters as particle IDs could migrate from one type to another redefining the topology of the entire interaction. The uncertainty on the ECal PID is constructed by looking at the difference in selection efficiencies between MC and data for all of the above-mentioned particles. The following criteria applied to the control samples in addition to MIP-EM > 0 and EM-HIP > 0 .

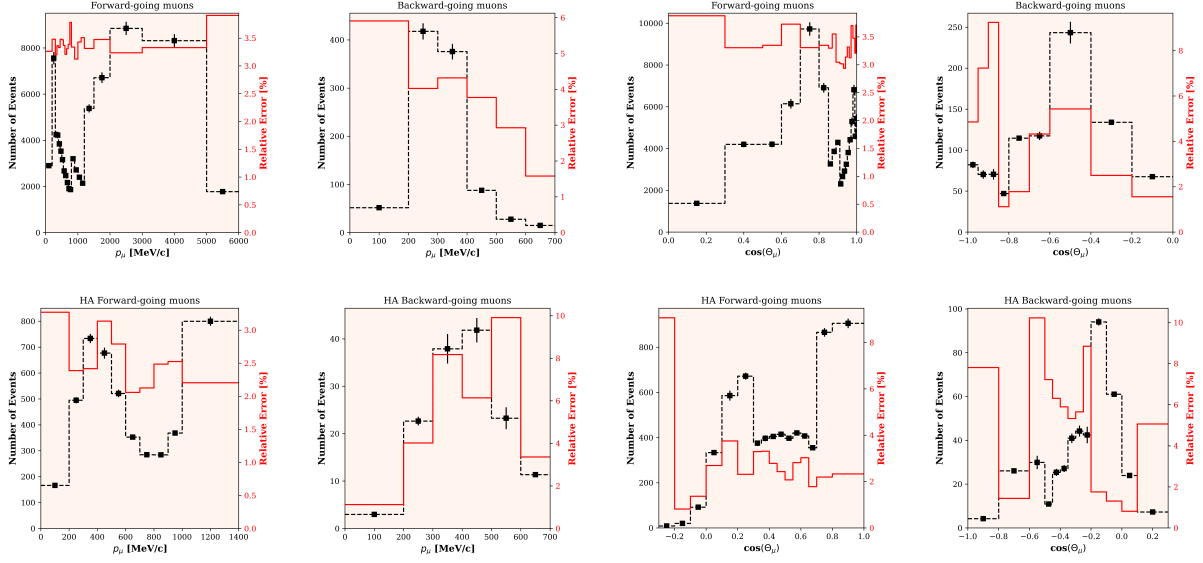


Figure C.11: Relative errors (using NEUT) as function of muon momentum (left-hand set) and muon cosine of theta (right-hand set) distributions for the ECAL EM HIP ID systematic for the CC1 π^+ sample.

- **Electrons:** a pair of oppositely charged tracks starting within 10 cm of each other and beginning in the FGD fiducial volume. Each track must have at least one TPC component with $-2 < e_{\text{pull}} < 2$ and the invariant mass of the pair must be below 50 MeV. At least one of the tracks must enter the ECal.
- **Through-going muons:** a track with three TPC components and one ECal component. Each TPC component must have $-2 < \mu_{\text{pull}} < 2$.
- **Cosmic muons:** a track with one TPC component and two ECal components. The TPC component must have at least 18 hits.
- **Protons:** a positive track in the TPC with $0 < p_{\text{pull}} < 2$ and $|\mu_{\text{pull}}| > 10$.

After calculating the efficiencies for each individual particle type, the systematic uncertainty can be evaluated. The uncertainty is only applied to events close to the limits set in the list above as the events with values very far away from these limits will not migrate across those boundaries by adding the additional uncertainty. In the case of the PIDEmHip variable, the largest uncertainty was found to be 3.9%. This means that domain: $y < \text{PIDEmHip} < x$ should contain 3.9% of ECal objects which is found to be: $-0.25 < \text{PIDEmHip} < 0.35$.

The relative errors for the ECal EM hip PID as a function of muon and positive pion kinematic variables can be found in figures C.11 and C.12.

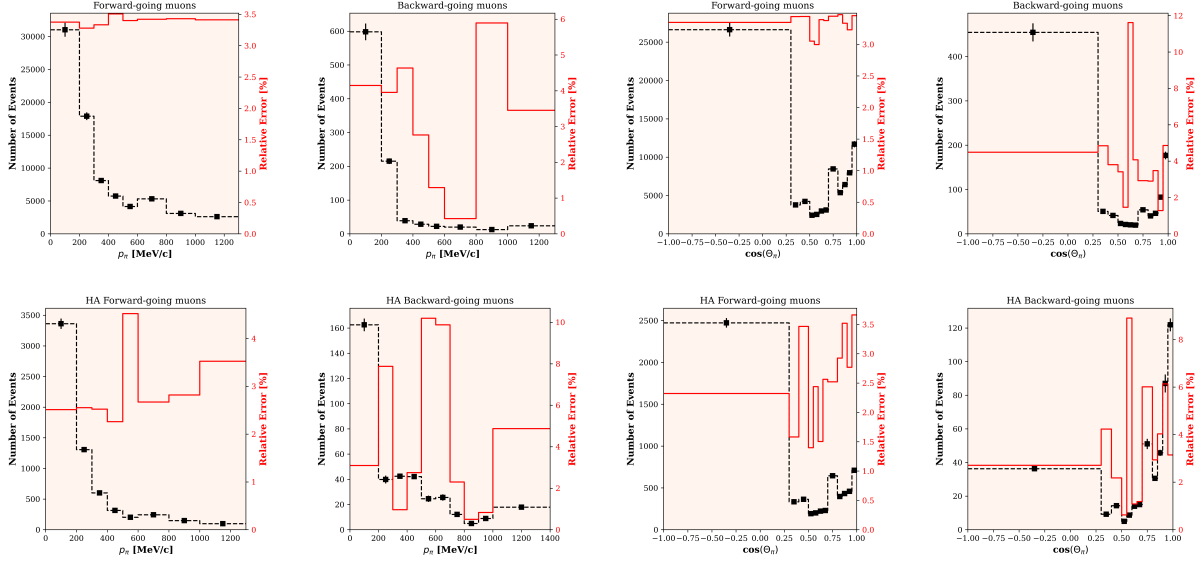


Figure C.12: Relative errors (using NEUT) as function of positive pion momentum (left-hand set) and positive pion cosine of theta (right-hand set) distributions for the ECAL EM HIP ID systematic for the CC1 π^+ sample.

C.19 MICHEL ELECTRON EFFICIENCY

Most of the low energy (200-400 MeV) pions in the signal region come from the identification of a Michel electron in the FGD. Both the detection of a suitable ME candidate and the level at which this is done correctly are taken into account in this systematic. They are however evaluated and studied separately.

The ME tagging efficiency is determined by looking at cosmic rays stopping in the fiducial volume of FGD1, have a quality track in TPC2 and no track in TPC1. To ensure that this is a muon dominated sample, the cosmic electrons are rejected by studying the momentum in TPC2 and comparing it to the stopping distance in FGD1 (TN-104) [200]. The Michel electron cut described earlier is applied and the efficiency is found by taking the remaining events and dividing it by the total number of stopping muon events. It was found to be $56.5 \pm 0.9\%$ for MC, and $56.4 \pm 0.2\%$ for data runs 2-4.

The purity of the sample after the selection cut is studied by estimating the contamination caused by particles entering the FGD from the outside and producing a similar signal to that of a Michel electron. They pass the cut and thus add to the external background rate. This rate is measured using periods of empty beam spills and hence no beam induced events in the FGD. The false identification rate is at $(0.7 \pm 0.009) \times 10^{-3}$ for MC and considerably larger in data at $(1.8 \pm 0.05) \times 10^{-3}$ [210].

C.20 PILE-UP

‘Sand’ muons are those that come from neutrino interactions in the materials surrounding the detector hall, which is primarily sand. They can still make it into the detector and pollute the neutrino events that do happen in the fiducial volume by depositing energy overlapping in time and space. Using the activity in TPC1 as a veto for this type of events, it can be shown that the majority of rejected events are not charged current interactions. This means that the coincidence of these muons with the magnet events can not be used directly and thus a correction must be made.

The correction is found by multiplying several parameters; Firstly, the number of TPC1 events N^{TPC} in a sand muon sample for a specific run period. Secondly, the data intensity POT/N_{spills} to find the effective number of spills and lastly the inverse of the POT and the inverse of the number of bunches per spill N_b . This correction is then applied to reduce the weight of MC events via:

$$w_{MC} = w_{MC} * (1 - C_{pileup}) \quad (C.3)$$

This however does not capture the full story. There is a 10% uncertainty in the sand muon simulation in addition to the differences between the actual and simulated beam intensity and between the description of the cavern materials, so a systematic on this pile-up contribution is included [201].

C.21 OUT OF FIDUCIAL VOLUME BACKGROUND

One of the final steps in the selection procedure was dedicated towards reducing the contamination from events coming from outside the fiducial volume (so-called ‘OOFV’ events). Especially in the backward-going direction, this background was very prominent. The general tendency is for these tracks to have been improperly matched between the FGD and the TPC [202]. Here the two contributions that make up the uncertainty in this background are discussed, namely the reconstruction and rate uncertainties.

In those categories where OOFV events are invalidly selected to be within the FGD fiducial volume, the reconstruction uncertainty reflects our misunderstanding of the probability to incorrectly reconstruct the vertex position.

The relative errors for the OOFV systematic as a function of muon and positive pion kinematic variables can be found in figures C.13 and C.14.

C.22 SAND MUON BACKGROUND

This background finds its origin in the sand that surrounds the detector hall. Beam neutrinos can interact with the sand and the resulting muons could enter the detector.

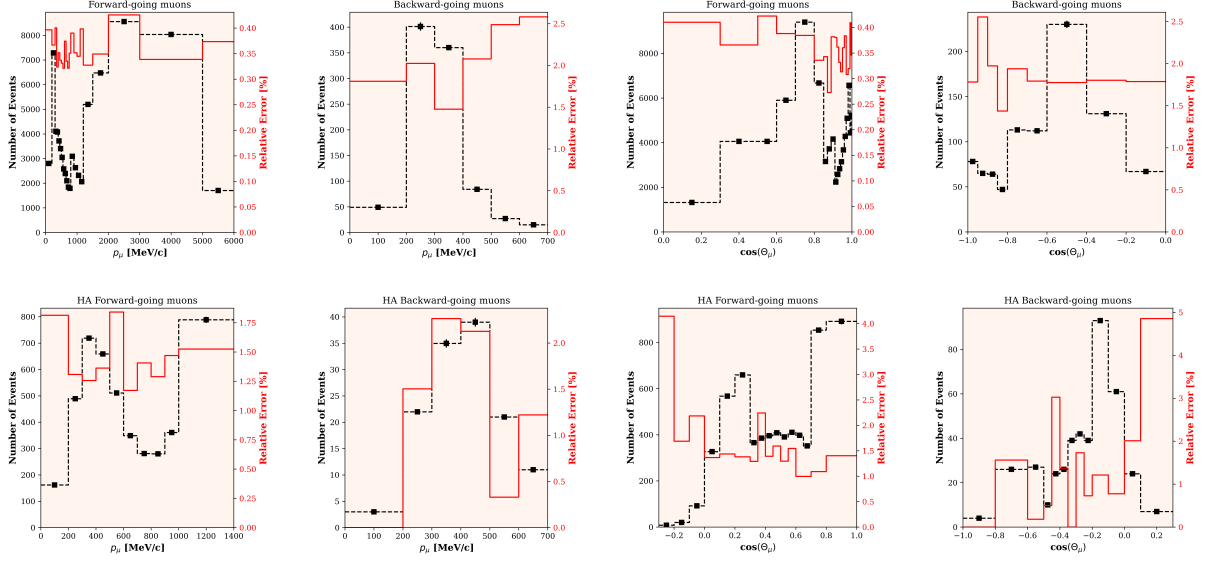


Figure C.13: Relative errors (using NEUT) as function of muon momentum (left-hand set) and muon cosine of theta (right-hand set) distributions for the OOFV systematic for the $\text{CC}1\pi^+$ sample.

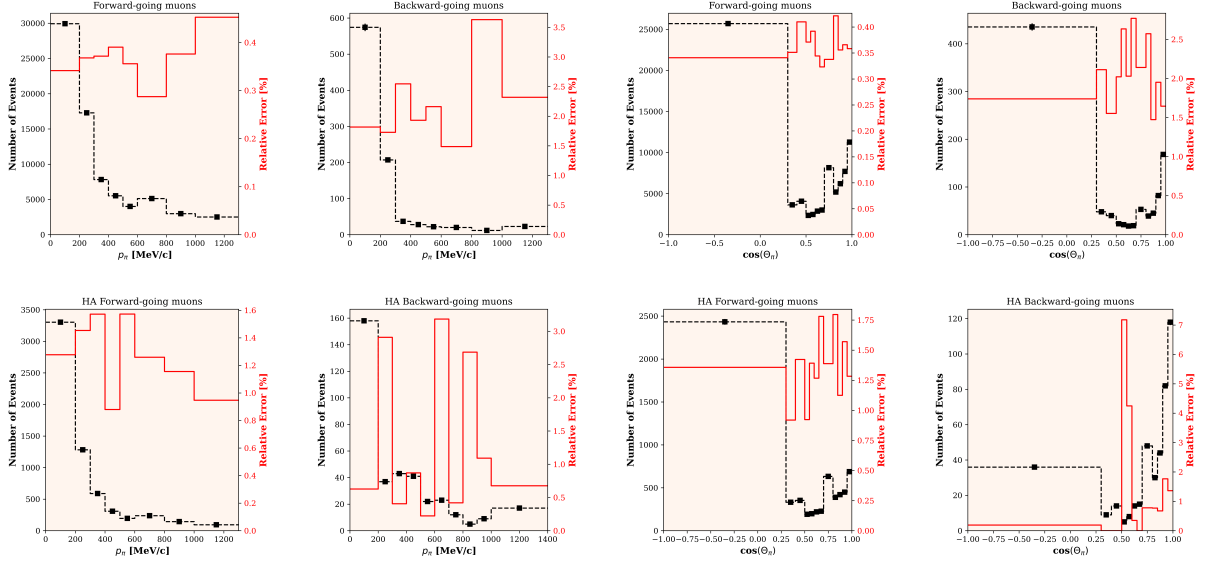


Figure C.14: Relative errors (using NEUT) as function of positive pion momentum (left-hand set) and positive pion cosine of theta (right-hand set) distributions for the OOFV systematic for the $\text{CC}1\pi^+$ sample.

The total event rate is compared to that in the data, through which a 10% discrepancy is observed [203].

C.23 TPC-FGD MATCHING EFFICIENCY

Tracing the charged particles in the TPC back to their origin would help identify the neutrino vertex which is required to be inside the FGD fiducial volume. As this leads to the track crossing multiple detectors, there has to be a mechanism to match both partial tracks to one another. This mechanism is not perfect and its accuracy can be determined by the TPC-FGD matching efficiency systematic uncertainties of which there are two in total[204].

On the one hand, we have the basic matching efficiency which describes the probability that the reconstructed track segments in the FGD and in the subsequent TPC coming from a single particle are actually reconstructed as such. To test this a through-going muon sample is utilized, where they cross the two TPCs surrounding the FGD. The systematic uncertainty is the result of comparing the matching efficiencies.

Its counterpart is the complete matching efficiency. This is introduced as the basic version is not sensitive to the chosen fiducial volume for either of the FGDs. "Complete" stands for the additional matching of the FGD-TPC segment to a track in the upstream TPC. There are two separate cases to study the full 3D behavior, one utilizing the sand muons (beam direction) and the other the cosmic rays (perpendicular directions). The results are listed in table C.3. An incomplete match occurs when the track originates

	< 200 MeV	> 200 MeV
ε_{Data}	99.35 $\pm$ 0.13%	99.979 $\pm$ 0.004%
ε_{MC}	99.71 $\pm$ 0.06%	99.98 $\pm$ 0.004%

Table C.3: TPC tracking efficiencies

from the fiducial volume of the FGD. Down the line this could lead to a misunderstanding of where the neutrino vertex is. As this considers out-of-fiducial-volume events, they are reweighted by the factor found from the incomplete matching study.

C.24 TPC-ECAL MATCHING EFFICIENCY

As is the case for any of the uncertainties associated with matching reconstructed objects between subdetectors, a comparison is made between the efficiency in data and in Monte Carlo. Here the segments that cross a TPC and one of the ECals (barrel or downstream) are used. To arrive at a control sample containing those segments, the tracks need to be of good quality, start in the FGD FV and have 18 clusters in the TPC. It is then split into tracks exiting through the side with an angle larger than 35° in the barrel case and pass through the end with an angle below 40° for the downstream case [196]. The efficiency

is calculated for each of the samples through equation C.4.

$$\epsilon = \frac{\text{Track passing selection with an ECal segment}}{\text{Track passing selection}} \quad (\text{C.4})$$

The error on this value is defined by the statistical uncertainties for MC and data added in quadrature.

C.25 TPC-P0D MATCHING EFFICIENCY

Assigning an efficiency to the matching of tracks between the TPC and the P0D is necessary as the timing information is used in the selection[187]. The efficiency is defined as the instances where an event in the control sample has a matched segment in the P0D. This sample consists of cosmic muons triggering the FGD with only one reconstructed track coming from at least 18 clusters in TPC1. On top of that, the event should be starting near the P0D and be within its integration window to ensure it is the same particle.

The systematic uncertainty is ultimately calculated through the comparison of these matching efficiencies for data and Monte Carlo and takes multiple factors into account such as the TPC-P0D matching, the P0D hit efficiency, and difference in detector dead material.

The relative errors for the TPC-P0D matching efficiency systematic as a function of muon and positive pion kinematic variables can be found in figures C.15 and C.16.

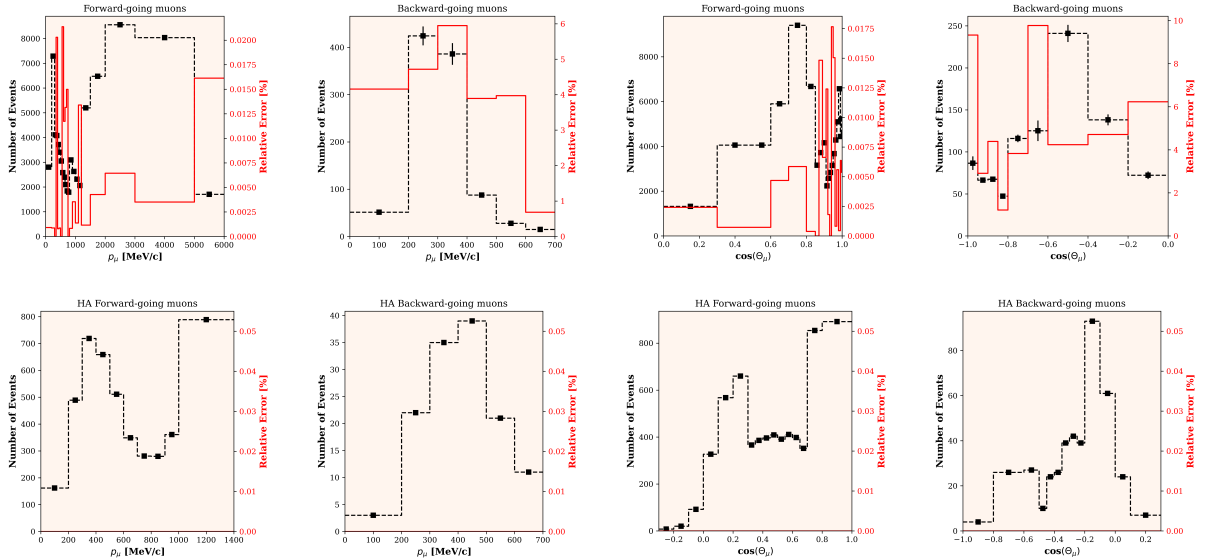


Figure C.15: Relative errors (using NEUT) as function of muon momentum (left-hand set) and cosine of theta (right-hand set) distributions for the TPC-P0D matching efficiency systematic for the CC1 π^+ sample (Note: Does not apply to HA samples).

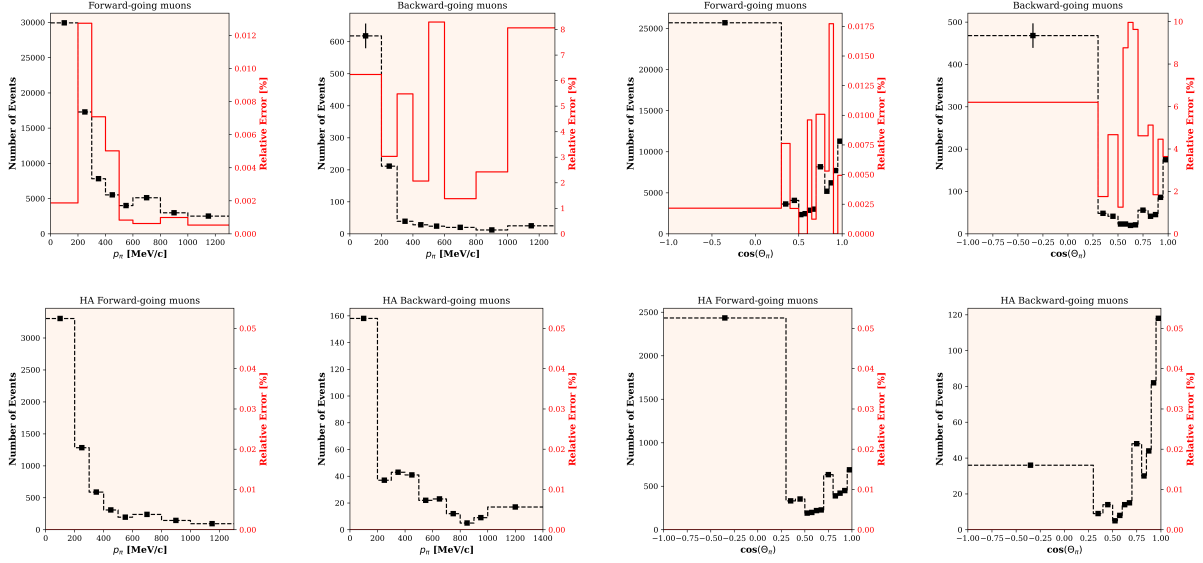


Figure C.16: Relative errors (using NEUT) as function of positive pion momentum (left-hand set) and cosine of theta (right-hand set) distributions for the TPC-P0D matching efficiency systematic for the $CC1\pi^+$ sample (Note: Does not apply to HA samples.)

C.26 FGD-ECAL MATCHING EFFICIENCY

Most particles that exit the FGD under high angles (near 90 degrees) will cross the electromagnetic calorimeter. The ECal now plays the role as seed for the FGD hits that the TPC played in the TPC-FGD matching scenario for the forward and backward-going samples. The efficiency is determined in control samples required to have no more than one track crossing the boundary between the FGD and the ECal and have enough information in the TPC to do a PID calculation on top of the conventional level of event quality. In tabel C.4 the efficiencies for both MC and data are shown. The systematic is based on the difference between these two values in each of the different cosine of the angle bins.

$\cos \theta$	ϵ_{Data}	ϵ_{MC}
$[-1, -0.4]$	$0.56^{+0.013}_{-0.013}$	0.638 ± 0.0064
$[-0.4, 0.4]$	$0.47^{+0.010}_{-0.010}$	0.522 ± 0.0048
$[0.4, 1]$	$0.42^{+0.022}_{-0.022}$	0.45 ± 0.010

Table C.4: FGD-ECal matching efficiencies in several cosine of the angle bins for data and MC

C.27 FGD-ECAL-SMRD MATCHING EFFICIENCY

Using the same logic as in the previous matching efficiency evaluations, here too the ratio is derived between the correctly matched segments in the FGD, ECal and SMRD and the total matched segments. The cuts to arrive at the desired control sample consist of one singular track in the SMRD, one in the FGD and enough information in the TPC

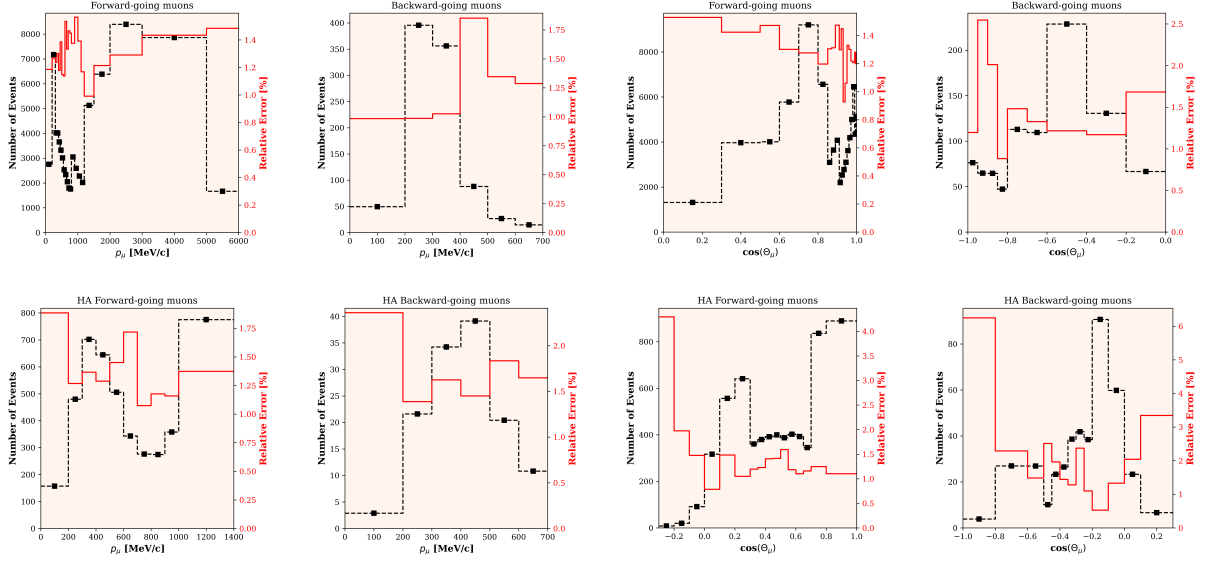


Figure C.17: Relative errors (using NEUT) as function of muon momentum (left-hand set) and muon cosine of theta (right-hand set) distributions for the pion secondary interactions systematic for the CC1 π^+ sample.

to do a PID estimation. Once that is done, the same data-MC comparisons are used to construct a systematic uncertainty. A more thorough overview can be found in TN-341 [211].

C.28 PION SECONDARY INTERACTIONS

Pions originating from the neutrino interaction vertex that made their way out of the nucleus can re-interact with the detector material. This is referred to as pion secondary interactions. There is a wide variety of different processes possible, but the protagonists are: Elastic scattering, Quasi-Elastic scattering, Absorption and Single Charge Exchange [206]. Each of these can lead to either a change in the pion's momentum or its type which could affect the reconstructed topology.

These secondary interactions have been studied for data and Geant4 based Monte Carlo and major discrepancies have been observed in the past. They were so prominent in fact that this has been the largest systematic uncertainty in many T2K analyses. To reduce these systematics a fit with all the available external pion scattering data was performed to reduce the pion interaction cross-section uncertainties used in computing the pionSI systematic uncertainty.

The relative errors for the pion secondary interaction systematic as a function of muon and positive pion kinematic variables can be found in figures C.17 and C.18.

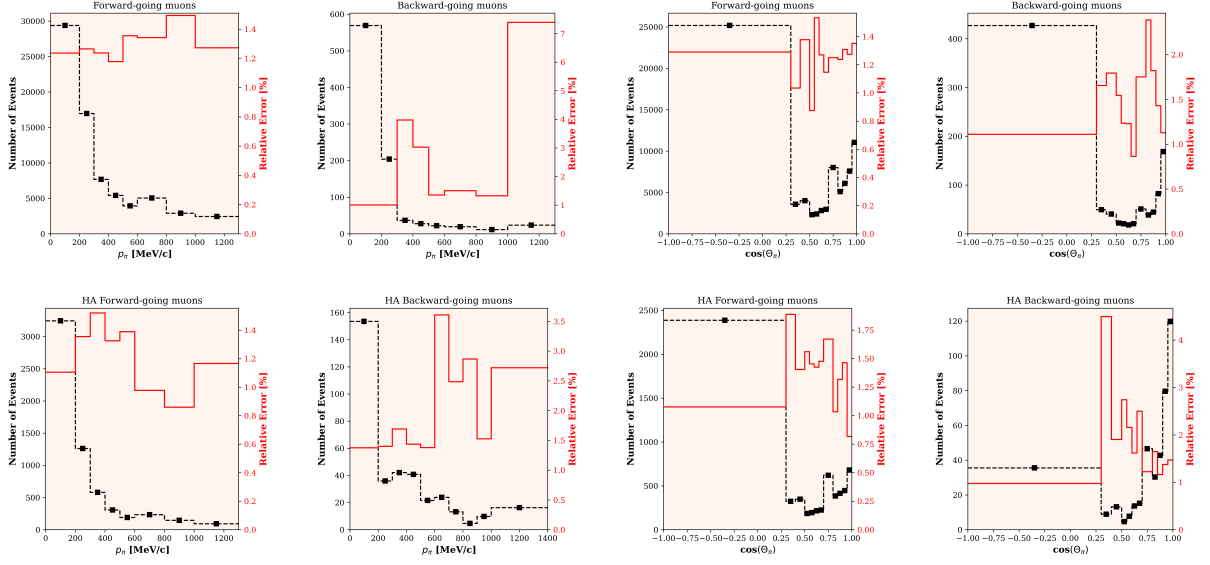


Figure C.18: Relative errors (using NEUT) as function of positive pion momentum (left-hand set) and positive pion cosine of theta (right-hand set) distributions for the pion secondary interactions systematic for the CC1 π^+ sample.

C.29 PROTON SECONDARY INTERACTIONS

Protons can also have secondary interactions after they leave the neutrino vertex. By varying the proton interaction cross section as protons are stepped through the detector based on the introduced uncertainty, the final weight can be calculated [194].

FAKE DATA STUDIES

D

This appendix covers additional fake data studies.

D.1 BASIC CHECKS

D.1.1 Random Template Priors

The next test in the fitting procedure is to apply a small variation to the previous Asimov fit, which will consist of introducing a random prior value to the truth bins. This value is determined by drawing from a Gaussian distribution with a mean of one and a standard deviation of 0.1 (10%). The goal here is to assess if the fitter can still find the correct minima now that it does not start at the best-fit points. In figure [D.1](#), the results of this test are summarized in similar fashion to section [10.1.1](#).

D.1.1.1 Parameters

In the top-left image of this figure, the randomized prior values can be found for each of the 4D template parameter bins. Upon closer inspection, it can be identified that the post-fit and pre-fit values coincide in every situation and the errors either overlap or improve. The same statement can be made about the other three sets of parameters that show similar behavior to the pure Asimov. The test is repeated 100 times.

The percentage of successful fits is shown in the title (95% in this scenario). The expected χ^2 PDF for the available #DoF is shown in orange. The dashed red line represents a Gaussian fit to the χ^2 histogram, of which the mean is used in the green graph to display the PDF for the post-fit #DoF. The χ^2 is indeed zero.

The post-fit correlation and covariance between template and flux parameters are shown in figure D.2, while the detector and cross-section equivalents can again be found in the subsequent figure D.3. Compared to the Asimov fit, the template parameters are significantly less (anti-)correlated as indicated by color bar's reduced range. The cross-section model parameters show more anti-correlation in the dials affecting single and multiple pions.

D.1.1.2 Samples

The individual signal and sideband samples displayed in figures D.4 and D.5 all return a χ^2 of precisely zero indicating once again that the fitter is able to retrieve the nominal number of events for each bin in 4D reconstructed space. This indicates that the choice of template priors does not affect performance.

D.1.1.3 Cross-section calculation

In contrast to the preceding discussion, a discrepancy in cross-sections between the pre-fit and post-fit values can now be observed (see figure D.6). The blue graph (pre-fit) shows the cross-section based on the nominal values for the input parameters, which is clearly different from the calculated cross-section as a result of the fake data with random template priors (red). However, as expected, the post-fit results do coincide with the fake-data values for every bin and the returned χ^2 is zero.

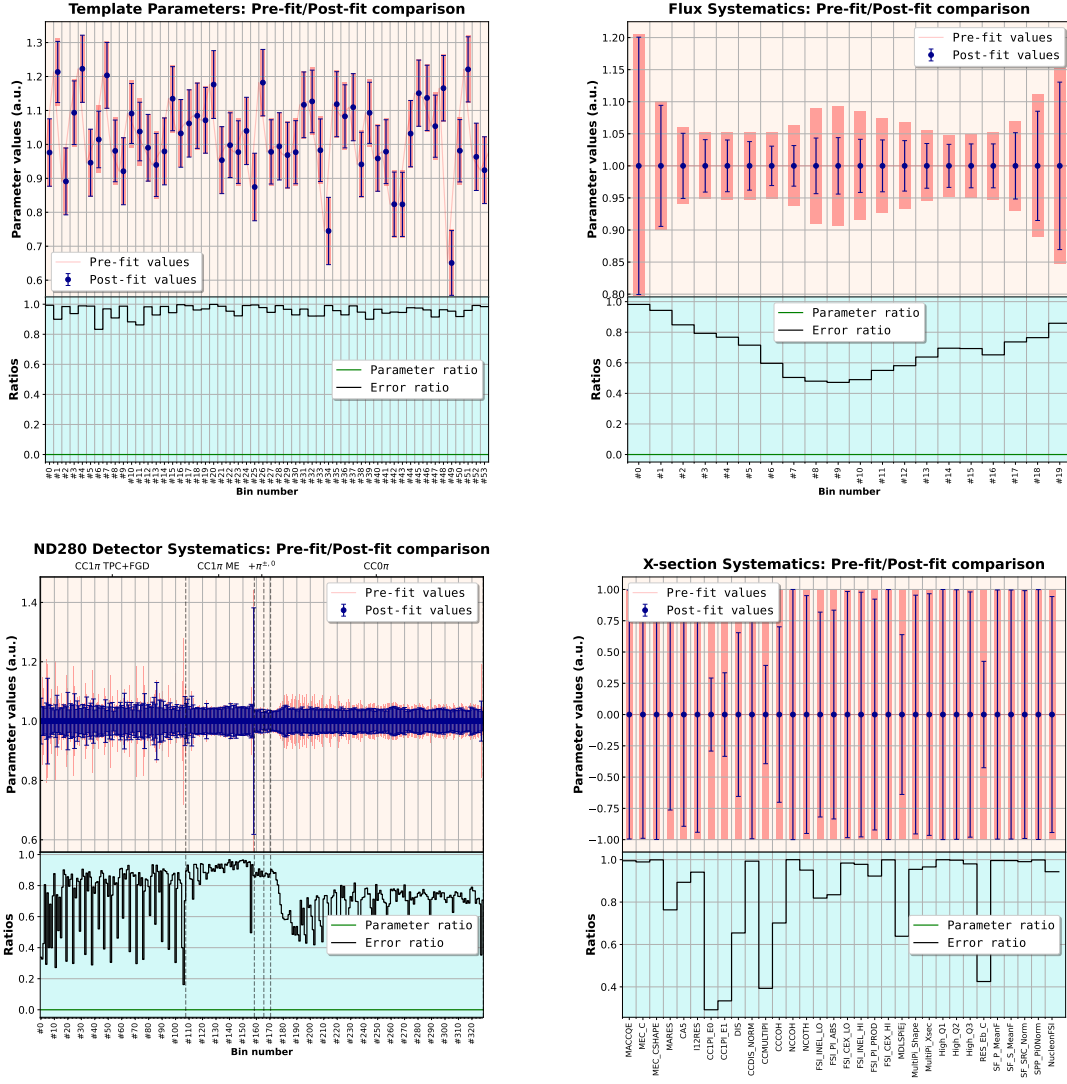


Figure D.1: Comparisons between the pre-fit and post-fit parameter values with error bounds for an Asimov fit with randomized starting values for the template parameters as indicated in the top-left image. These parameters are binned in 4D true kinematics variables, where bins 52 through 54 indicate out-of-phase-space (i.e. overflow) bins. The flux parameters, binned in neutrino energy, are displayed on the top-right. For the detector parameters in the center, the binning is done in 4D reconstructed variables for each sample individually. The separation between samples can be found at the top and is marked by the vertical dashed black line. The model parameters' nominal values are normalized and shown on the bottom. The red line and red shaded region represent the pre-fit nominal value and associated uncertainty, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

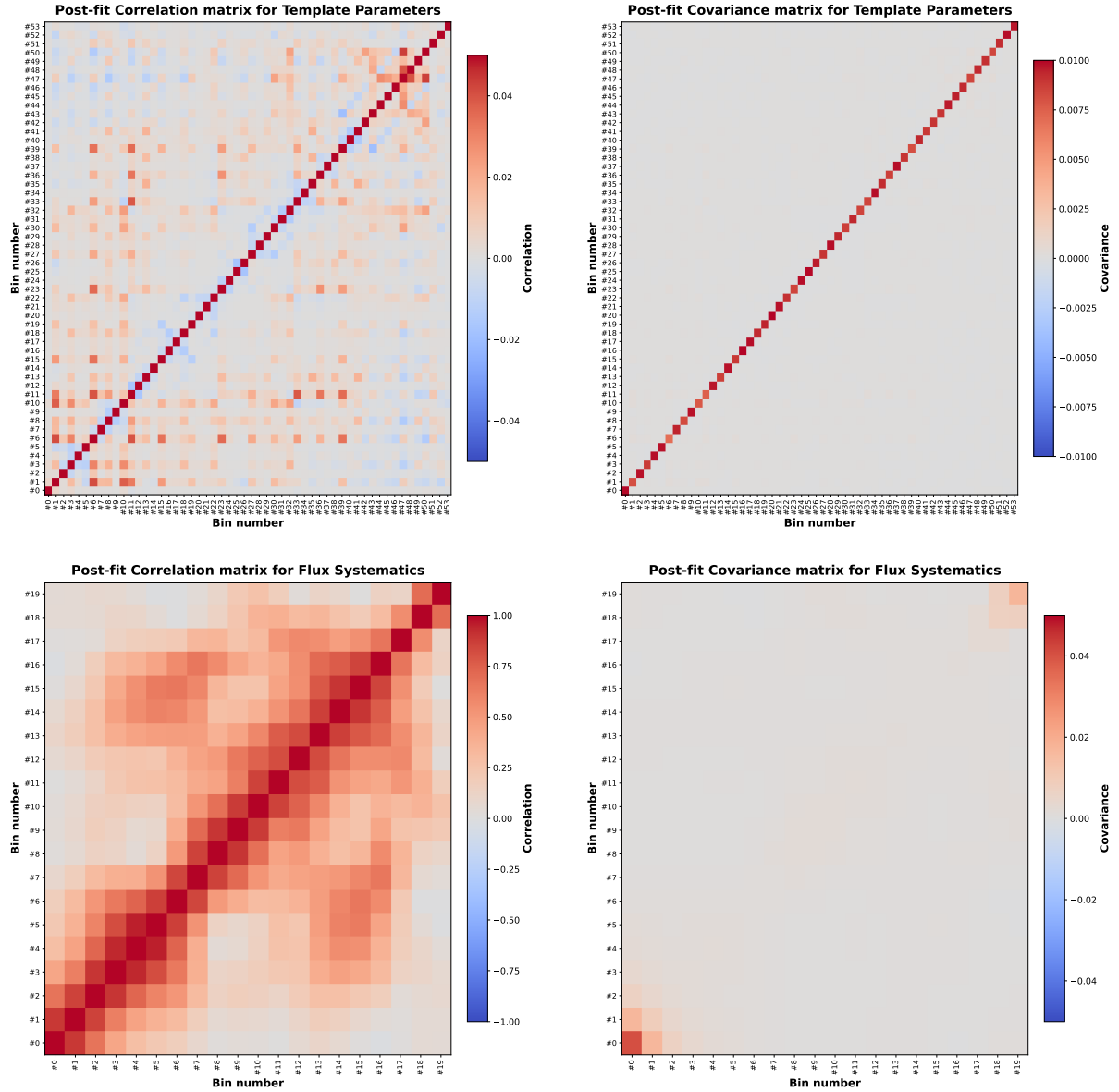


Figure D.2: Random template prior post-fit correlation (left column) and covariance (right column) matrices for the Template (top) and Flux parameters (bottom). The color bar for the covariance is set at a different (smaller) range to reveal the matrix' structure.

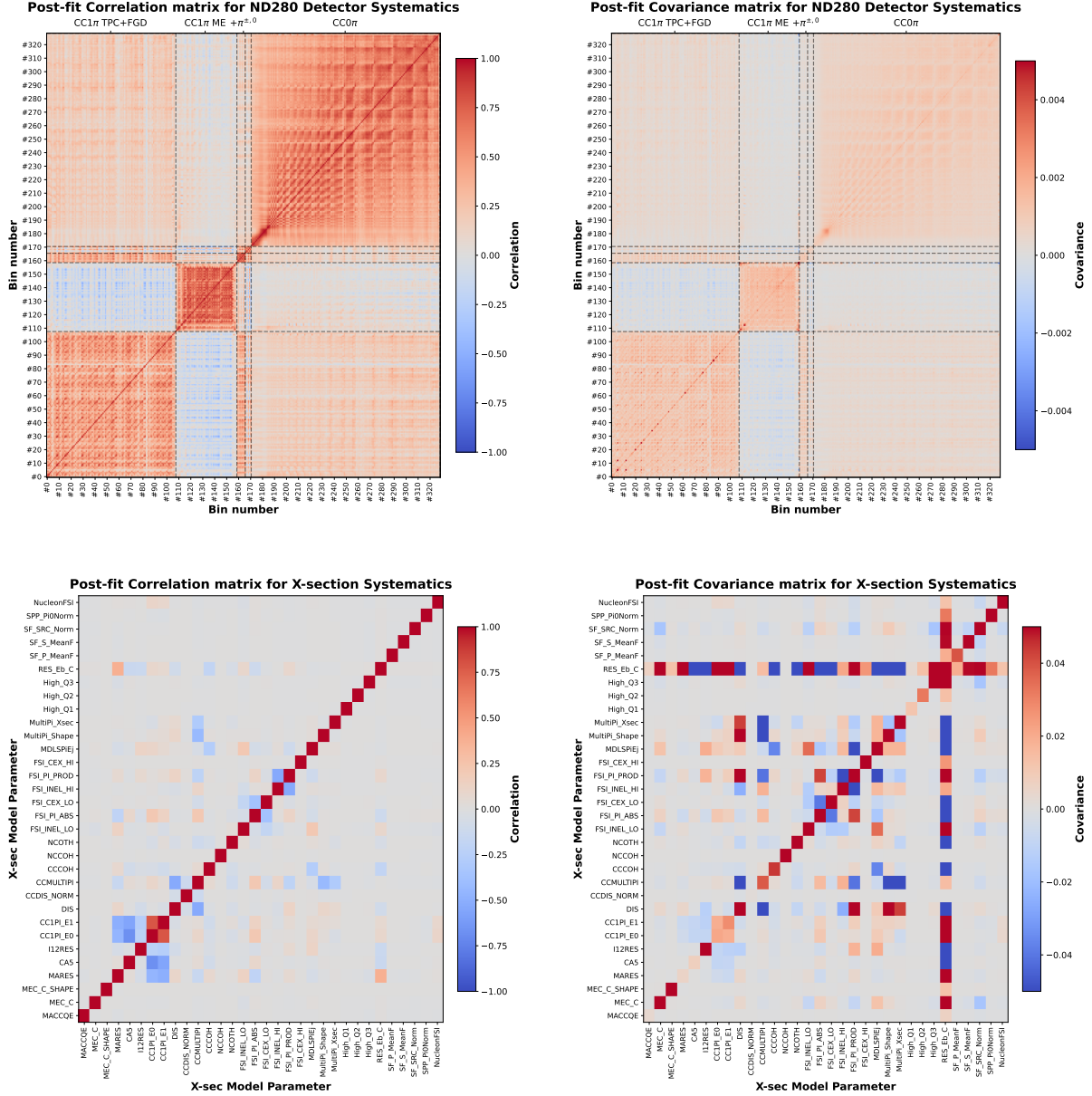


Figure D.3: Random template prior post-fit correlation (left column) and covariance (right column) matrices for the Detector (top) and Cross-section model parameters (bottom). The color bar for the covariance is set at a different (smaller) range to reveal the matrix' structure.

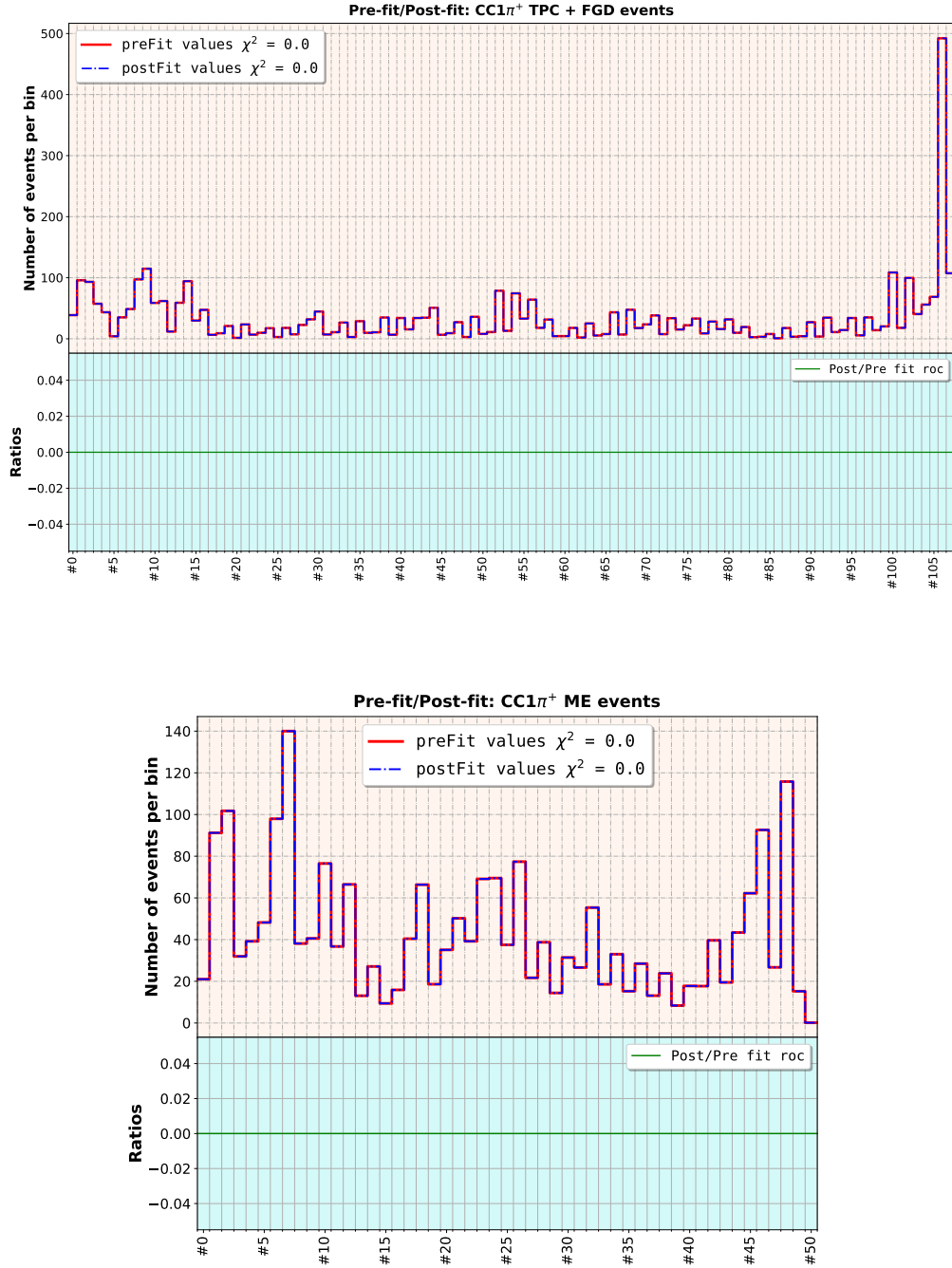


Figure D.4: Comparisons between the pre-fit and post-fit signal event numbers with error bounds for an Asimov fit with random template prior values starting at the true best-fit points or nominal values. CC1 π^+ events identified through a pion candidate in the TPC or FGD are shown on the top. Events identified through the subsequent Michel electron on the bottom.

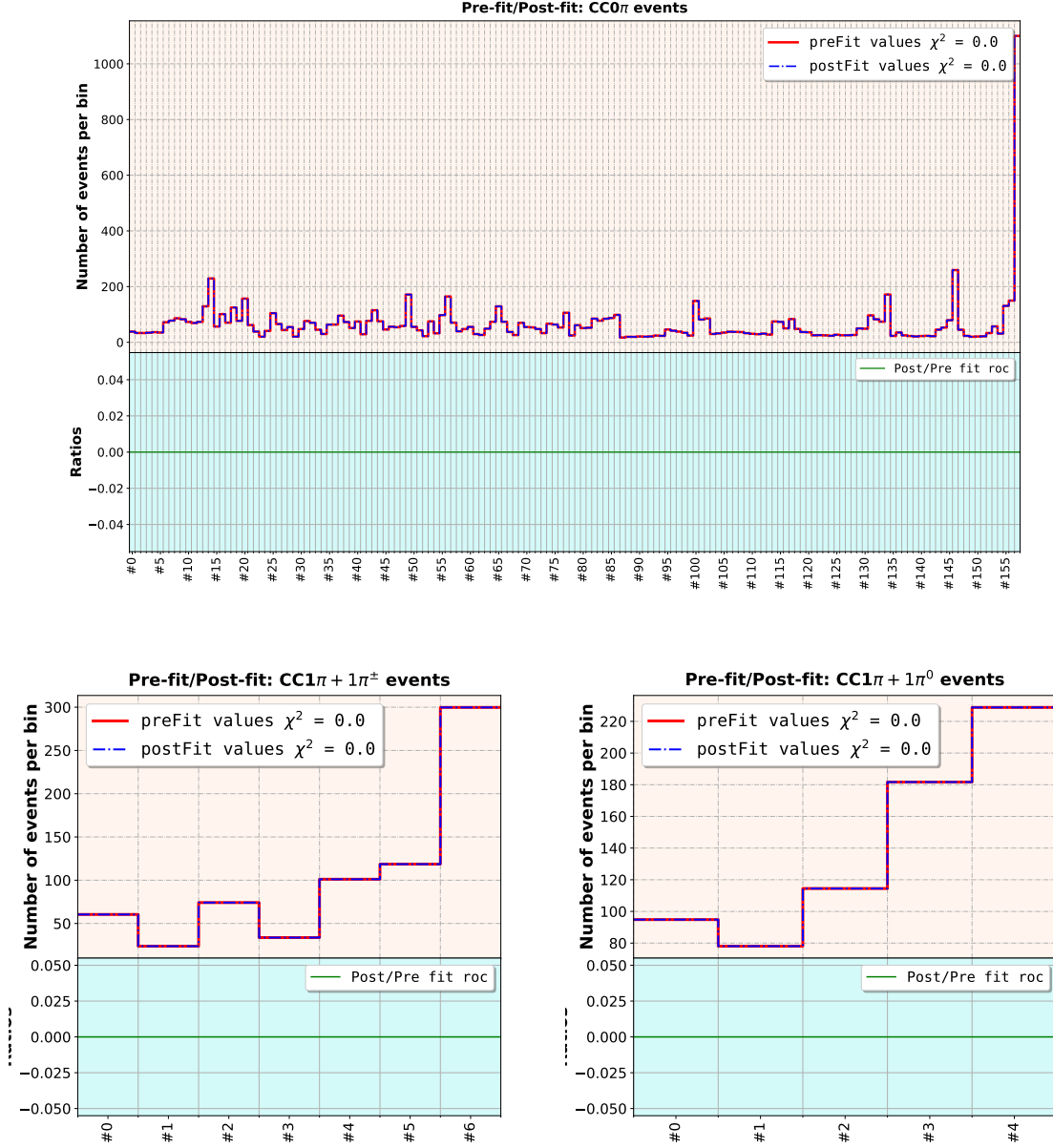


Figure D.5: Comparisons between the pre-fit and post-fit sideband event numbers with error bounds for an Asimov fit with random template prior values starting at the true best-fit points or nominal values. Three sidebands in total with the top image representing the CC0 π samples and the bottom row displaying the CC1 π^+ signal with an additional pion.

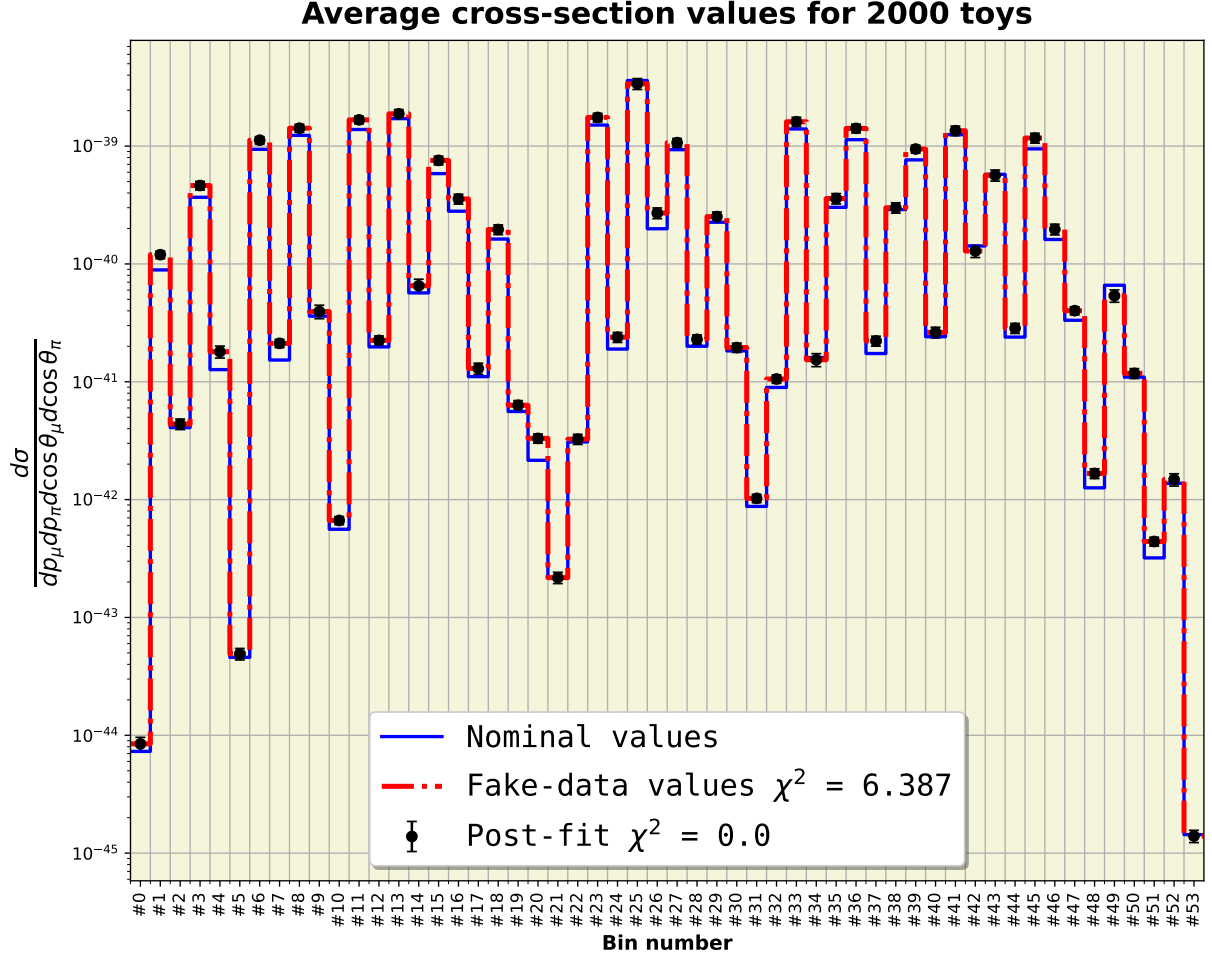


Figure D.6: Calculated cross-section for template binning in true 4D kinematic variables for an Asimov fit with randomized prior values for the template parameters. Each data point refers to a specific region in phase space spun by a range in muon momentum & angle and pion momentum & angle. Blue represents the cross-section based on the nominal MC parameters. The dashed red line refers to cross-section values based on the inserted fake data set used as ‘data’, which is identical to the nominal MC in an Asimov fit. The black scatter points with error bars are the cross-section values derived from the post-fit template parameters.

D.2 FAKE DATA STUDIES

D.2.1 Out-of-phase-space enhancement

This fake-data study entails an increase of the out-of-phase-space weights by 10%, which includes all events with $p_\mu < 200$ MeV or $p_\pi < 80$ MeV. These correspond to the last three bins in the template parameter space and the last bin for every category (FGD+TPC, ME, $+1\pi^{0,\pm}$, CC0 π) separated by the dashed black line in the detector parameters.

D.2.1.1 Parameters

The results of the all parameter fit with increased OOPS event weights can be seen in figure D.7. It can be seen that the Template Parameters shift occurs in the designated bins with the largest change occurring in bin 52, which is understandable as it covers both criteria (exact kinematic range: $p_\mu < 200$ MeV & $p_\pi < 30000$ MeV) for the entire range of muon and pion angles. Bin 53 sees a smaller effect as the overall statistics are lower in this regime ($p_\mu > 200$ MeV & $p_\pi < 80$ MeV). The fitter thus behaves accordingly.

For the detector parameters, binned in 4D reconstructed kinematic variables for both signal and sideband samples, a similar statement can be made. Investigating the ratio plot (green line in the bottom sub figure), the dominantly affected bins are the ones at the end of each individual sample category. It is precisely those that refer to the out-of-phase-space regions. A shift can also be observed in the CC0 π parameters, albeit a very minimal one. These bins refer to the cases in which muons traverse the detector under high-angles. Furthermore, the pion kinematic enhancement will again mostly affect the model parameters related to single (CC1Pi_E0, CC1Pi_E1) and multiple pions (DIS, CCMULTIPI) as well as final state interactions. If compared to the pure Asimov case, the biggest difference resides in the error for the CC1Pi_E0 dial (improved by 15%). As the correct bins see a change in value, it can be concluded that the fitter is performing well with regards to this weight change.

The post-fit correlation and covariance matrices in figures D.8 and D.9 display similar behavior to the pure Asimov fit of section 10.1.1 with added anti-correlating bins for the CC1Pi_E0 and CC1Pi_E1 dials (i.e. the two energy regimes for CC1Pi production). Something that was also observed in the signal enhancement. New here is the spike in covariance for the RES_Eb_C dial across several bins related to pion production or FSI effects.

D.2.1.2 Samples

The CC1 π^+ and CC0 π samples showcased in figure D.10 and at the top of figure D.11 are the only ones influenced by the increase in the event weights. This is to be expected as the samples containing additional pions do not have overflow bins associated with them (pre-fit and post-fit χ^2 of zero as well). The fit returns a distribution that more closely

resembles the fake-data provided. A pre/post-fit comparison of the χ^2 shows a similar result where its value is reduced for all available samples proving the fit's capability of retrieving the changes made to the MC.

D.2.1.3 Cross-section calculation

Finally, upon inspecting the extracted cross-section in figure [D.12](#) a clear improvement can be found between the nominal and fake-data calculations in all bins yielding a χ^2 of zero.

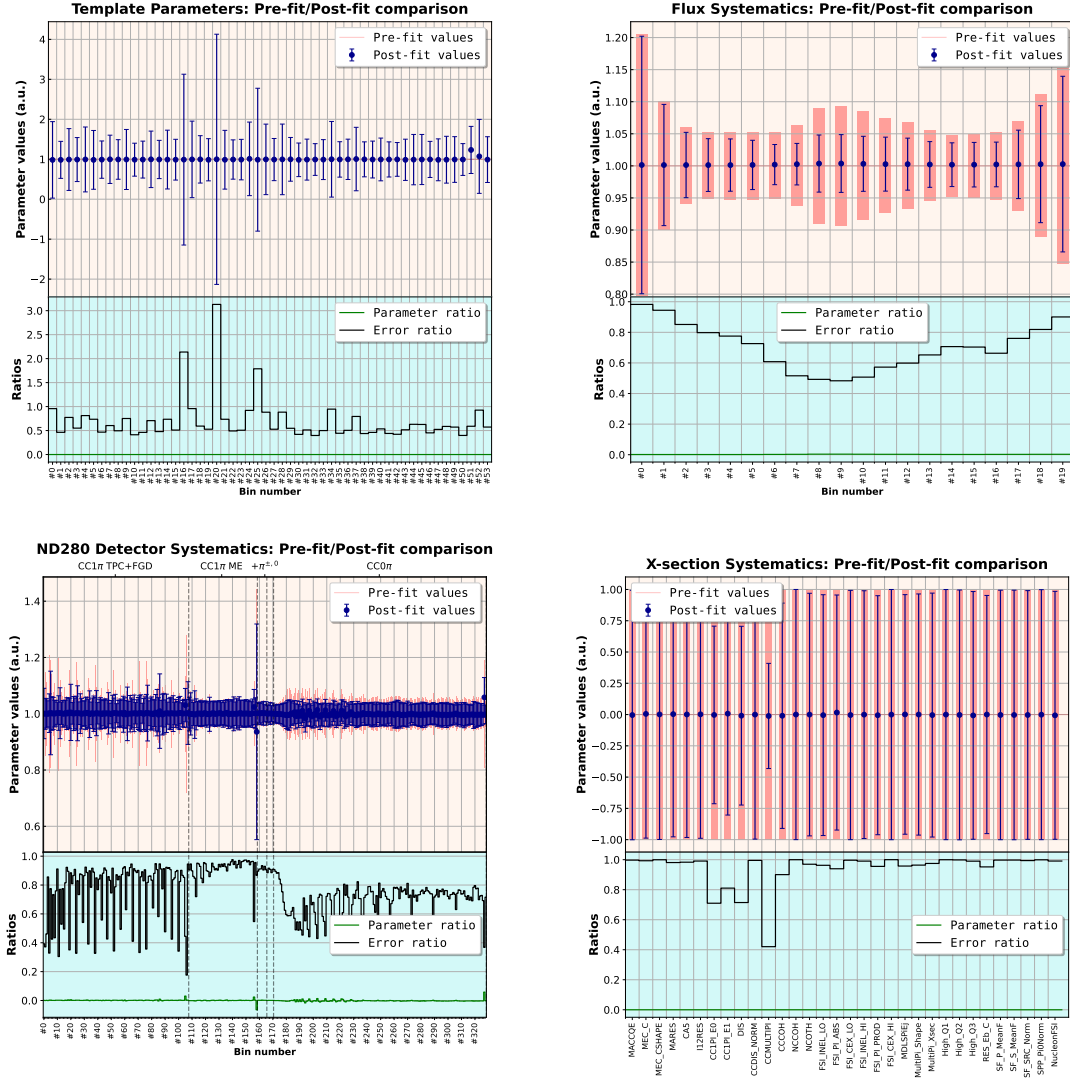


Figure D.7: Comparisons between the pre-fit and post-fit parameter values with error bounds for a fake data fit with increased out-of-phase-space event rates of 10%. Template parameters are displayed in the top-left image. These parameters are binned in 4D true kinematics variables, where bins 52 through 54 indicate out-of-phase-space (i.e. overflow) bins. The flux parameters, binned in neutrino energy, are displayed on the top-right. For the detector parameters in the center, the binning is done in 4D reconstructed variables for each sample individually. The separation between samples can be found at the top and is marked by the vertical dashed black line. The model parameters' nominal values are normalized and shown on the bottom. The red line and red shaded region represent the pre-fit nominal value and associated uncertainty, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

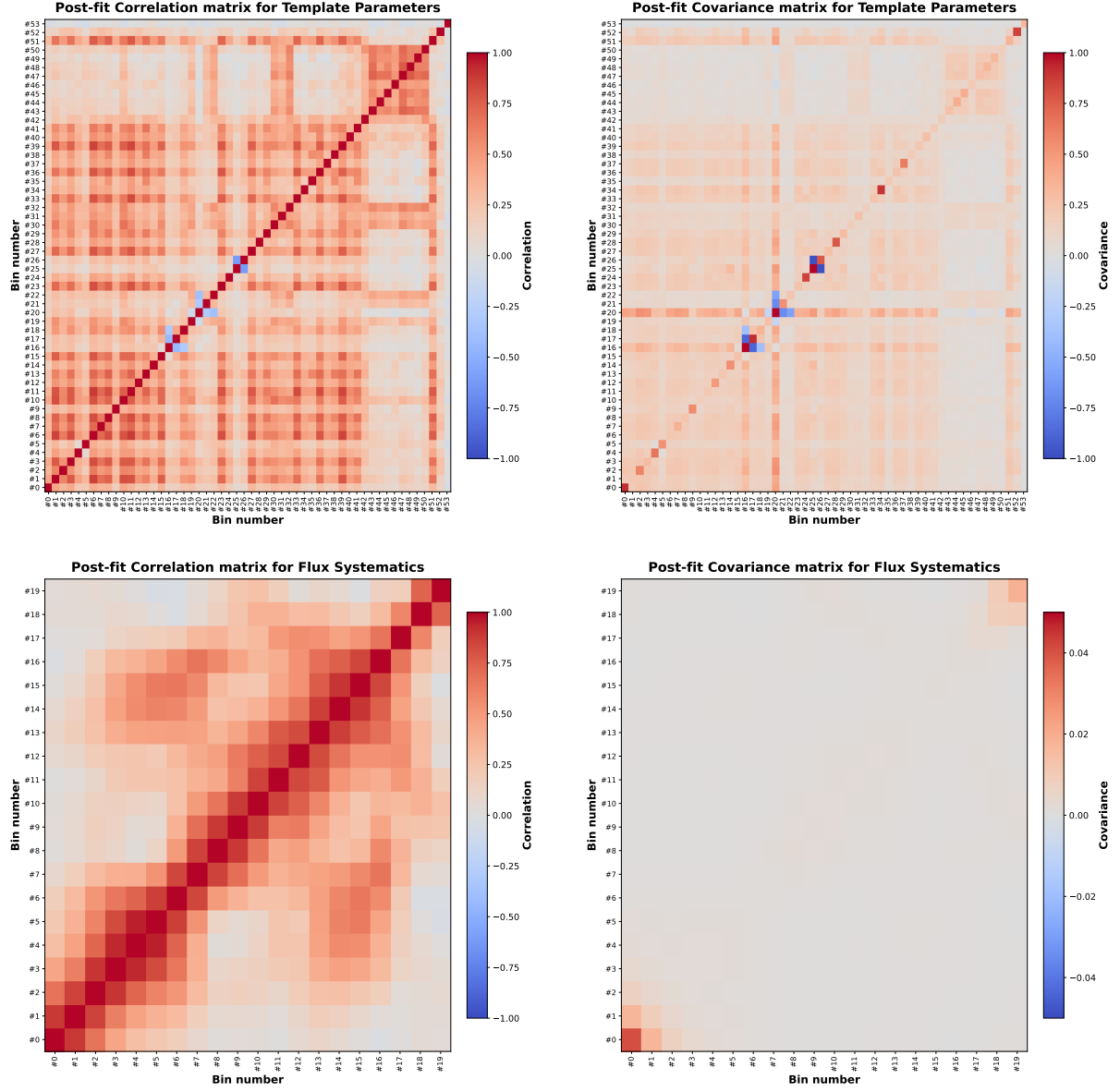


Figure D.8: Out-of-phase-space enhanced post-fit correlation (left column) and covariance (right column) matrices for the Template (top) and Flux parameters (bottom). The color bar for the covariance is set at a different (smaller) range to reveal the matrix' structure.

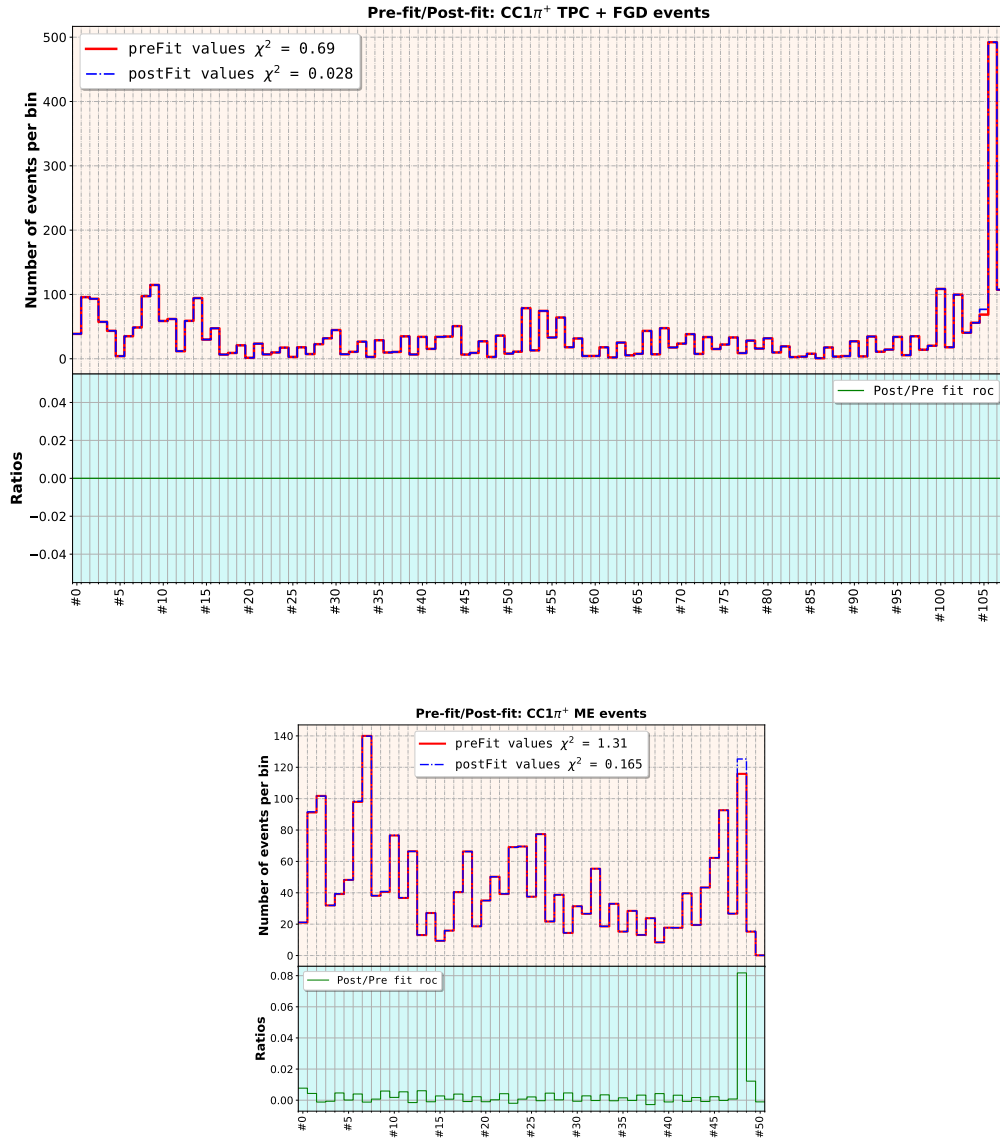


Figure D.10: Comparisons between the pre-fit and post-fit signal event numbers with error bounds for an out-of-phase-space enhanced fit with randomized prior values for the template parameters. CC1 π^+ events identified through a pion candidate in the TPC or FGD are shown on the top. Events identified through the subsequent Michel electron on the bottom.

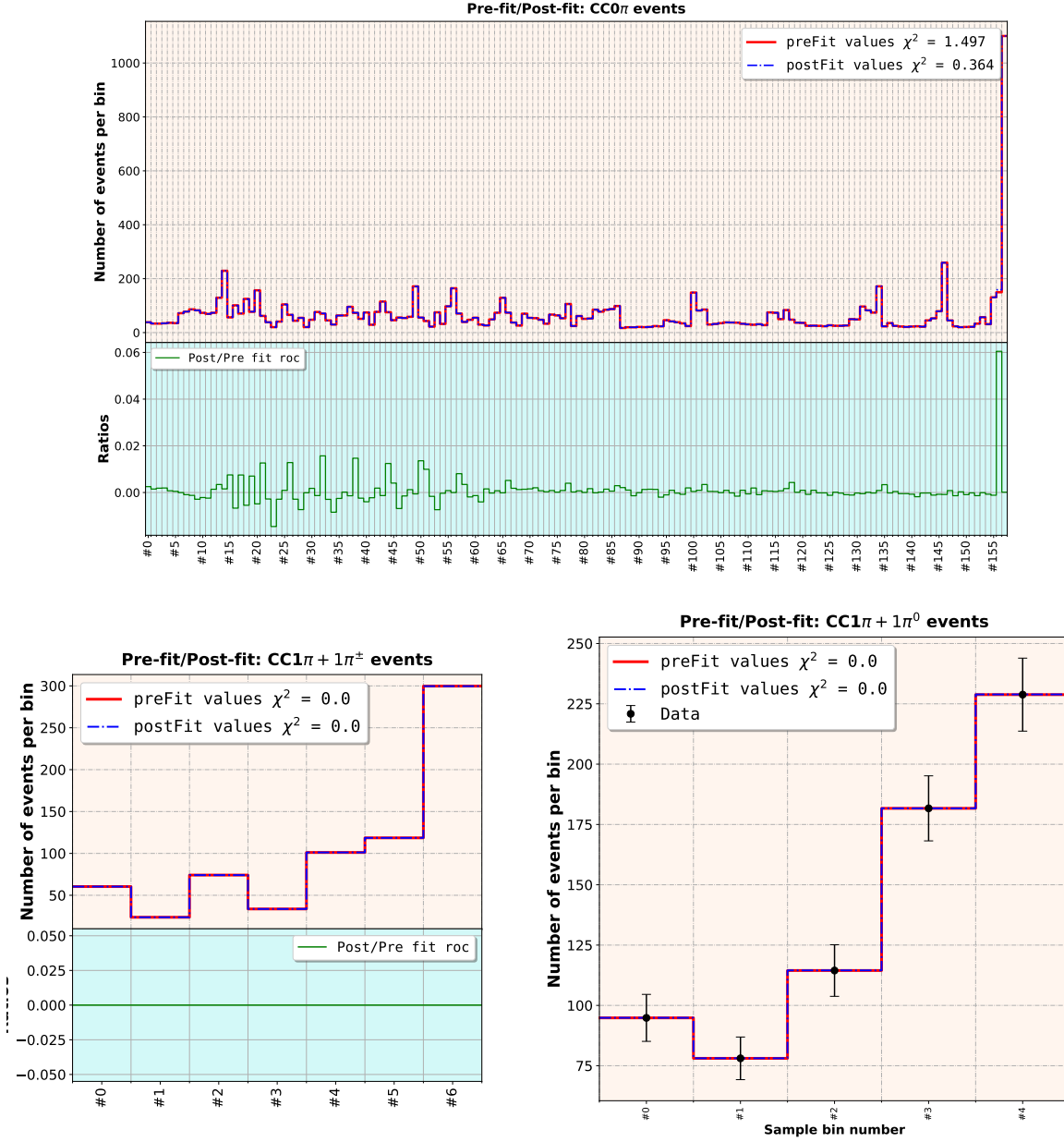


Figure D.11: Comparisons between the pre-fit and post-fit sideband event numbers with error bounds for an out-of-phase-space enhanced fit with randomized prior values for the template parameters. Three sidebands in total with the top image representing the CC0 π samples and the bottom row displaying the CC1 π^+ signal with an additional pion

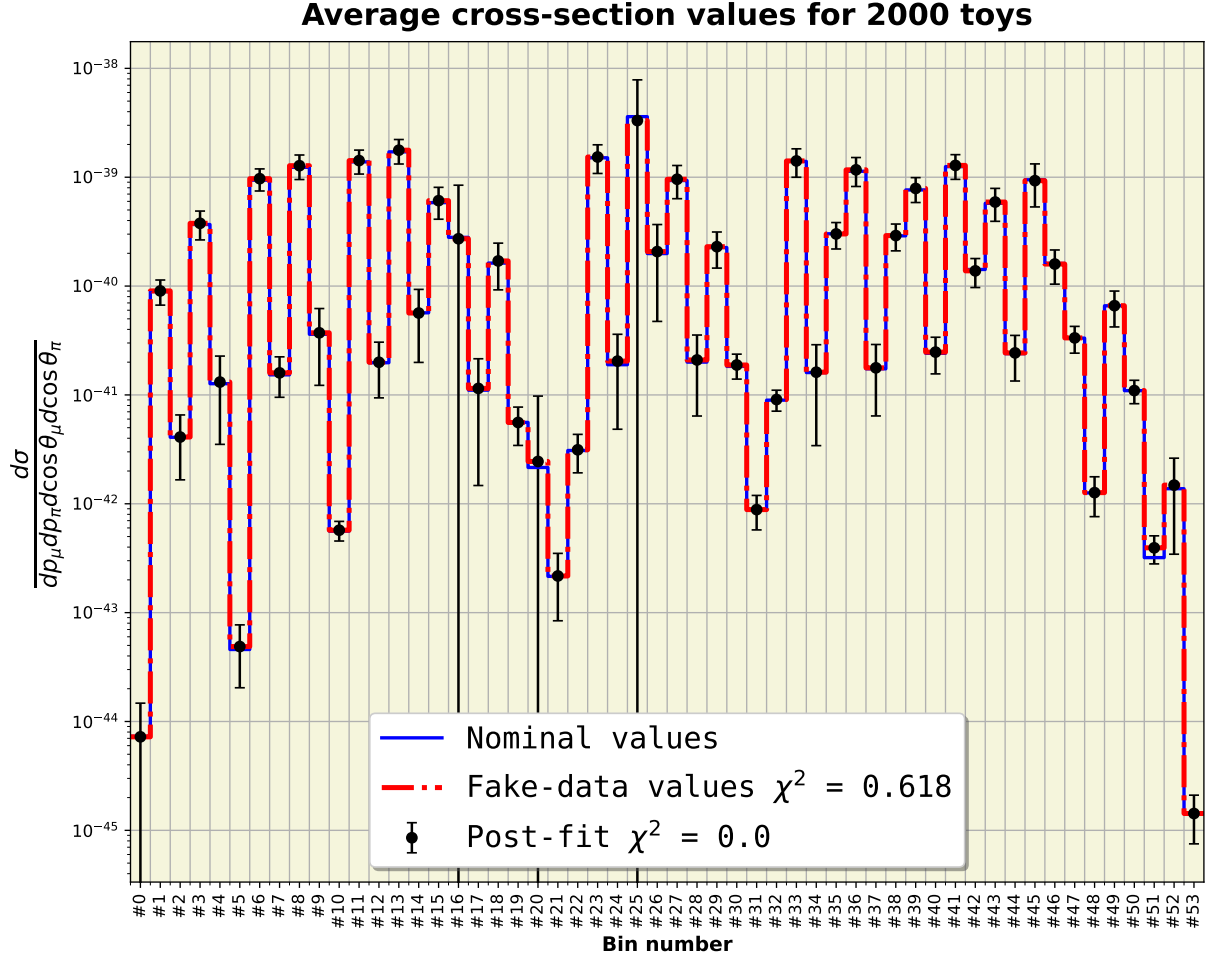


Figure D.12: Calculated cross-section for template binning in true 4D kinematic variables. Each data point refers to a specific region in phase space spun by a range in muon momentum & angle and pion momentum & angle. Blue represents the cross-section based on the nominal MC parameters. The dashed red line refers to cross-section values based on the inserted fake data set used as ‘data’, which is identical to the nominal MC in an Asimov fit. The black scatter points with error bars are the cross-section values derived from the post-fit template parameters.

D.2.2 Out-of-fiducial-volume reduction

At this point, it must have become abundantly clear that the out-of-fiducial-volume events constitute a large fraction of the total statistics available, especially in the backward-going direction even after all the attempts to try and reduce it. Hence this fake-data set was created to test the effect of an inaccurate prediction of those events in the Monte Carlo. A ten percent reduction is applied to the weights for any event classified as OOFV. Given that this topology is present in each and every sample, altering the weight should be able to affect any of the detector parameters (in contrast to OOPS, where only the $CC1\pi^+$ and $CC0\pi$ bins could be affected).

D.2.2.1 Parameters

The results of the all parameter fit with decreased OOFV event weights can be seen in figure D.13. The primary thing of importance here is the absence of any significant parameter shift. The reduction of the OOFV weights does not seem to impact the fitter's capability of finding the nominal positions. Comparing the error ratios to those of the Asimov fit, the only observable difference resides in the Cross-section model parameters. The error on the $CC1PiLE0$ and RES_Eb_C dials is less well constrained here.

The post-fit correlation and covariance matrices in figures D.14 and D.15 display similar behavior to the pure Asimov fit of section 10.1.1 with added anti-correlating bins for the $CC1PiLE0$ and $CC1PiLE1$ dials (i.e. the two energy regimes for $CC1Pi$ production). Something that was also observed in the signal enhancement. The same holds for the spike in covariance for the RES_Eb_C dial across several bins related to pion production or FSI effects.

D.2.2.2 Samples

The $CC1\pi^+$ and $CC0\pi$ samples showcased in figure D.16 and at the top of figure D.17 are the only ones influenced by the decrease in the event weights, but even for those samples it is very minimal. This is to be expected as the total OOFV contribution is overshadowed by the massive amount of statistics in the forward-going bins. In fact, there is only a single bin containing the both the backward and high-angle backward-going directions (which are hardly populated as shown in the selection). The fit returns a almost the exact distributions the fake-data provided. A pre/post-fit comparison of the χ^2 shows a similar result where its value is reduced for all available samples proving the fit's capability of retrieving the changes made to the MC.

D.2.2.3 Cross-section calculation

Finally, upon inspecting the extracted cross-section in figure D.18 a clear improvement can be found between the nominal and fake-data calculations in all bins yielding a χ^2 of zero.

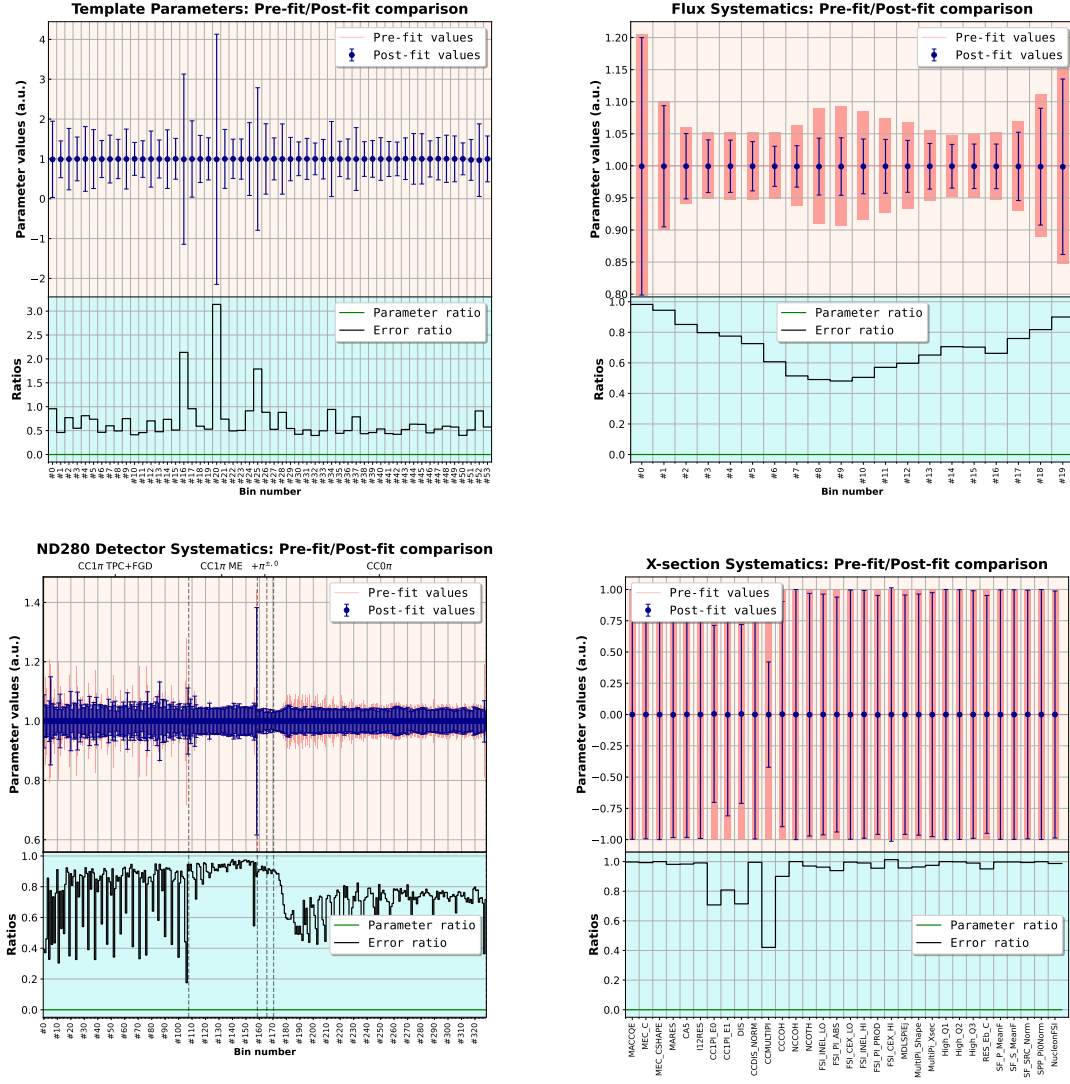


Figure D.13: Comparisons between the pre-fit and post-fit parameter values with error bounds for a fake data fit with reduced out-of-fiducial-volume event rates of 10%. Template parameters are displayed in the top-left image. These parameters are binned in 4D true kinematics variables, where bins 52 through 54 indicate out-of-phase-space (i.e. overflow) bins. The flux parameters, binned in neutrino energy, are displayed on the top-right. For the detector parameters in the center, the binning is done in 4D reconstructed variables for each sample individually. The separation between samples can be found at the top and is marked by the vertical dashed black line. The model parameters' nominal values are normalized and shown on the bottom. The red line and red shaded region represent the pre-fit nominal value and associated uncertainty, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

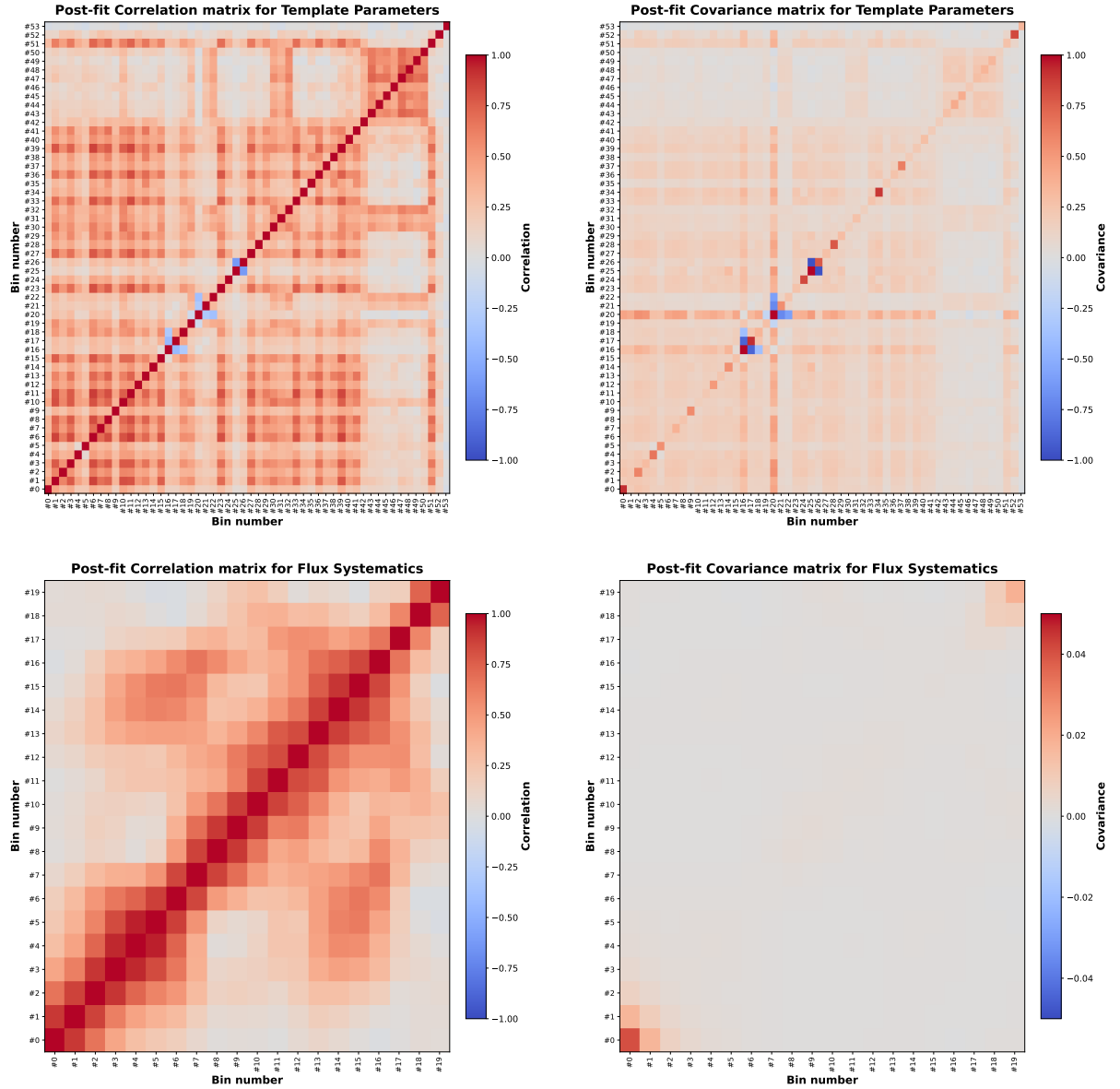


Figure D.14: Out-of-fiducial-volume reduced post-fit correlation (left column) and covariance (right column) matrices for the Template (top) and Flux parameters (bottom). The color bar for the covariance is set at a different (smaller) range to reveal the matrix' structure.

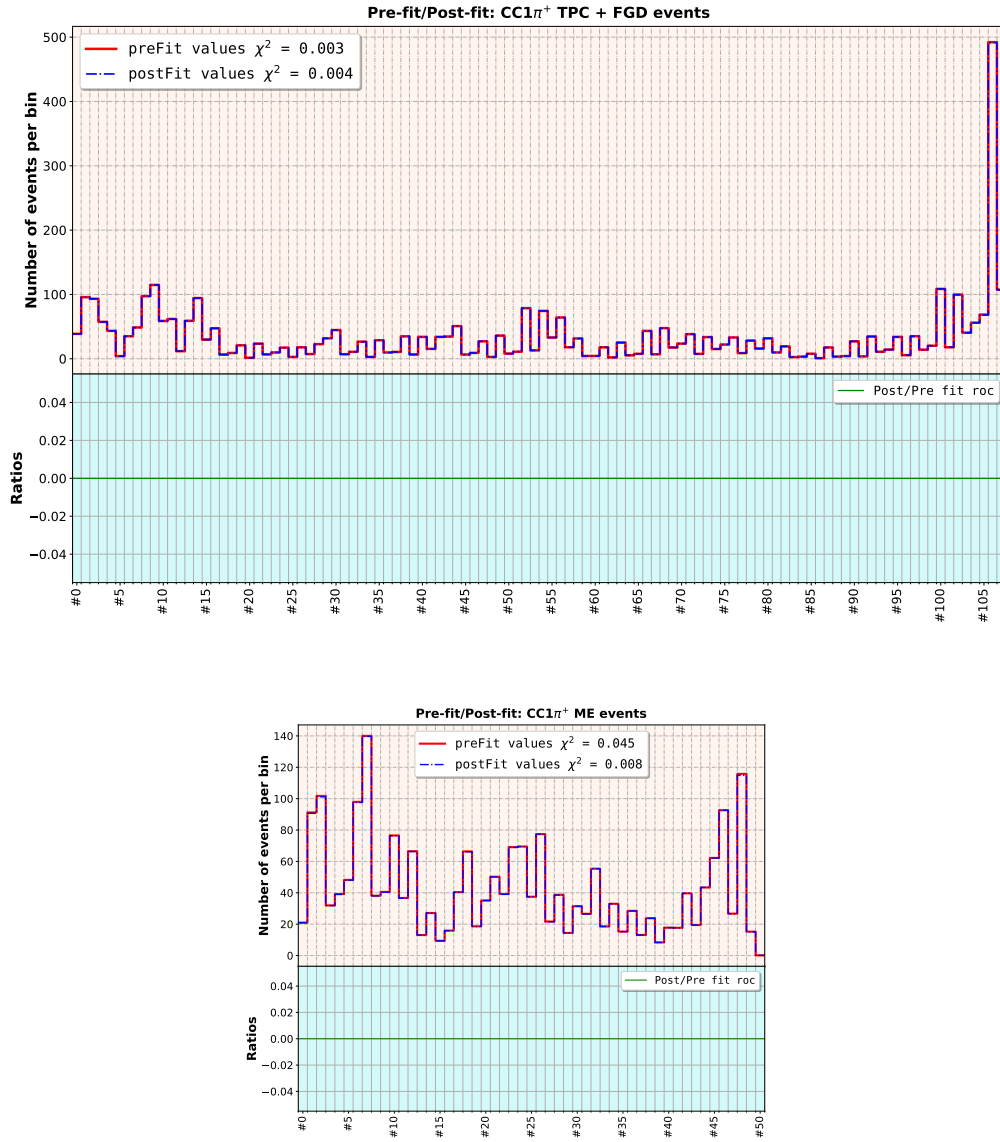


Figure D.16: Comparisons between the pre-fit and post-fit signal event numbers with error bounds for an out-of-fiducial-volume reduced fit with randomized prior values for the template parameters. CC1 π^+ events identified through a pion candidate in the TPC or FGD are shown on the top. Events identified through the subsequent Michel electron on the bottom.

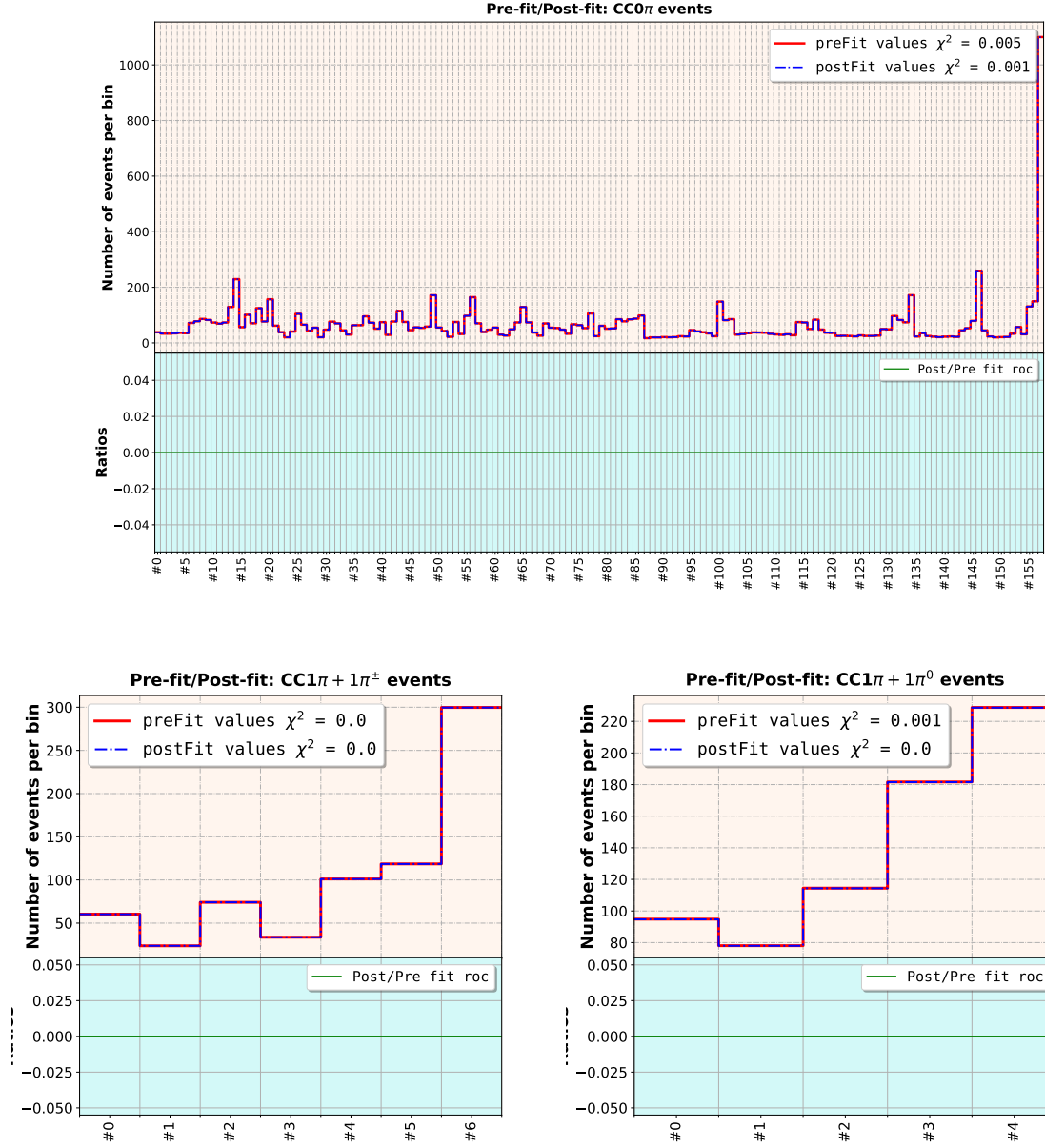


Figure D.17: Comparisons between the pre-fit and post-fit sideband event numbers with error bounds for an out-of-fiducial-volume reduced fit with randomized prior values for the template parameters. Three sidebands in total with the top image representing the CC0 π samples and the bottom row displaying the CC1 π^+ signal with an additional pion

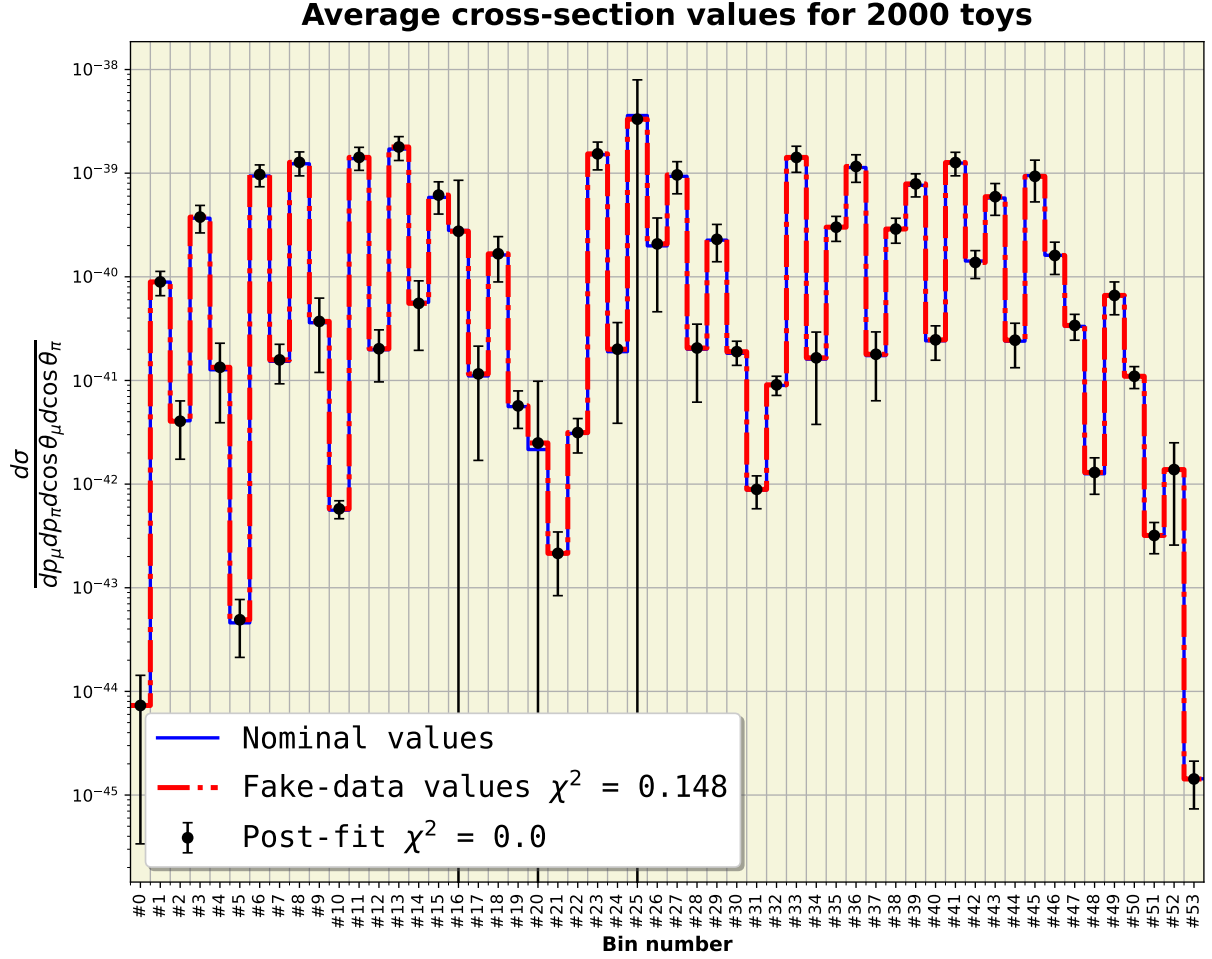


Figure D.18: Out-of-fiducial-volume reduced calculated cross-section for template binning in true 4D kinematic variables. Each data point refers to a specific region in phase space spun by a range in muon momentum & angle and pion momentum & angle. Blue represents the cross-section based on the nominal MC parameters. The dashed red line refers to cross-section values based on the inserted fake data set used as ‘data’, which is identical to the nominal MC in an Asimov fit. The black scatter points with error bars are the cross-section values derived from the post-fit template parameters.

D.2.3 CCOther reduction

In the forward-going direction, which contains most of the statistics, CCOther events are the main background to the $\text{CC}1\pi^+$ signal. Because of the distribution of statistics over the four angular samples, this topology also provides the largest overall background to this analysis. The fake-data set was generated by reweighting specifically these events by a factor of 0.9. Both of the additional pion control samples are a subset of the CCOther topology, so it is expected that the change will be captured by the detector parameters as well as in a few of the cross-section model dials involving pions.

D.2.3.1 Parameters

The results of the all parameter fit with decreased CCOther event weights can be seen in figure D.19. The fitter is recovering this change by increasing the Template Parameters over the entire space with the exception of bin 16 and 25. The flux remains almost unaffected. For the Detector Parameters, the region covering the subsets of the CCOther is shifted slightly. More interesting is the post-fit result for the Cross-section model parameters. The CCMULTIPI and DIS dials see a substantial difference in their values compared to the pure Asimov fit. This is expected as the DIS reaction makes up over 70% of the control samples' neutrino interaction processes. Additionally, the FSI absorption and Multi_Pi_Shape dials are moved up and down respectively.

The post-fit correlation and covariance matrices in figures D.20 and D.21 display similar behavior to the pure Asimov fit of section 10.1.1 with added anti-correlating bins for the CC1Pi_E0 and CC1Pi_E1 dials (i.e. the two energy regimes for CC1Pi production). Something that was also observed in the signal enhancement and the OOPS situation. Also present here is the spike in covariance between the RES_Eb_C dial across several bins related to pion production or FSI effects.

D.2.3.2 Samples

The $\text{CC}1\pi^+ + \pi^{0,\pm}$ samples showcased in figure D.23 are the ones most heavily influenced by the decrease in the event weights. This is to be expected as the samples containing additional pions are most closely related to the CCOther topology (pre-fit χ^2 highest for those samples). The fit returns a distribution that more closely resembles the fake-data provided. A pre/post-fit comparison of the χ^2 shows a similar result where its value is reduced for all available samples proving the fit's capability of retrieving the changes made to the MC.

D.2.3.3 Cross-section calculation

Finally, upon inspecting the extracted cross-section in figure D.24 a clear improvement can be found between the nominal and fake-data calculations in all bins yielding a χ^2 of zero.

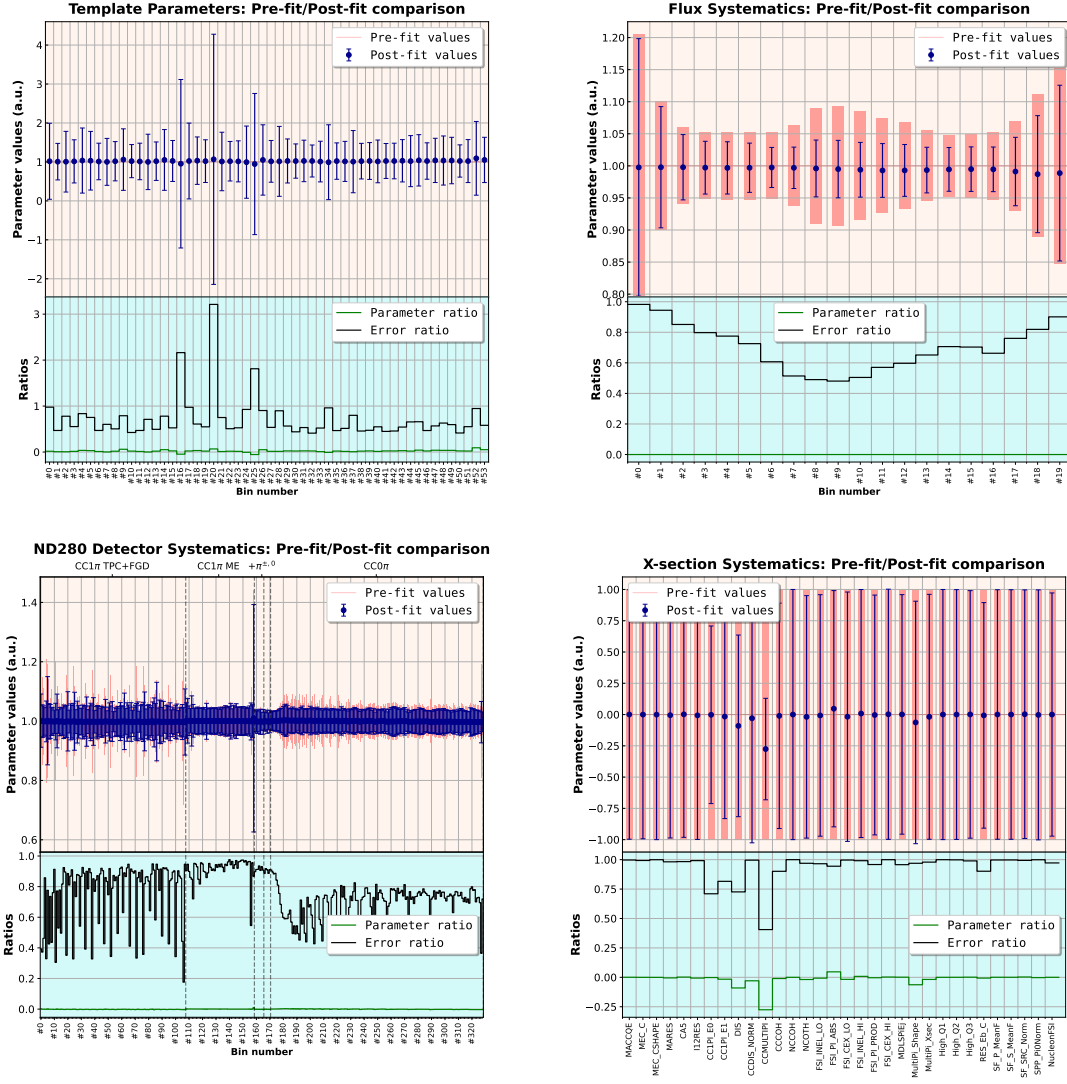


Figure D.19: Comparisons between the pre-fit and post-fit parameter values with error bounds for a fake data fit with decreased CCOther event rates of 10%. Template parameters are displayed in the top-left image. These parameters are binned in 4D true kinematics variables, where bins 52 through 54 indicate out-of-phase-space (i.e. overflow) bins. The flux parameters, binned in neutrino energy, are displayed on the top-right. For the detector parameters in the center, the binning is done in 4D reconstructed variables for each sample individually. The separation between samples can be found at the top and is marked by the vertical dashed black line. The model parameters' nominal values are normalized and shown on the bottom. The red line and red shaded region represent the pre-fit nominal value and associated uncertainty, while the blue dots with the blue end caps show the post-fit value and standard deviation on those. The bottom half showcases the change in parameter value in green and the ratio of the errors (post-fit to pre-fit) in black.

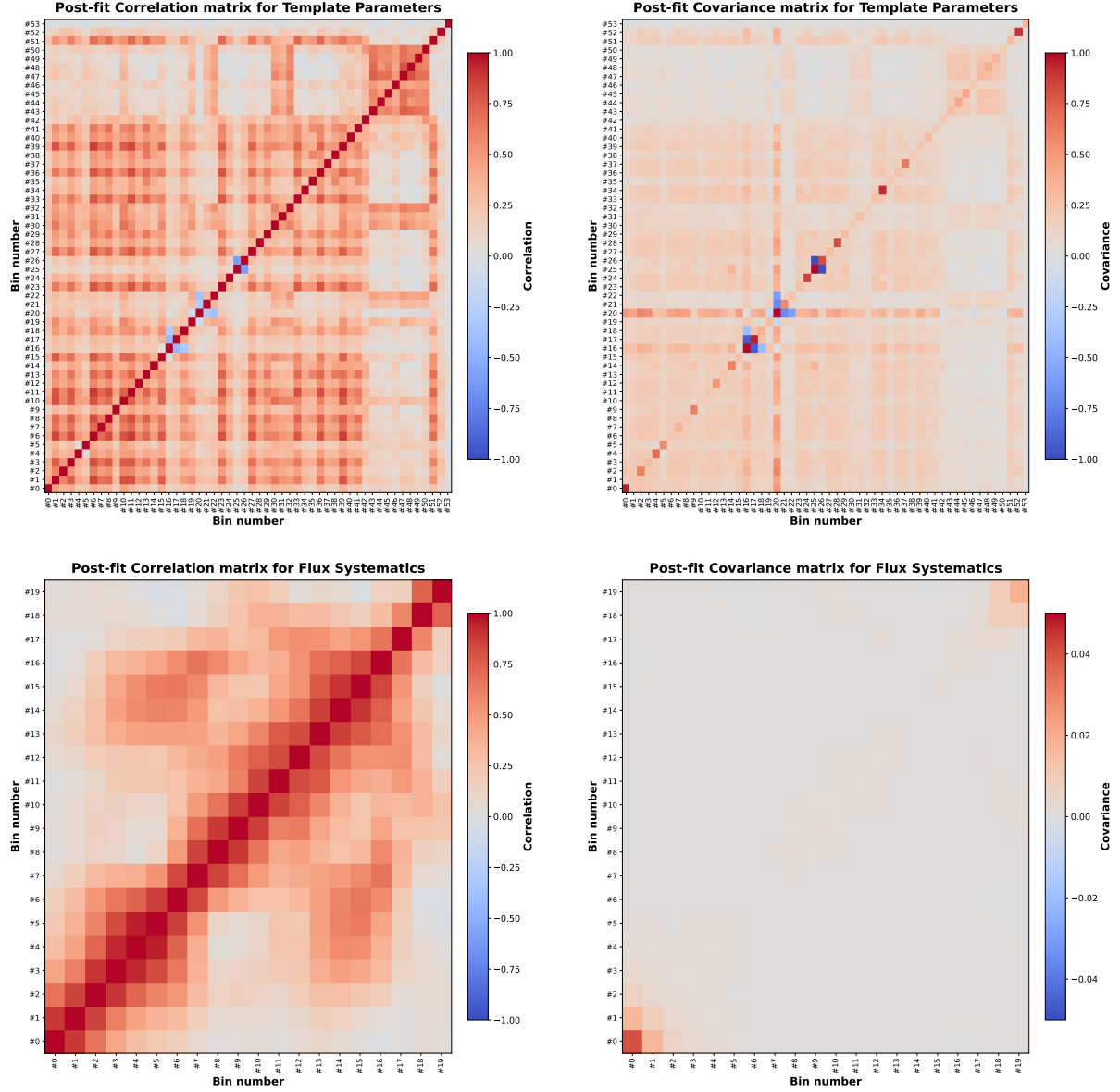


Figure D.20: CCOther reduction post-fit correlation (left column) and covariance (right column) matrices for the Template (top) and Flux parameters (bottom). The color bar for the covariance is set at a different (smaller) range to reveal the matrix' structure.

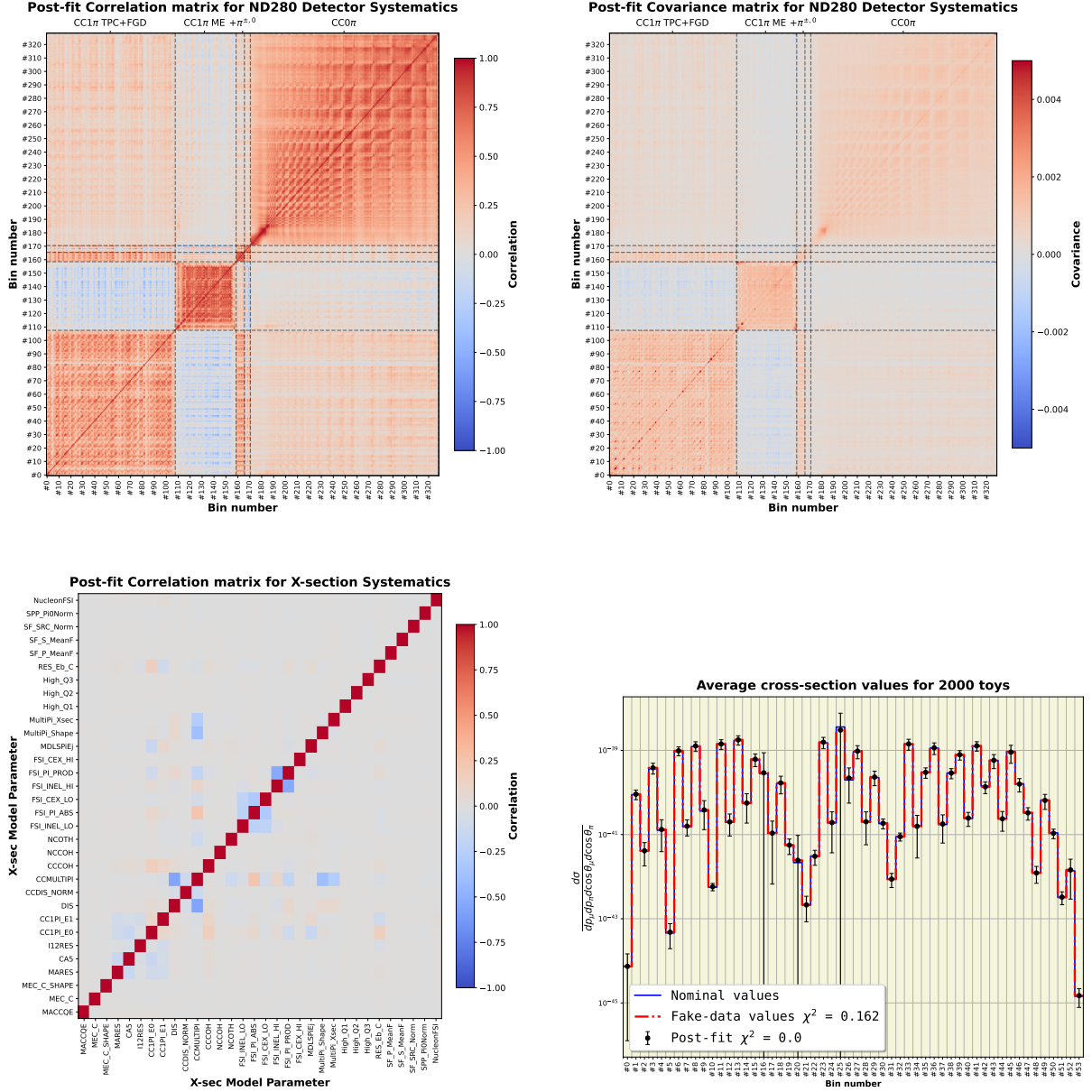


Figure D.21: CCOther reduction post-fit correlation (left column) and covariance (right column) matrices for the Detector (top) and Cross-section model parameters (bottom). The color bar for the covariance is set at a different (smaller) range to reveal the matrix' structure.

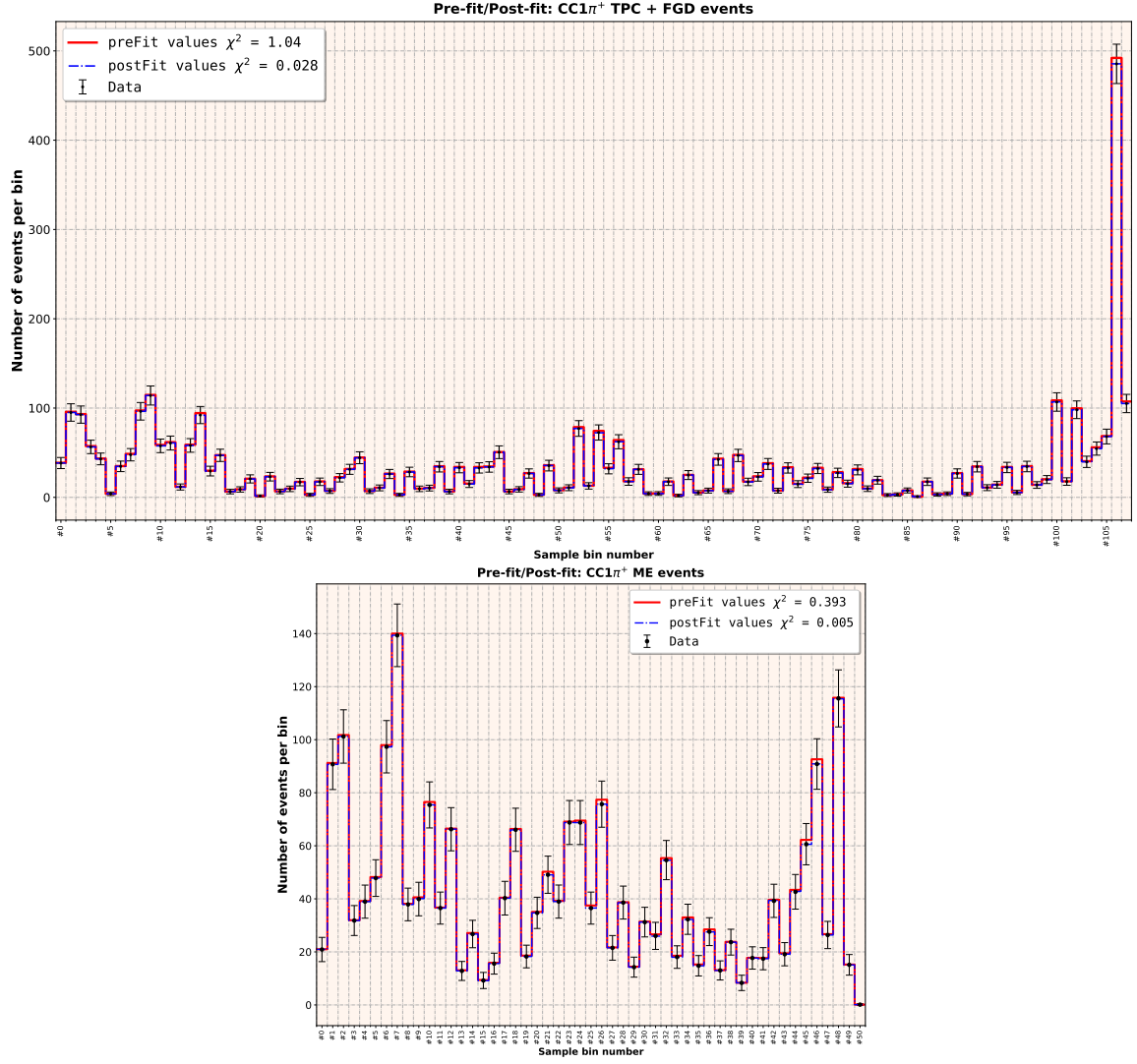


Figure D.22: Comparisons between the pre-fit and post-fit signal event numbers with error bounds for a CCOther reduced fit with randomized prior values for the template parameters. CC1 π^+ events identified through a pion candidate in the TPC or FGD are shown on the top. Events identified through the subsequent Michel electron on the bottom.

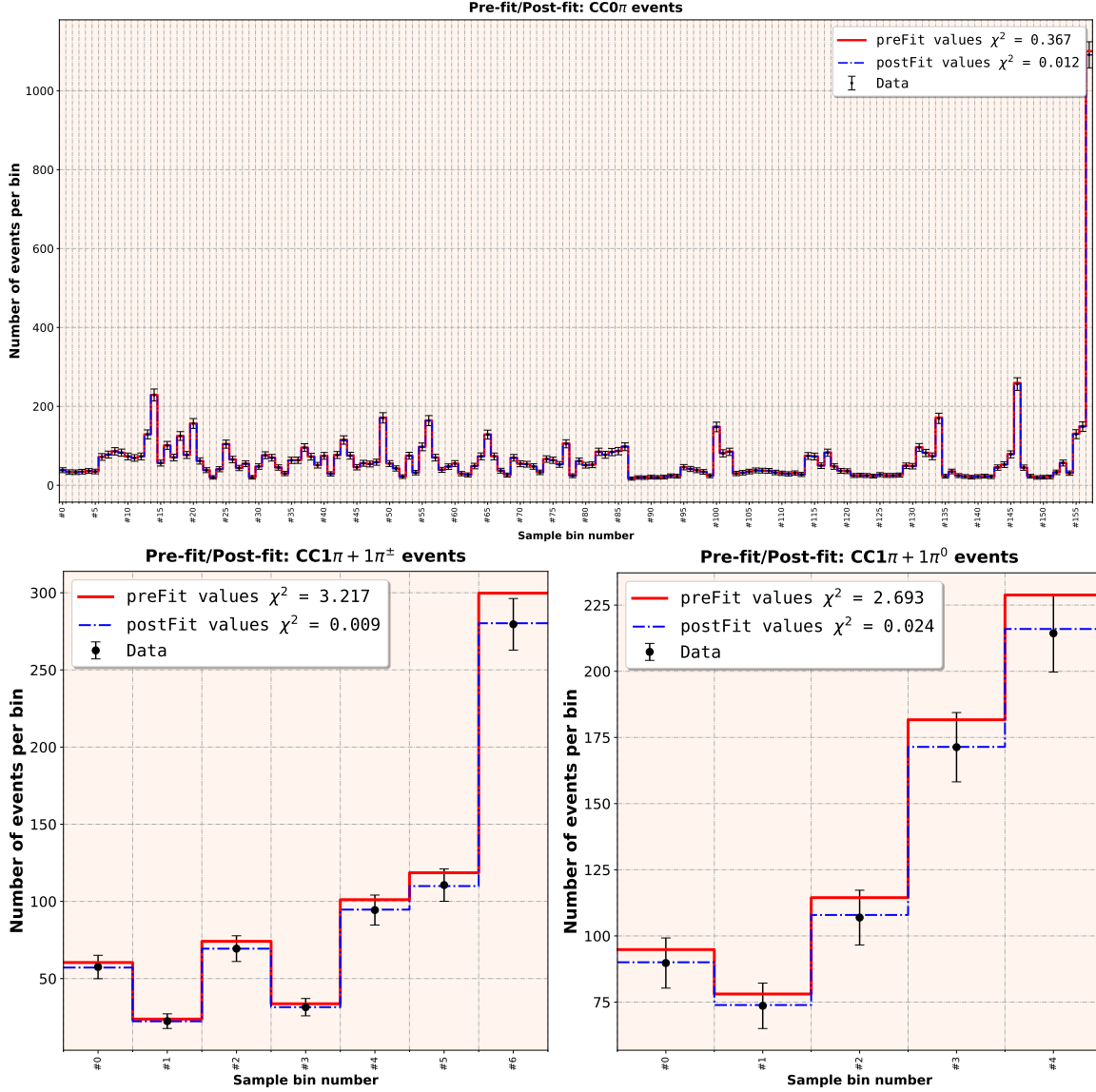


Figure D.23: Comparisons between the pre-fit and post-fit sideband event numbers with error bounds for a CC0 π reduced fit with randomized prior values for the template parameters. Three sidebands in total with the top image representing the CC0 π samples and the bottom row displaying the CC1 π^+ signal with an additional pion

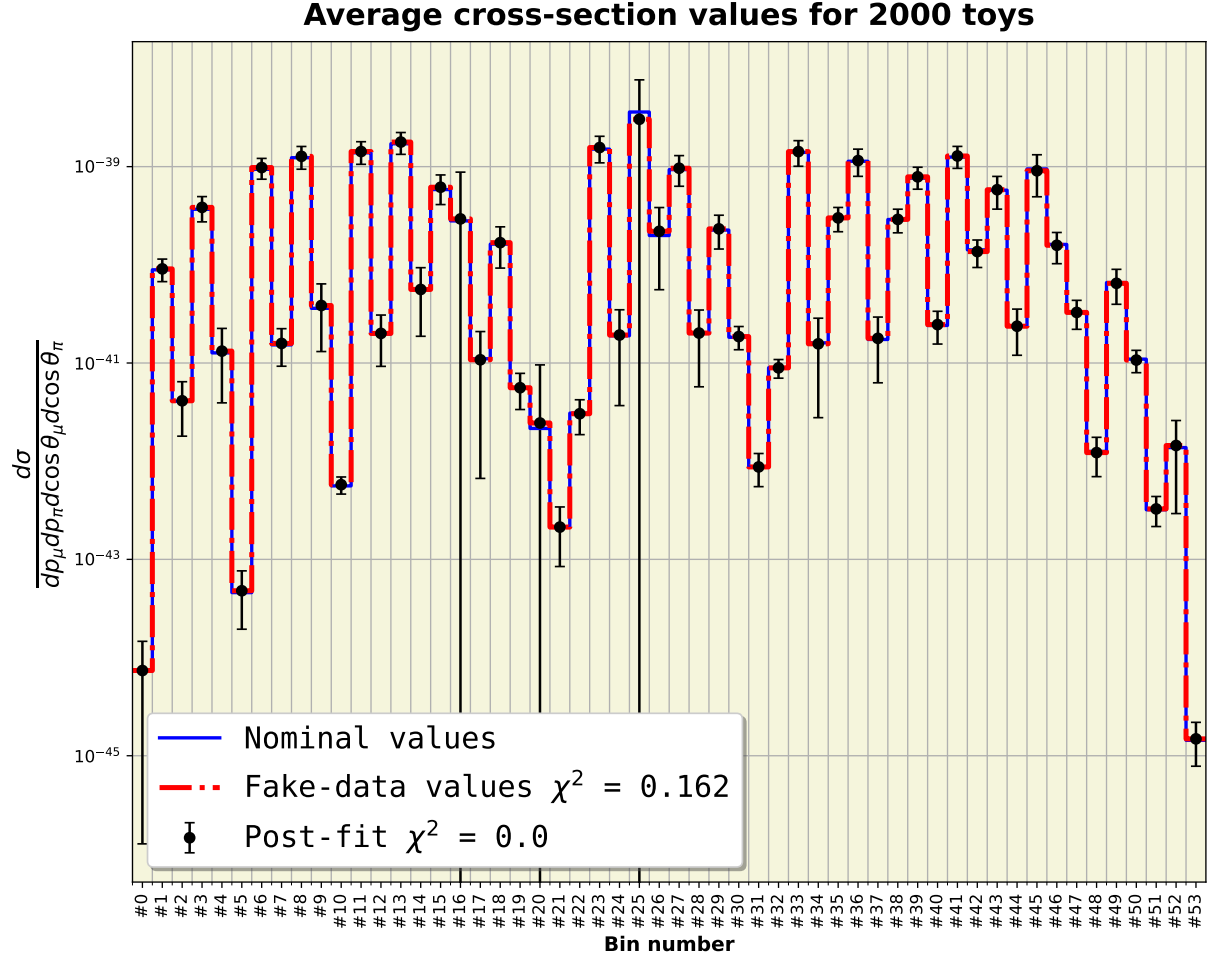


Figure D.24: CCOther reduced calculated cross-section for template binning in true 4D kinematic variables. Each data point refers to a specific region in phase space spun by a range in muon momentum & angle and pion momentum & angle. Blue represents the cross-section based on the nominal MC parameters. The dashed red line refers to cross-section values based on the inserted fake data set used as ‘data’, which is identical to the nominal MC in an Asimov fit. The black scatter points with error bars are the cross-section values derived from the post-fit template parameters.

DUNE ANALYSIS ADDENDUM

E

In this appendix, the remaining results for the liquid argon prototyping for the DUNE experiment will be shown.

E.1 TRACK PROPERTIES MODULE-0

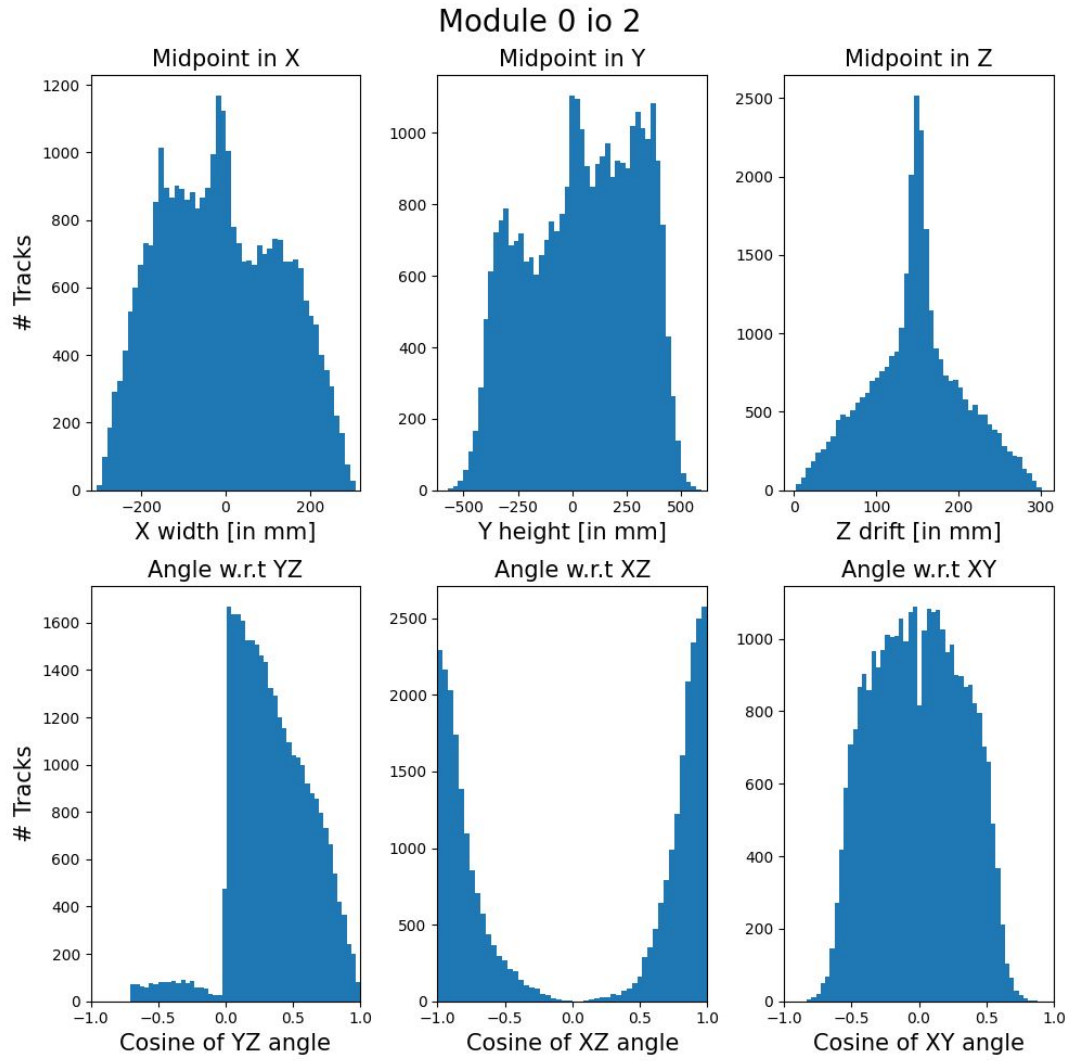


Figure E.1: Midpoints and angles for data from the second drift volume of Module-0.

E.2 ARGONCUBE 2X2 EVENT DISPLAYS

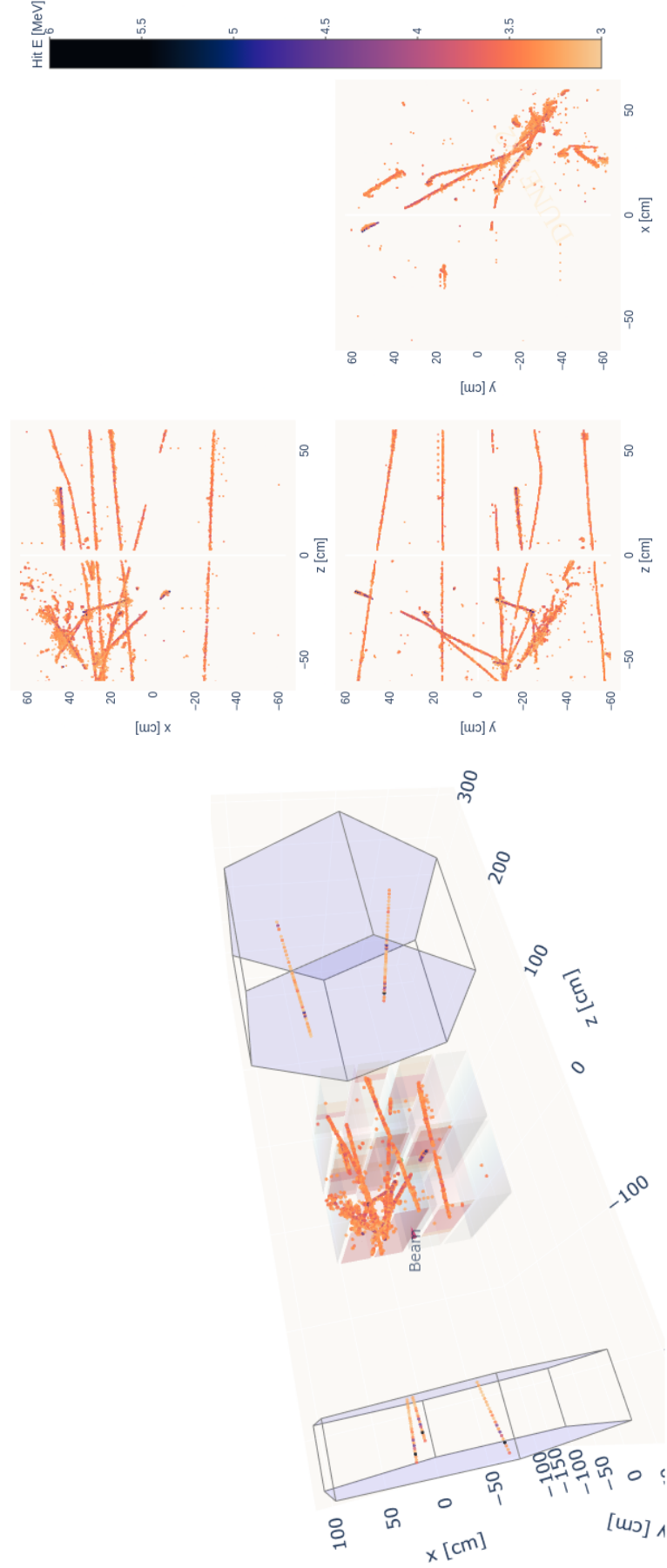


Figure E.2: Event display of the MINERvA 2x2 showing multiple through-going muons on top of a neutrino interaction in 3D (left) and 2D (right) representations taken from <https://larnddisplay.lbl.gov/>.

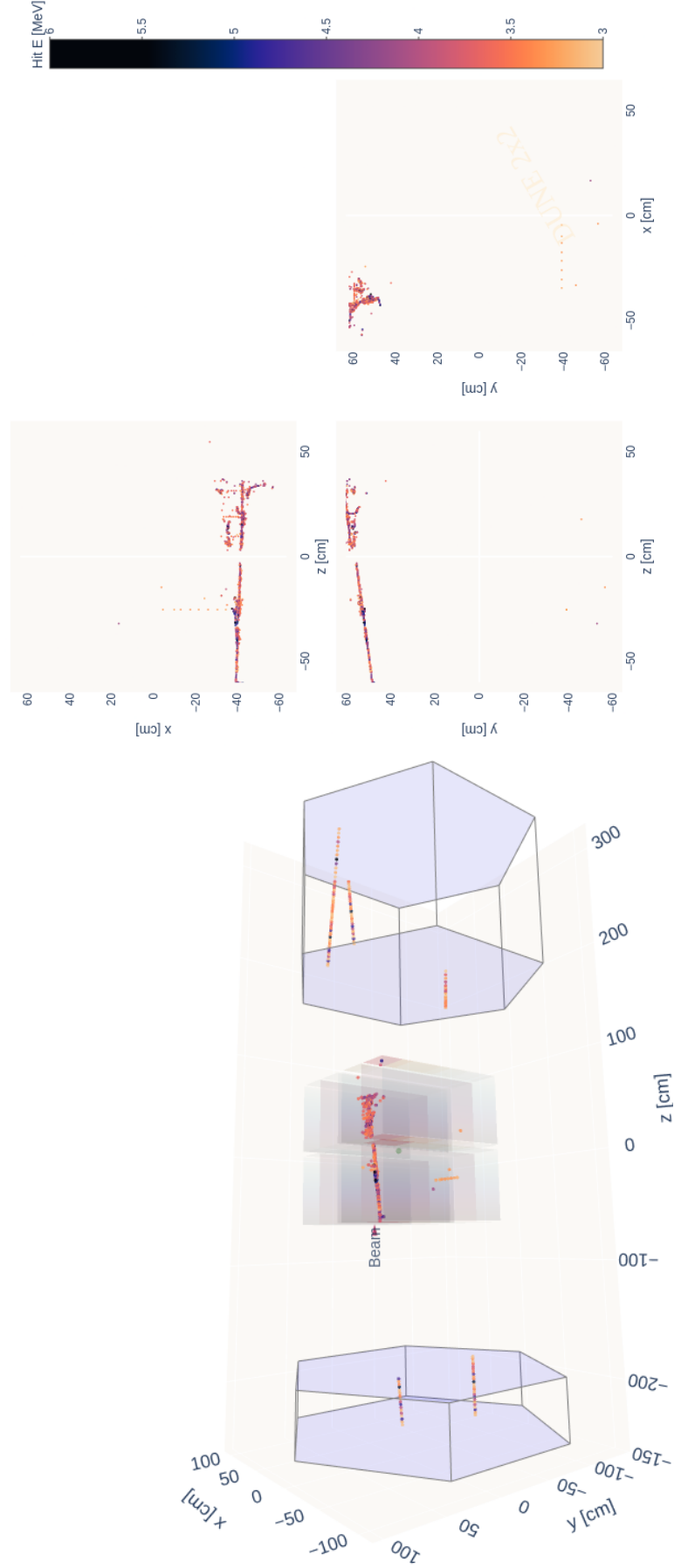


Figure E.3: Event display of the MINERvA 2x2 showing a muon that enters the 2 by 2 and comes to a complete stop in 3D (left) and 2D (right) representations taken from <https://larnddisplay.lbl.gov/>.