

1 Impact of PØD NuMu Samples in BANFF

2 Hogan, Matthew¹ and Toki, Walter¹

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4 ¹Colorado State University, Fort Collins, USA

5 **Abstract**

6 This is the abstract

7 **Contents**

8	1 Introduction	10
9	1.1 ND280	10
10	1.1.1 The PØD	11
11	1.2 Usage of ND280 Psyche Software	12
12	2 BANFF Likelihood Maximization	14
13	2.1 Motivation	14
14	2.2 Introduction to Conditional PDFs and Likelihoods	15
15	2.3 BANFF Fit Test Statistic	16
16	2.3.1 Flux, Cross Section, and Detector Systematics	19
17	3 PØD Selections and Data Samples	23
18	3.1 Global Reconstruction	23
19	3.2 PØD Selection Cuts	25
20	3.2.1 Pre-Selection Cuts	25
21	3.2.2 ν_μ CC Inclusive in FHC Cut	27
22	3.2.3 $\bar{\nu}_\mu$ CC Inclusive in RHC Cuts	27
23	3.2.4 ν_μ Background CC Inclusive in RHC Cuts	28
24	3.3 Sample Kinematics and Validation	28
25	3.4 PØD Water-Out Samples	28
26	3.4.1 CC Inclusive	30
27	3.4.1.1 ν_μ Selection in FHC Mode:	30
28	3.4.1.2 $\bar{\nu}_\mu$ Selection in RHC Mode:	37
29	3.4.1.3 ν_μ Background Selection in RHC Mode:	44
30	3.4.2 CC 1-Track (CCQE Enhanced)	51

31	3.4.2.1	ν_μ Selection in FHC Mode:	51
32	3.4.2.2	$\bar{\nu}_\mu$ Selection in RHC Mode:	58
33	3.4.2.3	ν_μ Background Selection in RHC Mode:	65
34	3.4.3	CC N-Tracks (CCnQE Enhanced)	65
35	3.4.3.1	ν_μ Selection in FHC Mode:	65
36	3.4.3.2	$\bar{\nu}_\mu$ Selection in RHC Mode:	72
37	3.4.3.3	ν_μ Background Selection in RHC Mode:	79
38	3.5	PØD Water-In Samples	79
39	3.5.1	CC Inclusive	80
40	3.5.1.1	ν_μ Selection in FHC Mode:	80
41	3.5.1.2	$\bar{\nu}_\mu$ Selection in RHC Mode:	87
42	3.5.1.3	ν_μ Background Selection in RHC Mode:	94
43	3.5.2	CC 1-Track (CCQE Enhanced)	94
44	3.5.2.1	ν_μ Selection in FHC Mode:	94
45	3.5.2.2	$\bar{\nu}_\mu$ Selection in RHC Mode:	101
46	3.5.2.3	ν_μ Background Selection in RHC Mode:	108
47	3.5.3	CC N-Tracks (CCnQE Enhanced)	108
48	3.5.3.1	ν_μ Selection in FHC Mode:	108
49	3.5.3.2	$\bar{\nu}_\mu$ Selection in RHC Mode:	109
50	3.5.3.3	ν_μ Background Selection in RHC Mode:	109
51	3.5.4	Differences Between Water-Out and Water-In Samples	109
52	4	PØD-Only BANFF Parameterization	110
53	5	Fitter Validation	111
54	6	Fitter Results	112

55	7 Discussion	113
56	References	114
57	Nomenclature	116

58 **List of Figures**

59	1.1 Exploded view of the off-axis detectors of ND280	10
60	1.2 Cartoon of the PØD	11
61	1.3 Cartoon of an Individual PØDule	12
62	1.4 Fluxing Tuning Histogram for FHC Events	13
63	2.1 BANFF Pre-fit Flux Covariance Matrix	20
64	2.2 BANFF ND280 NuMu and ANuMu Flux Binning Parameters	20
65	2.3 Cross Section Parameters Pre-fit Correlation Matrix	21
66	3.1 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. Momentum by True Particle	31
67	3.2 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Particle . . .	32
68	3.3 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. Momentum by NEUT Mode	33
69	3.4 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. $\cos\theta$ by NEUT Mode . . .	34
70	3.5 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. Momentum by True Topology	35
71	3.6 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Topology . . .	36
72	3.7 PØD Air FHC ν_μ CC Inc. Lepton Cand. True E_ν by NEUT Mode	37
73	3.8 PØD Air RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. Momentum by True Particle	38
74	3.9 PØD Air RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Particle . . .	39
75	3.10 PØD Air RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. Momentum by NEUT Mode	40
76	3.11 PØD Air RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. $\cos\theta$ by NEUT Mode . . .	41
77	3.12 PØD Air RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. Momentum by True Topology	42
78	3.13 PØD Air RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Topology . . .	43
79	3.14 PØD Air FHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. True E_ν by NEUT Mode	44
80	3.15 PØD Air RHC ν_μ CC Inc. Lepton Cand. Reco. Momentum by True Particle	45
81	3.16 PØD Air RHC ν_μ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Particle	46
82	3.17 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. Momentum by NEUT Mode	47

83	3.18 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. $\cos\theta$ by NEUT Mode	48
84	3.19 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. Momentum by True Topology	49
85	3.20 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Topology	50
86	3.21 PØD Air FHC ν_μ CC Inc. Lepton Cand. True E_ν by NEUT Mode	51
87	3.22 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. Momentum by True Particle	52
88	3.23 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Particle	53
89	3.24 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. Momentum by NEUT Mode	54
90	3.25 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. $\cos\theta$ by NEUT Mode	55
91	3.26 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. Momentum by True Topology	56
92	3.27 PØD Air FHC ν_μ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Topology	57
93	3.28 PØD Air FHC ν_μ CC Inc. Lepton Cand. True E_ν by NEUT Mode	58
94	3.29 PØD Air RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. Momentum by True Particle	59
95	3.30 PØD Air RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Particle	60
96	3.31 PØD Air RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. Momentum by NEUT Mode	61
97	3.32 PØD Air RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. $\cos\theta$ by NEUT Mode	62
98	3.33 PØD Air RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. Momentum by True Topology	63
99	3.34 PØD Air RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Topology . . .	64
100	3.35 PØD Air FHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. True E_ν by NEUT Mode	65
101	3.36 PØD Air FHC ν_μ CC N-Tracks Lepton Cand. Reco. Momentum by True	
102	Particle	66
103	3.37 PØD Air FHC ν_μ CC N-Tracks Lepton Cand. Reco. $\cos\theta$ by True Particle .	67
104	3.38 PØD Air FHC ν_μ CC N-Tracks Lepton Cand. Reco. Momentum by NEUT	
105	Mode	68
106	3.39 PØD Air FHC ν_μ CC N-Tracks Lepton Cand. Reco. $\cos\theta$ by NEUT Mode .	69
107	3.40 PØD Air FHC ν_μ CC N-Tracks Lepton Cand. Reco. Momentum by True	
108	Topology	70

109	3.41 PØD Air FHC ν_μ CC N-Tracks Lepton Cand. Reco. $\cos\theta$ by True Topology	71
110	3.42 PØD Air FHC ν_μ CC N-Tracks Lepton Cand. True E_ν by NEUT Mode . . .	72
111	3.43 PØD Air RHC $\bar{\nu}_\mu$ CC N-Tracks Lepton Cand. Reco. Momentum by True	
112	Particle	73
113	3.44 PØD Air RHC $\bar{\nu}_\mu$ CC N-Tracks Lepton Cand. Reco. $\cos\theta$ by True Particle .	74
114	3.45 PØD Air RHC $\bar{\nu}_\mu$ CC N-Tracks Lepton Cand. Reco. Momentum by NEUT	
115	Mode	75
116	3.46 PØD Air RHC $\bar{\nu}_\mu$ CC N-Tracks Lepton Cand. Reco. $\cos\theta$ by NEUT Mode .	76
117	3.47 PØD Air RHC $\bar{\nu}_\mu$ CC N-Tracks Lepton Cand. Reco. Momentum by True	
118	Topology	77
119	3.48 PØD Air RHC $\bar{\nu}_\mu$ CC N-Tracks Lepton Cand. Reco. $\cos\theta$ by True Topology	78
120	3.49 PØD Air FHC $\bar{\nu}_\mu$ CC N-Tracks Lepton Cand. True E_ν by NEUT Mode . .	79
121	3.50 PØD Water FHC ν_μ CC Inc. Lepton Cand. Reco. Momentum by True Particle	81
122	3.51 PØD Water FHC ν_μ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Particle .	82
123	3.52 PØD Water FHC ν_μ CC Inc. Lepton Cand. Reco. Momentum by NEUT Mode	83
124	3.53 PØD Water FHC ν_μ CC Inc. Lepton Cand. Reco. $\cos\theta$ by NEUT Mode .	84
125	3.54 PØD Water FHC ν_μ CC Inc. Lepton Cand. Reco. Momentum by True Topology	85
126	3.55 PØD Water FHC ν_μ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Topology .	86
127	3.56 PØD Water FHC ν_μ CC Inc. Lepton Cand. True E_ν by NEUT Mode . . .	87
128	3.57 PØD Water RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. Momentum by True Particle	88
129	3.58 PØD Water RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Particle .	89
130	3.59 PØD Water RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. Momentum by NEUT Mode	90
131	3.60 PØD Water RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. $\cos\theta$ by NEUT Mode .	91
132	3.61 PØD Water RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. Momentum by True	
133	Topology	92
134	3.62 PØD Water RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Topology .	93

135	3.63 PØD Water FHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. True E_ν by NEUT Mode	94
136	3.64 PØD Water FHC ν_μ CC 1-Track Lepton Cand. Reco. Momentum by True	
137	Particle	95
138	3.65 PØD Water FHC ν_μ CC 1-Track Lepton Cand. Reco. $\cos\theta$ by True Particle	96
139	3.66 PØD Water FHC ν_μ CC 1-Track Lepton Cand. Reco. Momentum by NEUT	
140	Mode	97
141	3.67 PØD Water FHC ν_μ CC 1-Track Lepton Cand. Reco. $\cos\theta$ by NEUT Mode	98
142	3.68 PØD Water FHC ν_μ CC 1-Track Lepton Cand. Reco. Momentum by True	
143	Topology	99
144	3.69 PØD Water FHC ν_μ CC 1-Track Lepton Cand. Reco. $\cos\theta$ by True Topology	100
145	3.70 PØD Water FHC ν_μ CC 1-Track Lepton Cand. True E_ν by NEUT Mode . .	101
146	3.71 PØD Water RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. Momentum by True Particle	102
147	3.72 PØD Water RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Particle . .	103
148	3.73 PØD Water RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. Momentum by NEUT Mode	104
149	3.74 PØD Water RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. $\cos\theta$ by NEUT Mode . .	105
150	3.75 PØD Water RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. Momentum by True	
151	Topology	106
152	3.76 PØD Water RHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. Reco. $\cos\theta$ by True Topology .	107
153	3.77 PØD Water FHC $\bar{\nu}_\mu$ CC Inc. Lepton Cand. True E_ν by NEUT Mode	108

154 **List of Tables**

155 3.1 PØD WT FV and Corridor Definition	27
156 3.2 POT Used in This Analysis	29

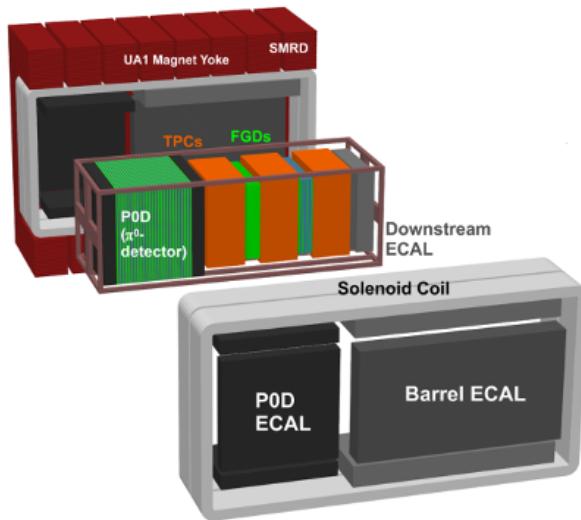


Figure 1.1: Exploded view of the off-axis detectors of ND280. The neutrino beam is directed from left to right along the figure.

157 1 Introduction

158 The primary goal of an oscillation experiment is to measure the parameters in a neutrino
 159 mixing matrix. All other parameters, with some having some theoretical importance to
 160 fundamental physics, are nuisance parameters. To understand the methodology of Beam
 161 and Near detector Flux task Force (BANFF) fit, it is relevant to understand how likelihood
 162 fitting works.

163 1.1 ND280

164 The T2K near detector (ND) complex consists of on-axis and off-axis detectors at 280m away
 165 from the secondary beamline proton target. The off-axis detector is used in this analysis
 166 which consists of several subdetectors housed inside the UA1/NOMAD magnet yoke as
 167 shown in figure 1.1. A similar analysis was also performed with the on-axis detector and is
 168 available in T2K-TN-335[13]. . The magnet provides a 0.2T magnetic field which is designed
 169 to provide momentum and particle identification for the tracker region.

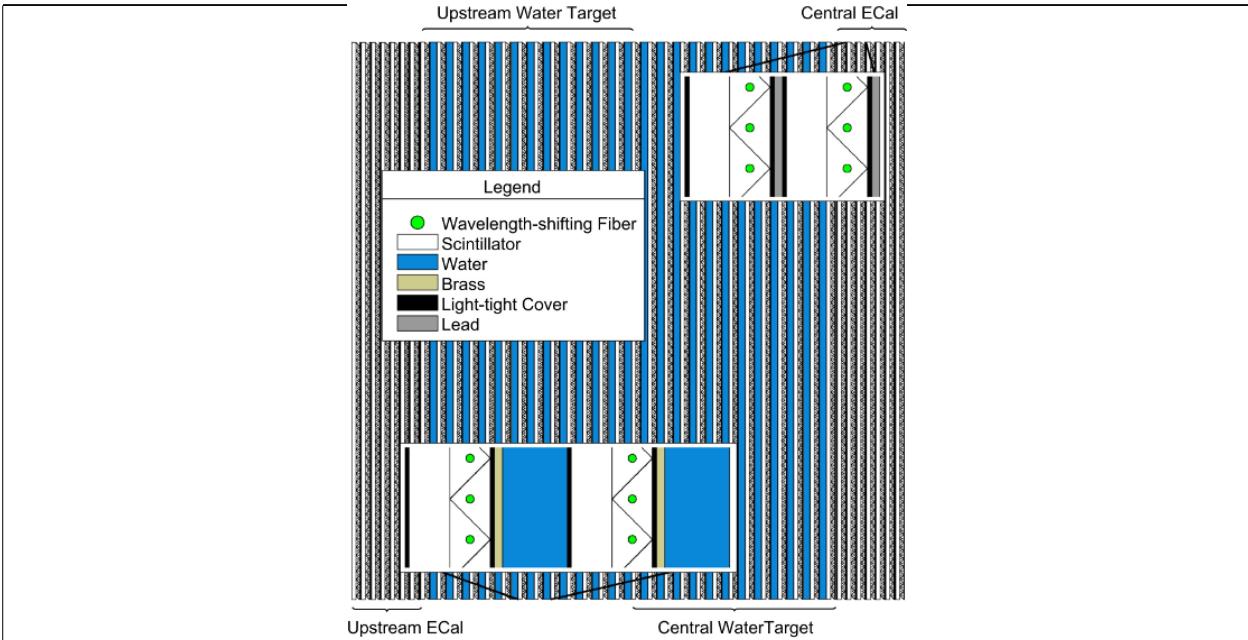


Figure 1.2: This cartoon illustrates the concept design of the PØD where the neutrino beam is approaching from the left.

¹⁷⁰ **1.1.1 The PØD**

¹⁷¹ The PØD, short for π^0 Detector, is a plastic scintillator based tracking calorimeter inside the
¹⁷² ND280 basket. The PØD is constructed as many sandwiches of active and inactive materials
¹⁷³ designed to fully contain π^0 decay photons. The four primary regions inside the PØD in
¹⁷⁴ order of upstream to downstream of the neutrino beam are the upstream ECal (USECal),
¹⁷⁵ upstream water target (WT), central WT, and central ECal (CECal). A representation of
¹⁷⁶ the entire PØD can be seen in Figure 1.2. Each active module, also called a PØDule, consists
¹⁷⁷ of two orthogonally oriented sheets of triangular, scintillator-doped plastic bars as shown in

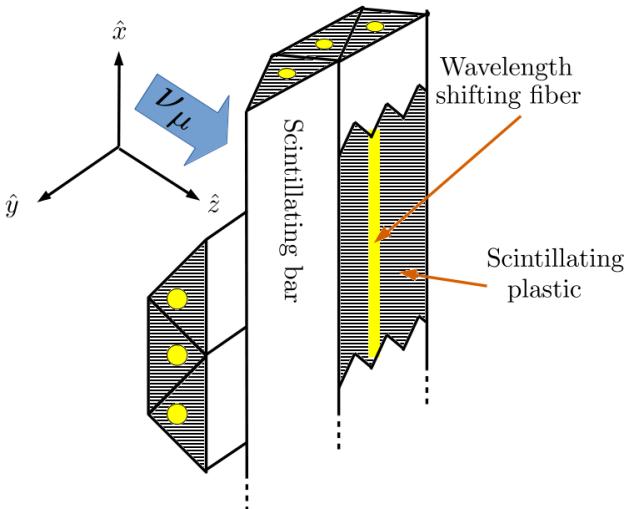


Figure 1.3: This cartoon illustrates the design of a PØDule with orthogonal layers of scintillating, triangular bars. When a charged particle travels through the bar such as a muon from CC interaction, the scintillation light is captured and wavelength shifted inside a fiber bored in the center of each bar. The wavelength shifted light is later observed by a photon counter.

178 Figure 1.3. The ECal regions are designed to contain decay photons inside the PØD by
 179 alternating the scintillator planes with lead sheets. The WT regions, as compared to the lead
 180 sheets in the ECals, alternate a thin brass sheet and water filled bags between the PØDules.
 181 A unique feature of the PØD is that the water can be drained out resulting in two detector
 182 configurations: water-in and water-out.

183 1.2 Usage of ND280 Psyche Software

184 Psyche is a general framework for data handling, event selections, and systematic evaluations
 185 with toy experiments. Psyche is a “lean” package from the perspective of analyzing MC
 186 events since that functionality is built heavily into Highland2. The analysis performed in
 187 this technical note required making additions to psyche in order replicate features available
 188 in Highland2. It would be wise for future analyses to build a selection in Highland2 and
 189 migrate that psyche once mature.

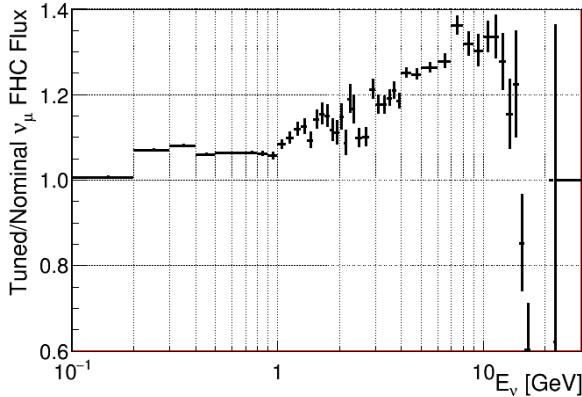


Figure 1.4: Fluxing tuning histogram for ν_μ FHC events taken from the 13av3 flux release.

BANFF uses a psyche package called psycheSteering that interfaces with all the psyche tools to manage the migration of samples into its analysis code. New PØD selections were added to the psycheSelections package and validated using the psycheSteering AnalysisManager class. The AnalysisManager provides the functionality to get the true and reconstructed detector observables from each reconstructed event along with the flux tuning and detector systematic weights.

Flux tuning is the process of applying an event weight based on the true neutrino energy, flavor, and run period. Since the ND280 MC uses a series of models to describe the expected neutrino flux, it cannot perfectly model the true flux nor know the beam conditions at run time. The beam group is responsible for releasing the expected and measured neutrino flux in order to account for these differences. To flux tune an event, the relevant neutrino flavor flux histogram must be referenced. The weight is extracted by taking the ratio of the tuned flux to the nominal flux in the MC for a given neutrino energy. As an example Figure 1.4 shows the flux tuning weights for true ν_μ FHC events.

204 **2 BANFF Likelihood Maximization**

205 The BANFF likelihood maximization procedure is the method of performing a binned like-
206 lihood maximization fit of the ND280 data separate from the Super-Kamiokande (SK) data.
207 In a joint ND280 and SK joint fit, the measurements from both detectors are considered along
208 with their respective nuisance parameters. This approach is computationally expensive since
209 the time to perform a fit increases non-linearly with dimensionality. It is, however, pursued
210 in the Markov Chain Monte Carlo analysis (MaCh3) and will not be explained here. The
211 BANFF likelihood maximization, hitherto referred to as the “BANFF-fit”, includes nuisance
212 parameters that while affect the measurement of the oscillation parameters, are not physics
213 goals of T2K. The BANFF-fit parameters and their respective covariances are then used
214 as inputs in the oscillation analysis. This “divide-and-conquer” approach allows for more
215 rapidly completed studies on the effects of model parameters and biases present. Also this
216 approach should provide the same result with a joint ND280 and SK analysis as is performed
217 in MaCh3. However, information encoded in the ND280 measurements for shared nuisance
218 parameters like the neutrino flux is inevitably lost in the BANFF-fit.

219 The modern BANFF-fit likelihood is described in detail in TN-220[10]. While subsequent
220 updates to the BANFF analysis[11, 4, 3] increase the sample sizes and systematic parame-
221 terizations, the method has remained unchanged. It uses a frequentist approach to find the
222 best nuisance parameter set to maximize a binned likelihood.

223 **2.1 Motivation**

224 Curve fitting is commonly found in the particle physics community literature due to the
225 need to compare two models or constrain unknown model parameters using one or more
226 histograms. For the first case, this involves two competing models, H_0 and H_1 , in order to
227 establish if the data supports new Physics (H_1) not predicted in the Standard Model (H_0).

228 The second case finds the “best” set of the model predictions, θ , that match the data as is the
 229 case for the BANFF-fit. In both cases, chi-squared tests are performed to provide goodness
 230 of fit, parameter estimation (also referred to as “best fit parameters”), and error/confidence
 231 estimation.

232 **2.2 Introduction to Conditional PDFs and Likelihoods**

233 Consider the problem of extracting physics parameters \vec{y} given some data vector \vec{N} . The
 234 conditional probability density function (PDF) \mathcal{P} to measure these parameters is given as

$$\mathcal{P}(\vec{y}|\vec{N}) = \frac{\mathcal{L}(\vec{N}|\vec{y})\mathcal{P}(\vec{y})}{\int \mathcal{L}(\vec{N}|\vec{x})\mathcal{P}(\vec{x})d\vec{x}}, \quad (2.1)$$

235 where anything right of a vertical line represents a condition on the probability, $\mathcal{L}(\vec{N}|\vec{y})$
 236 is the likelihood of the model with parameters \vec{y} , $\mathcal{P}(\vec{y})$ is the probability for the model,
 237 and the denominator is the normalization over all possible constraints on the observations.
 238 A frequentist interpretation of a PDF is a proportion of outcomes of repeated trials or
 239 experiments. A likelihood function is an expression of the probability of observing data as a
 240 function of the model parameters in their appropriate ranges.

241 One arrives at (2.1) by using the definition of compound probabilities

$$\mathcal{P}(A, B) = \mathcal{P}(B|A)\mathcal{P}(A) \quad (2.2)$$

242 to evaluate $\mathcal{P}(\vec{y}|\vec{N})$ as

$$\mathcal{P}\left(\underbrace{\vec{y}}_B \middle| \underbrace{\vec{N}}_A\right) = \frac{\mathcal{P}(\vec{N}, \vec{y})}{\mathcal{P}(\vec{N})} \quad (2.3)$$

243 with the denominator here is recognized as the normalization of the PDF. The compound

244 PDF $\mathcal{P}(\vec{N}, \vec{y})$ can expanded using Bayes' theorem which states

$$\mathcal{P}(A|B)\mathcal{P}(B) = \mathcal{P}(B|A)\mathcal{P}(A), \quad (2.4)$$

245 and combined with (2.2) yielding

$$\mathcal{P}\left(\underbrace{\vec{N}}_A, \underbrace{\vec{y}}_B\right) = \mathcal{P}(\vec{N}|\vec{y}) \times \mathcal{P}(\vec{y}), \quad (2.5)$$

246 where the PDFs to the left and right of the \times operator are recognized as the likelihoods and
247 priors, respectively. Combining resulting in (2.3) and (2.5) reproduces the original expression
248 of (2.1).

249 2.3 BANFF Fit Test Statistic

250 For the BANFF fit, one considers the problem of trying to maximize the agreement between
251 measured and predicted data histograms. This is equivalent to maximizing a binned likeli-
252 hood function \mathcal{L} of the data given the a set of parameters that predict the measured rate.
253 The use of likelihood functions in fits to histogram is explained further in reference [2] and
254 the PDG review on Statistics. By invoking Wilks' theorem, also known as the likelihood ratio
255 theorem, the likelihood maximization procedure is converted into a minimization problem
256 involving a test statistic denoted as a chi-squared. Below is an explanation of the BANFF
257 test statistic, $\Delta\chi^2$, and its systematic model terms.

258 Consider many binned samples that select different charged current topologies. A conve-
259 nient choice of observables for all the samples are the outgoing charged lepton l momentum P_l
260 and angle $\cos\theta_l$ as measured in ND280. Much of this is also documented in TN-220[10] where
261 additional details can be found. For each $(P_l, \cos\theta_l)$ analysis bin $i = 1, 2, \dots, M - 1, M$, the

262 likelihood is given by

$$\mathcal{L}(\vec{N}^d | \vec{N}^p) = \left(\prod_{i=1}^M \left(\vec{N}_i^p \right)^{\vec{N}_i^d} \frac{e^{-\vec{N}_i^p}}{\vec{N}_i^d!} \right) \quad (2.6)$$

263 where \vec{N}_i^d is the number of observed data events in the i th bin and \vec{N}_i^p is the number of
 264 predicted events as a function of nuisance parameters in the i th bin. One recognizes the
 265 likelihood function in (2.6) as a Poisson distribution given this is a counting experiment.
 266 The sets of dependent nuisance parameters, also sometimes called systematics, that affect
 267 the predicted event rate are

- 268 • cross section physics models, labeled as “xsec”,
- 269 • neutrino flux, and
- 270 • detector biases and inefficiencies.

271 Given these three sets of systematics, the number of predicted CC events from any neutrino
 272 flavor ν_l at ND280 is calculated considering the general formula

$$N_{\nu_l} = \Phi_{\nu_l} \times \sigma_{\nu_l} \times \epsilon_{\nu_l}, \quad (2.7)$$

273 where Φ_{ν_l} is the flux of l flavor neutrinos, σ_{ν_l} is the cross section of the interaction for neutrino
 274 flavor l , and ϵ_{ν_l} is the total efficiency to reconstruct and properly identify the event as ν_l CC
 275 interactions. Each term in (2.7) is modeled carefully and the efficiency term is estimated
 276 using Monte Carlo (MC) simulations and control samples. The number of predicted events
 277 from the MC for a given analysis bin i is given by

$$\vec{N}_i^p(\vec{b}, \vec{x}, \vec{d}) = w_i^{\text{POT}} d_i^{\text{Det}} \sum_{j=1}^{N_i^{\text{MC}}} \left[\sum_{k=1}^{N^{\text{Flux}}} \left(\delta_{j,k}^{\text{Flux}} \vec{b}_k \right) \prod_{l=1}^{N^{\text{xSyst}}} w_{j,l}(\vec{x}_l^{\text{xsec}}) \right]. \quad (2.8)$$

278 Here w_i^{POT} is the protons on target (POT) weight for the i th analysis which normalizes

the MC statistics to expected data statistics. To account for the detector inefficiencies, the \vec{d}_i^{Det} parameters are normalization parameters that vary the total number of predicted events in the i th bin. Each \vec{d}_i^{Det} is determined prior to the fit by surveying over a large number of toy experiments with the detector systematics varied in each. The sum over $j = 1, 2, \dots, N_i^{\text{MC}} - 1, N_i^{\text{MC}}$ considers the contribution of all MC events in the i th analysis bin. The \vec{b}_k parameters, out of a total of N^{Flux} , are flux normalization systematics for each flux bin. Since the flux bins are categorized not only by neutrino energy, but also by energy and horn current, the $\delta_{j,k}^{\text{Flux}}$ term in the sum over k selects the correct flux bin. And finally the parameters $w_{j,l}$ are pre-calculated weights as a function for the l th cross section model, \vec{x}_l^{xsec} , with a total of N^{xSyst} cross section model terms.

Using the likelihood ratio test theorem, a test statistic is defined as taking -2 times the natural logarithm of the ratio of predicted to observed likelihoods

$$\Delta\chi_{\text{LLR}}^2 = -2 \log \frac{\mathcal{L}(\vec{N}^d | \vec{N}^p)}{\mathcal{L}(\vec{N}^d | \vec{N}^d)}, \quad (2.9)$$

where this test statistic $\Delta\chi_{\text{LLR}}^2$ obeys a true chi-squared distribution for asymptotically large statistics and the likelihood functions are of the form (2.6). Penalty terms from the cross section, flux, and detector systematics are included in order to prevent overfitting of the data. The new test statistic for all of ND280, $\Delta\chi_{\text{ND280}}^2$, is given by

$$\begin{aligned} \Delta\chi_{\text{ND280}}^2 &= \Delta\chi_{\text{LLR}}^2 + \Delta\chi_{\text{xsec}}^2 + \Delta\chi_{\text{Flux}}^2 + \Delta\chi_{\text{Det}}^2 \\ &\quad - 2 \left(\log \frac{\mathcal{L}(\vec{N}^d | \vec{N}^p)}{\mathcal{L}(\vec{N}^d | \vec{N}^d)} + \underbrace{\log \pi(\vec{x})}_{\text{xsec}} + \underbrace{\log \pi(\vec{b})}_{\text{Flux}} + \underbrace{\log \pi(\vec{d})}_{\text{Det}} \right), \end{aligned} \quad (2.10)$$

295 where each of the PDFs $\pi(\vec{y} = \vec{x}, \vec{b}, \vec{d})$ are assumed multivariate normal distributions

$$\pi(\vec{y}) = C_y e^{\left(-\frac{1}{2}\Delta\vec{y} \cdot V_y^{-1} \cdot \Delta\vec{y}^T\right)}, \quad (2.11)$$

296 $\Delta\vec{y}$ is a vector with the difference between the current/explored and nominal set of vector
297 parameters \vec{y} , T corresponds to the transpose operator, and the normalization is given by

$$C_y = \left((2\pi)^{k_y} \det(V_y)\right)^{-\frac{1}{2}} \quad (2.12)$$

298 with V_y being the covariance matrix for a vector \vec{y} with k_y rows. The expanded form of the
299 test statistic $\Delta\chi_{\text{ND280}}^2$ is given by

$$\begin{aligned} \Delta\chi_{\text{ND280}}^2 = & 2 \sum_{i=1}^M \left[\vec{N}_i^p - \vec{N}_i^d + \vec{N}_i^d \log\left(\frac{\vec{N}_i^d}{\vec{N}_i^p}\right) \right] \\ & + \Delta\vec{x} \cdot (V_x^{-1}) \cdot \Delta\vec{x}^T + \Delta\vec{b} \cdot (V_b^{-1}) \cdot \Delta\vec{b}^T + \Delta\vec{d} \cdot (V_d^{-1}) \cdot \Delta\vec{d}^T \end{aligned} \quad (2.13)$$

300 where the “ \cdot ” is the matrix multiplication operator. It must be stated that the test statistic
301 (2.13) purposefully **excludes normalization terms**. Once the global minimum of the test
302 statistic is found, the postfit covariance matrix V is calculated as the inverse of the Hessian
303 matrix H

$$V_{i,j}(\hat{\vec{y}}) = (H_{i,j})^{-1} = \left(\frac{\partial^2}{\partial y_i \partial y_j} (\Delta\chi_{\text{ND280}}^2) \Big|_{\vec{y}=\hat{\vec{y}}} \right)^{-1} \quad (2.14)$$

304 where $y_i, y_j \in \vec{y}$ and $\hat{\vec{y}}$ is the maximum likelihood estimate for the parameters \vec{y} .

305 2.3.1 Flux, Cross Section, and Detector Systematics

306 Below is a description for each of the systematics in the BANFF likelihood and test statistic
307 penalty terms. First is a description of flux, followed by the cross section, and finally the
308 detector systematics.

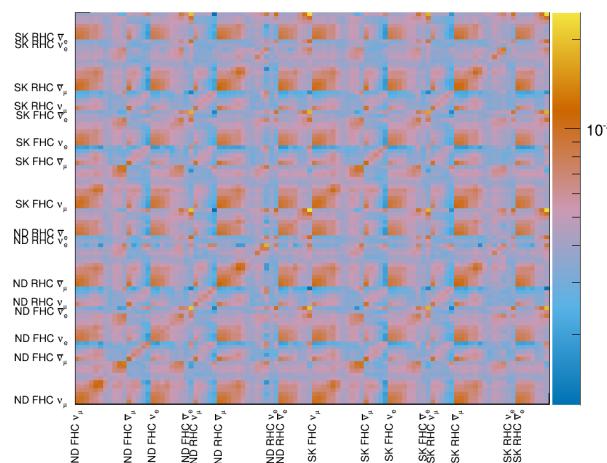


Figure 2.1: BANFF pre-fit flux covariance matrix shown with respective detector, horn current, and neutrino flavor.

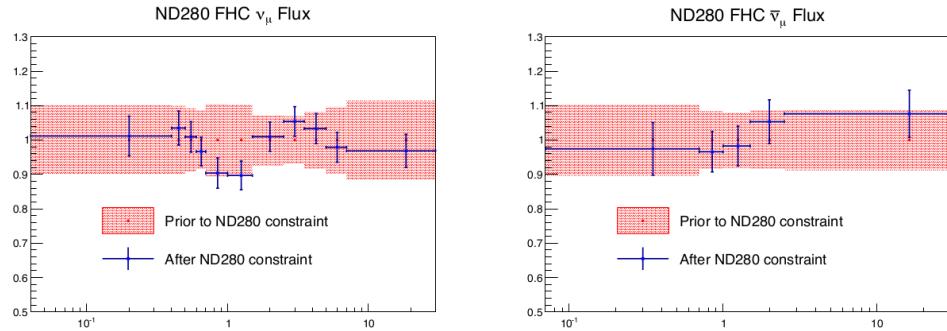


Figure 2.2: BANFF ND280 flux ν_μ and $\bar{\nu}_\mu$ binning parameters from T2K-TN-324 data post-fit results. The uncertainties are extracted from the pre-fit and post-fit covariance matrices.

Flux: The flux weight is binned as a function of neutrino energy, horn current/polarity (FHC and RHC), and neutrino flavor (ν_μ , $\bar{\nu}_\mu$, ν_e , and $\bar{\nu}_e$). There are 50 ND280 and 50 SK parameters with an associated covariance matrix as shown in Figure 2.1. The binning and covariance matrix is provided by the T2K flux group prior to the BANFF analysis. Each flux bin is assigned a normalization parameter with initial value of one (1) for all events in that neutrino energy bin. A value of 1.1 indicates that any event in that energy bin has an additional weight of 1.1, or 10% increase in events. An example of the flux normalizations and uncertainties used in the 2017 analysis are shown in Figure 2.2.

Cross Section: There are a number of cross section model systematics implemented in

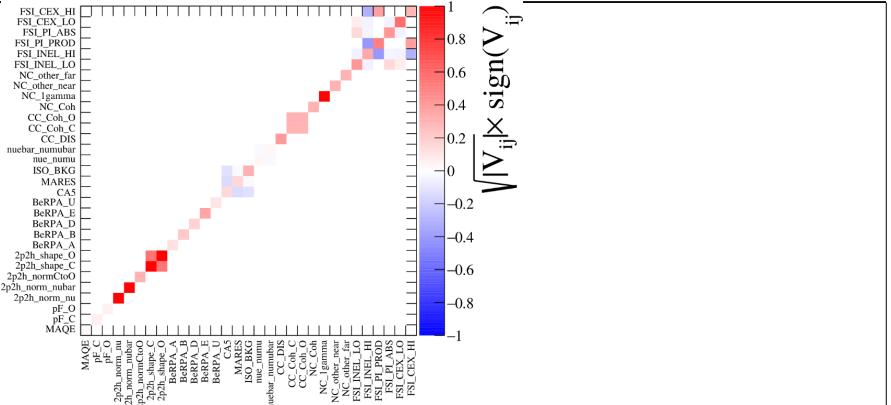


Figure 2.3: Cross section parameters pre-fit correlation matrix from the 2017 BANFF analysis.

318 BANFF to account for the uncertainties in cross section measurements. The cross section
 319 models used in this analysis are the 2017 Neutrino Interactions Working Group (NIWG)
 320 parameterization, which is a canonical set of parameters and covariance matrix shared among
 321 all analyses in T2K. A technical description of the 2017 parameterization is given in TN-
 322 315[5] and TN-307[14]. There are a total of 25 cross section parameters for interactions like
 323 meson exchange current that affect the shape and normalization of the cross section. The
 324 cross section covariance matrix is shown in Figure 2.3[4].

325 **Detector Systematics:** Detector systematics are implemented in BANFF to account for
 326 detector inefficiencies. Since neutrino interaction events can migrate from sample-to-sample,
 327 bin-to-bin, or both depending on the relevant systematics, numerous toy experiments are
 328 performed by varying parameters that model known detector systematics. After many toy
 329 experiments, usually 2000, a covariance matrix is constructed by measuring the spread of
 330 event rate in each analysis bin. While there could be one detector systematic normalization
 331 for each analysis bin, also called a observable normalization, a single one can be assigned
 332 to multiple analysis bins to reduce the number of fit parameters. This procedure requires
 333 careful consideration of the shared detector systematics among analysis bins. A considerable
 334 drawback to designing normalizations in this way is that not all detector systematics are

335 Gaussian with respect to the observables ($P_l, \cos \theta_l$), and so the covariance matrix is not a
336 accurate representation of the detector systematics.

337 **3 PØD Selections and Data Samples**

338 This section describes the development of ν_μ and $\bar{\nu}_\mu$ CC Inclusive selections in both FHC
339 and RHC beam configuration for PØD-based analyses. These selections are the continuation
340 of previous works that developed ν_μ CC Inclusive selections between the PØD and TPC1.
341 The first such analyses were T2K-TN-80 and T2K-TN-100 which described the ν_μ CC In-
342 clusive event selection and, later, cross-section analysis using ND280 Production 5 software,
343 respectively[7, 8]. These analyzes relied on each sub-detector’s reconstruction software and
344 developed a track matching algorithm since the ND280 “Global” reconstruction matching
345 was problematic in Production 5. As the inter-detector matching reconstruction improved in
346 “Global”, two CC-0 π cross section analyzes, T2K-TN-258 and T2K-TN-328, were developed
347 that also used the CC Inclusive selection as pre-selection cuts[16, 6]. The selections described
348 in this technical note also employ the same pre-selection cuts. What follows from here in
349 this section is a layout of the following topic discussions.

350 The first topic discussed in this section is a description of the π^0 Detector (PØD). The
351 next topic is the event reconstruction using the “Global” reconstruction software. Following
352 that is the pre-selection cut flow. With the pre-selection cuts established, each of the three
353 CC Inclusive selection’s cut flow is described. Concluding this section is a discussion of the
354 three samples in the following order: ν_μ in FHC mode, $\bar{\nu}_\mu$ in RHC, and ν_μ background in
355 RHC.

356 **3.1 Global Reconstruction**

357 The task of the Global reconstruction is to combine all the ND280 information into a com-
358 bined reconstructed object. It was originally designed to analyze “CCQE-like” events in the
359 Tracker region and has been extended to operate with all of ND280. A brief description
360 of the Global reconstruction is described below. First the specific detector technologies and

361 electronics of ND280 are explained. That is followed by the calibration procedure to properly
362 tune each detector’s response. And finally a general outline of the reconstruction algorithms
363 to form tracks and vertices in ND280 is presented.

364 ND280 events are first collected in the form of electronic signals from either multipixel
365 photon counters (MPPCs) in the scintillator-based sub-detectors or charge collected collec-
366 tion planes of the time projection chambers (TPCs). MPPCs were chosen for the scintillator-
367 based sub-detectors since they are insensitive to the strong 0.2T magnetic field present in
368 ND280. The PØD, ECals, and SMRD all share the same “Trip-T” frontend board (TFB)
369 electronics of which collect the photoelectrons released when photons interact with a pixel
370 in the MPPCs. The FGDs operate with the same MPPC technology while using different
371 frontend electronics. The TPCs utilize a locally strong electric field to collect ionization elec-
372 trons from an Argon-based gas. Collected charge in the TPCs are collected and enhanced
373 using micromega technology[1]. With the collected information from each sub-detector, the
374 next step is the data calibration.

375 Data calibration in ND280 is the process where the charge and timing information col-
376 lected from each sub-detector is adjusted to match with expected parameters. This is an
377 important process that takes into account environmental changes, aging effects, and other
378 behavior that might be present. Calibration data is collected frequently before and during
379 operational runtime and is stored in a database for later use. A common calibration is to
380 measure the detector’s cosmic ray response since most cosmic rays deposit the same energy
381 per unit length. After the data has been calibrated, reconstruction algorithms now attempt
382 to find charged particle tracks in the data.

383 The Global reconstruction is a software package that attempts to recognize patterns of
384 data to form tracks and find vertices for those tracks. Particle shower reconstruction in
385 Global will not be discussed in this TN since no shower objects are used. Each sub-detector
386 reconstruction is run to seeds Global’s track matching algorithms. Global attempts to then

387 re-fit sub-detector tracks using a Kalman filter while correcting for particle energy loss as a
388 function of length (dE/dx) and multi-scattering processes. A vertex is then associated with
389 the re-fit track using another Kalman filter algorithm. A further detailed description of the
390 track matching and vertex finding algorithms for Global is described in T2K-TN-46[15].

391 **3.2 PØD Selection Cuts**

392 The selection of CC Inclusive events use a series of cuts to select the primary lepton. The
393 pre-selection cuts (“precuts”) are applied first to extract events that start in the PØD FV.
394 A MIP is more likely to reach TPC1 from the PØD FV since the PØD is constructed out
395 of heavy materials especially in the CECal. So the main track each selection is designed to
396 select a muon.

397 This following sections will describe the precuts common to all CC Inclusive selections
398 and the branching of different cuts, after the precuts, to select the main track.

399 **3.2.1 Pre-Selection Cuts**

400 The pre-selection (“precuts”) were initially developed to select ν_μ CC Inclusive using the PØD
401 and TPC sub-detector reconstruction softwares separately[7]. They were then used with the
402 Global reconstruction software for the ν_μ CC-0 π selection in the FHC beam configuration as
403 described in technical note T2K-TN-258[16]. The description and flow of the precuts are
404 described here as well since there is an incomplete description of the selection precuts.

405 The precuts are performed on each bunch per beam spill as follows

- 406 1. The event has a “good” data quality flag.
 - 407 • An event is rejected if any sub-detector or electronics in ND280 reported as “bad”
408 during that bunch.
- 409 2. There is at least one (1) track reconstructed in TPC1.

- 410 • There are no restrictions on the number of tracks fully contained in the PØD or
411 exiting into other sub-detectors.

412 3. The track in TPC1 must have more than 18 nodes.

- 413 • The TPC reconstruction gathers vertical and horizontal hits into clusters of hits.
414 The charge distribution of the cluster is used to get a vertical (horizontal) position
415 that is more accurate than the individual readout pads. A node is constructed
416 out of each cluster with associated track state information. The set of nodes are
417 used to fit the track helix[12].

418 4. The reconstructed vertex is within the PØD WT FV.

- 419 • The PØD FV is defined to include as much as the WT regions as possible. Its
420 X and Y borders are 25 cm away from the PØDule edges while its Z borders
421 intersect the last and first half downstream PØDule in the USECal and CECal,
422 respectively. The enumerated volume edges are shown in table 3.1. This volume,
423 while used for track-based analyzes in the past, was optimized for π^0 and ν_e
424 analyzes[9].

425 5. All tracks that enter TPC1 pass the veto cut

- 426 • An event is rejected if any PØD track enters TPC1 from outside the “corridor”
427 volume. This cut was designed to eliminate broken tracks between the PØD and
428 TPC1 when the separate sub-detector reconstructions were used[7]. In practice,
429 this cut ensures that Global tracks entering TPC1 away from its X and Y edges.
430 The corridor definition is the same as defined in T2K-TN-208 and shown in Ta-
431 ble 3.1.

PØD WT FV			Corridor Volume		
-836	< X <	764	-988	< X <	910
-871	< Y <	869	-1020	< Y <	1010
-2969	< Z <	1264	-3139	< Z <	-900

Table 3.1: The PØD WT FV (left) and veto corridor volume (right) in the ND280 coordinate system. The corridor spans from the 5th (8th) to 40th (80th) PØDule (scintillator layer). All the units are given in millimeters.

432 After passing all the precuts, a single, global track, which is observed in TPC1, is as-
 433 signed as the “main track” of a selection. The main track for ν_μ selections is the highest
 434 momentum, negatively-charged track (HMNT). Similarly the highest momentum, positively-
 435 charged track (HMPT) is assigned the main track for $\bar{\nu}_\mu$ selections.

436 This concludes the application of precuts to all the CC Inclusive selections. The following
 437 subsubsections describe the CC Inclusive selection cuts, first in FHC mode and then RHC
 438 mode.

439 **ν_μ CC Inclusive in FHC Cut**

440 As discussed in Section section 3.2.1 on page 25, this selection is the basis for the ν_μ CC-0 π
 441 PØD+TPC1 analysis. In FHC mode, the vast majority of neutrino interactions are ν_μ CC
 442 events producing an outgoing, negatively charged muon. So if there is no negatively charged
 443 track in the TPC, the event is rejected. The highest momentum negatively charged track
 444 (HMNT) is the lepton candidate.

445 **$\bar{\nu}_\mu$ CC Inclusive in RHC Cuts**

446 In RHC, the majority of neutrinos in the beam is $\bar{\nu}_\mu$ since the horn focuses negatively charged
 447 pions. To select $\bar{\nu}_\mu$ CC interaction events by selecting positively charged muons, the lepton
 448 candidate is the highest momentum positively charged track (HMPT) in the TPC. However,

449 since the RHC mode beam is not as $\bar{\nu}_\mu$ pure as the FHC beam, another cut was added to
450 reduce this effect.

451 Since RHC neutrino beam can be described as a $\bar{\nu}_\mu$ -enhanced beam, the HMPT must also
452 be the highest momentum track (HMT). due to the significant “wrong-sign” ν_μ background.
453 This effect is two fold due to the nature of the neutrino source and the cross section between
454 neutrinos and antineutrinos. Since the source of neutrinos are from protons, the excess of
455 positive charge is more likely to produce positively charged pions than negatively charged
456 one. are many more positively charged pions produced that are not deflected Due to this
457 background, an additional cut was

458 **3.2.4 ν_μ Background CC Inclusive in RHC Cuts**

459 **3.3 Sample Kinematics and Validation**

460 This section examines the kinematics for each of selections while differentiating between
461 water-in and water-out mode. The selection cuts were implemented in Psyche which is the
462 software interface that BANFF uses to select events. An analysis of the kinematics are care-
463 fully cross validated with the same selection cuts in the T2K high level analysis framework
464 called Highland. Comparing the results between Highland and Psyche is important since
465 they are complementary frameworks within T2K. The data sets used in this analysis are
466 runs 2-8 in both PØD water-in and water-out (air) modes as shown in Table 3.2.

467 **3.4 PØD Water-Out Samples**

468 This section shows the kinematic distributions for the PØD water-out samples. First an
469 examination of the CC Inclusive samples and the effects of the systematic weights will be
470 explored. The samples are then examined as CC 1-track and CC N-tracks.

Run Period	Horn Current	PØD Status	Data POT ($\times 10^{20}$)	MC POT ($\times 10^{20}$)
2	+250 kA	Water	0.4339	12.03
		Air	0.3591	9.239
3b	+205 kA		0.2172	4.478
3c	+250 kA		1.364	26.32
4			1.782	34.99
		Water	1.642	34.97
5c	-250 kA		0.4346	22.77
6b		Air	1.288	14.17
6c			0.5058	5.275
6d			0.7753	6.884
6e			0.8479	8.594
7b		Water	2.436	33.70
8	+250 kA		1.580	26.46
		Air	4.148	36.06
Sand	FHC		-	11.19
Sand	RHC		-	12.92
2, 3b, 3c, 4, 8		FHC	Air	7.872
2, 4, 8			Water	3.657
6b, 6c, 6d, 6e		RHC	Air	3.417
5c, 7b			Water	2.871
				56.48

Table 3.2: T2K MC and data POT divided by run periods. The bottom four rows are the aggregated periods grouped by horn current and PØD status which is how the data analysis is performed.

471 **3.4.1 CC Inclusive**

472 The CC Inclusive sample cuts are discussed 3.2.1. Since both flux and systematic weights
473 are applied to all MC events in BANFF, it is important to validate the event weights. Using
474 neither set of weights is referred to as the nominal MC.

475 **3.4.1.1 ν_μ Selection in FHC Mode:** Shown in Figures 3.1 to 3.7 are the momentum
476 and $\cos\theta$ distributions for ν_μ CC Inclusive events in FHC mode. There are three pairs of
477 P, θ figures with the same truth information break down accompanied by one of neutrino
478 energy. The truth information categories are lepton candidate particle, NEUT reaction, and
479 topology. Each figure consists of a set of four sub-figures which illustrate the application of
480 flux and detector systematic weights.

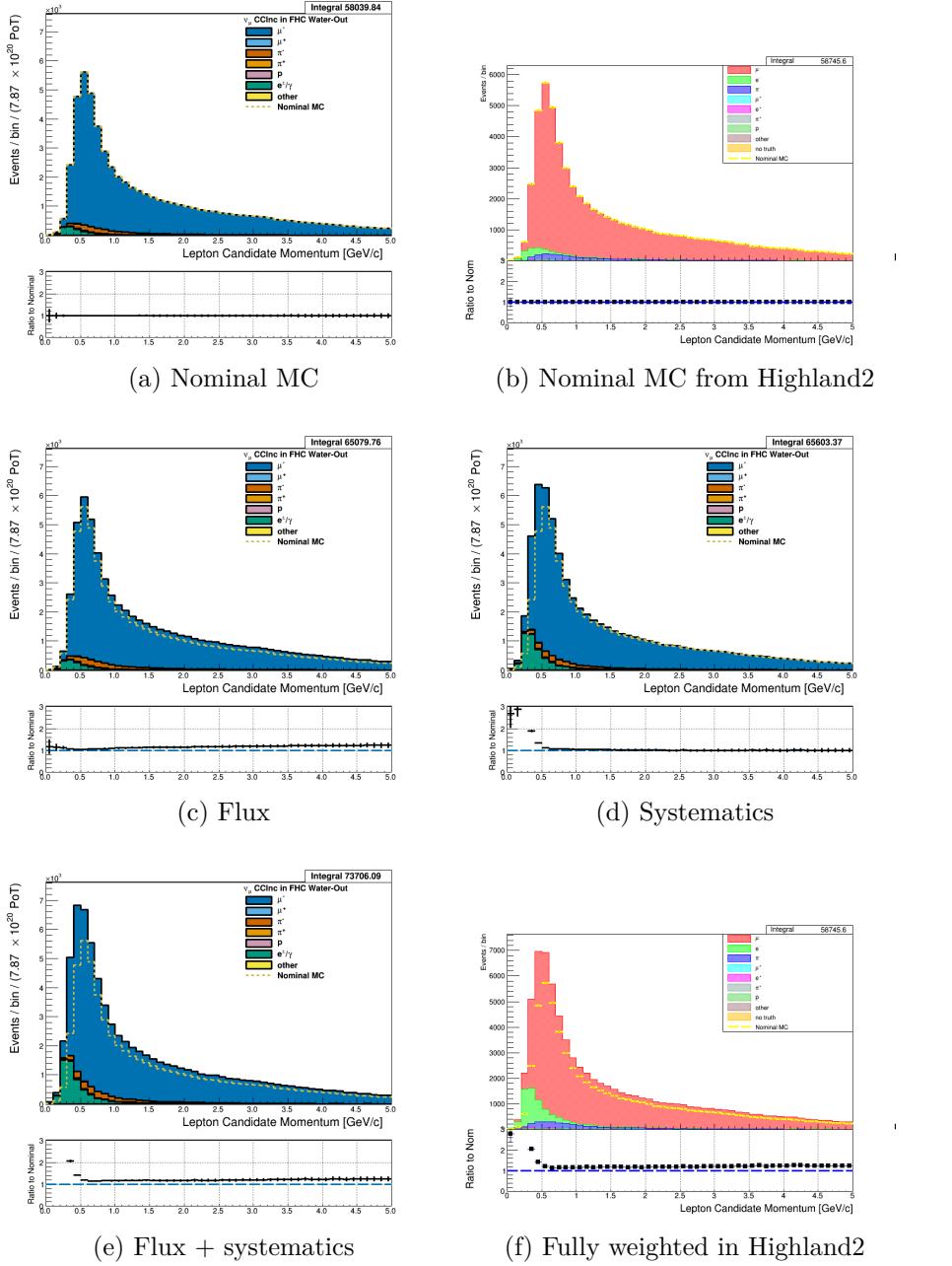


Figure 3.1: Reconstructed lepton candidate momentum separated by true particle species for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) Highland2 comparison for (a) without any weights applied using the “NOW” draw option. (c) The flux tuning is applied. (d) The systematic weighting is applied. (e) Both flux and systematic weighting is applied. (f) Highland2 comparison for (e).

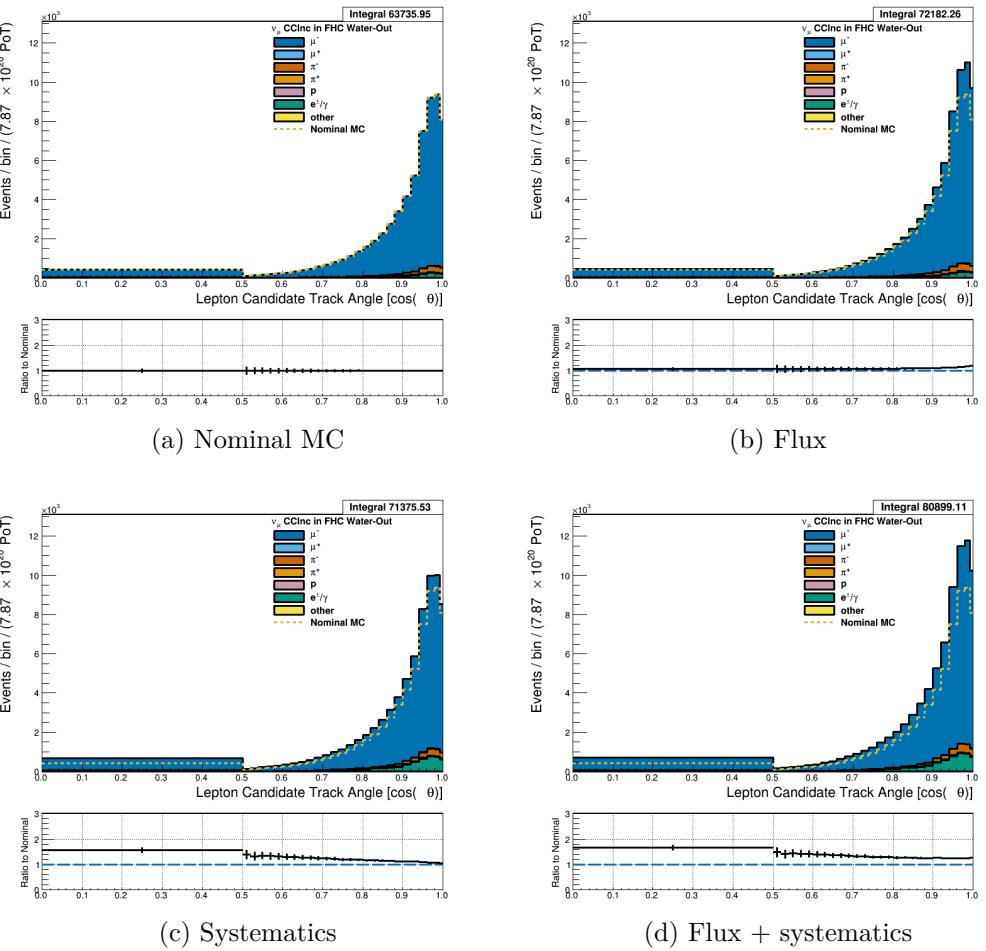


Figure 3.2: Reconstructed lepton candidate angle separated by true particle species for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

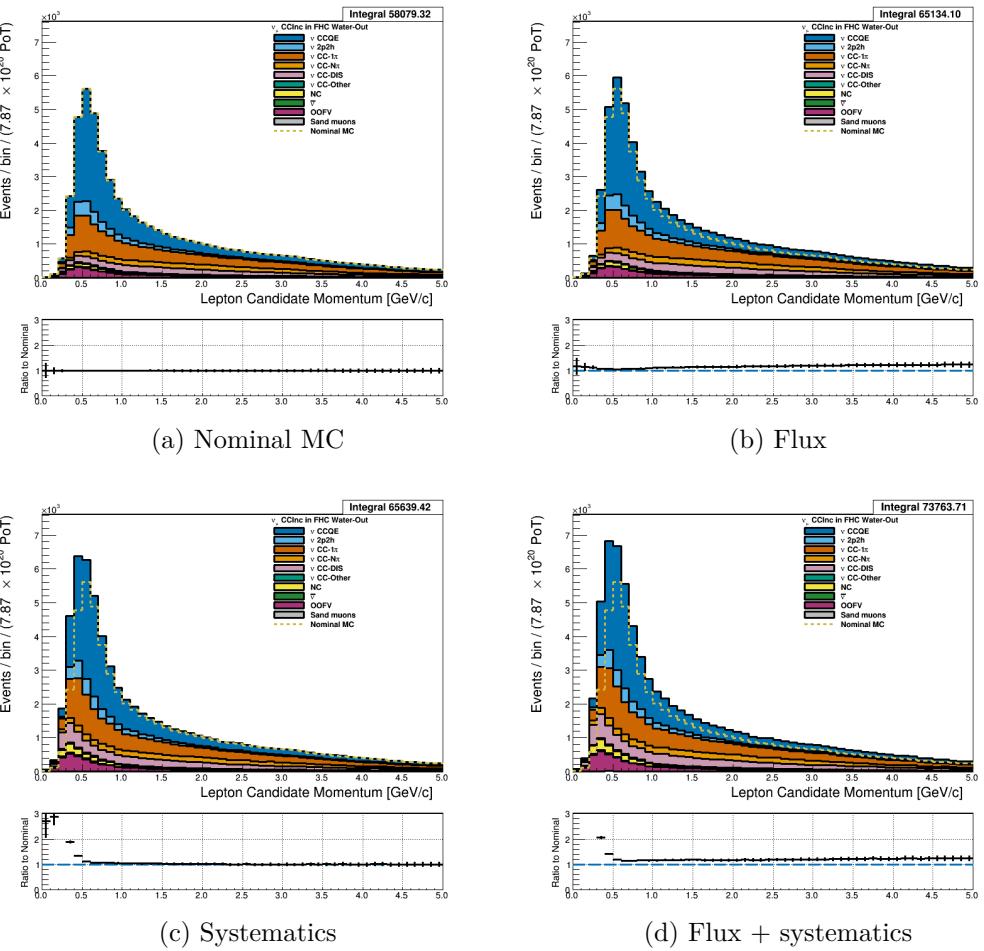


Figure 3.3: Reconstructed lepton candidate momentum separated by NEUT model interaction mode for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

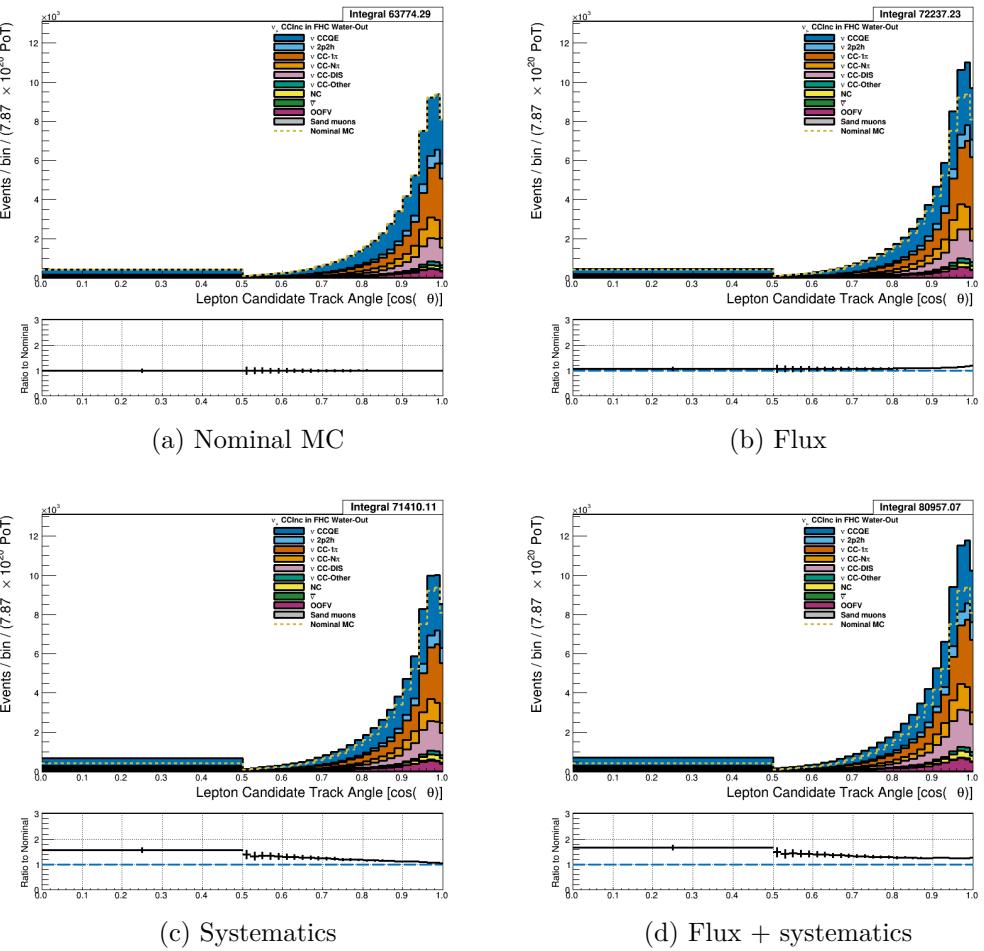


Figure 3.4: Reconstructed lepton candidate $\cos\theta$ separated by NEUT model interaction mode for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

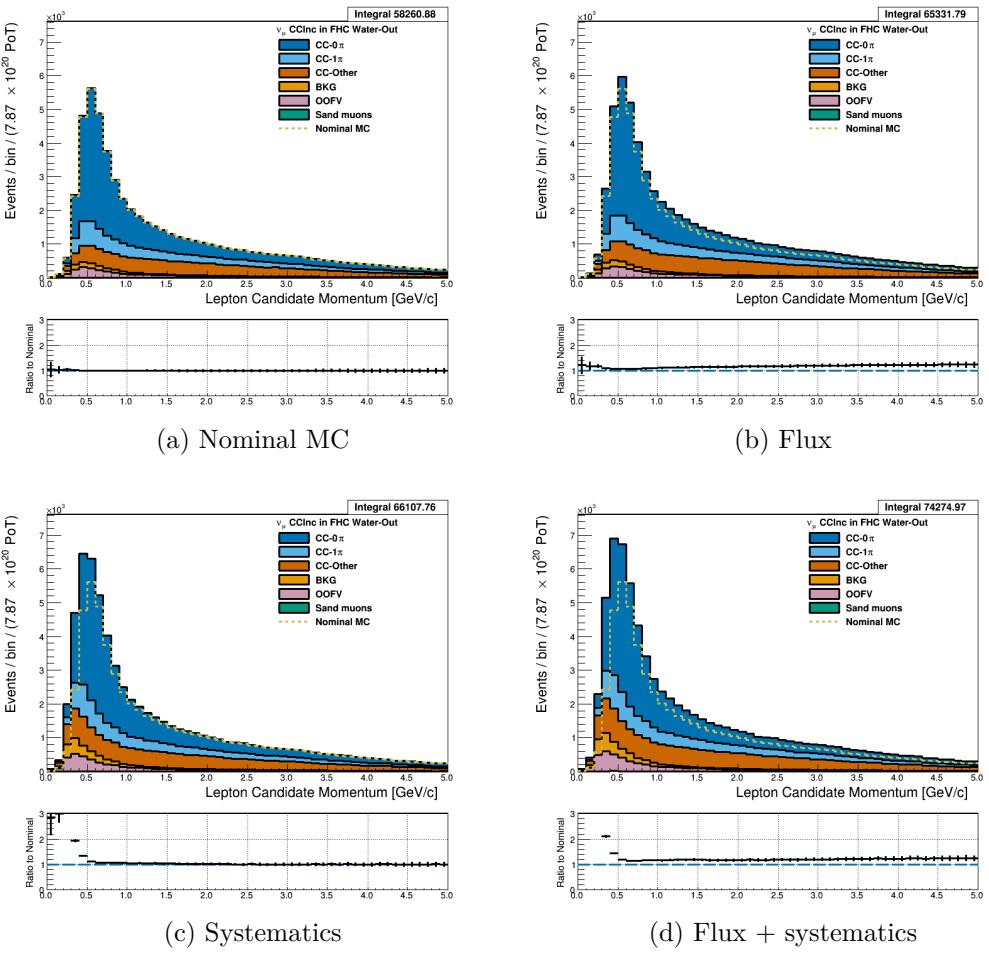


Figure 3.5: Reconstructed lepton candidate momentum separated by topology for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

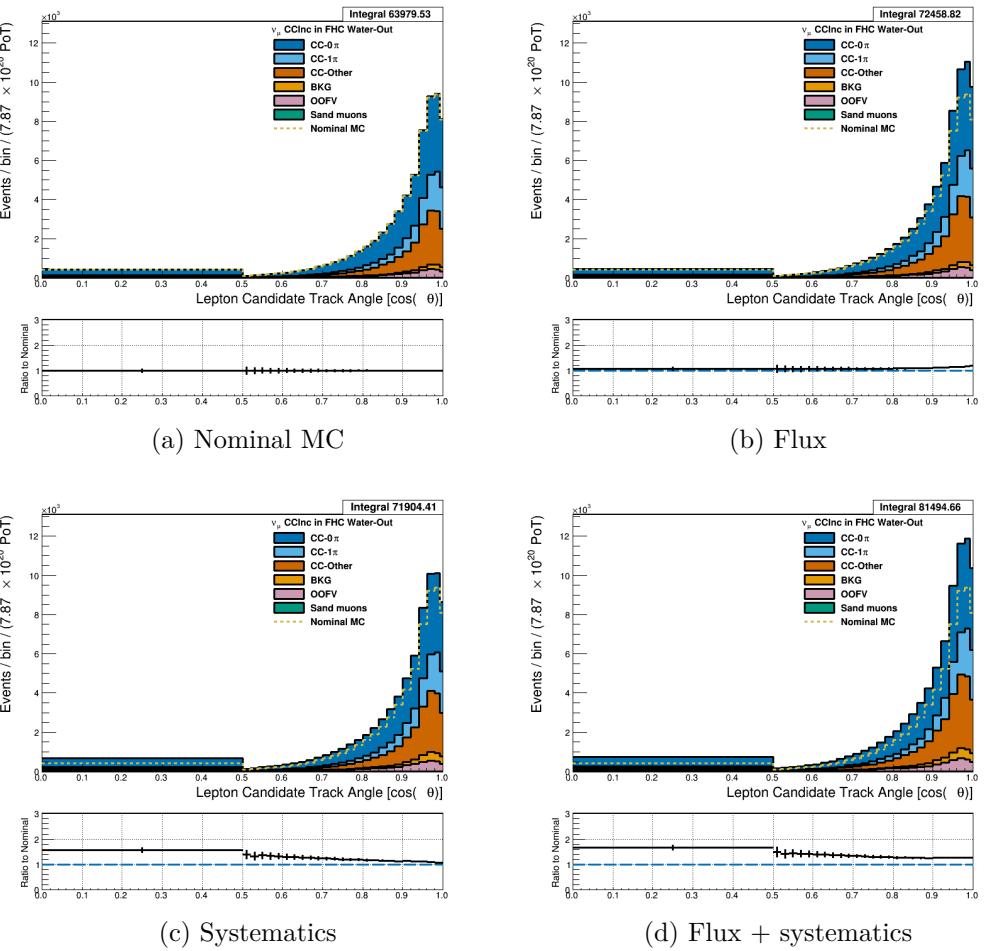


Figure 3.6: Reconstructed lepton candidate $\cos \theta$ separated by topology for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

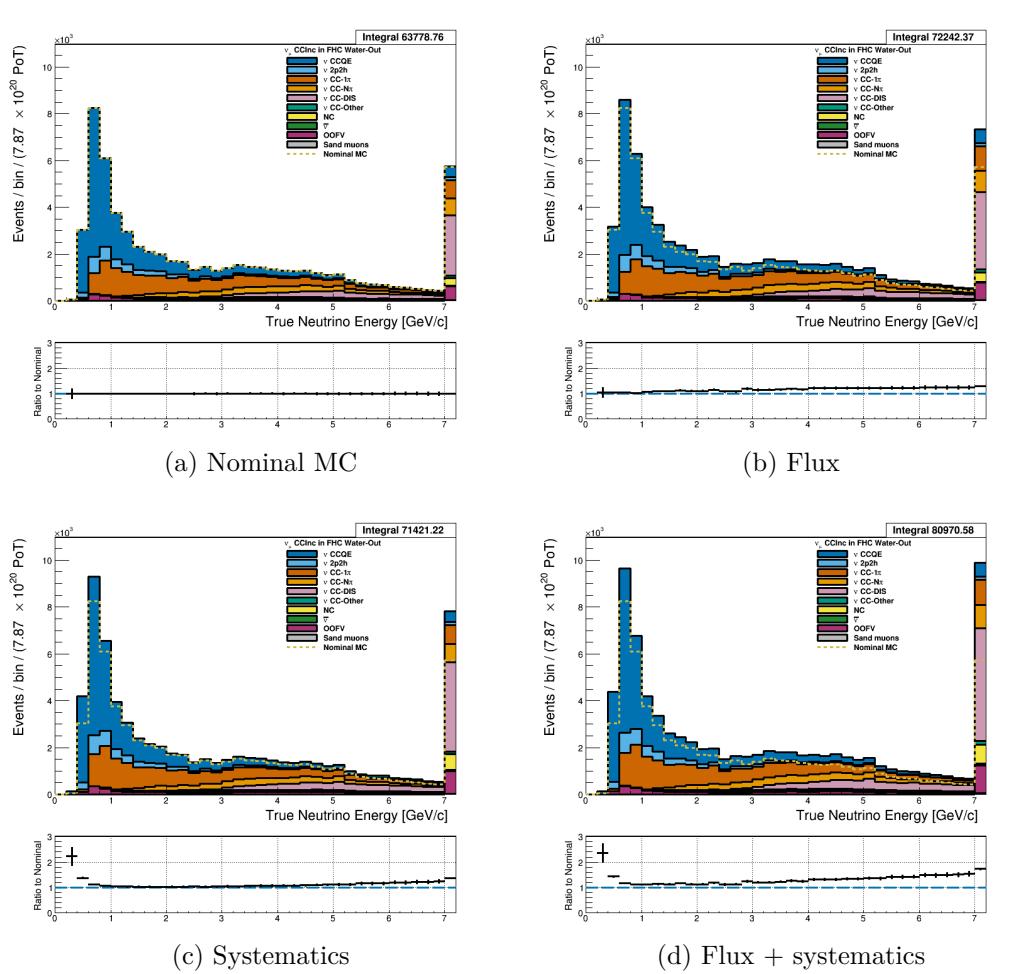
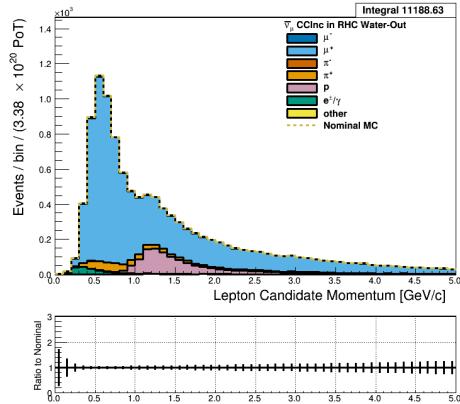
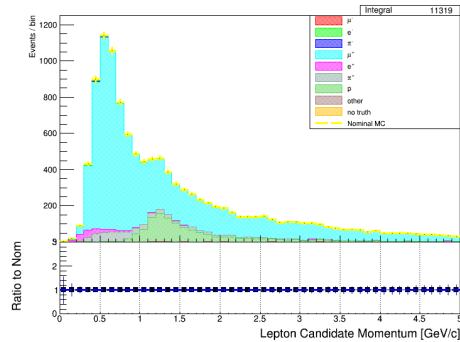


Figure 3.7: True neutrino energy associated with the lepton candidate separated by NEUT model interaction mode for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

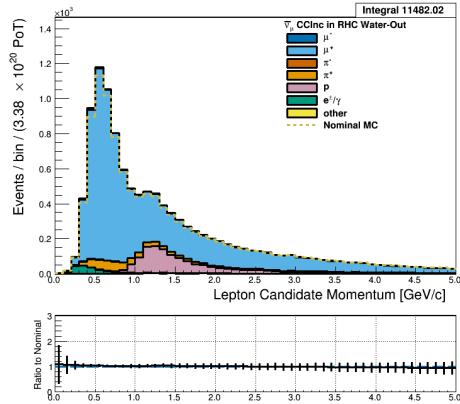
3.4.1.2 $\bar{\nu}_\mu$ Selection in RHC Mode: Shown in Figures 3.8 to 3.14 for $\bar{\nu}_\mu$ CC Inclusive events in RHC mode. There are three pairs of P, θ figures with the same truth information break down accompanied by one of neutrino energy. The truth information categories are lepton candidate particle, NEUT reaction, and topology. Each figure consists of a set of four sub-figures which illustrate the application of flux and detector systematic weights.



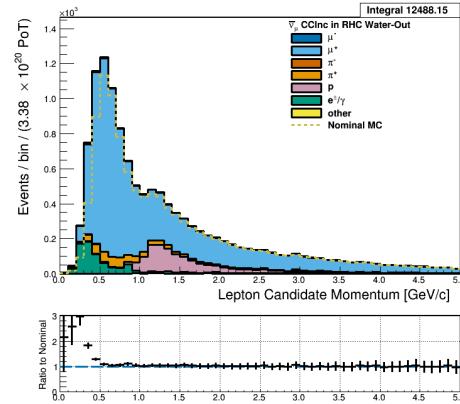
(a) Nominal MC



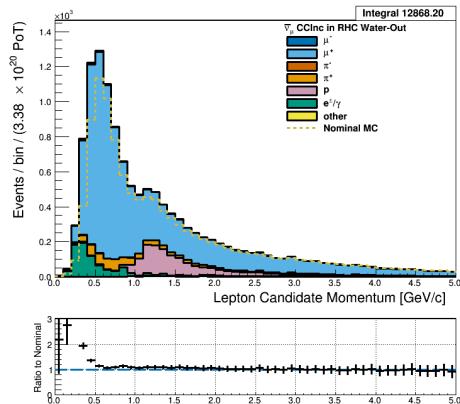
(b) Nominal MC from Highland2



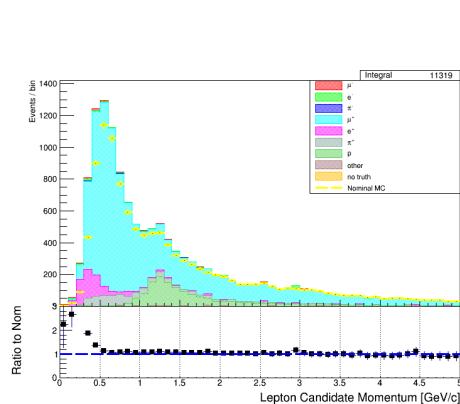
(c) Flux



(d) Systematics



(e) Flux + systematics



(f) Fully weighted in Highland2

Figure 3.8: Reconstructed lepton candidate momentum separated by true particle species for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. Reconstructed lepton candidate angle separated by true particle species for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) Highland2 comparison for (a) without any weights applied using the “NOW” draw option. (c) The flux tuning is applied. (d) The systematic weighting is applied. (e) Both flux and systematic weighting is applied. (f) Highland2 comparison for (e).

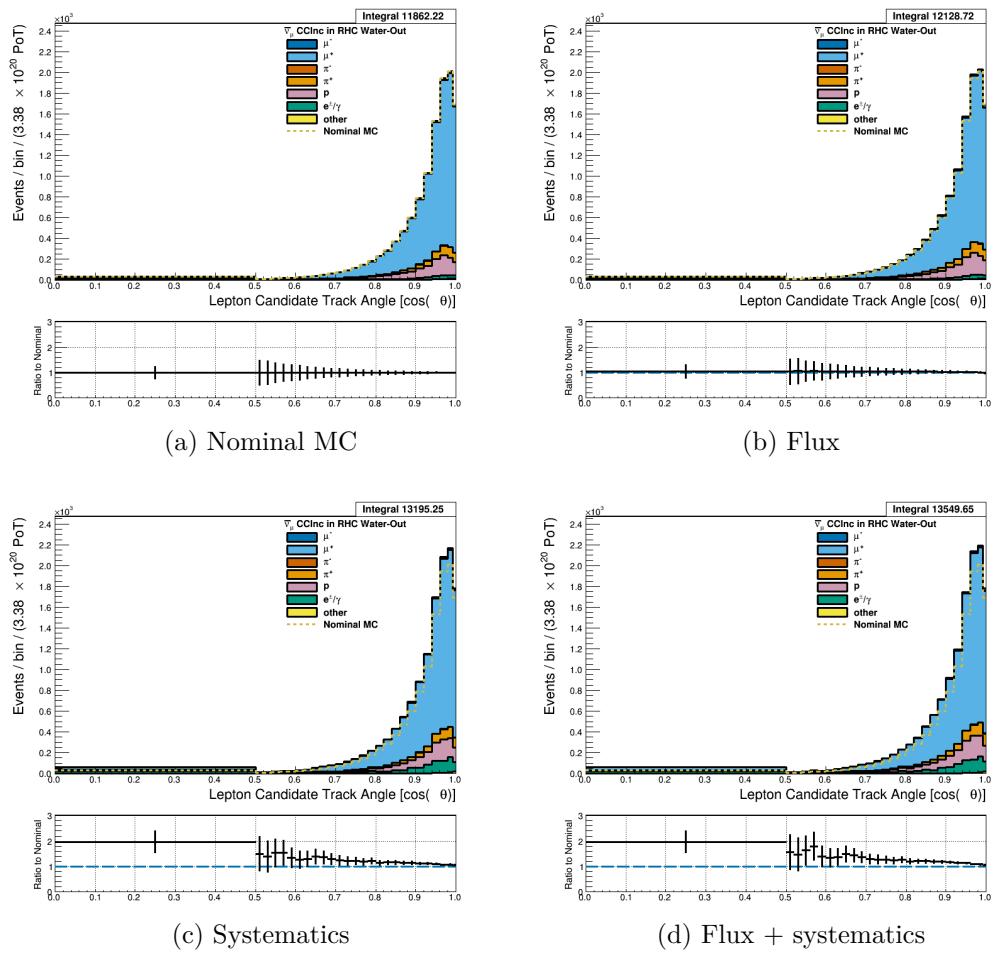


Figure 3.9: Reconstructed lepton candidate angle separated by true particle species for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

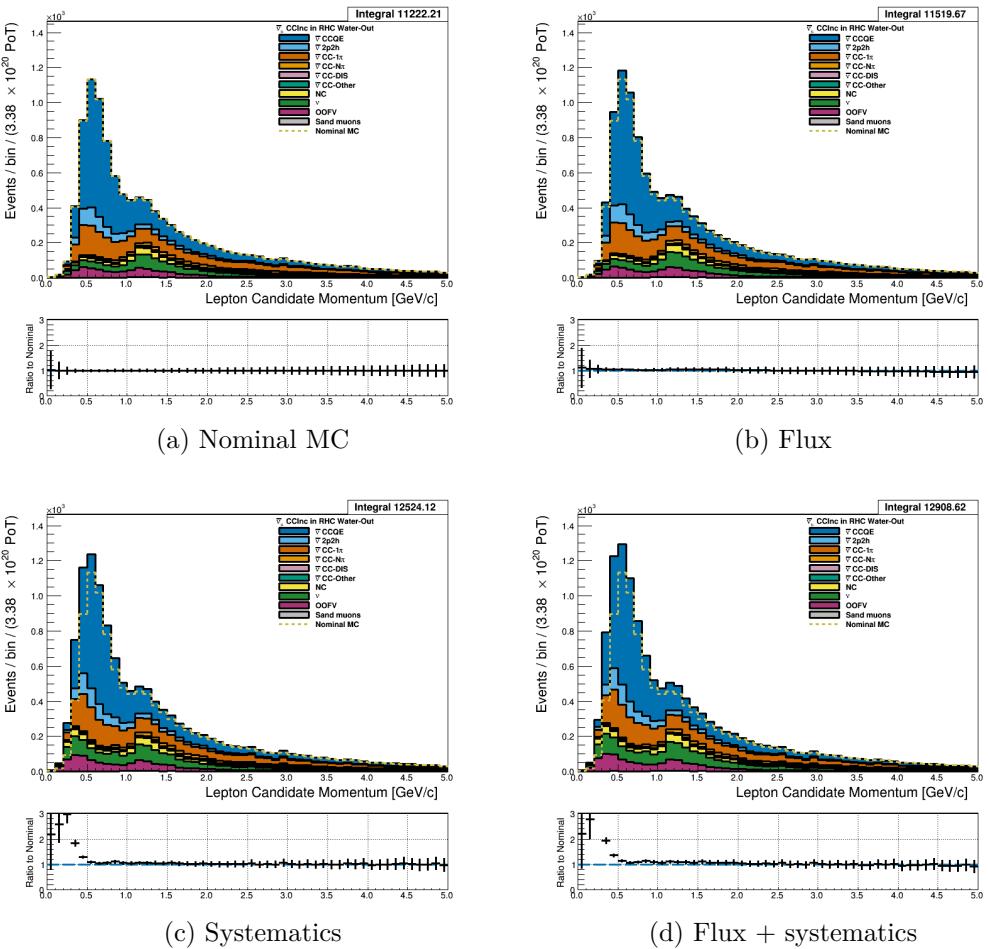


Figure 3.10: Reconstructed lepton candidate momentum separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

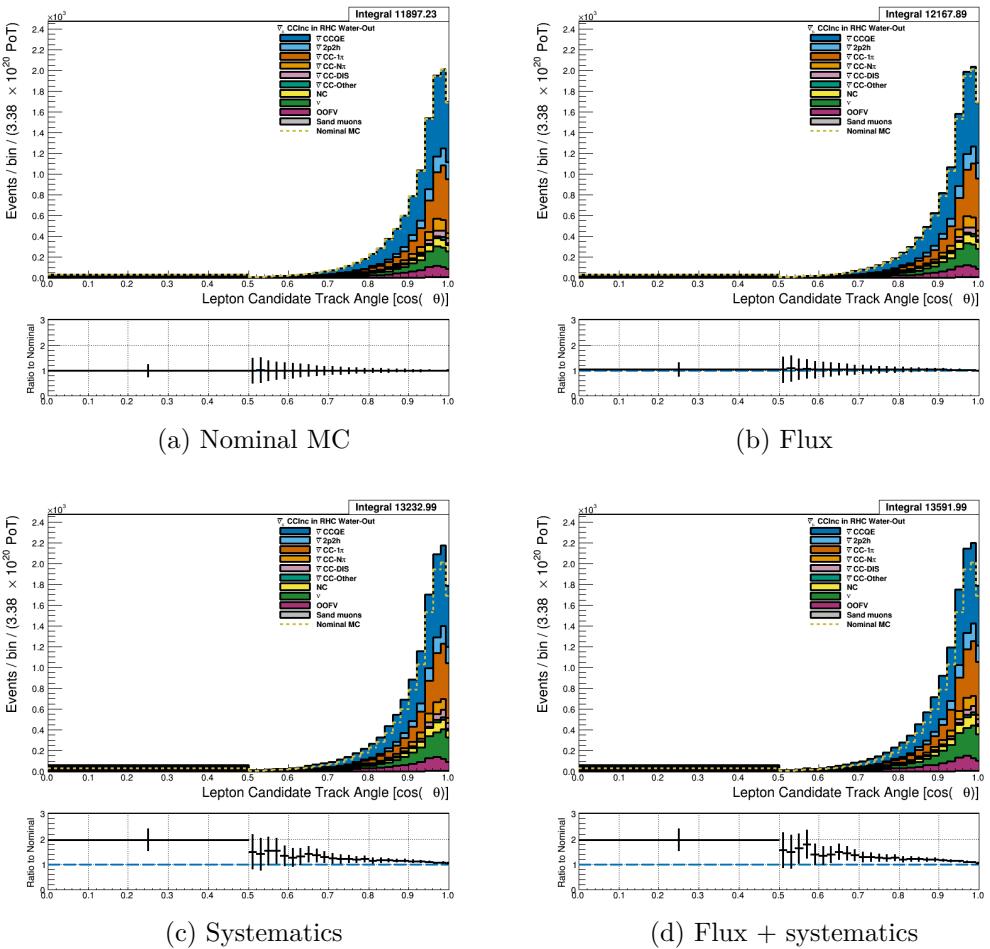


Figure 3.11: Reconstructed lepton candidate $\cos \theta$ separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

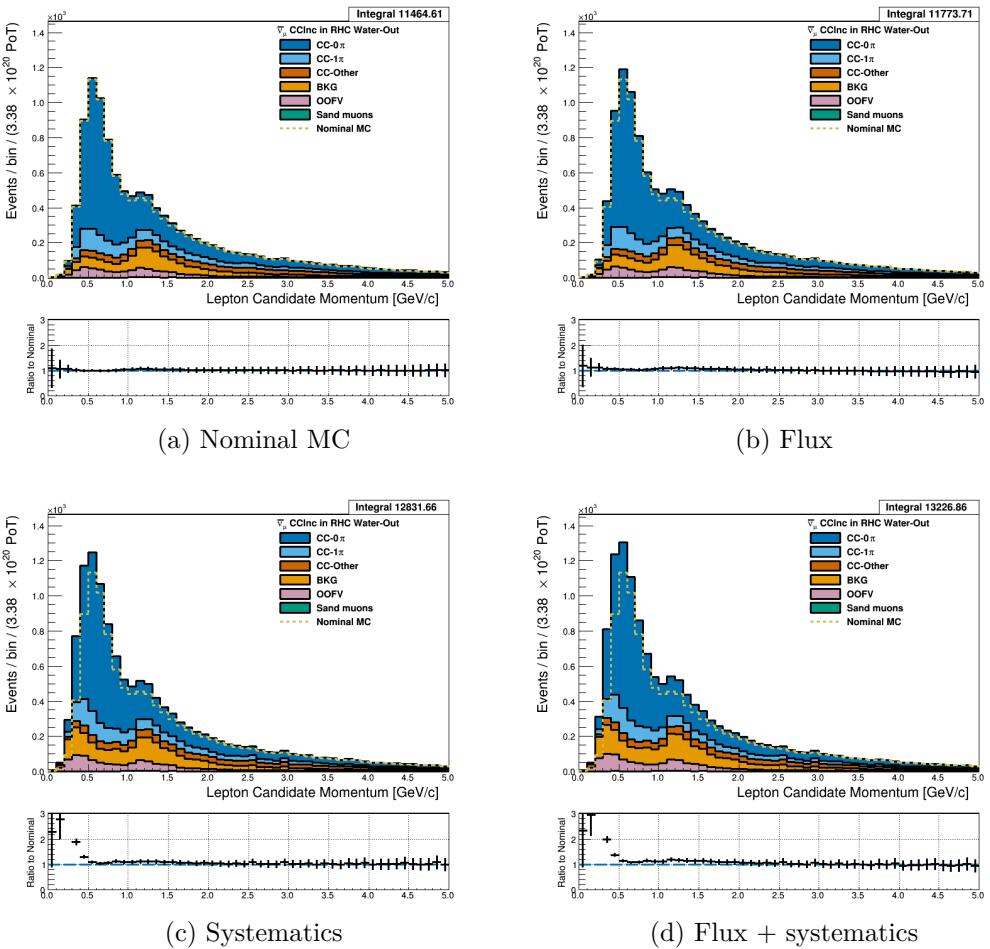


Figure 3.12: Reconstructed lepton candidate momentum separated by topology for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

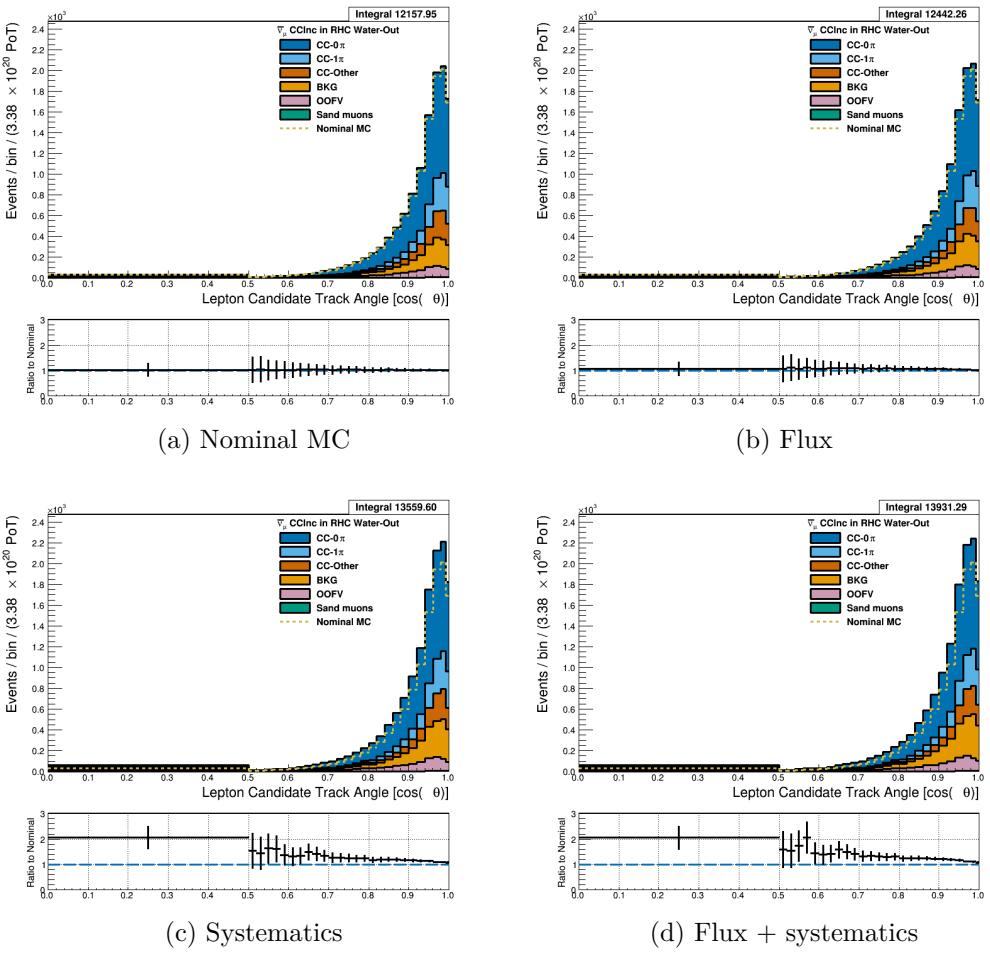


Figure 3.13: Reconstructed lepton candidate $\cos \theta$ separated by topology for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

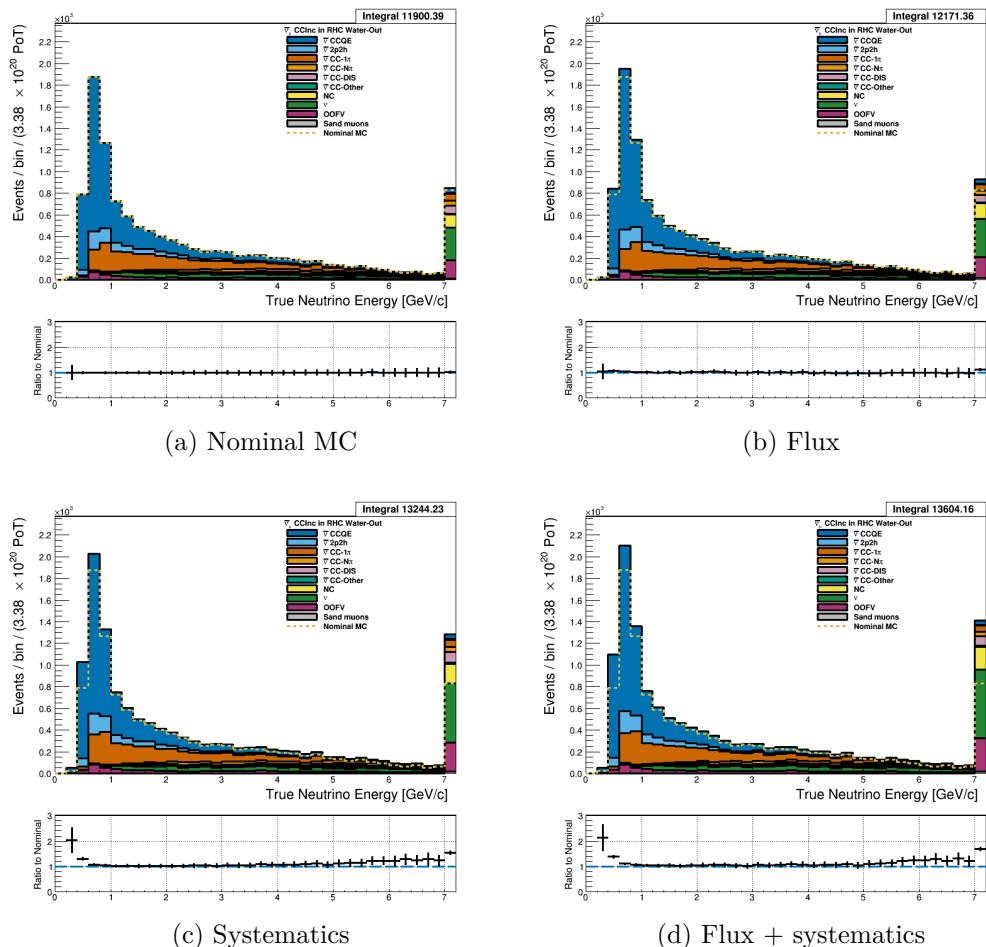
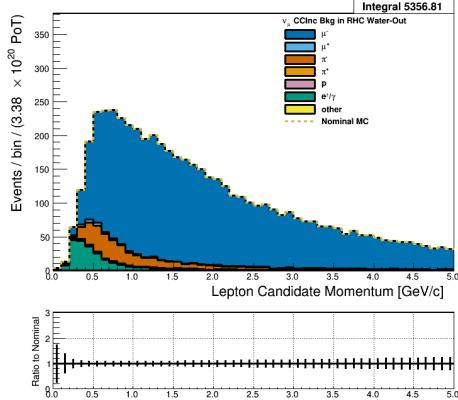


Figure 3.14: True neutrino energy associated with the lepton candidate separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

3.4.1.3 ν_μ Background Selection in RHC Mode: Shown in Figures 3.15, 3.16 and 3.19

to 3.21 and ????

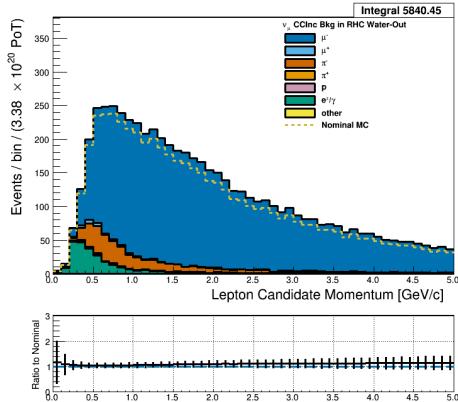
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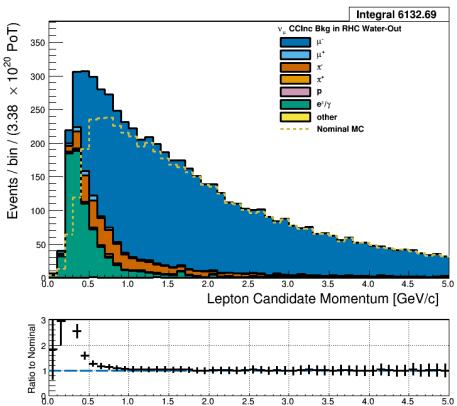
(a) Nominal MC

Sections/Figures/SamplesandSelections/numuFHC/CC1

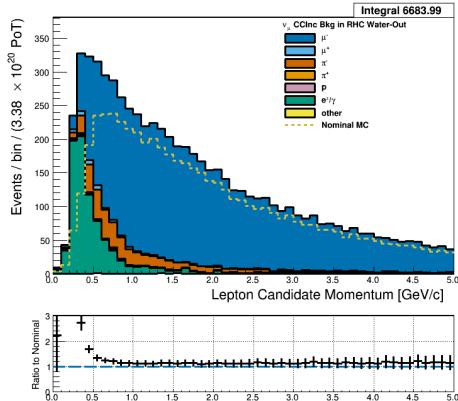
(b) Nominal MC from Highland2



(c) Flux



(d) Systematics

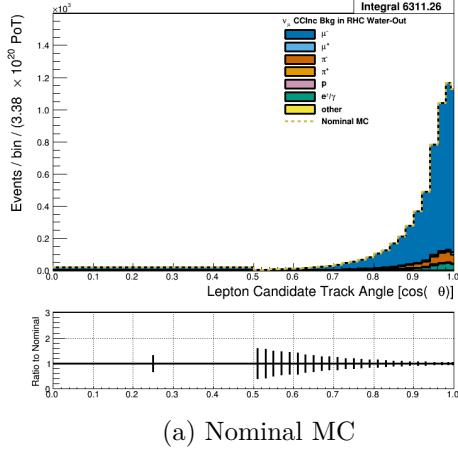


(e) Flux + systematics

Sections/Figures/SamplesandSelections/numuFHC/CC1

(f) Fully weighted in Highland2

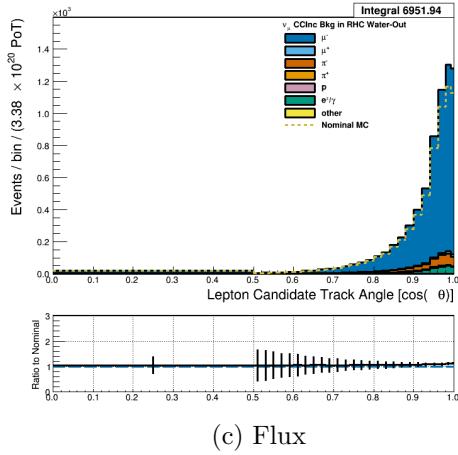
Figure 3.15: Reconstructed lepton candidate momentum separated by true particle species for RHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) Highland2 comparison for (a) without any weights applied using the “NOW” draw option. (c) The flux tuning is applied. (d) The systematic weighting is applied. (e) Both flux and systematic weighting is applied. (f) Highland2 comparison for (e).



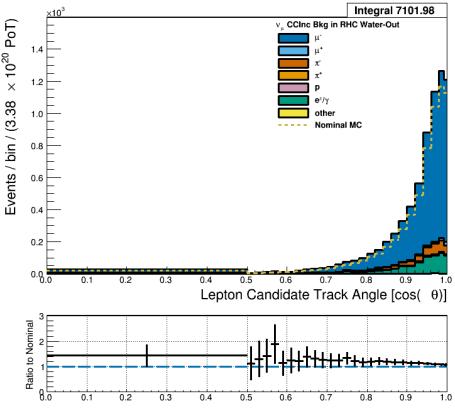
(a) Nominal MC

Sections/Figures/SamplesandSelections/numuFHC/CCInc

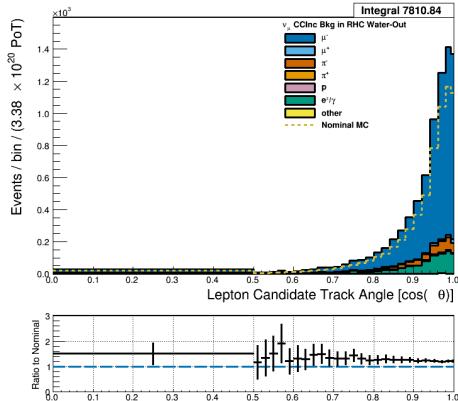
(b) Nominal MC from Highland2



(c) Flux



(d) Systematics



(e) Flux + systematics

Sections/Figures/SamplesandSelections/numuFHC/CCInc

(f) Fully weighted in Highland2

Figure 3.16: Reconstructed lepton candidate angle separated by true particle species for RHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) Highland2 comparison for (a) without any weights applied using the “NOW” draw option. (c) The flux tuning is applied. (d) The systematic weighting is applied. (e) Both flux and systematic weighting is applied. (f) Highland2 comparison for (e).

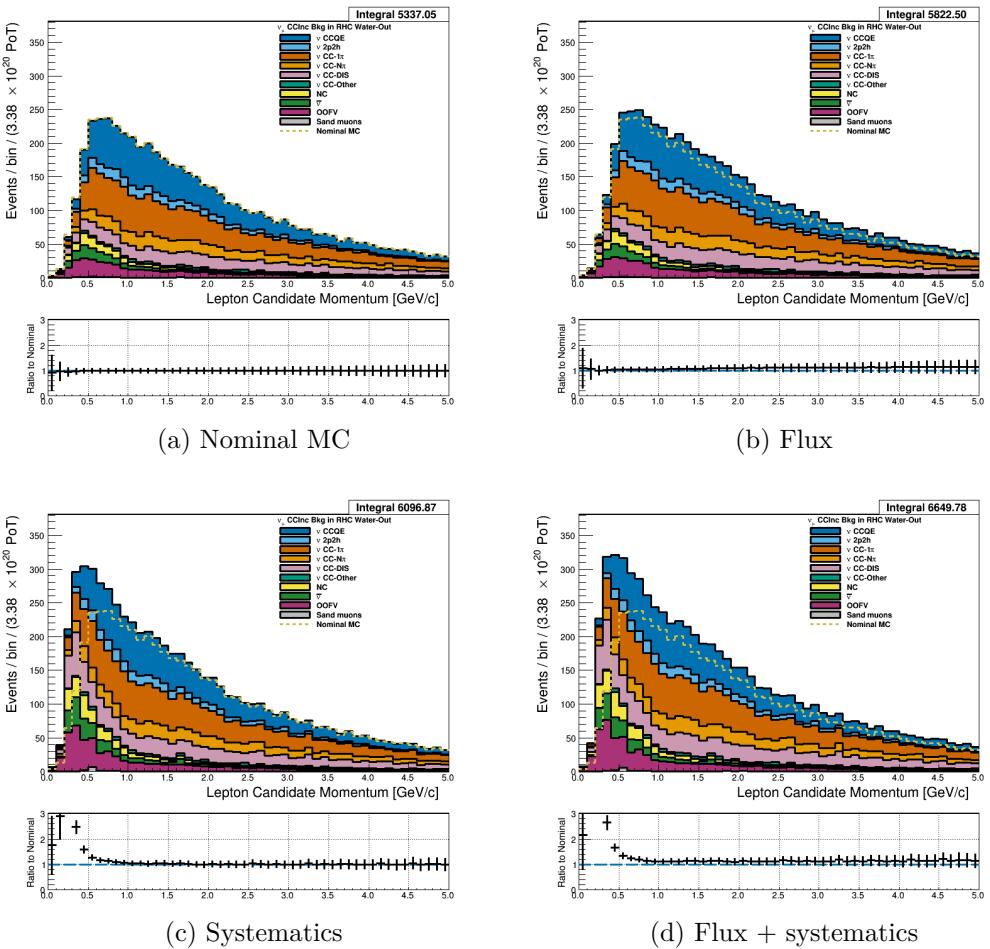


Figure 3.17: Reconstructed lepton candidate momentum separated by NEUT model interaction mode for RHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

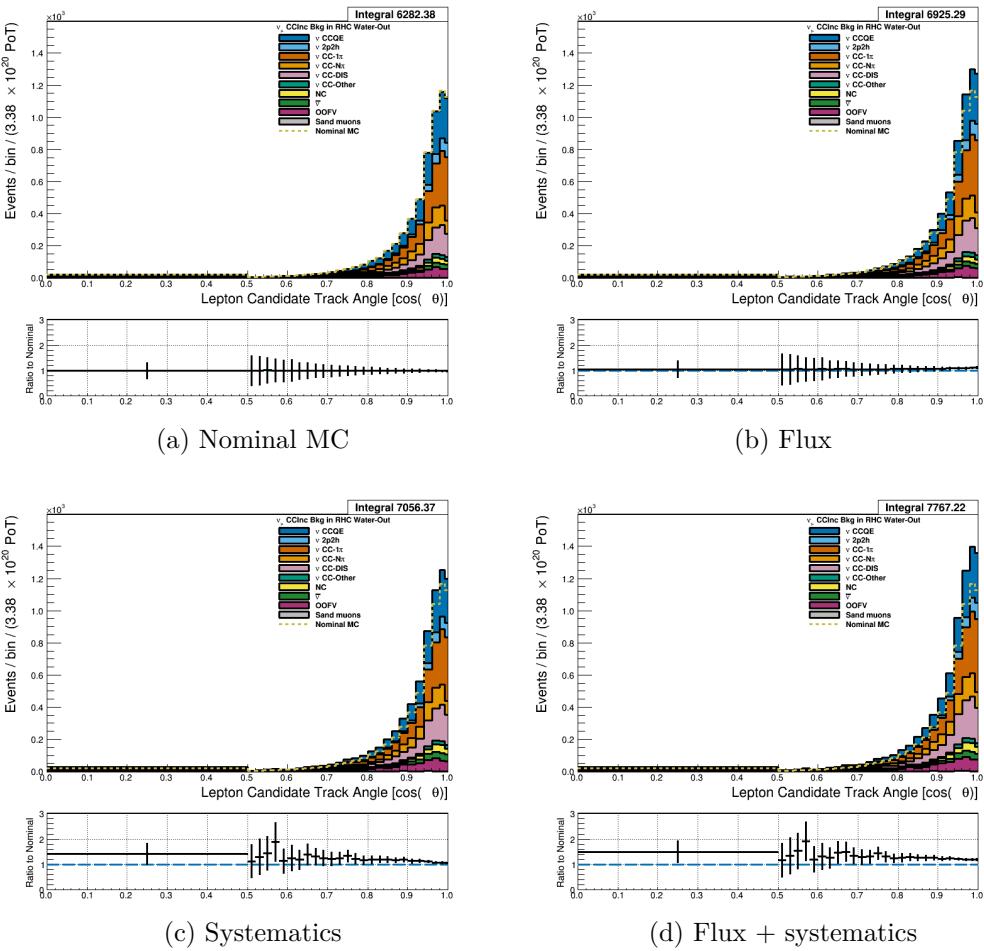


Figure 3.18: Reconstructed lepton candidate $\cos \theta$ separated by NEUT model interaction mode for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

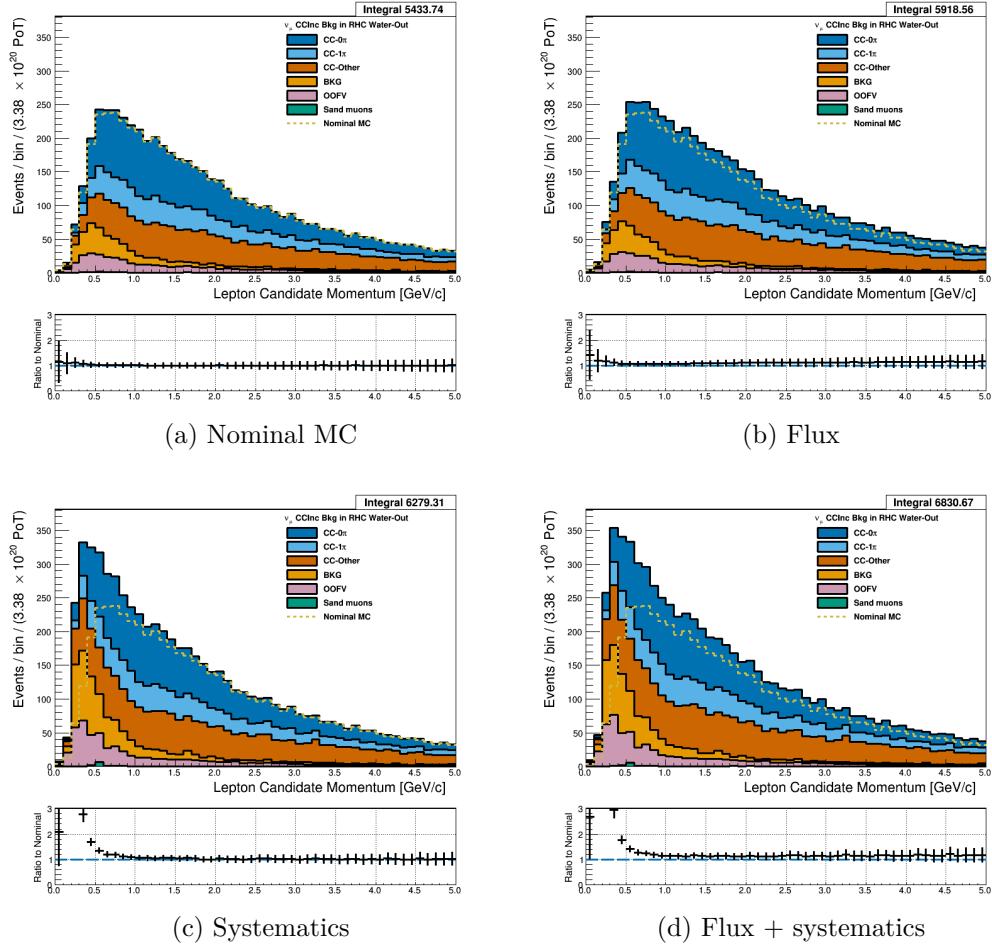


Figure 3.19: Reconstructed lepton candidate momentum separated by topology for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

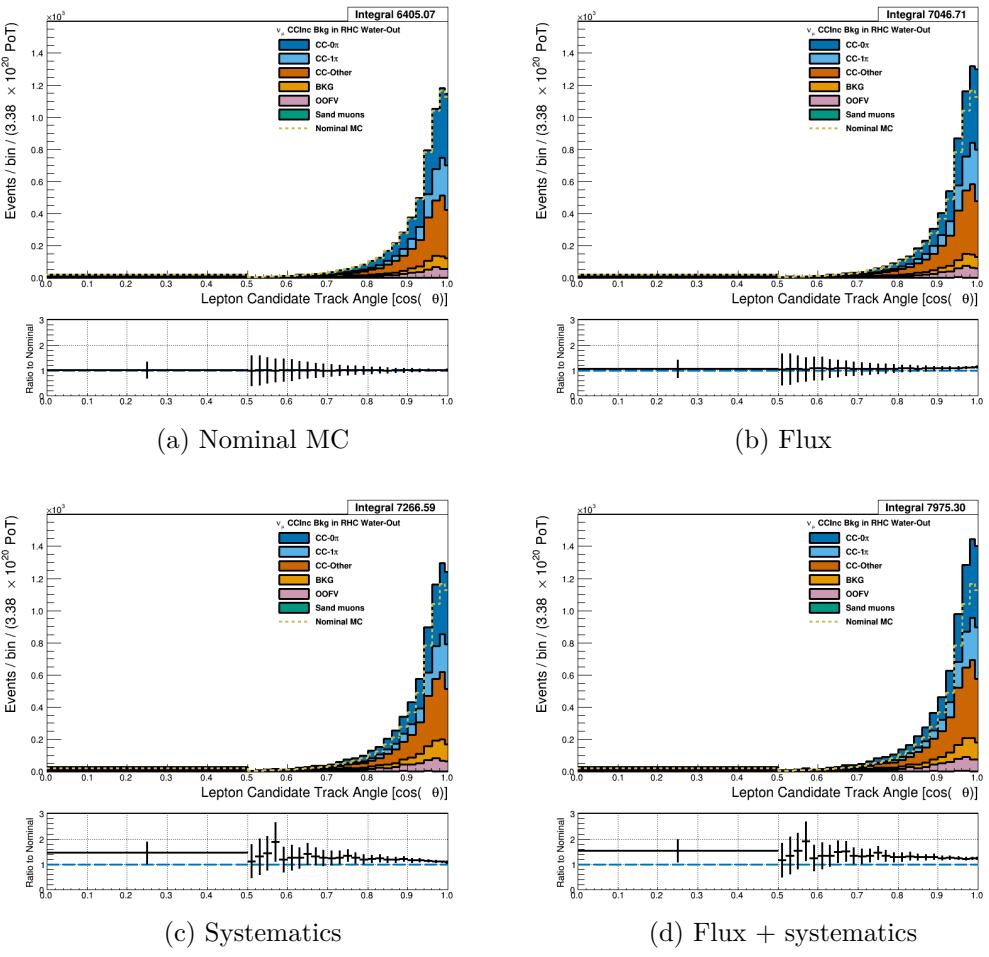


Figure 3.20: Reconstructed lepton candidate $\cos \theta$ separated by topology for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

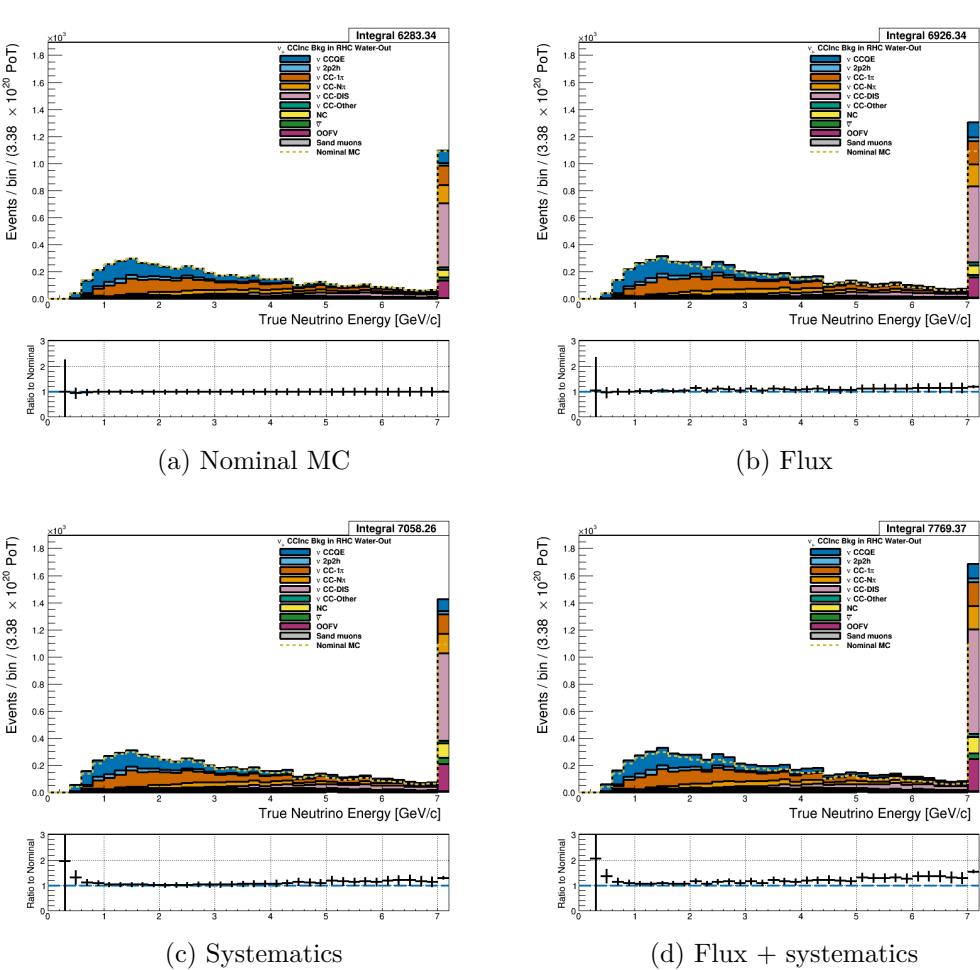


Figure 3.21: True neutrino energy associated with the lepton candidate separated by NEUT model interaction mode for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

3.4.2 CC 1-Track (CCQE Enhanced)

3.4.2.1 ν_μ Selection in FHC Mode: Shown in

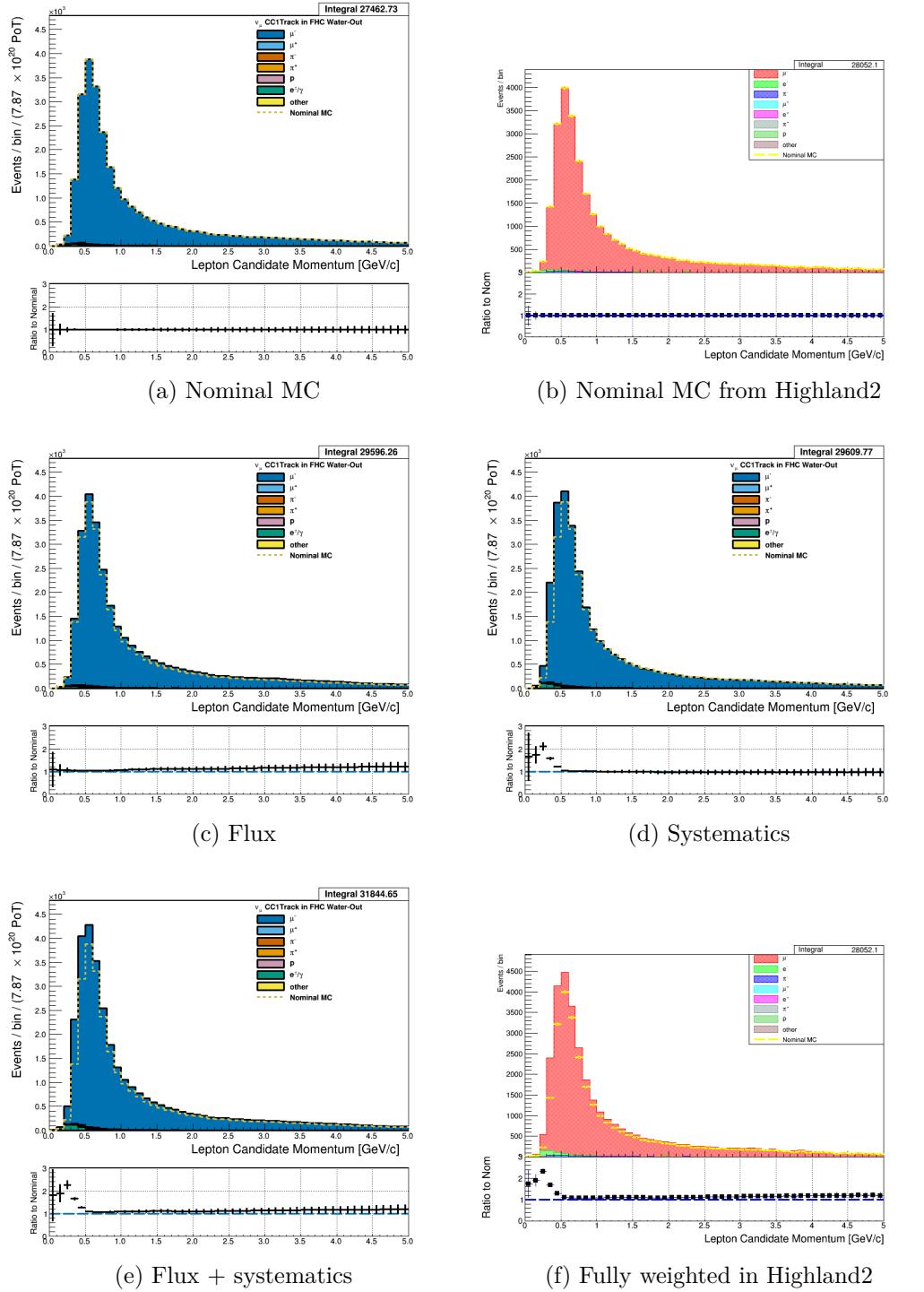


Figure 3.22: Reconstructed lepton candidate momentum separated by true particle species for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) Highland2 comparison for (a) without any weights applied using the “NOW” draw option. (c) The flux tuning is applied. (d) The systematic weighting is applied. (e) Both flux and systematic weighting is applied. (f) Highland2 comparison for (e).

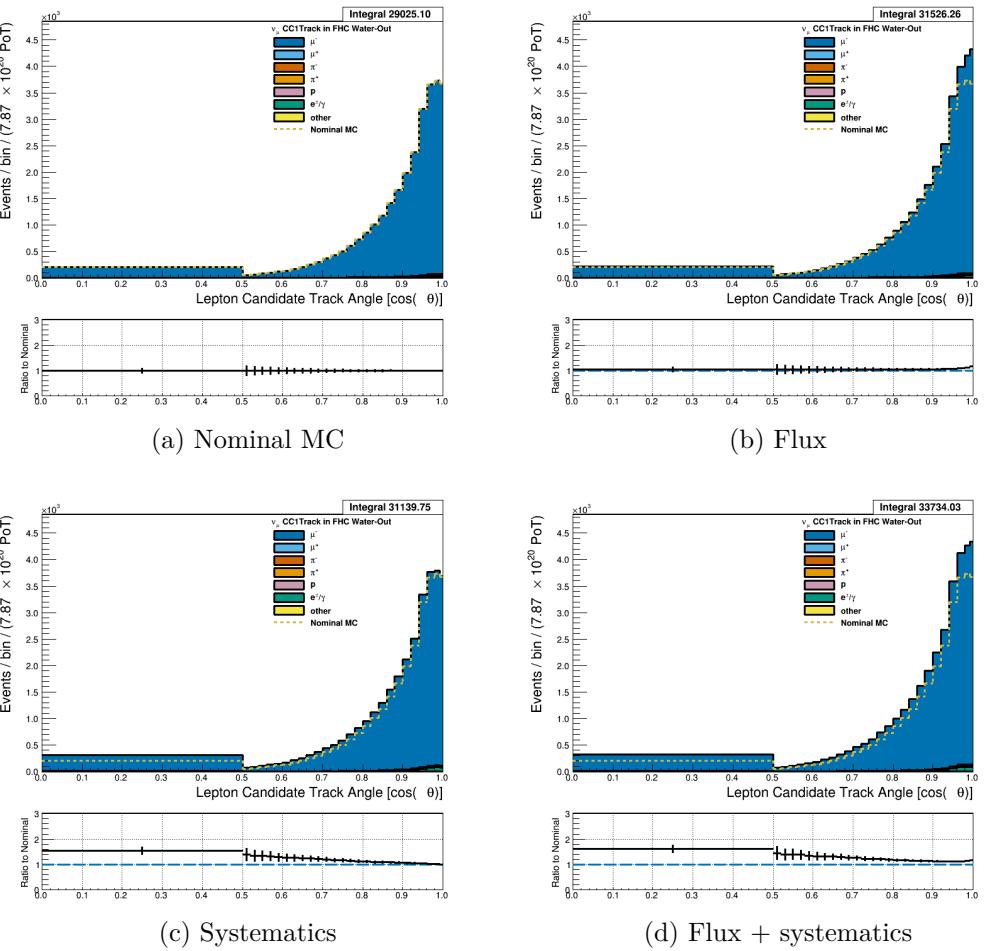


Figure 3.23: Reconstructed lepton candidate angle separated by true particle species for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

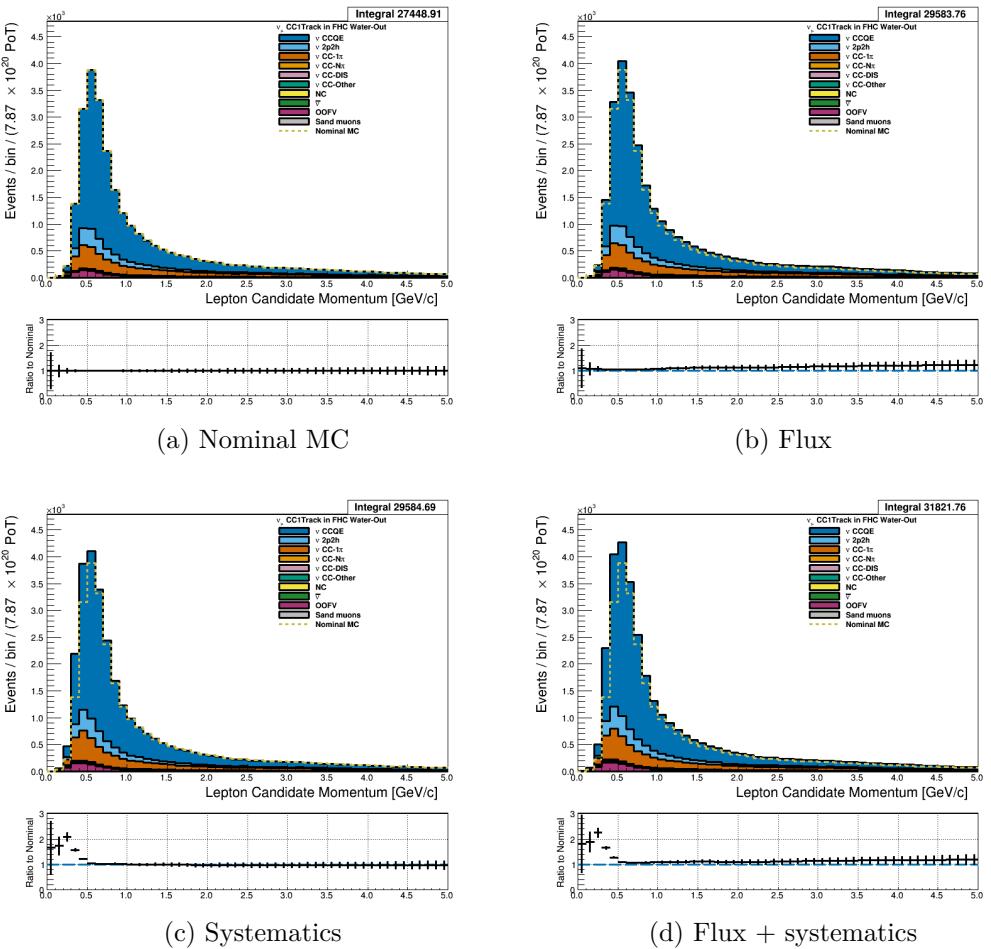


Figure 3.24: Reconstructed lepton candidate momentum separated by NEUT model interaction mode for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

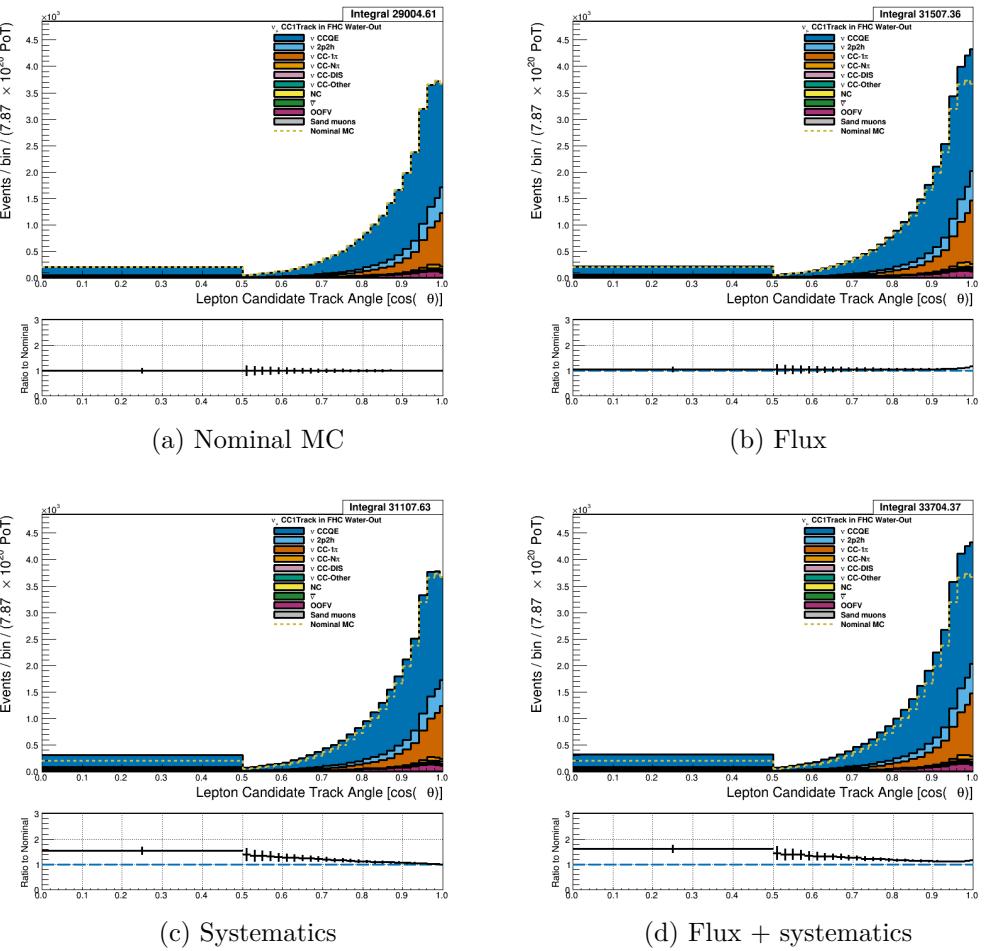


Figure 3.25: Reconstructed lepton candidate $\cos \theta$ separated by NEUT model interaction mode for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

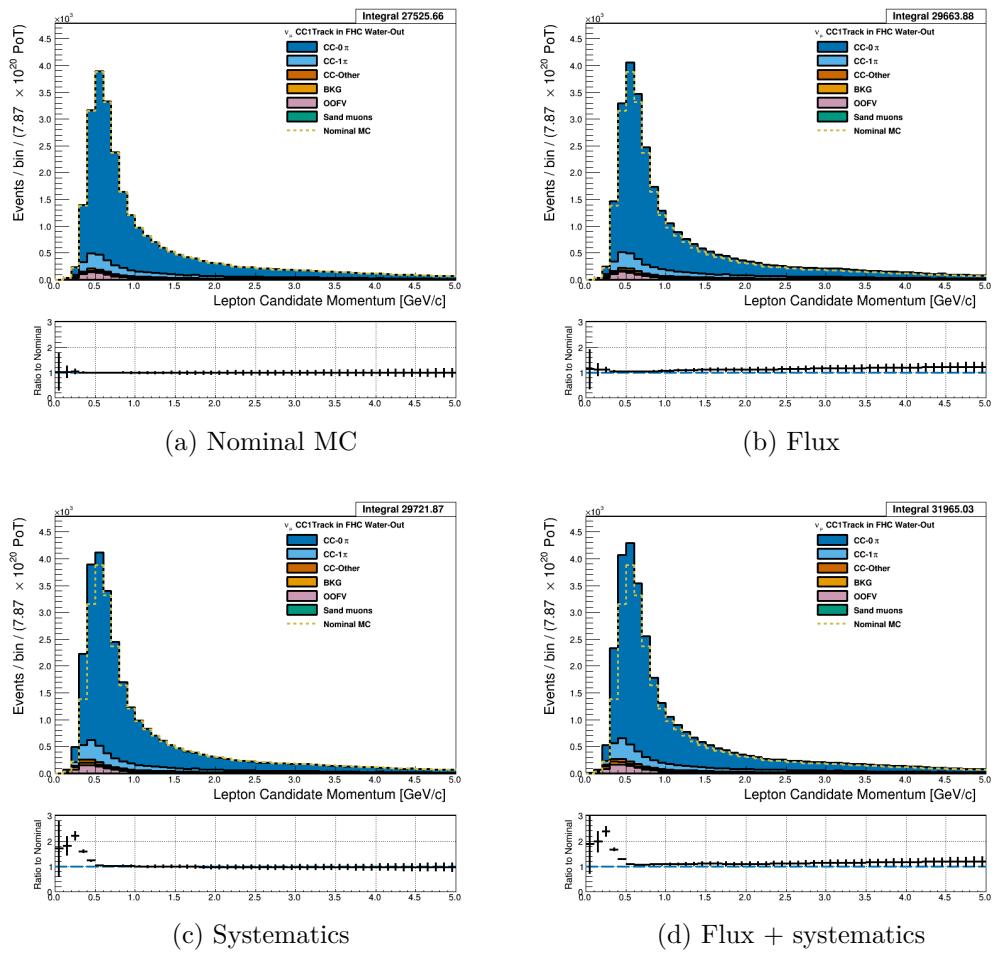


Figure 3.26: Reconstructed lepton candidate momentum separated by topology for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

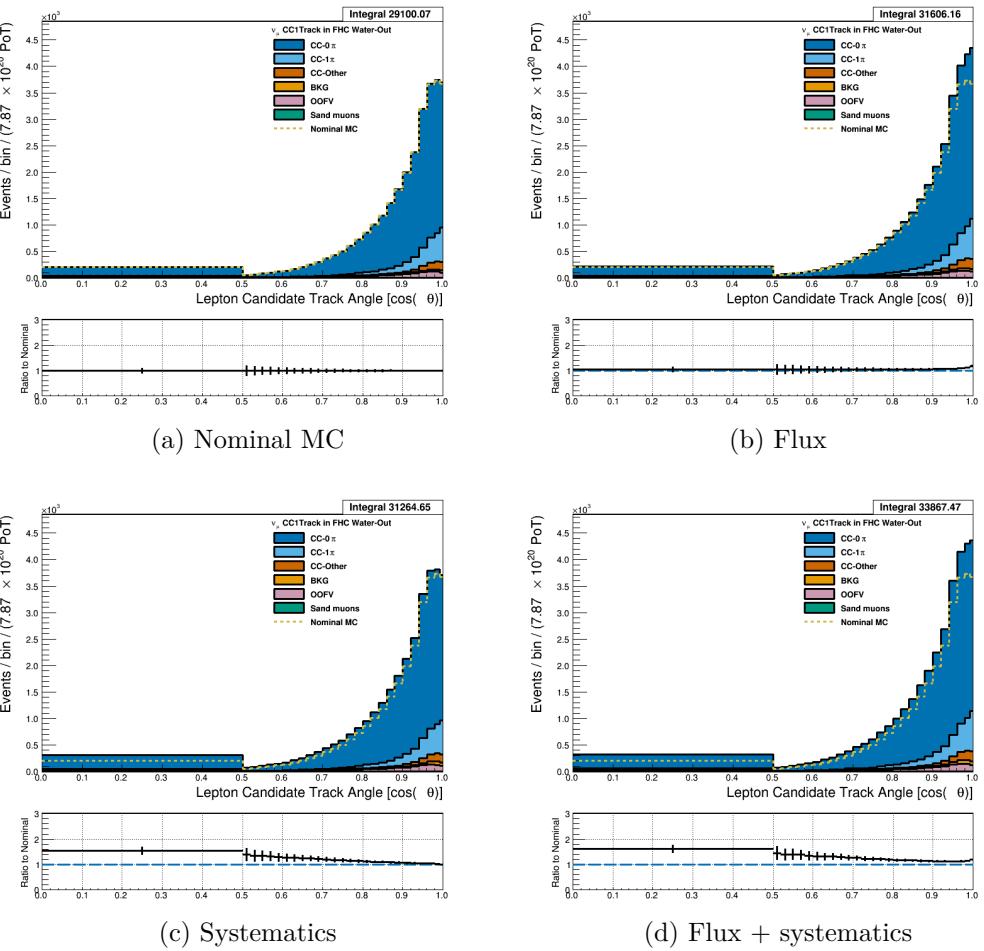


Figure 3.27: Reconstructed lepton candidate $\cos \theta$ separated by topology for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

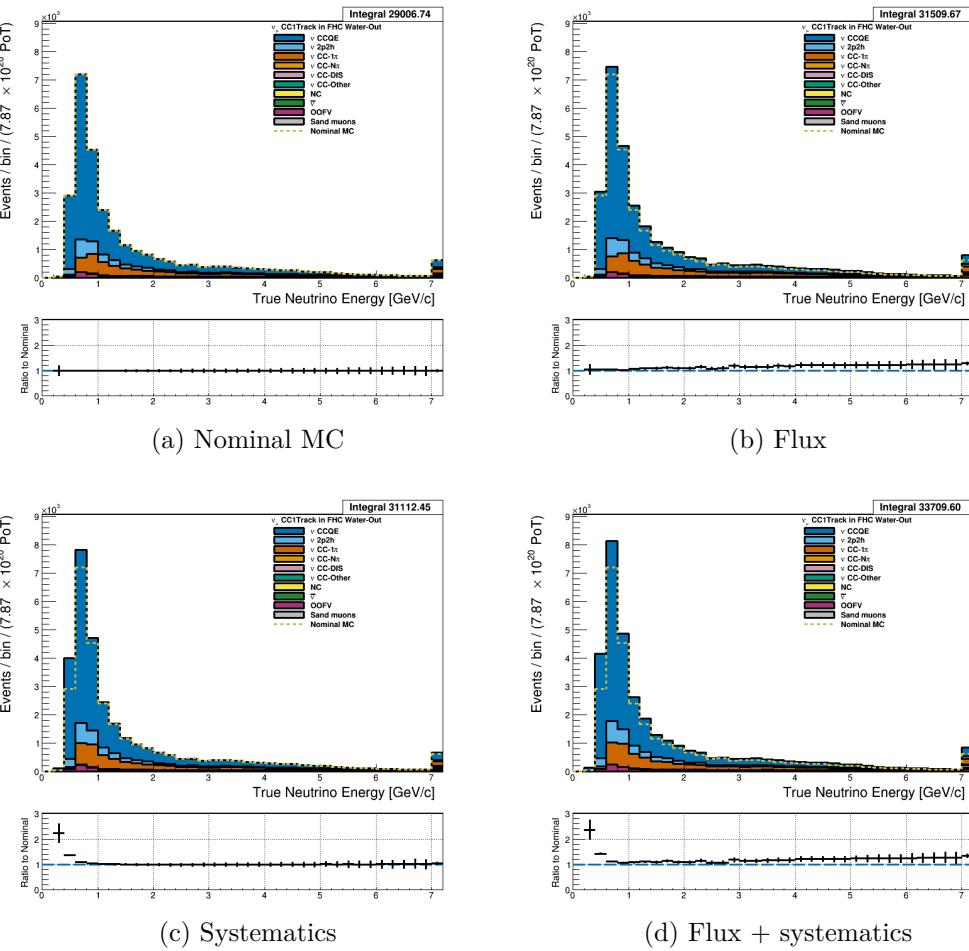


Figure 3.28: True neutrino energy associated with the lepton candidate separated by NEUT model interaction mode for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

491 3.4.2.2 $\bar{\nu}_\mu$ Selection in RHC Mode: Figures

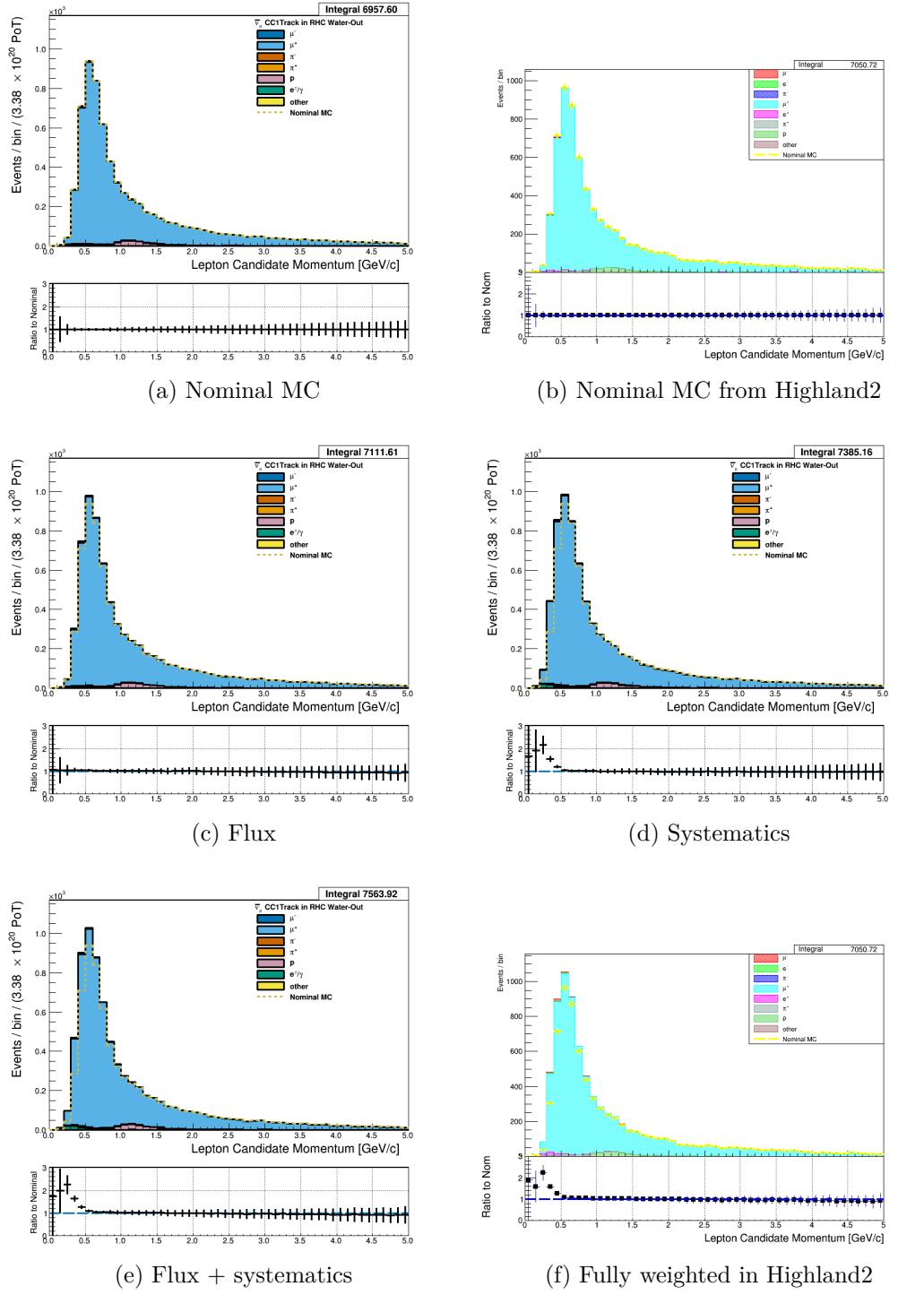


Figure 3.29: Reconstructed lepton candidate momentum separated by true particle species for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. Reconstructed lepton candidate angle separated by true particle species for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) Highland2 comparison for (a) without any weights applied using the “NOW” draw option. (c) The flux tuning is applied. (d) The systematic weighting is applied. (e) Both flux and systematic weighting is applied. (f) Highland2 comparison for (e).

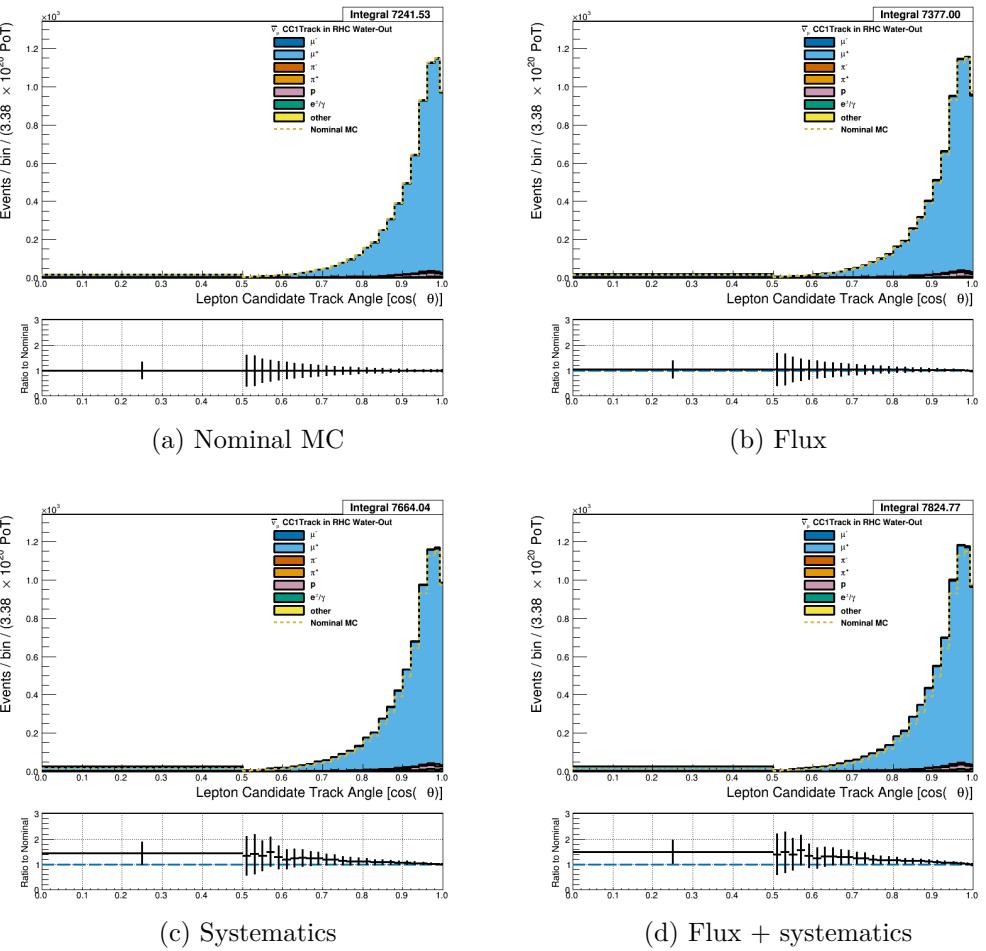


Figure 3.30: Reconstructed lepton candidate angle separated by true particle species for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

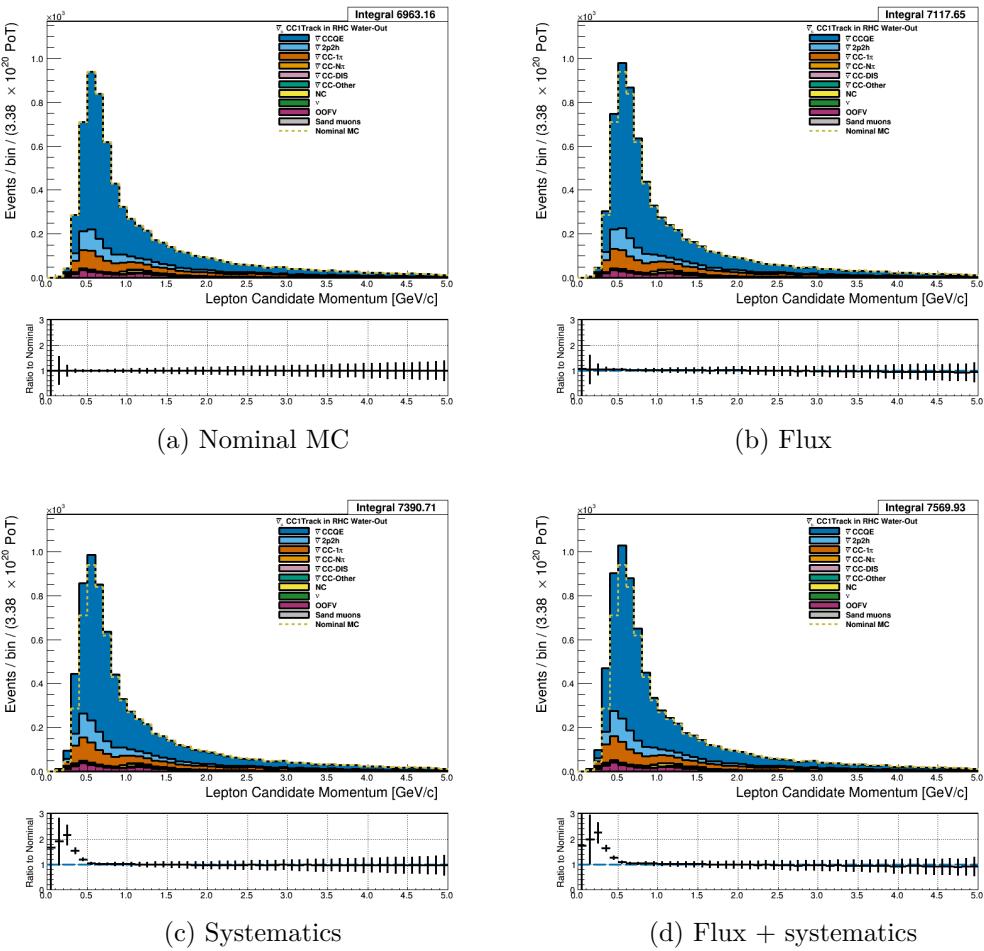


Figure 3.31: Reconstructed lepton candidate momentum separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

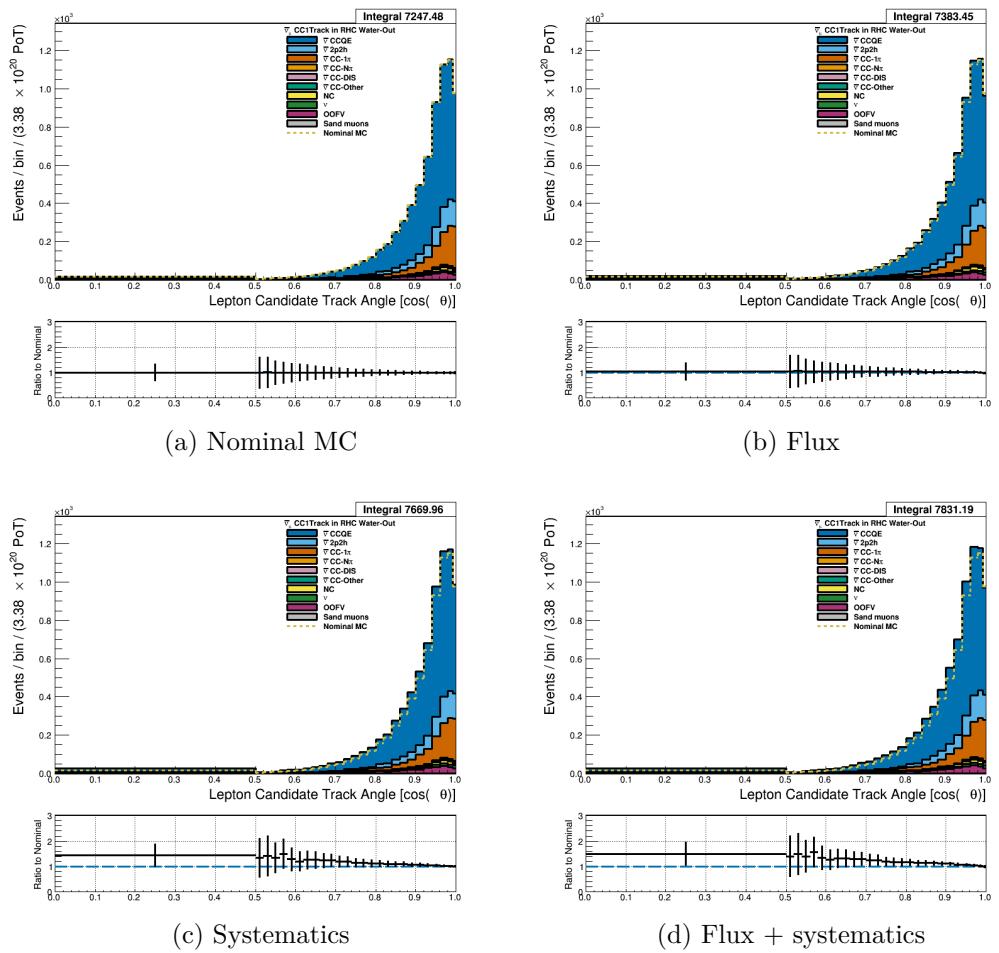


Figure 3.32: Reconstructed lepton candidate $\cos \theta$ separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

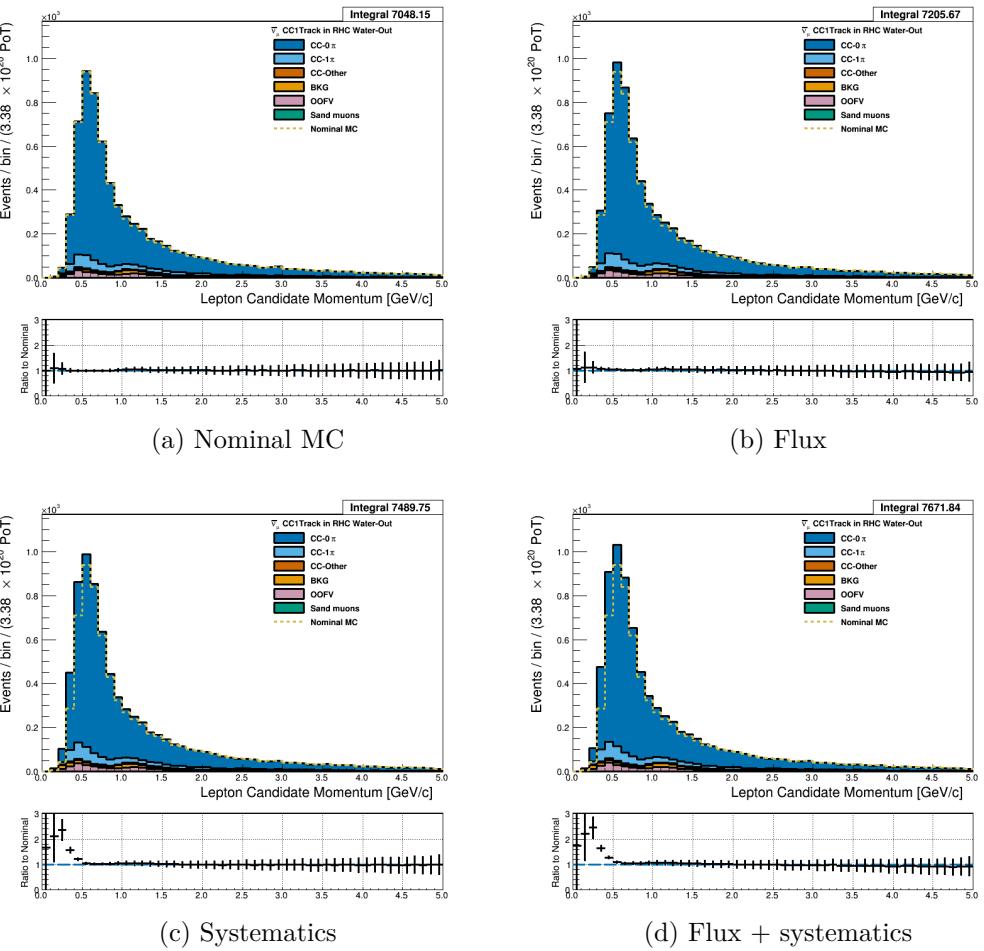


Figure 3.33: Reconstructed lepton candidate momentum separated by topology for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

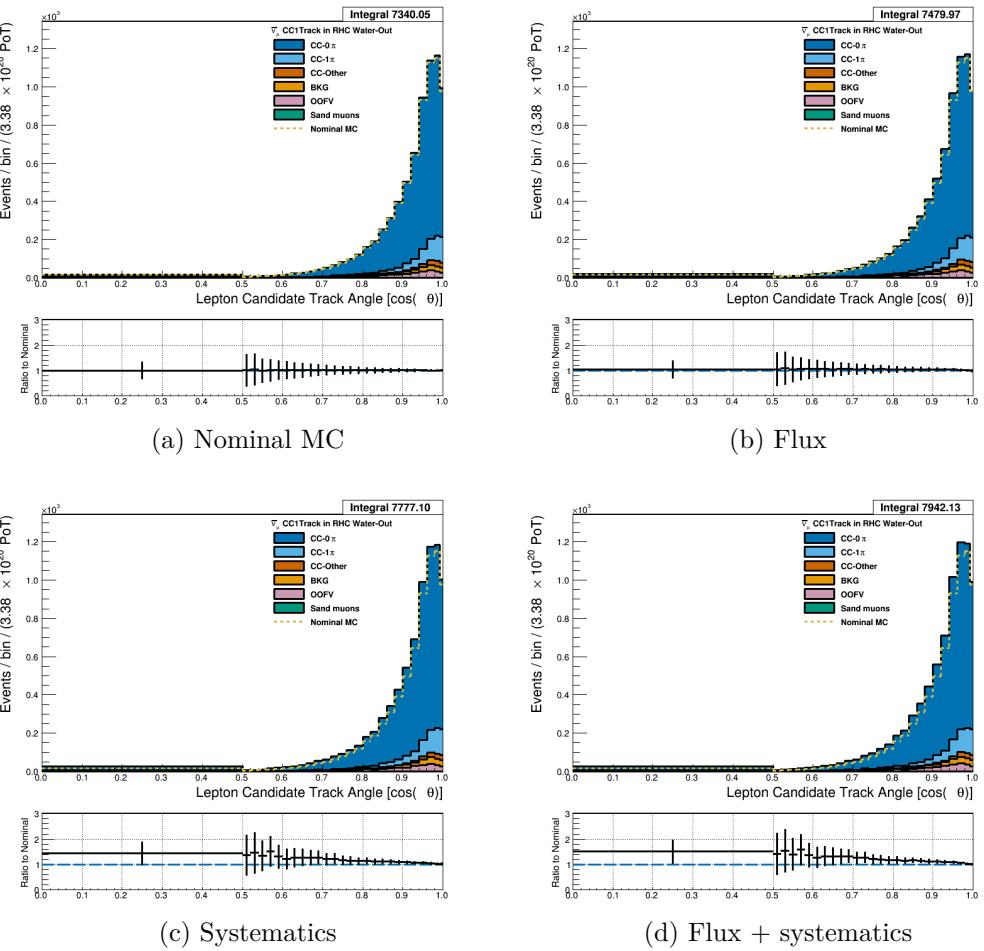


Figure 3.34: Reconstructed lepton candidate $\cos \theta$ separated by topology for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

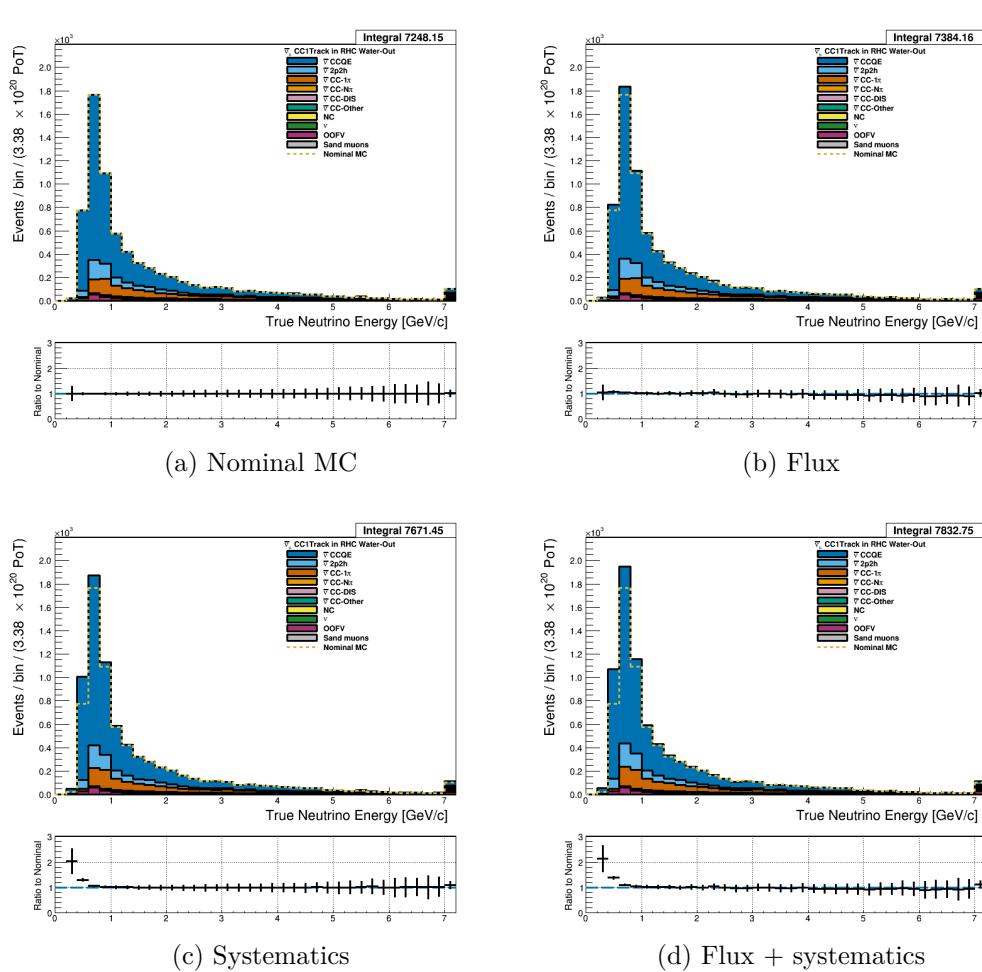


Figure 3.35: True neutrino energy associated with the lepton candidate separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

492 **3.4.2.3 ν_μ Background Selection in RHC Mode:** Text [Add figures here](#)

493 **3.4.3 CC N-Tracks (CCnQE Enhanced)**

494 Text [Add figures here](#)

495 **3.4.3.1 ν_μ Selection in FHC Mode:** Text

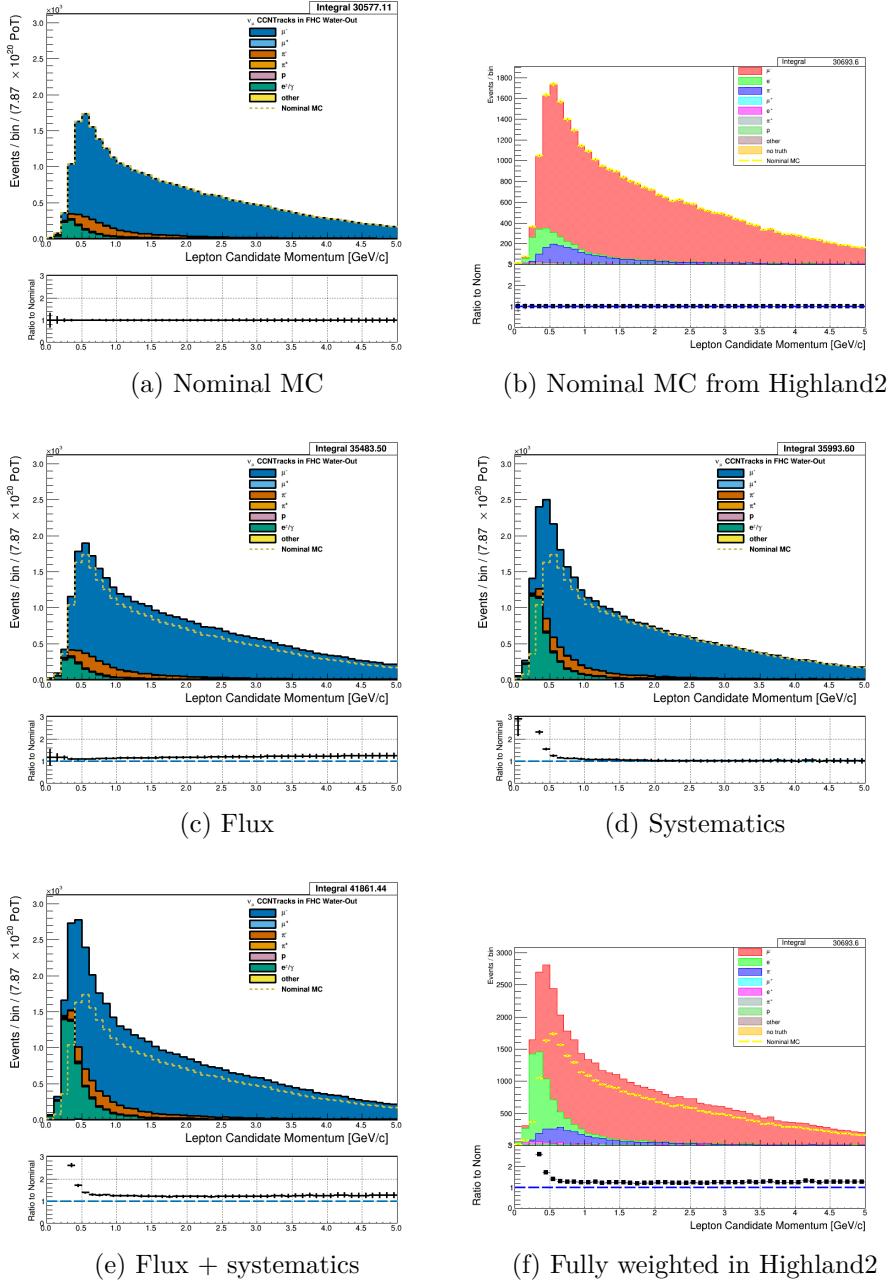


Figure 3.36: Reconstructed lepton candidate momentum separated by true particle species for FHC ν_μ CC N-Tracks events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) Highland2 comparison for (a) without any weights applied using the “NOW” draw option. (c) The flux tuning is applied. (d) The systematic weighting is applied. (e) Both flux and systematic weighting is applied. (f) Highland2 comparison for (e).

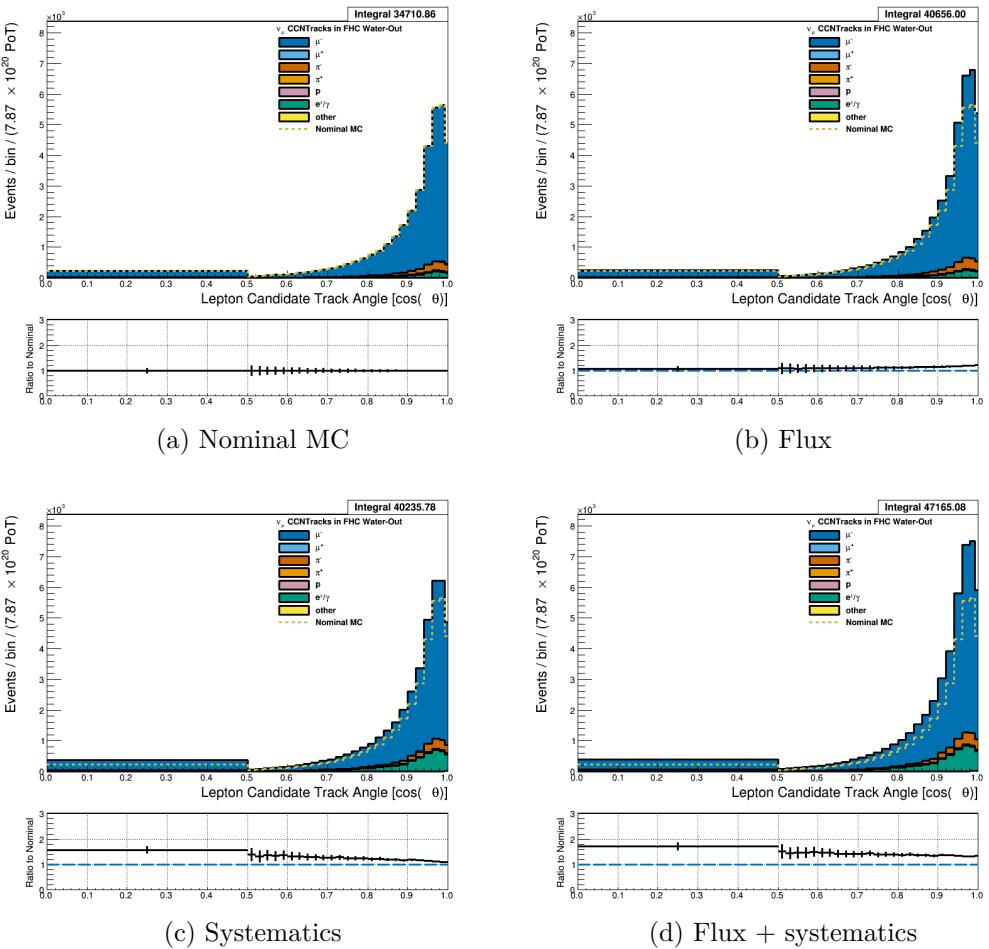


Figure 3.37: Reconstructed lepton candidate angle separated by true particle species for FHC ν_μ CC N-Tracks events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

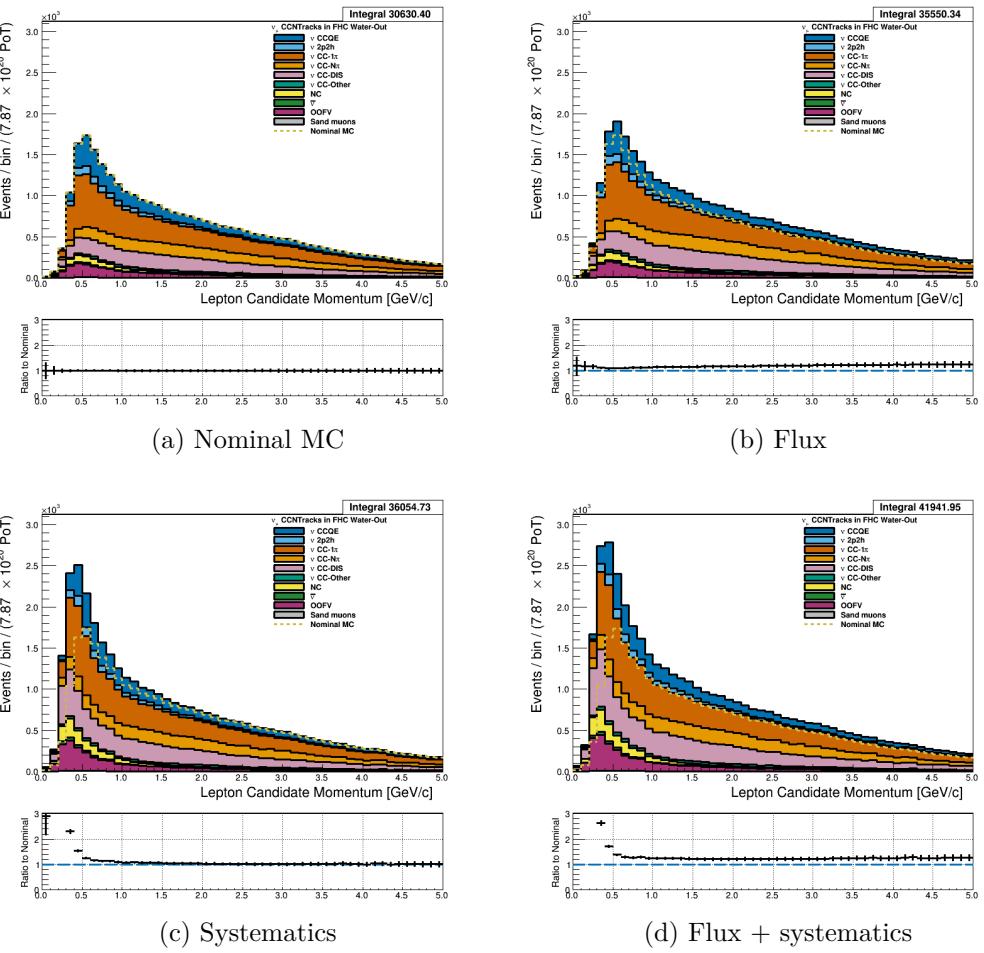


Figure 3.38: Reconstructed lepton candidate momentum separated by NEUT model interaction mode for FHC ν_μ CC N-Tracks events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

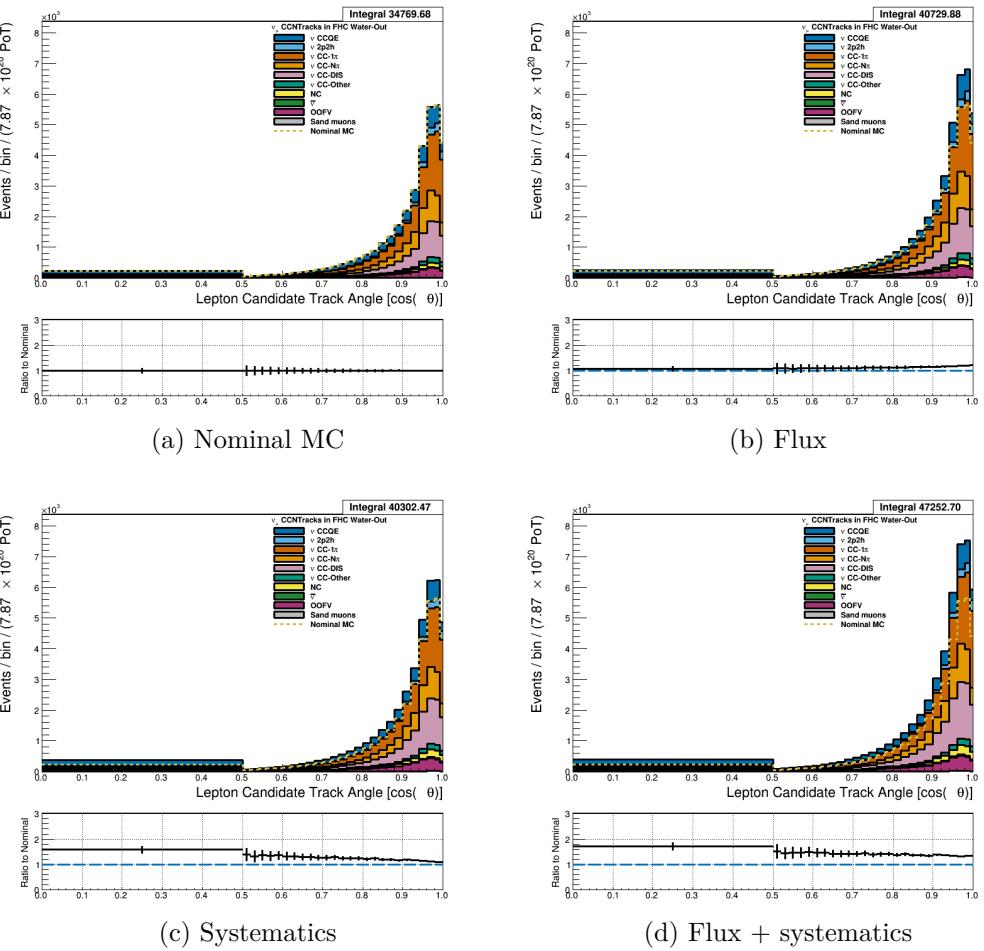


Figure 3.39: Reconstructed lepton candidate $\cos \theta$ separated by NEUT model interaction mode for FHC ν_μ CC N-Tracks events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

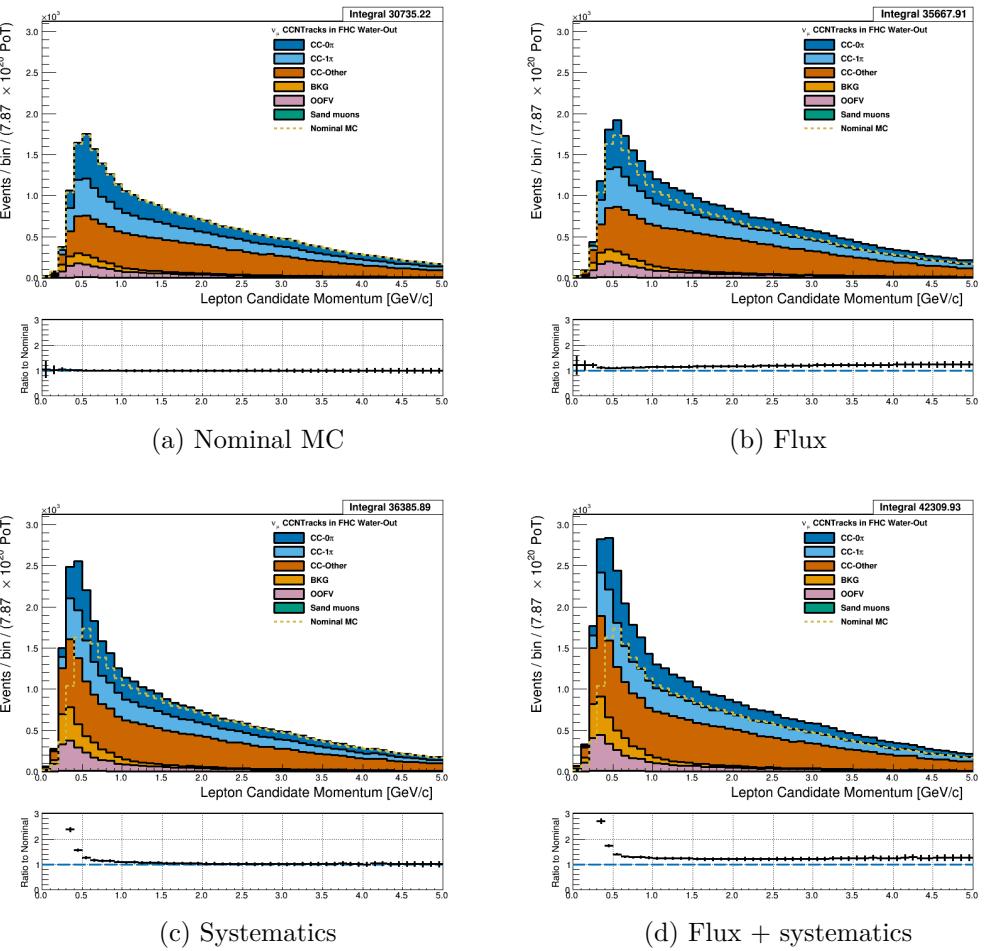


Figure 3.40: Reconstructed lepton candidate momentum separated by topology for FHC ν_μ CC N-Tracks events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

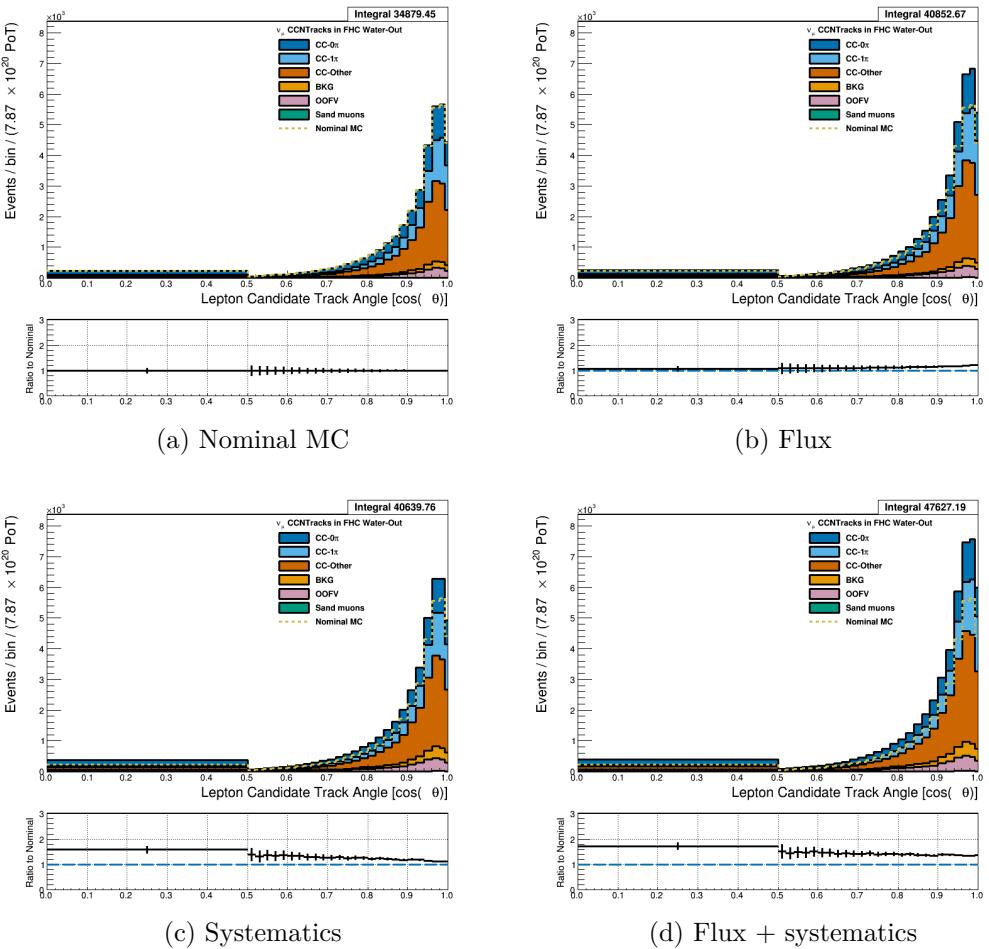


Figure 3.41: Reconstructed lepton candidate $\cos \theta$ separated by topology for FHC ν_μ CC N-Tracks events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

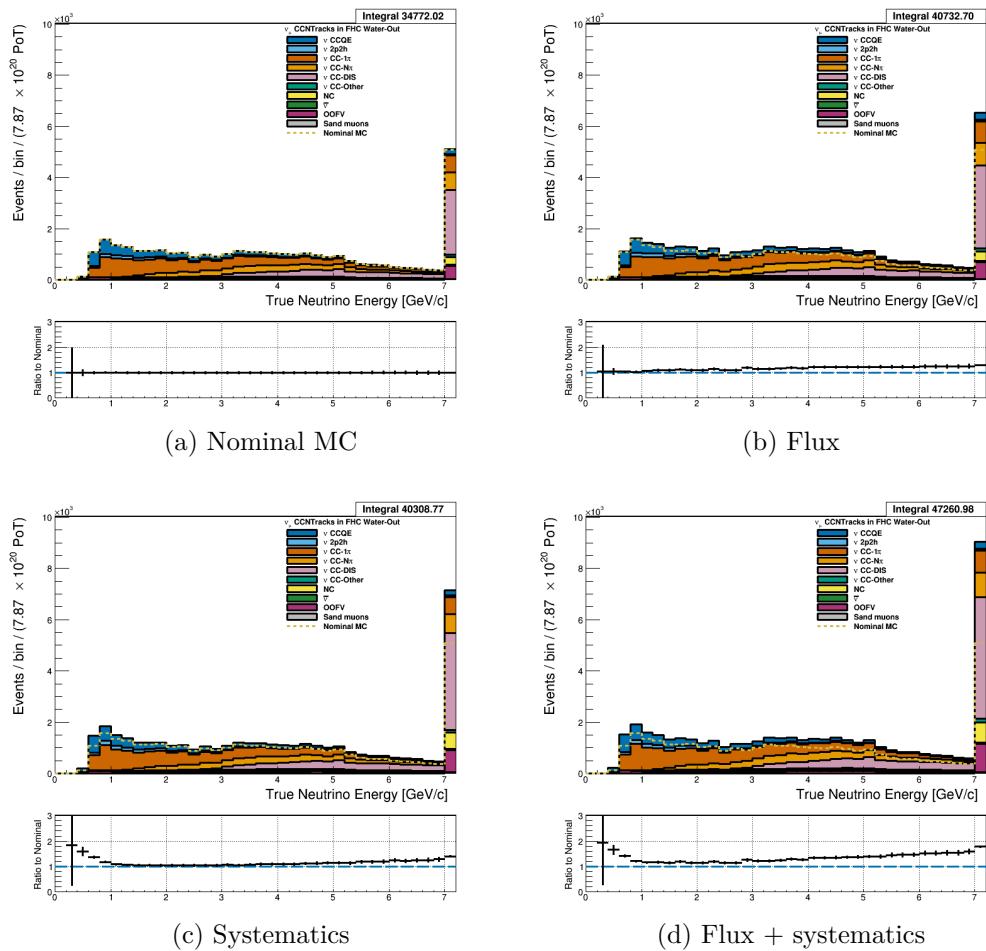
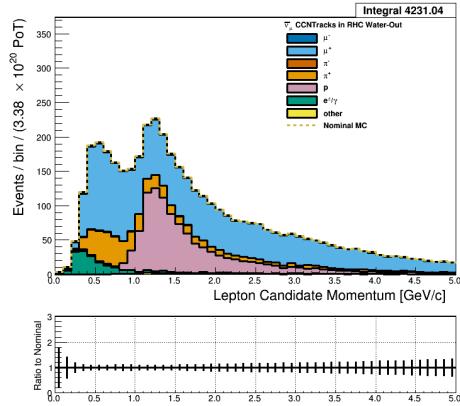
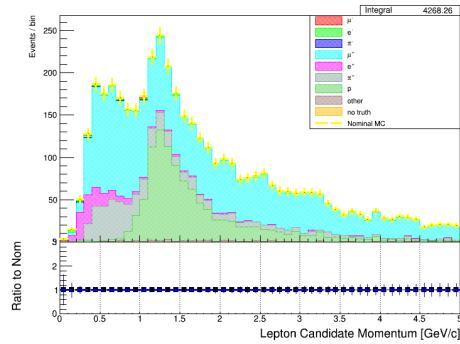


Figure 3.42: True neutrino energy associated with the lepton candidate separated by NEUT model interaction mode for FHC ν_μ CC N-Tracks events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

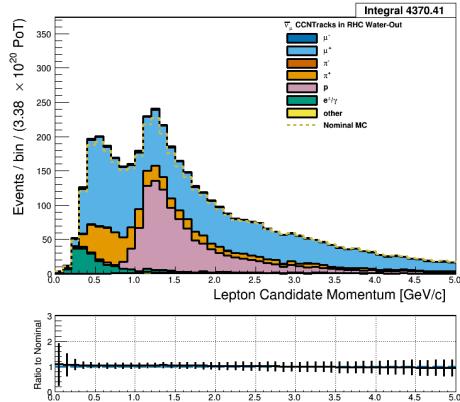
3.4.3.2 $\bar{\nu}_\mu$ Selection in RHC Mode: Text goes here



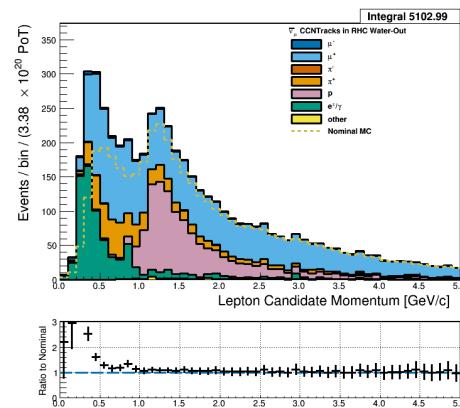
(a) Nominal MC



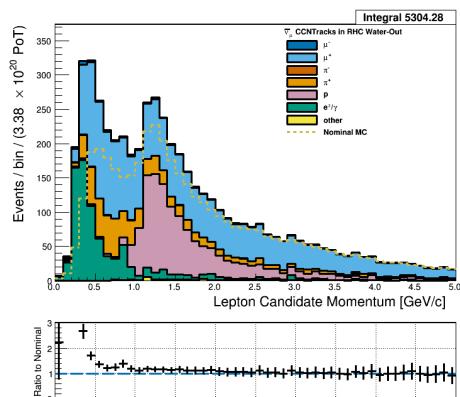
(b) Nominal MC from Highland2



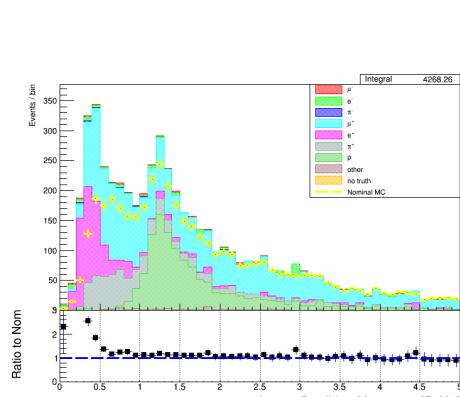
(c) Flux



(d) Systematics



(e) Flux + systematics



(f) Fully weighted in Highland2

Figure 3.43: Reconstructed lepton candidate momentum separated by true particle species for RHC $\bar{\nu}_\mu$ CC N-Tracks events occurring in the PØD in water-out mode. Reconstructed lepton candidate angle separated by true particle species for RHC $\bar{\nu}_\mu$ CC N-Tracks events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) Highland2 comparison for (a) without any weights applied using the “NOW” draw option. (c) The flux tuning is applied. (d) The systematic weighting is applied. (e) Both flux and systematic weighting is applied.⁷³ (f) Highland2 comparison for (e).

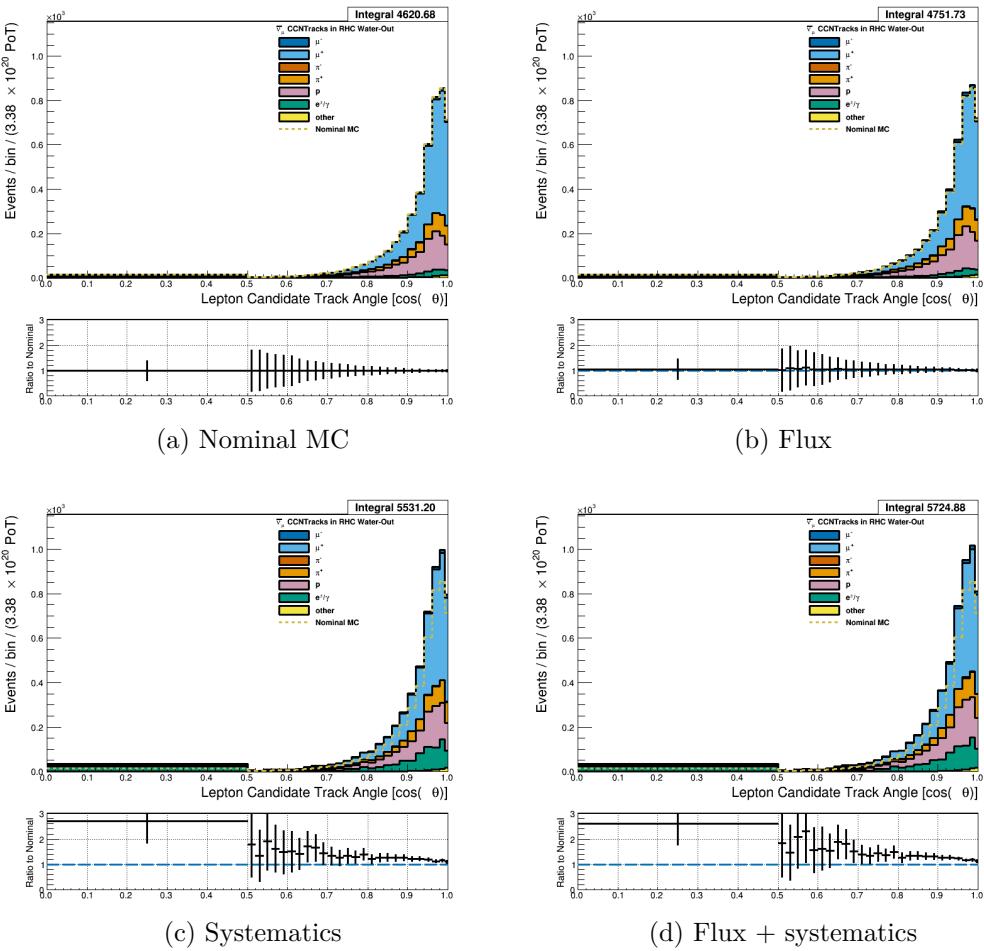


Figure 3.44: Reconstructed lepton candidate angle separated by true particle species for RHC $\bar{\nu}_\mu$ CC N-Tracks events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

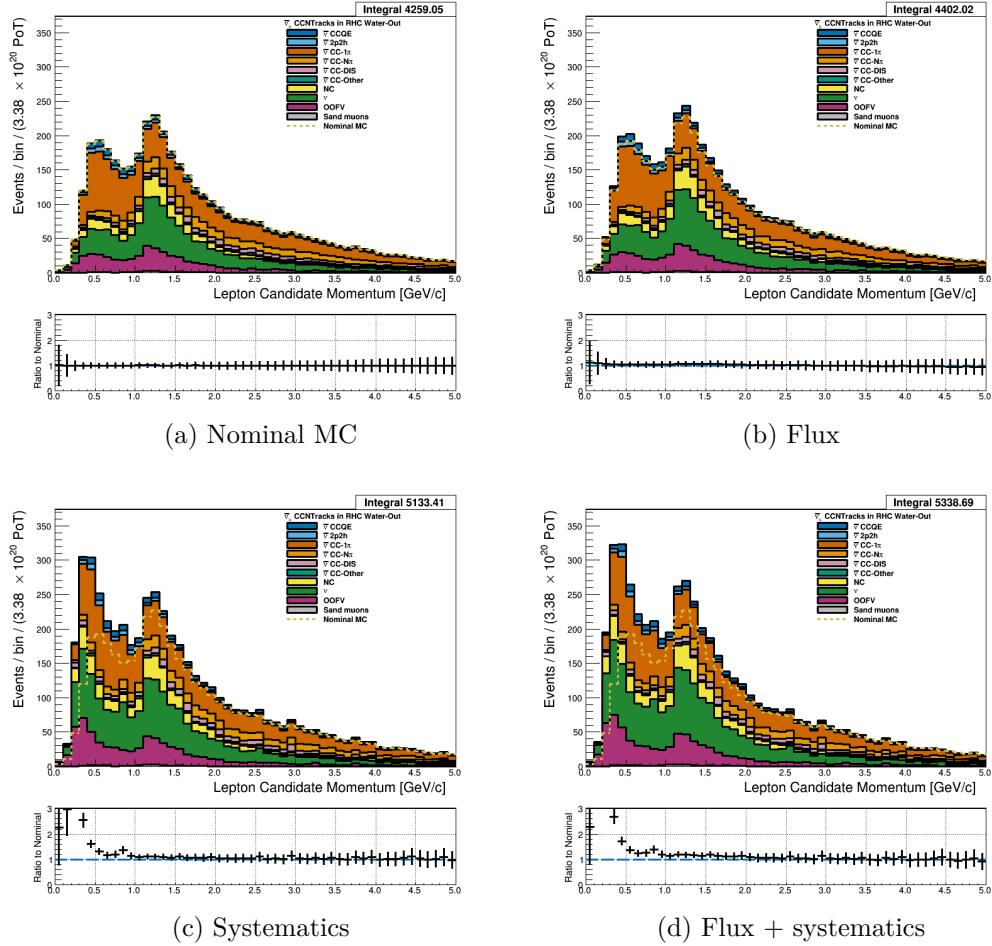


Figure 3.45: Reconstructed lepton candidate momentum separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC N-Tracks events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

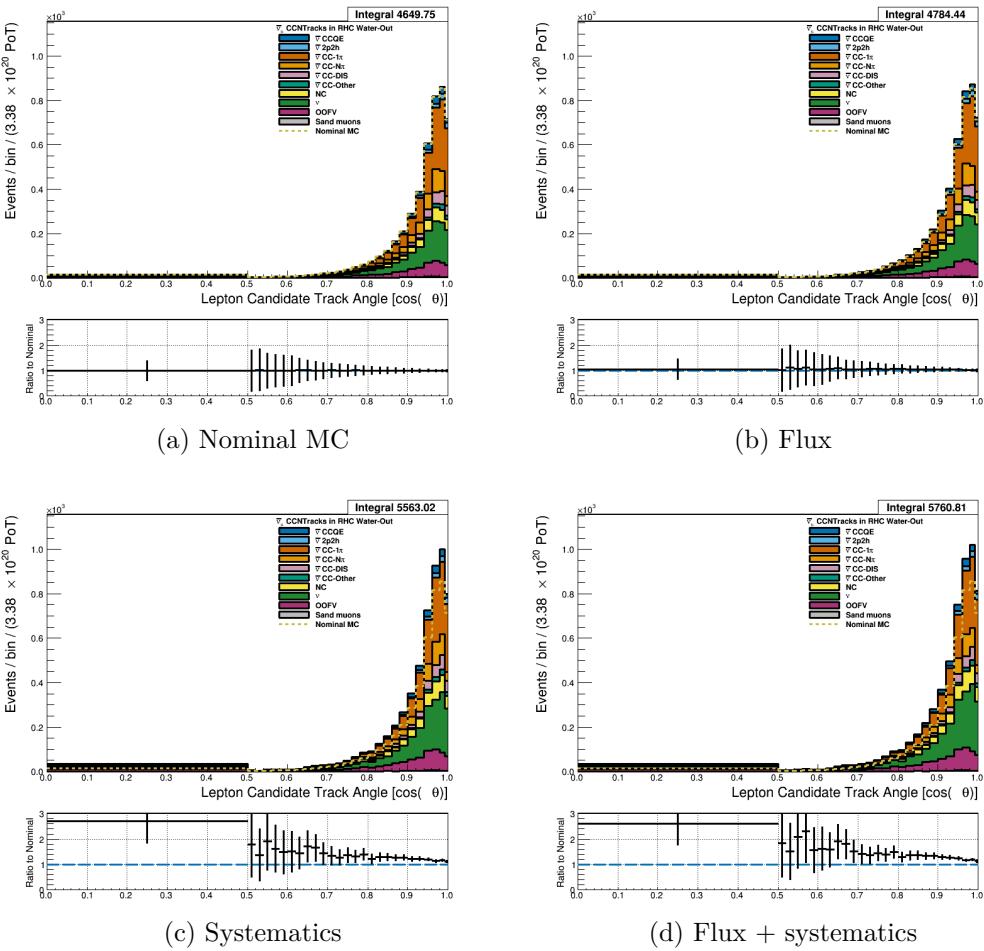


Figure 3.46: Reconstructed lepton candidate $\cos \theta$ separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC N-Tracks events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

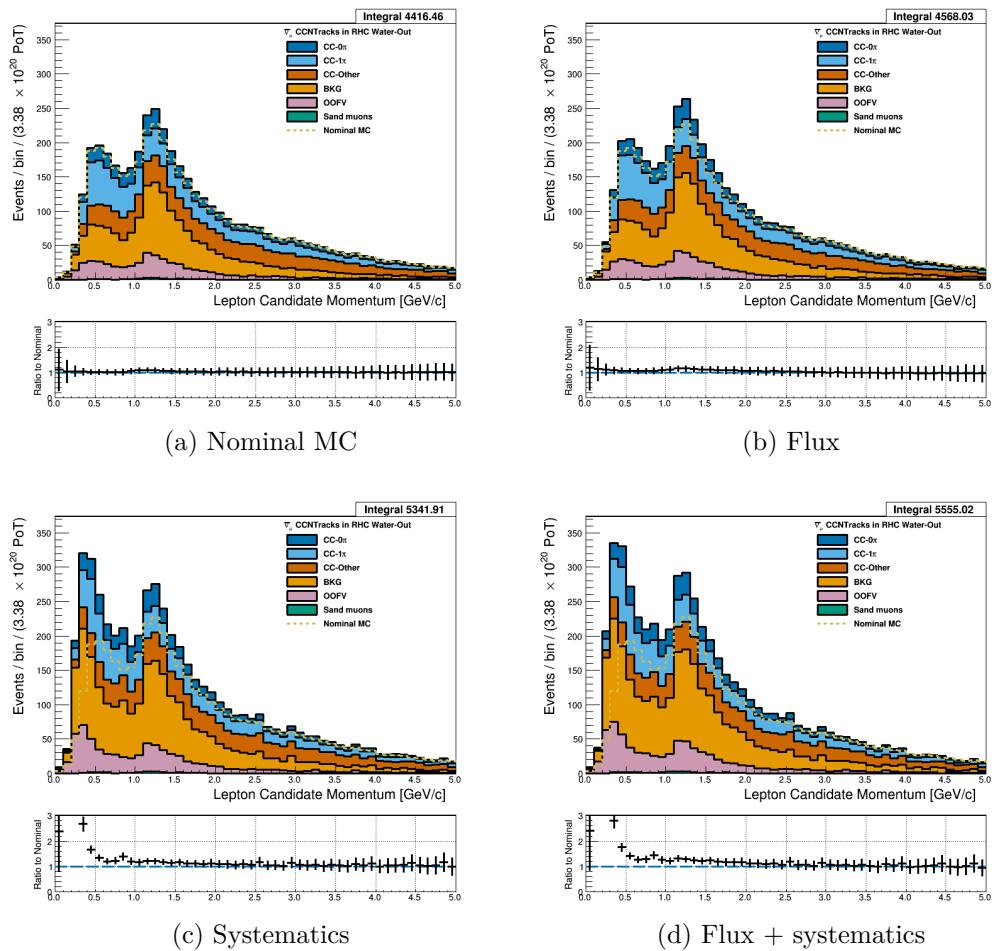


Figure 3.47: Reconstructed lepton candidate momentum separated by topology for RHC $\bar{\nu}_\mu$ CC N-Tracks events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

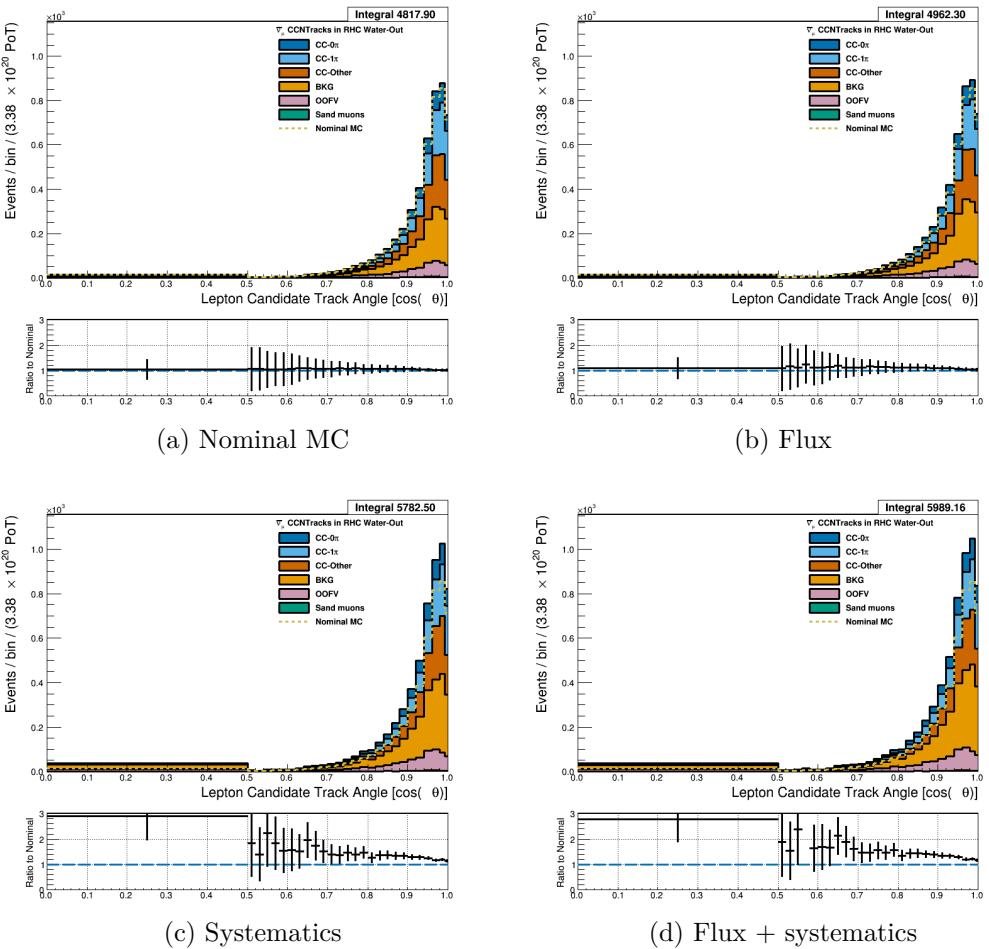


Figure 3.48: Reconstructed lepton candidate $\cos \theta$ separated by topology for RHC $\bar{\nu}_\mu$ CC N-Tracks events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

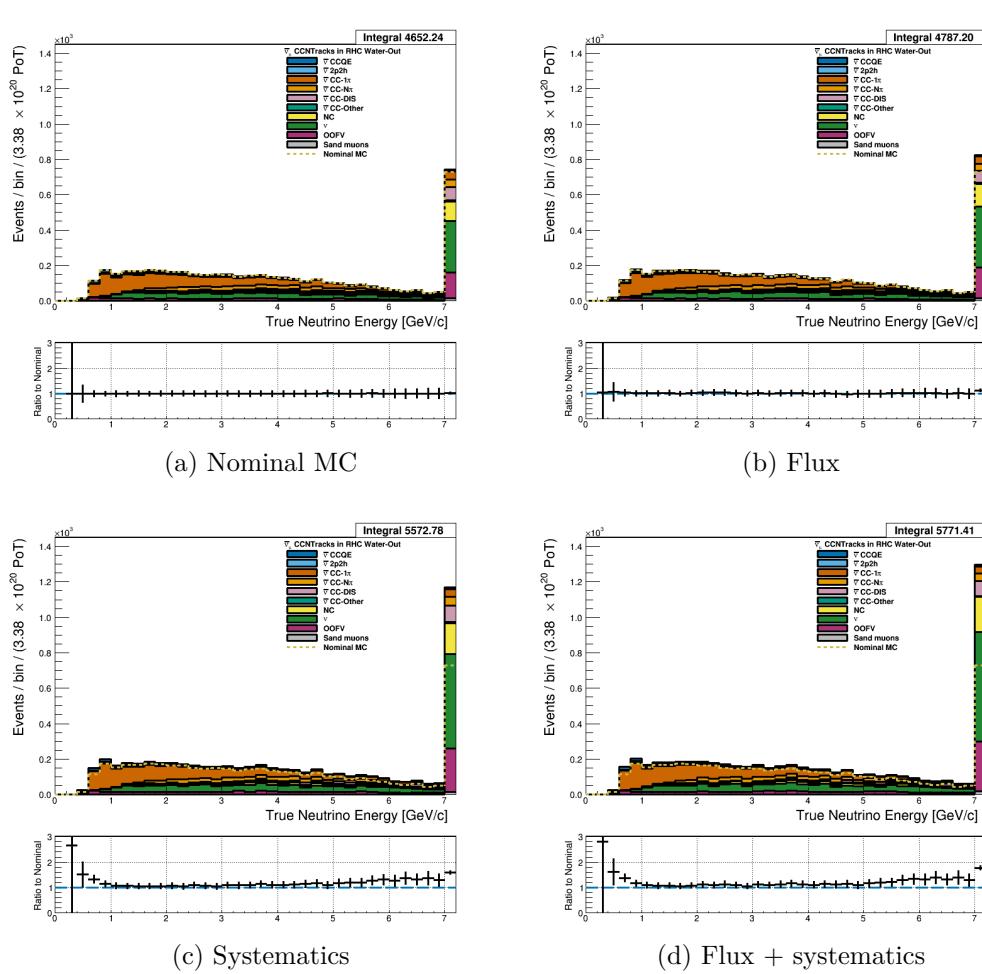


Figure 3.49: True neutrino energy associated with the lepton candidate separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC N-Tracks events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

497 **3.4.3.3 ν_μ Background Selection in RHC Mode:** Text

498 **3.5 PØD Water-In Samples**

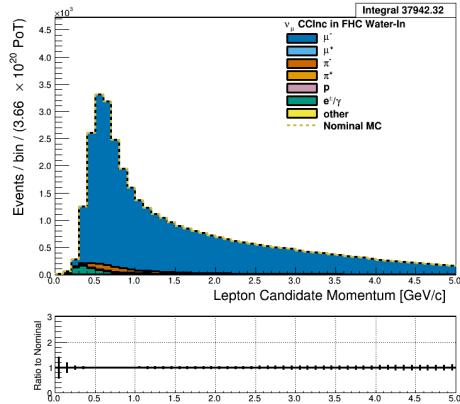
499 This section shows the kinematic distributions for the PØD water-in samples. These samples
500 will demonstrate the similarities between it and water-out modes. First an examination of
501 the CC Inclusive samples and the effects of the systematic weights will be explored. The

502 samples are then examined as CC 1-track and CC N-tracks.

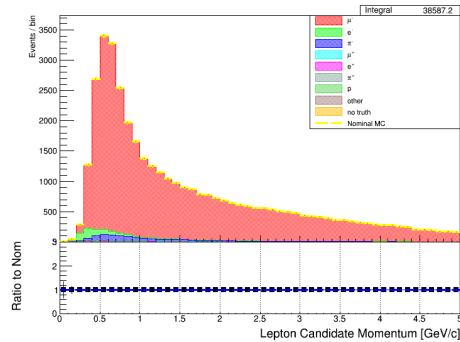
503 **3.5.1 CC Inclusive**

504 The CC Inclusive sample cuts are discussed 3.2.1. Since both flux and detector systematic
505 weights are applied to all MC events in BANFF, it is important to validate the event weights.
506 Using neither set of weights is referred to as the nominal MC.

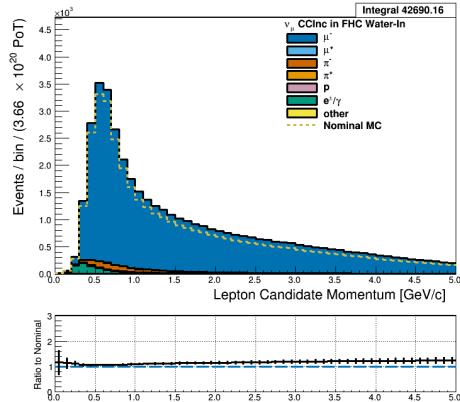
507 **3.5.1.1 ν_μ Selection in FHC Mode:** Shown in Figures 3.50 to 3.56 are the momentum
508 and $\cos\theta$ distributions for ν_μ CC Inclusive events in FHC mode. There are three pairs of
509 P, θ figures with the same truth information break down accompanied by one of neutrino
510 energy. The truth information categories are lepton candidate particle, NEUT reaction, and
511 topology. Each figure consists of a set of four sub-figures which illustrate the application of
512 flux and detector systematic weights.



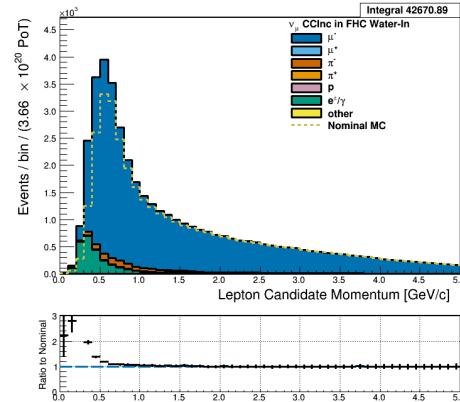
(a) Nominal MC



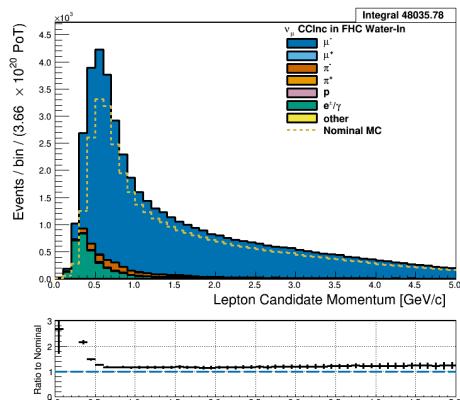
(b) Nominal MC from Highland2



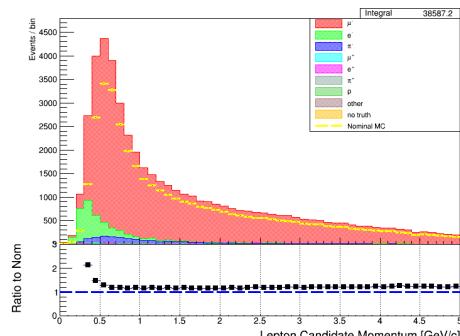
(c) Flux



(d) Systematics



(e) Flux + systematics



(f) Fully weighted in Highland2

Figure 3.50: Reconstructed lepton candidate momentum separated by true particle species for FHC ν_μ CC Inc. events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) Highland2 comparison for (a) without any weights applied using the “NOW” draw option. (c) The flux tuning is applied. (d) The systematic weighting is applied. (e) Both flux and systematic weighting is applied. (f) Highland2 comparison for (e).

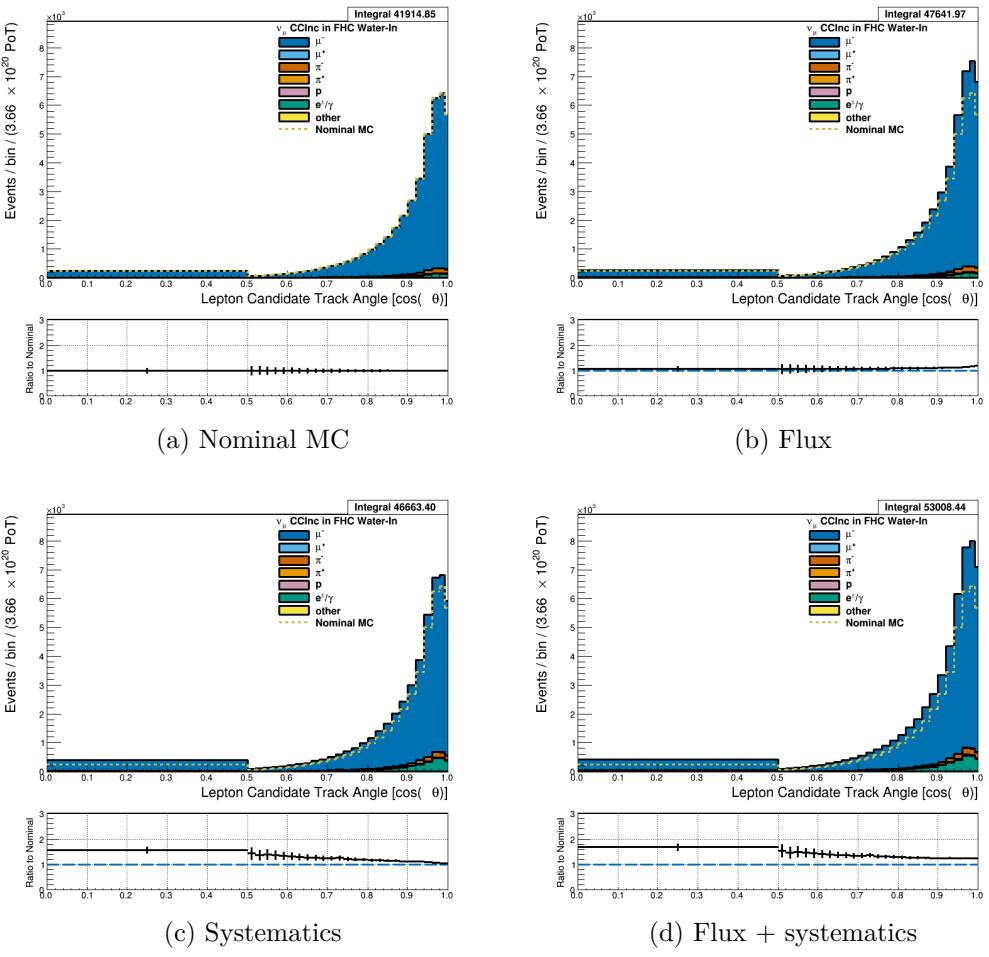


Figure 3.51: Reconstructed lepton candidate angle separated by true particle species for FHC ν_μ CC Inc. events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

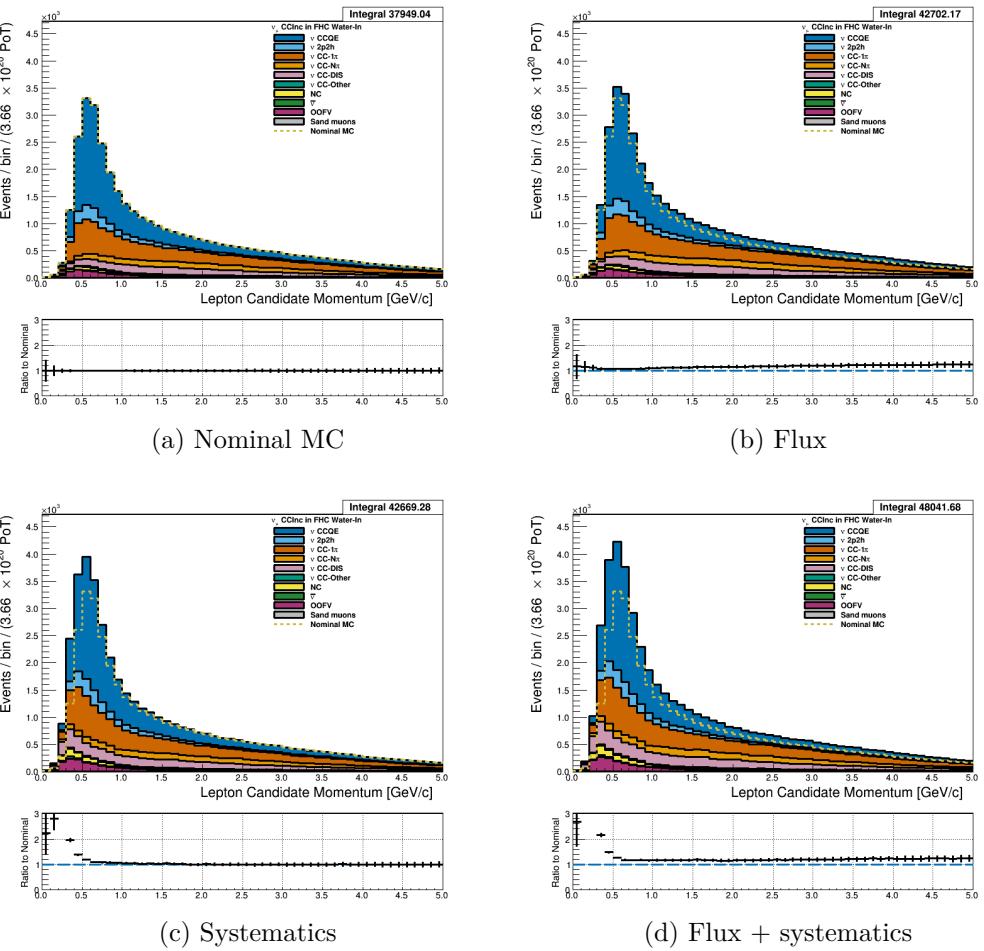


Figure 3.52: Reconstructed lepton candidate momentum separated by NEUT model interaction mode for FHC ν_μ CC Inc. events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

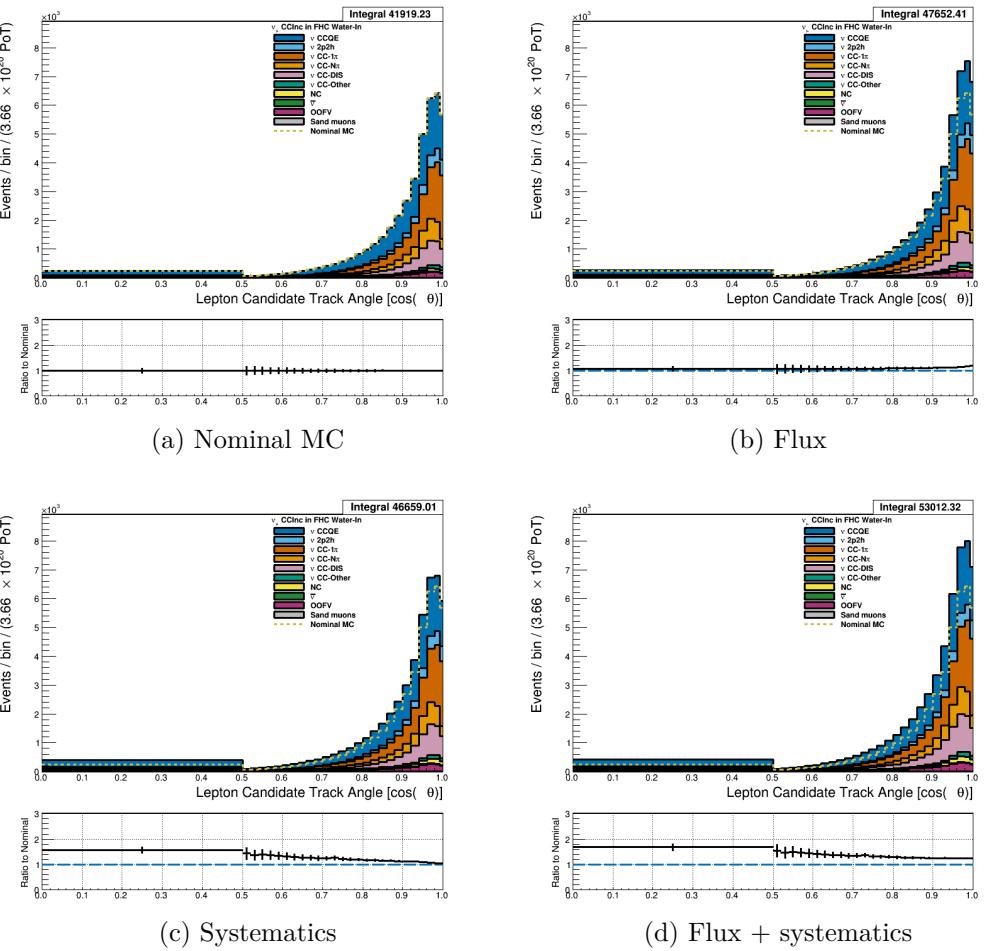


Figure 3.53: Reconstructed lepton candidate $\cos \theta$ separated by NEUT model interaction mode for FHC ν_μ CC Inc. events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

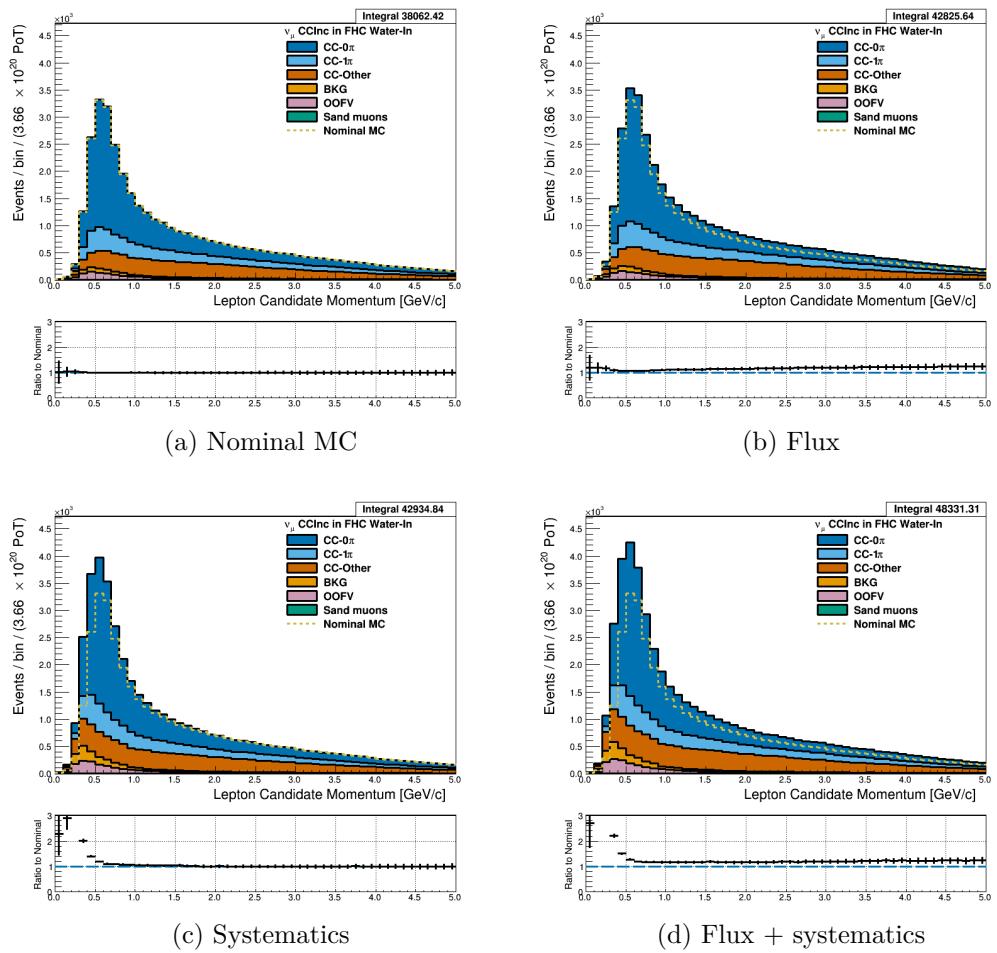


Figure 3.54: Reconstructed lepton candidate momentum separated by topology for FHC ν_μ CC Inc. events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

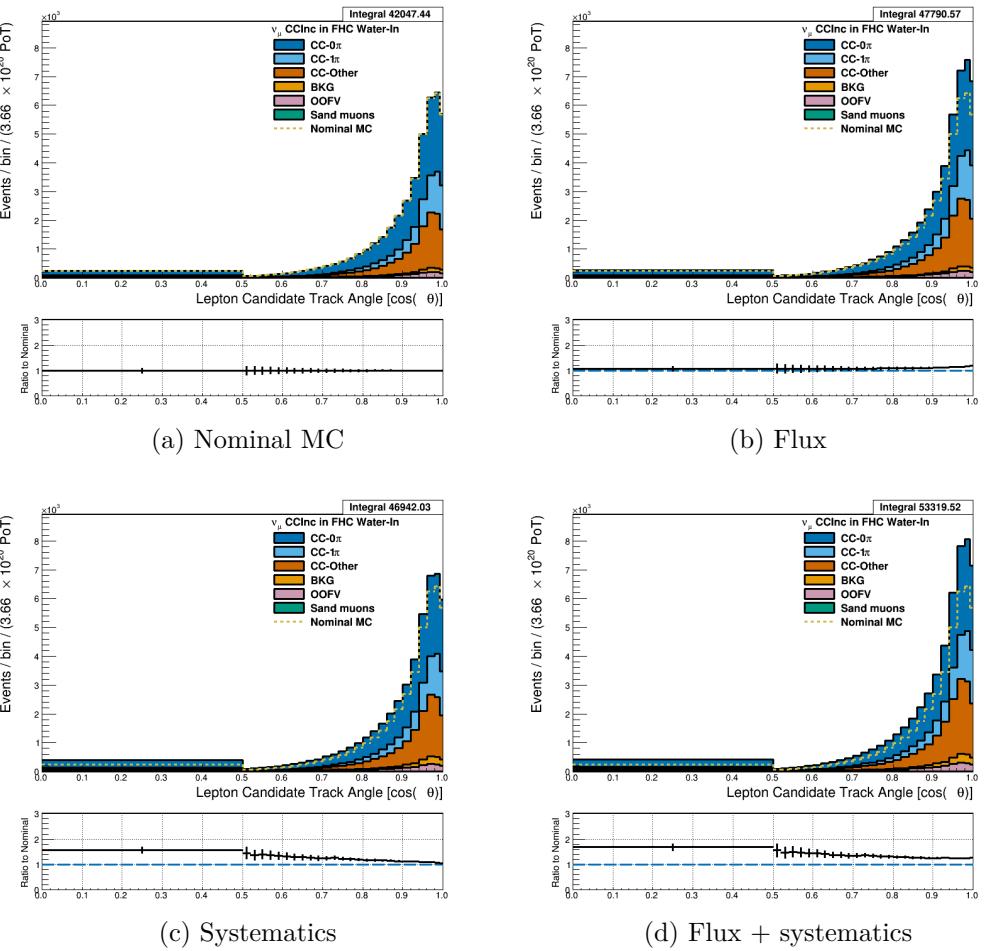


Figure 3.55: Reconstructed lepton candidate $\cos \theta$ separated by topology for FHC ν_μ CC Inc. events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

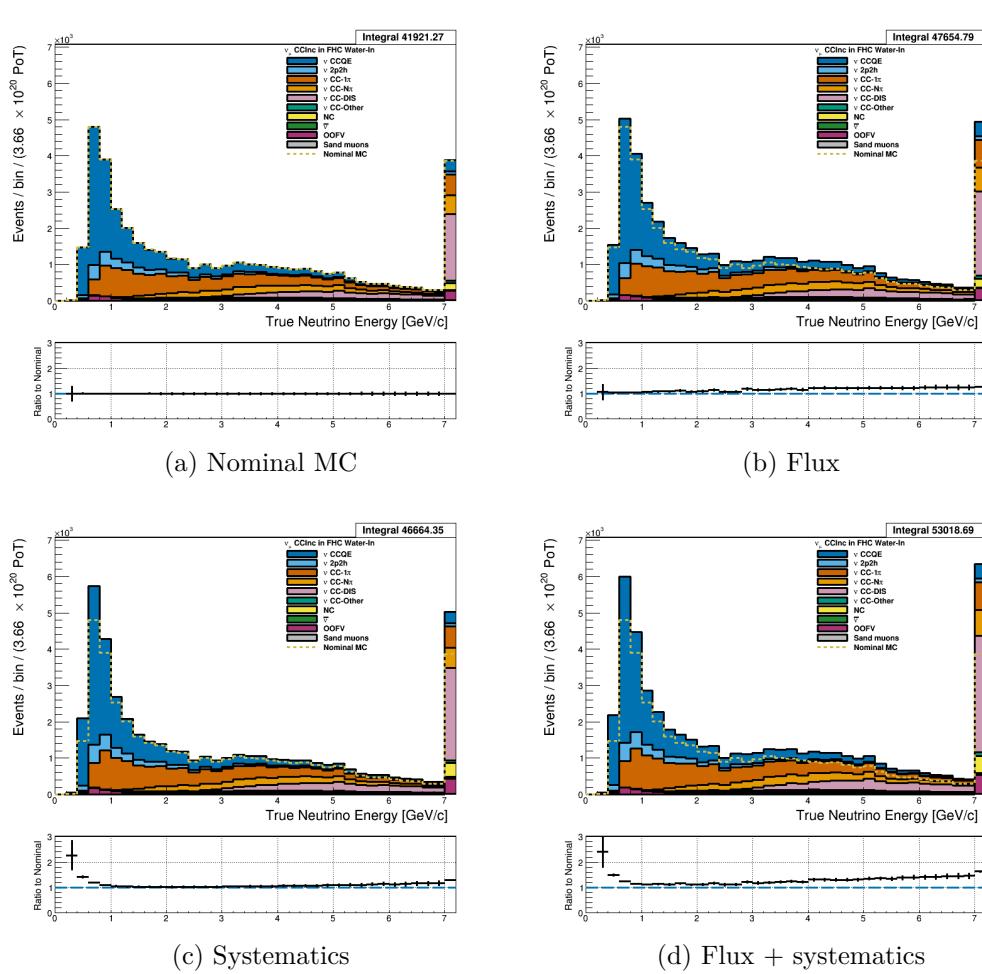
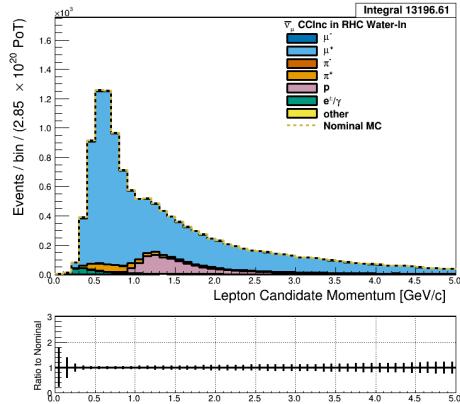
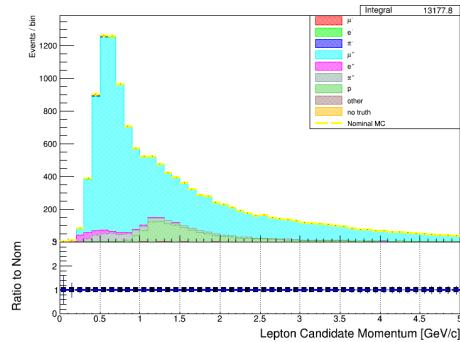


Figure 3.56: True neutrino energy associated with the lepton candidate separated by NEUT model interaction mode for FHC ν_μ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

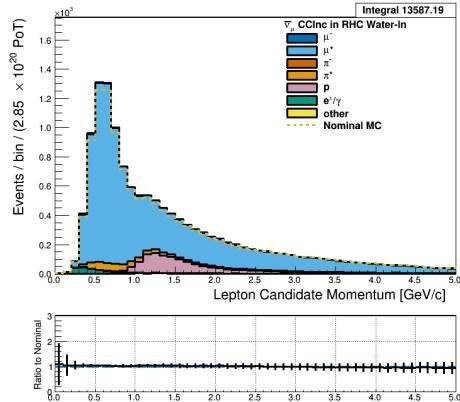
513 **3.5.1.2 $\bar{\nu}_\mu$ Selection in RHC Mode:** Shown in Figures 3.57 to 3.63 for $\bar{\nu}_\mu$ CC Inclusive
 514 events in RHC mode. There are three pairs of P, θ figures with the same truth information
 515 break down accompanied by one of neutrino energy. The truth information categories are
 516 lepton candidate particle, NEUT reaction, and topology. Each figure consists of a set of four
 517 sub-figures which illustrate the application of flux and detector systematic weights.



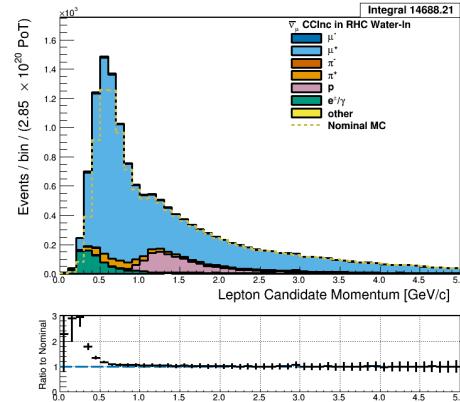
(a) Nominal MC



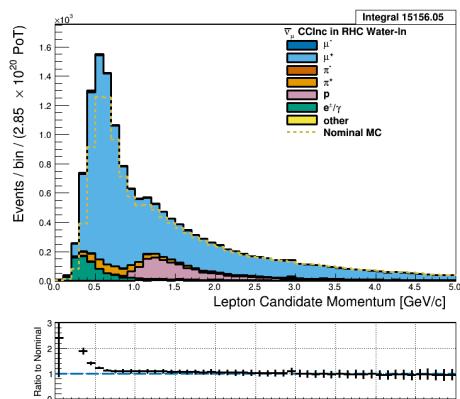
(b) Nominal MC from Highland2



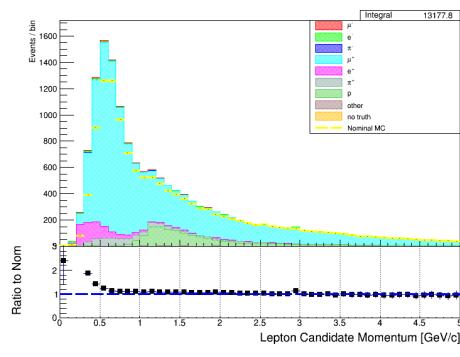
(c) Flux



(d) Systematics



(e) Flux + systematics



(f) Nominal MC from Highland2

Figure 3.57: Reconstructed lepton candidate momentum separated by true particle species for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) Highland2 comparison for (a) without any weights applied using the “NOW” draw option. (c) The flux tuning is applied. (d) The systematic weighting is applied. (e) Both flux and systematic weighting is applied. (f) Highland2 comparison for (e).

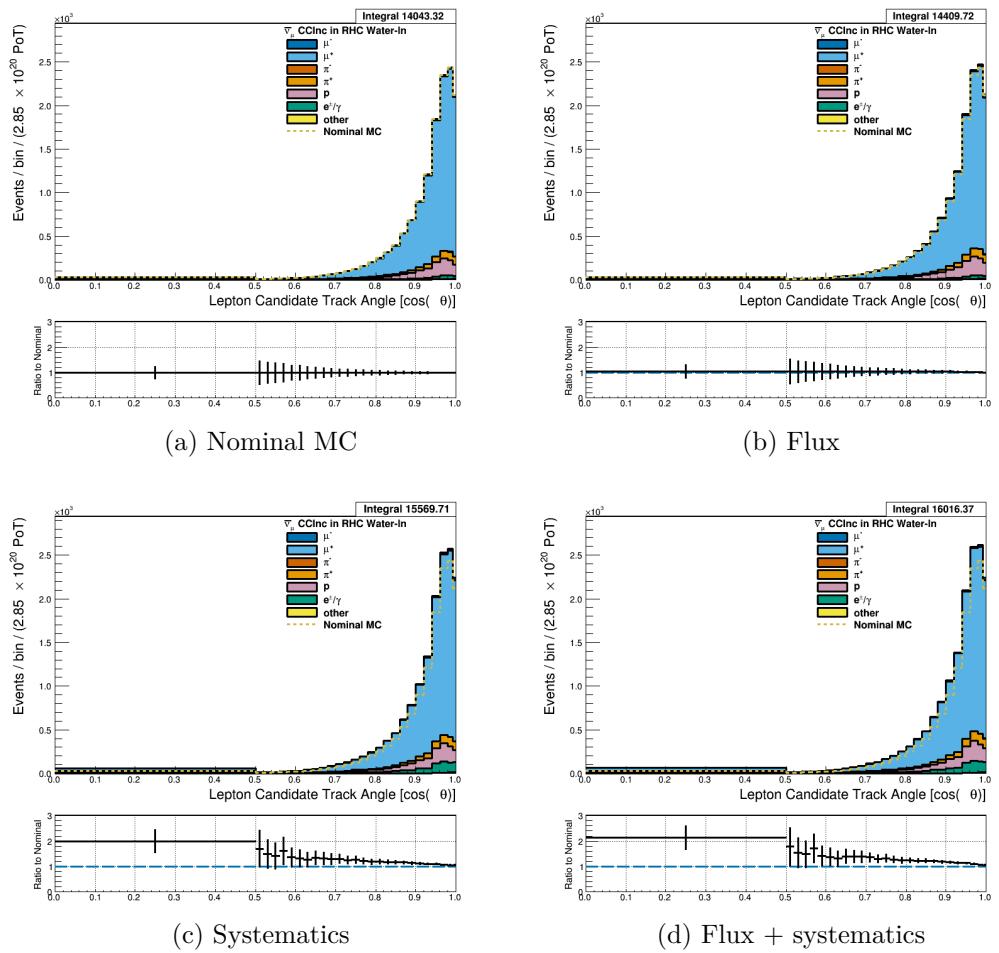


Figure 3.58: Reconstructed lepton candidate angle separated by true particle species for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

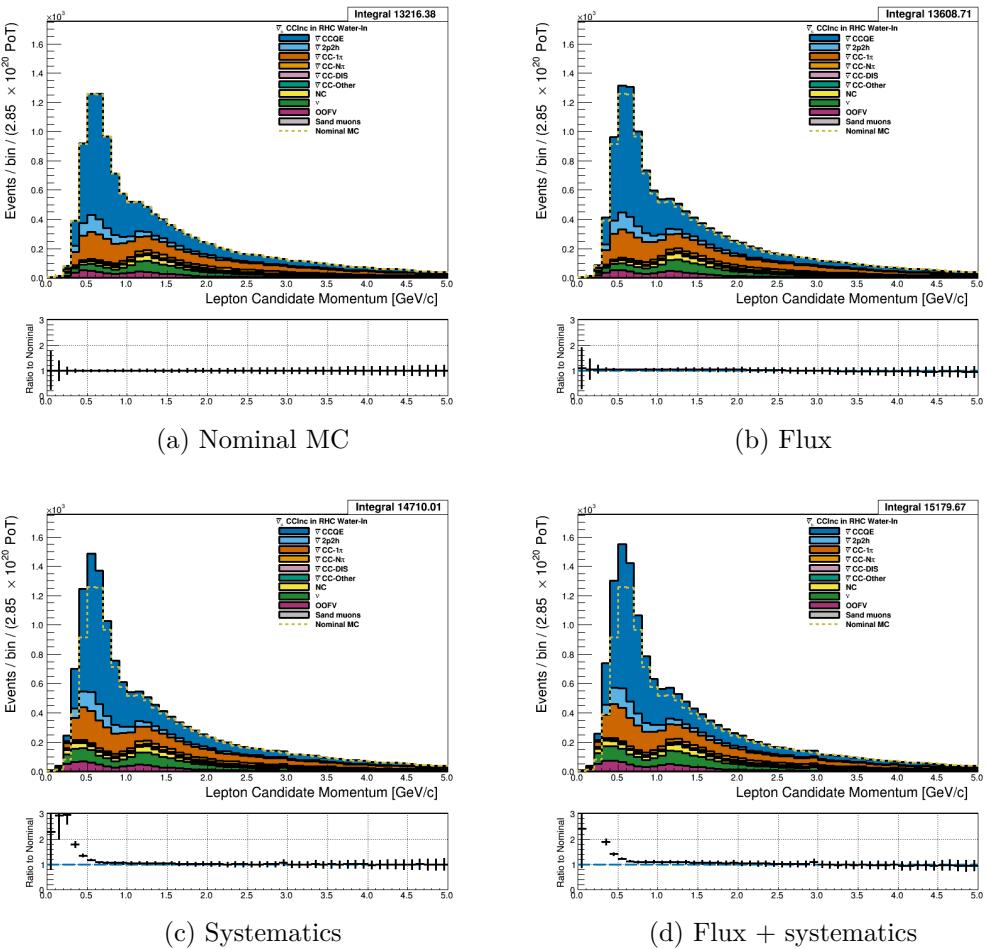


Figure 3.59: Reconstructed lepton candidate momentum separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

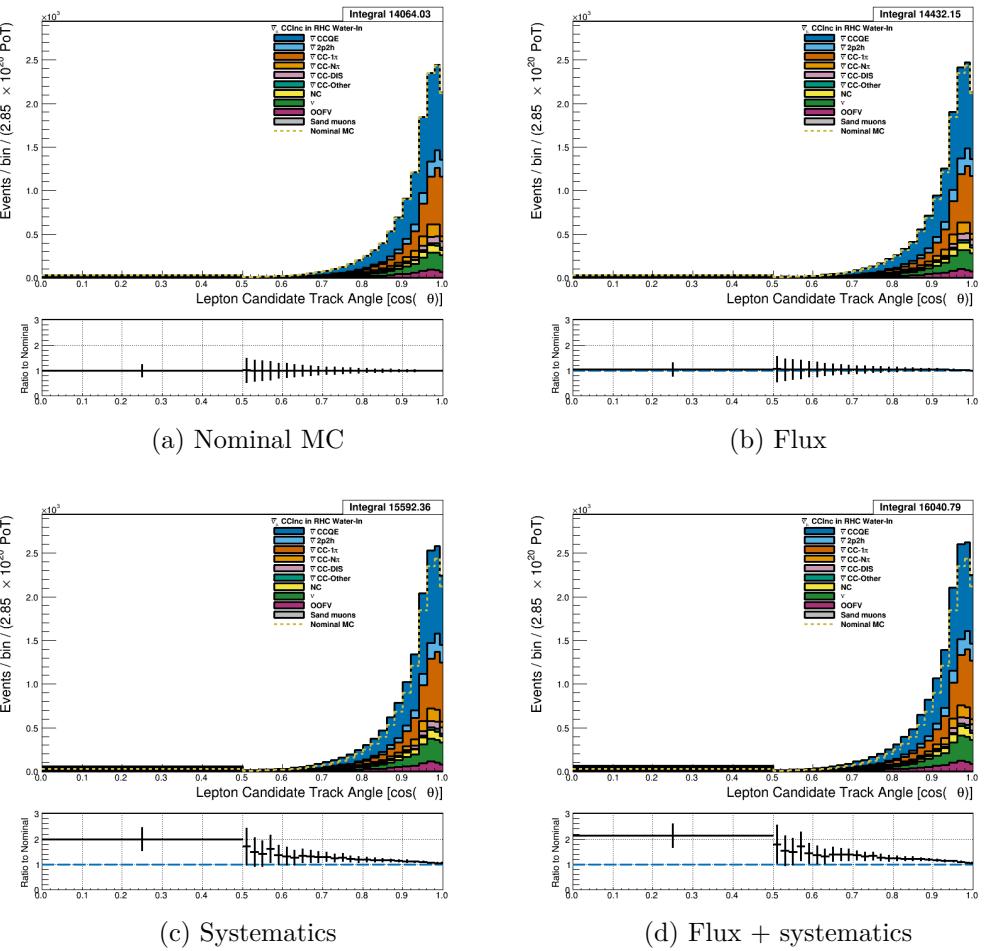


Figure 3.60: Reconstructed lepton candidate $\cos \theta$ separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

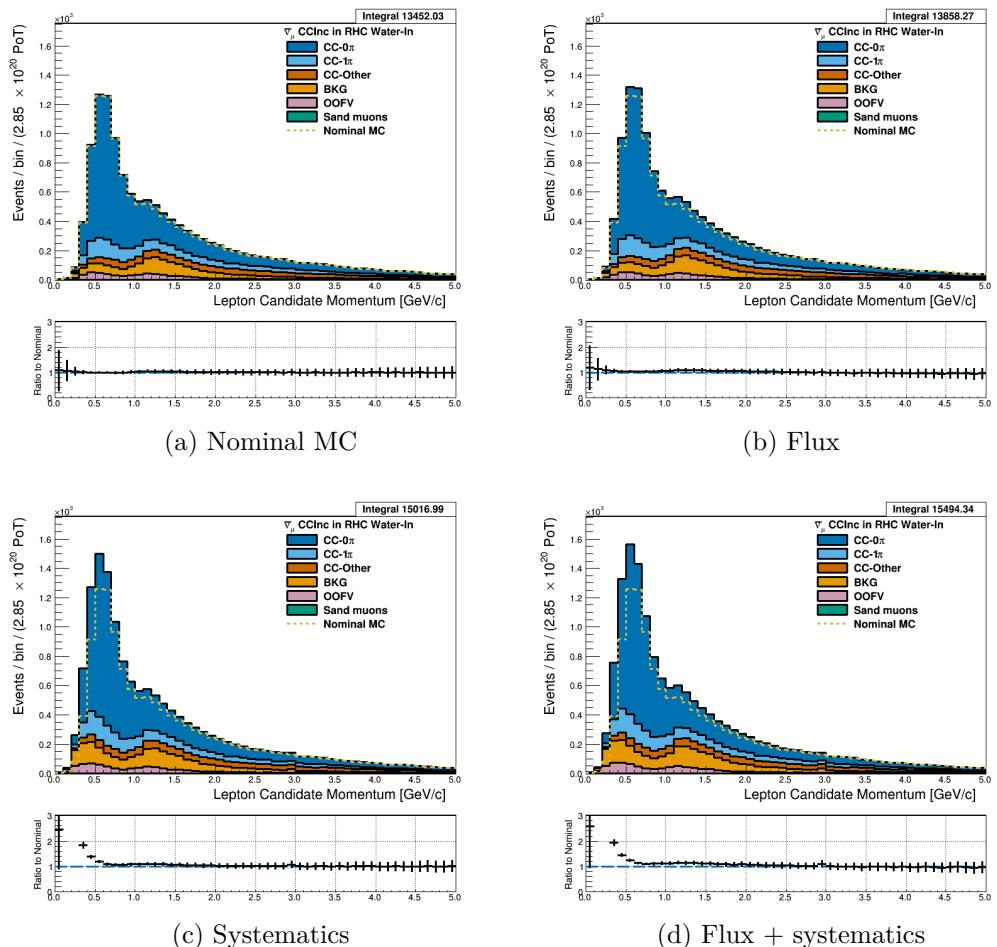


Figure 3.61: Reconstructed lepton candidate momentum separated by topology for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

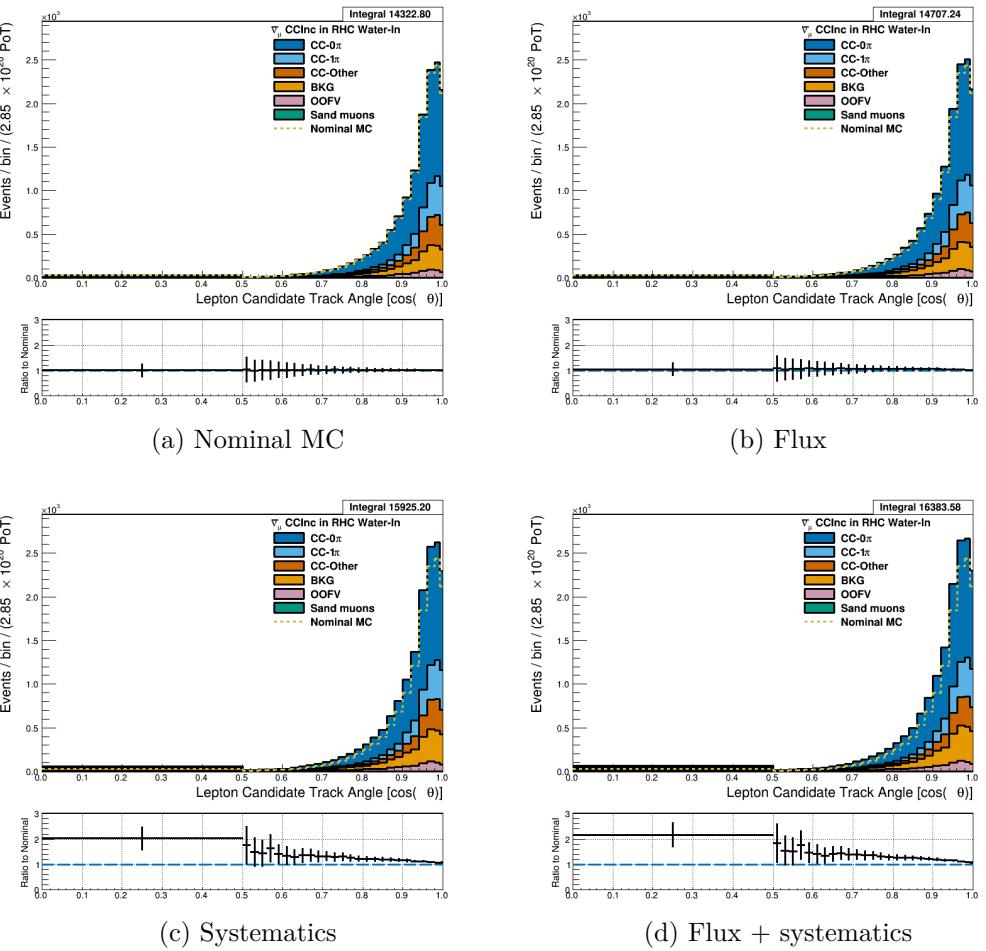


Figure 3.62: Reconstructed lepton candidate $\cos \theta$ separated by topology for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

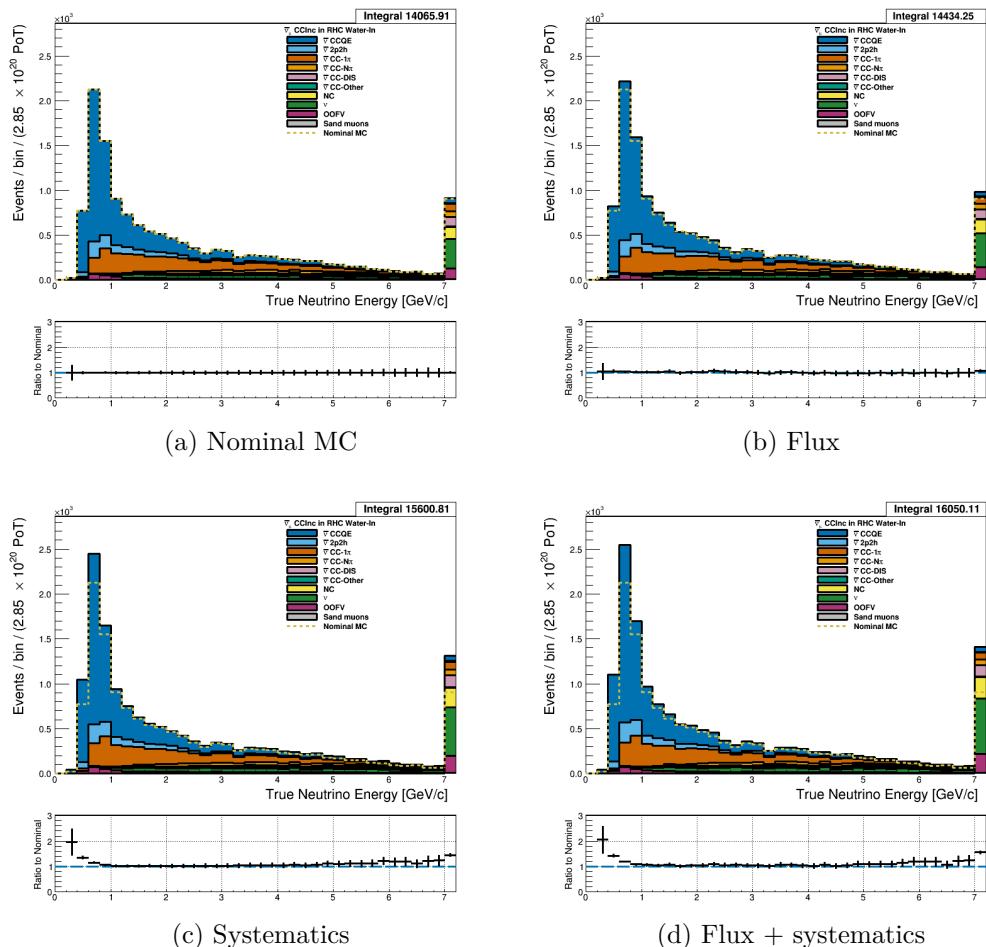


Figure 3.63: True neutrino energy associated with the lepton candidate separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

3.5.1.3 ν_μ Background Selection in RHC Mode: Add figures here

3.5.2 CC 1-Track (CCQE Enhanced)

Text

3.5.2.1 ν_μ Selection in FHC Mode: Text

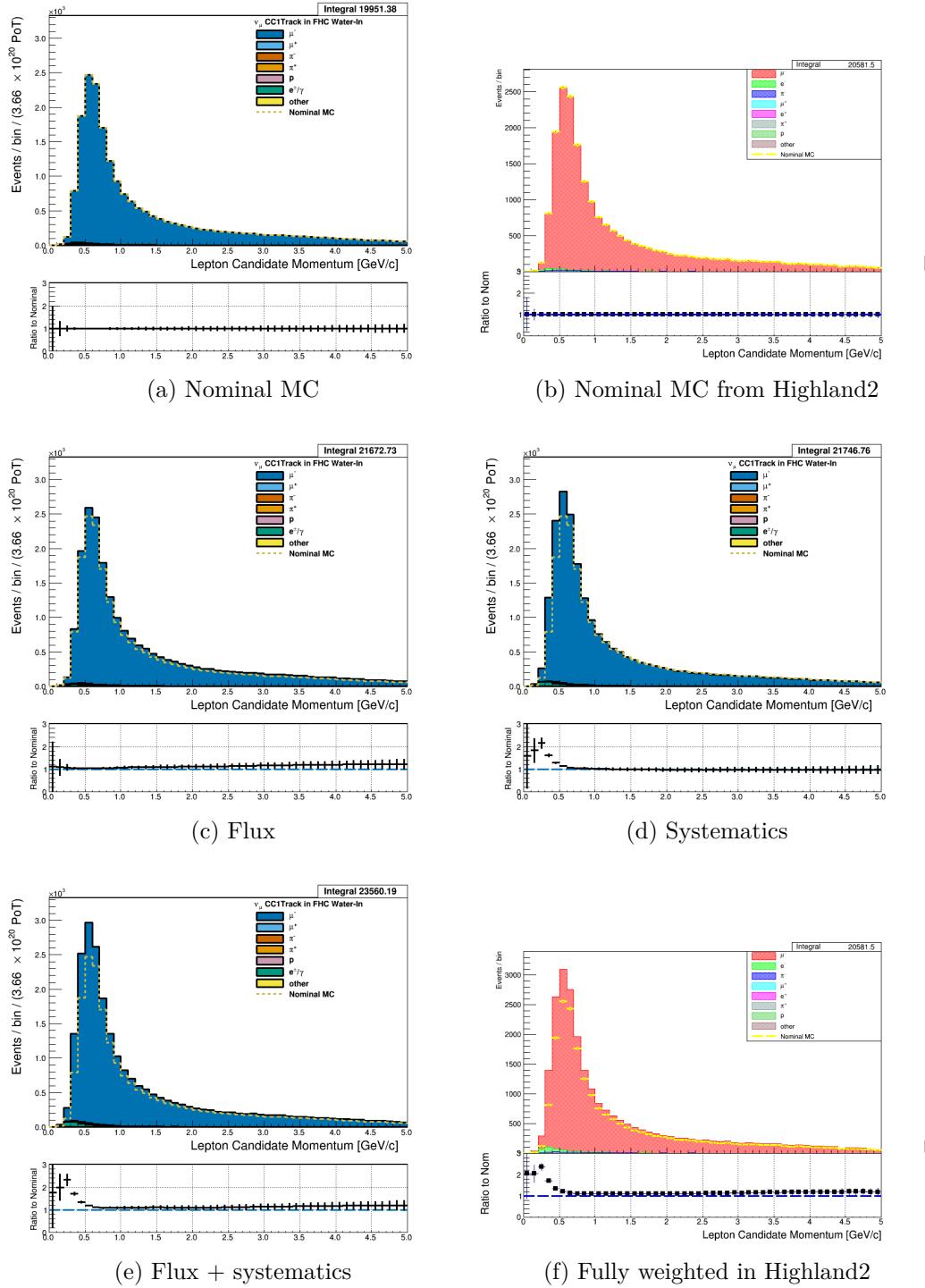


Figure 3.64: Reconstructed lepton candidate momentum separated by true particle species for FHC ν_μ CC 1-Track events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) Highland2 comparison for (a) without any weights applied using the “NOW” draw option. (c) The flux tuning is applied. (d) The systematic weighting is applied. (e) Both flux and systematic weighting is applied. (f) Highland2 comparison for (e).

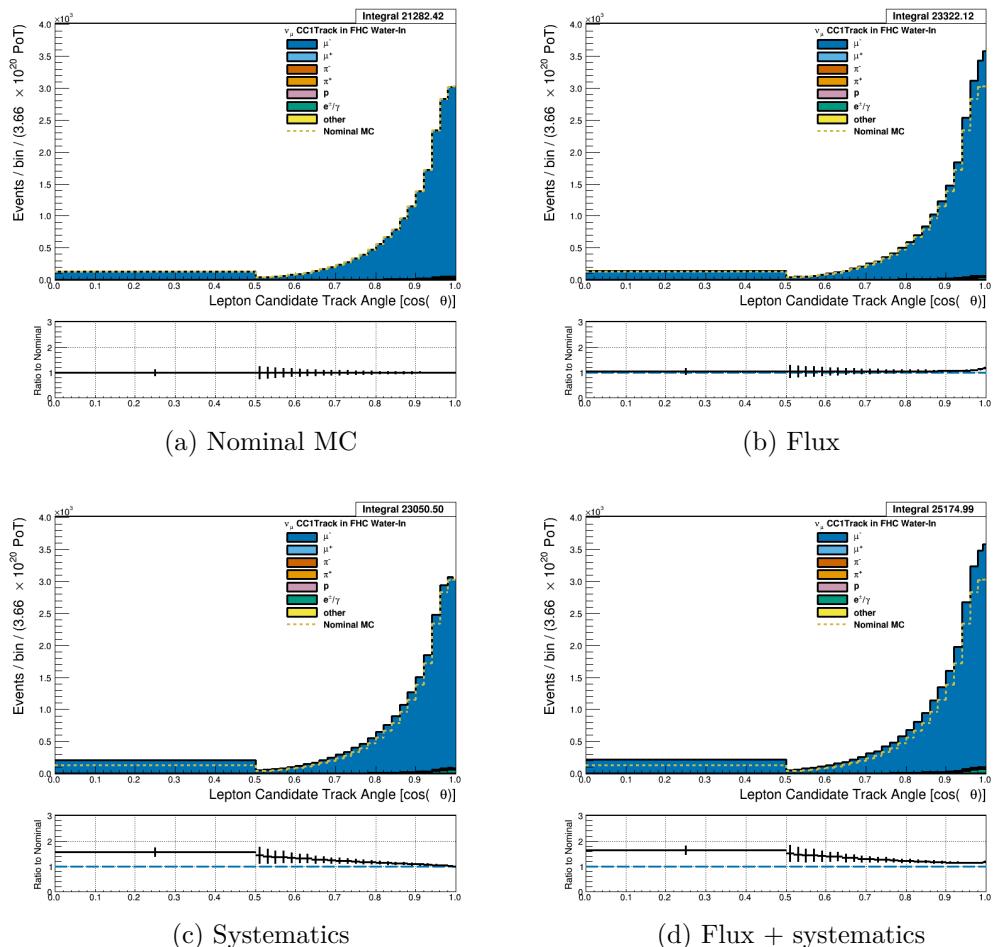


Figure 3.65: Reconstructed lepton candidate angle separated by true particle species for FHC ν_μ CC 1-Track events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

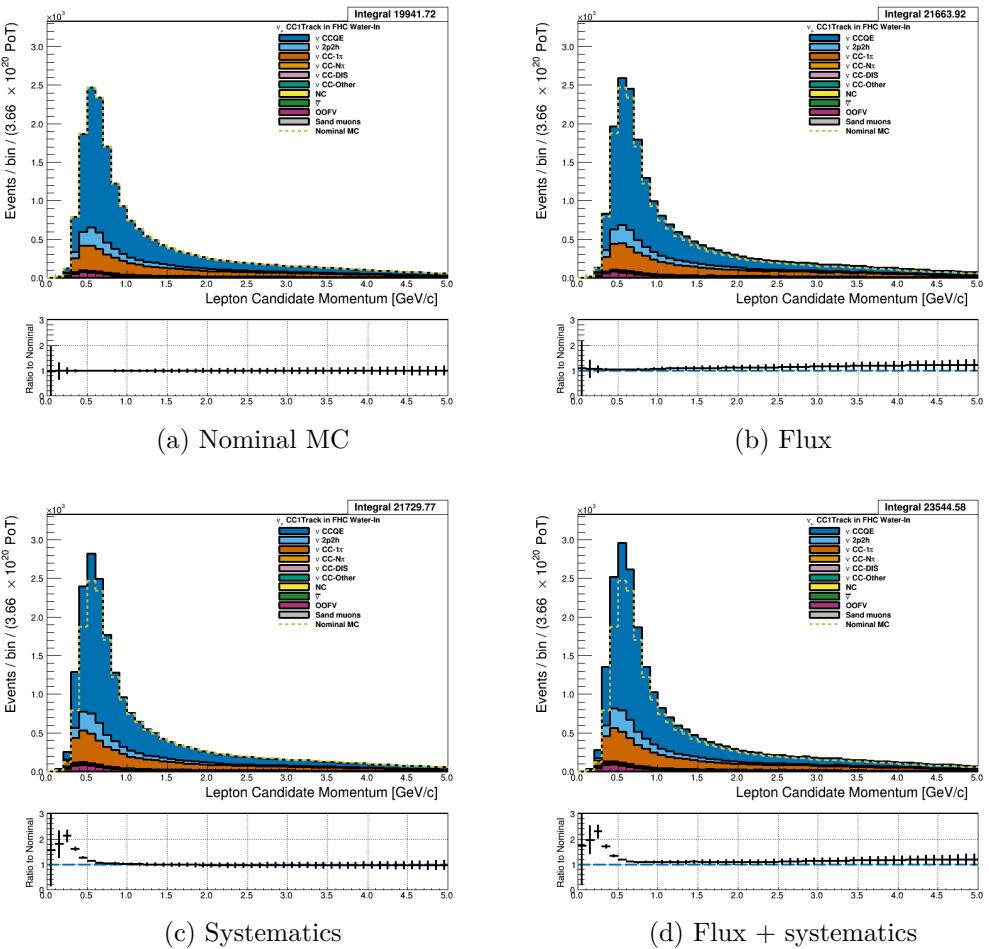


Figure 3.66: Reconstructed lepton candidate momentum separated by NEUT model interaction mode for FHC ν_μ CC 1-Track events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

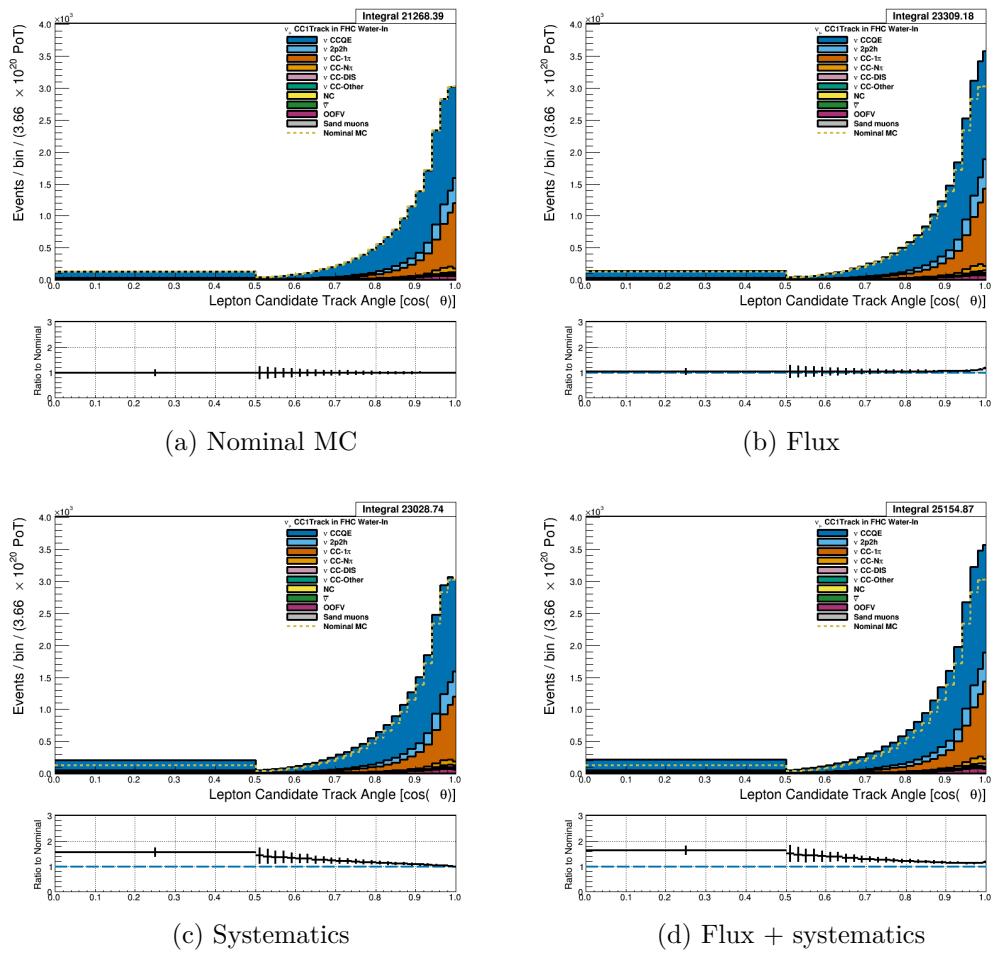


Figure 3.67: Reconstructed lepton candidate $\cos \theta$ separated by NEUT model interaction mode for FHC ν_μ CC 1-Track events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

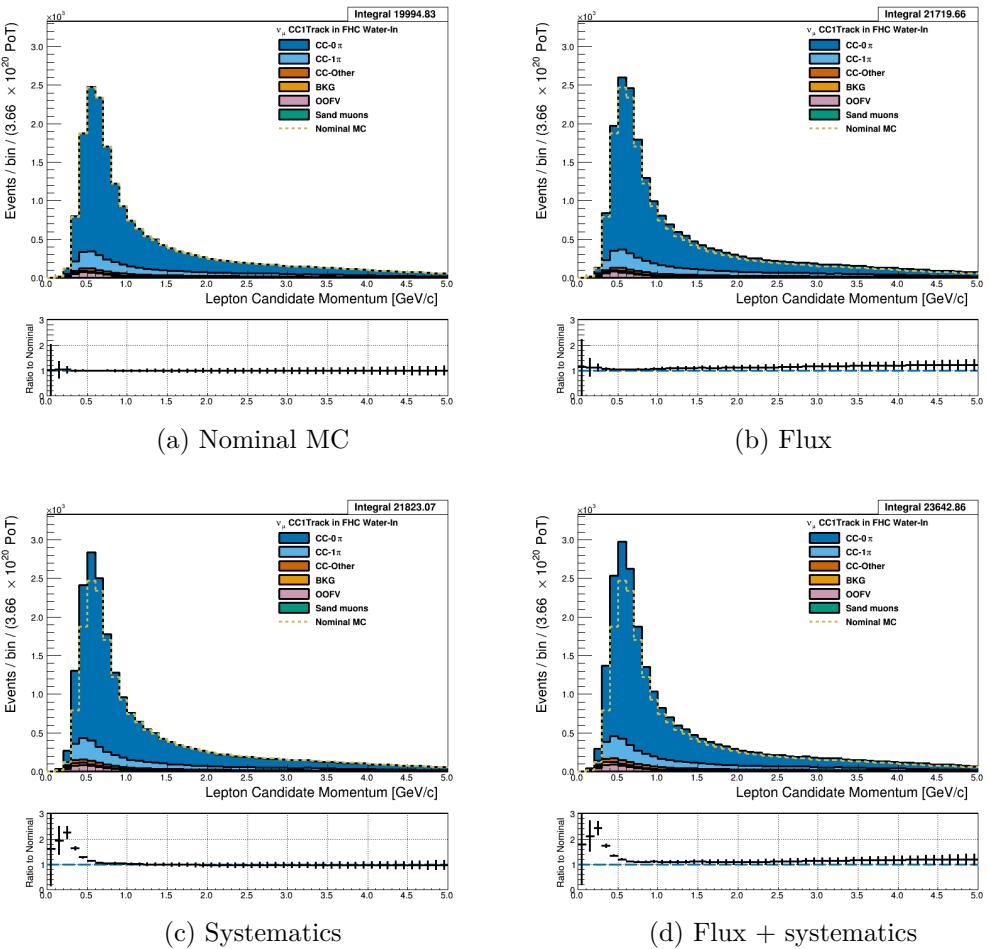


Figure 3.68: Reconstructed lepton candidate momentum separated by topology for FHC ν_μ CC 1-Track events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

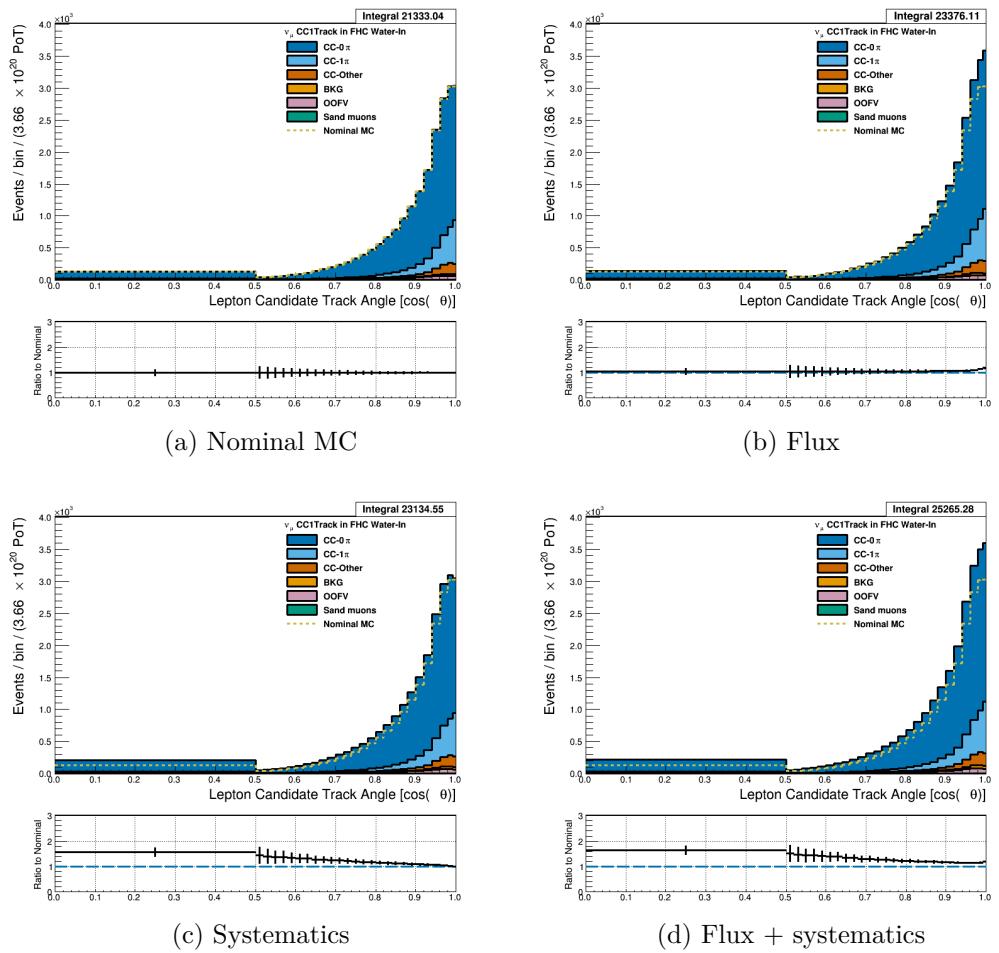


Figure 3.69: Reconstructed lepton candidate $\cos \theta$ separated by topology for FHC ν_μ CC 1-Track events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

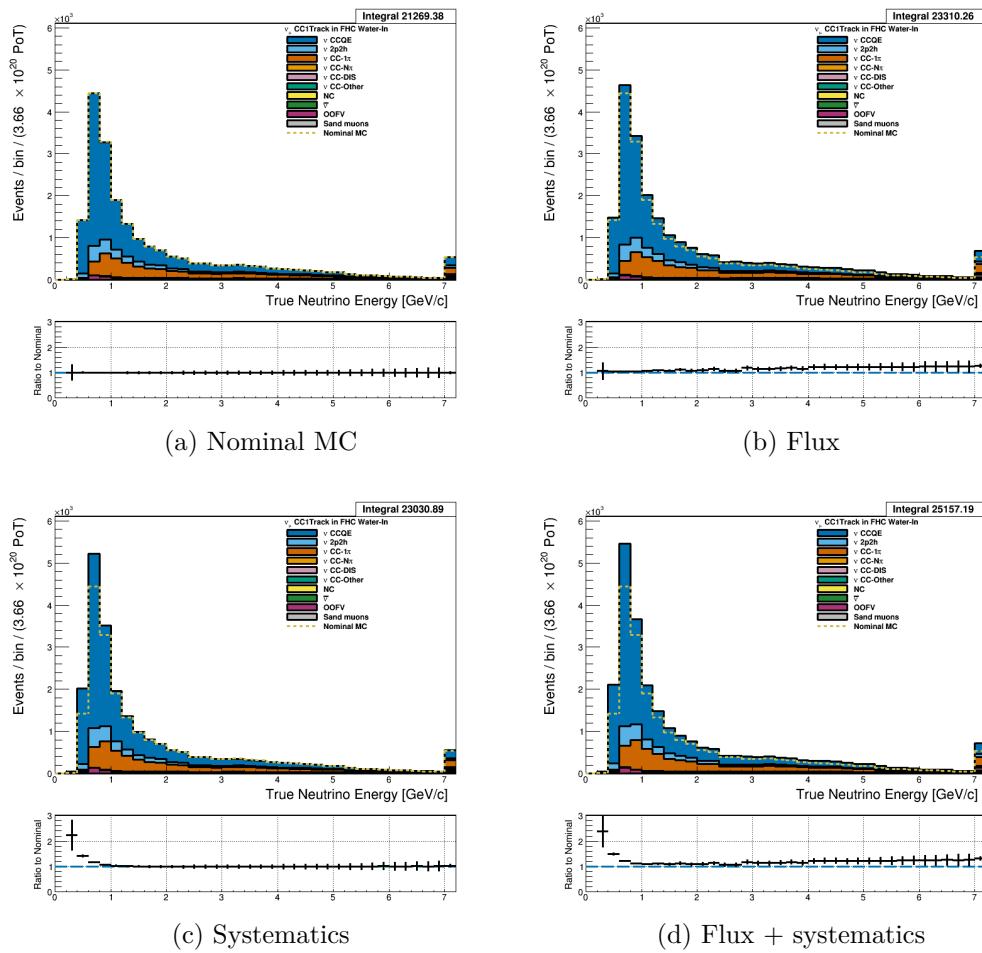


Figure 3.70: True neutrino energy associated with the lepton candidate separated by NEUT model interaction mode for FHC ν_μ CC 1-Track events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

522 3.5.2.2 $\bar{\nu}_\mu$ Selection in RHC Mode: Text

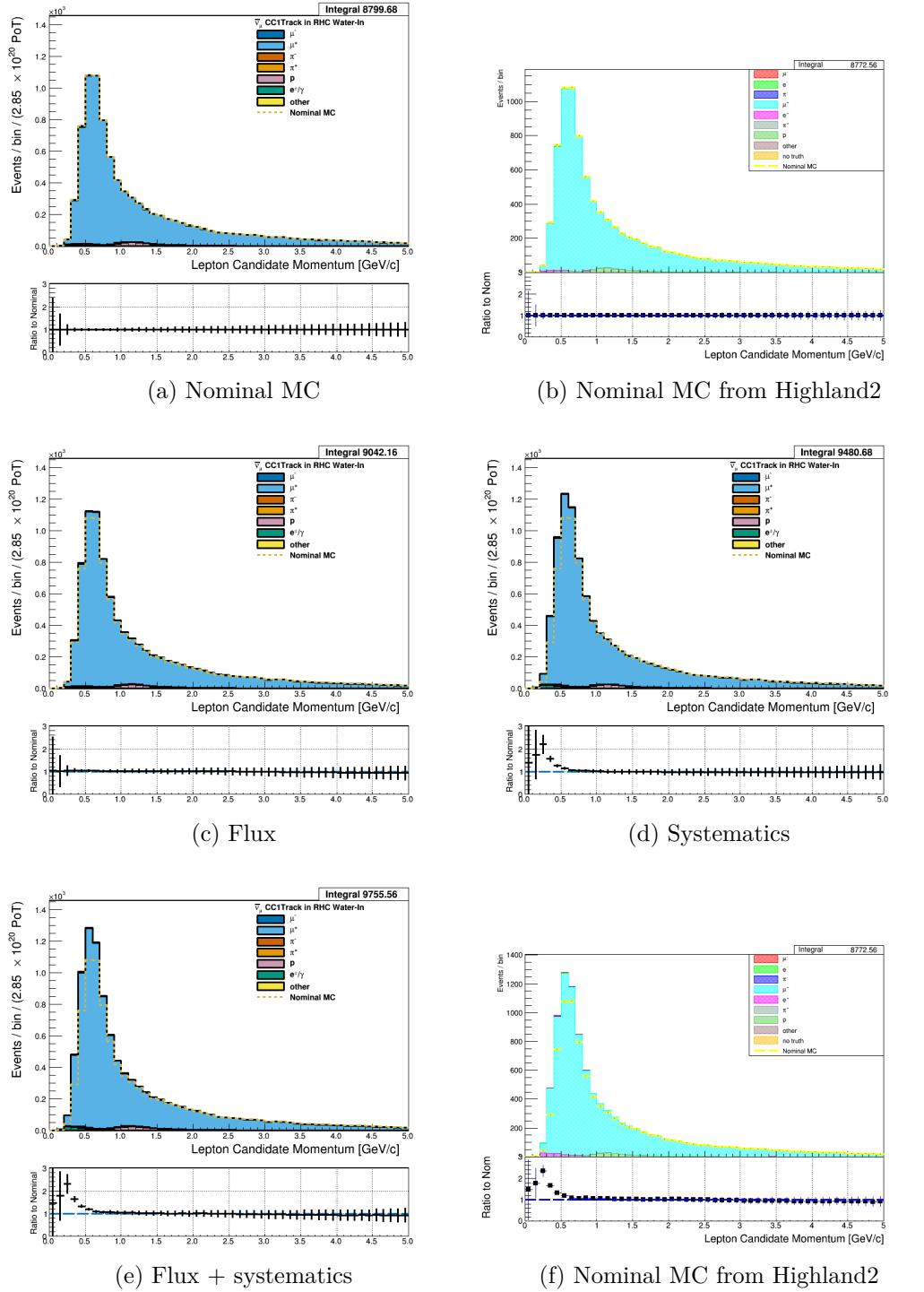


Figure 3.71: Reconstructed lepton candidate momentum separated by true particle species for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) Highland2 comparison for (a) without any weights applied using the “NOW” draw option. (c) The flux tuning is applied. (d) The systematic weighting is applied. (e) Both flux and systematic weighting is applied. (f) Highland2 comparison for (e).

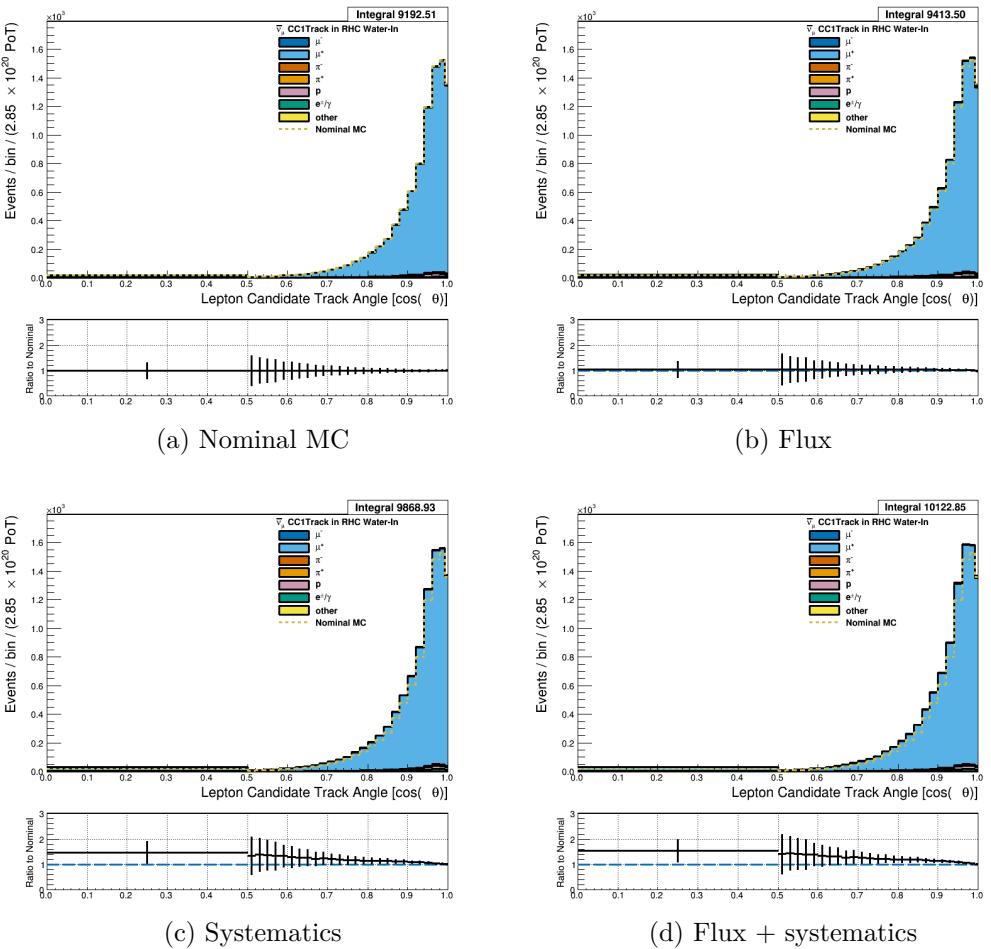


Figure 3.72: Reconstructed lepton candidate angle separated by true particle species for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

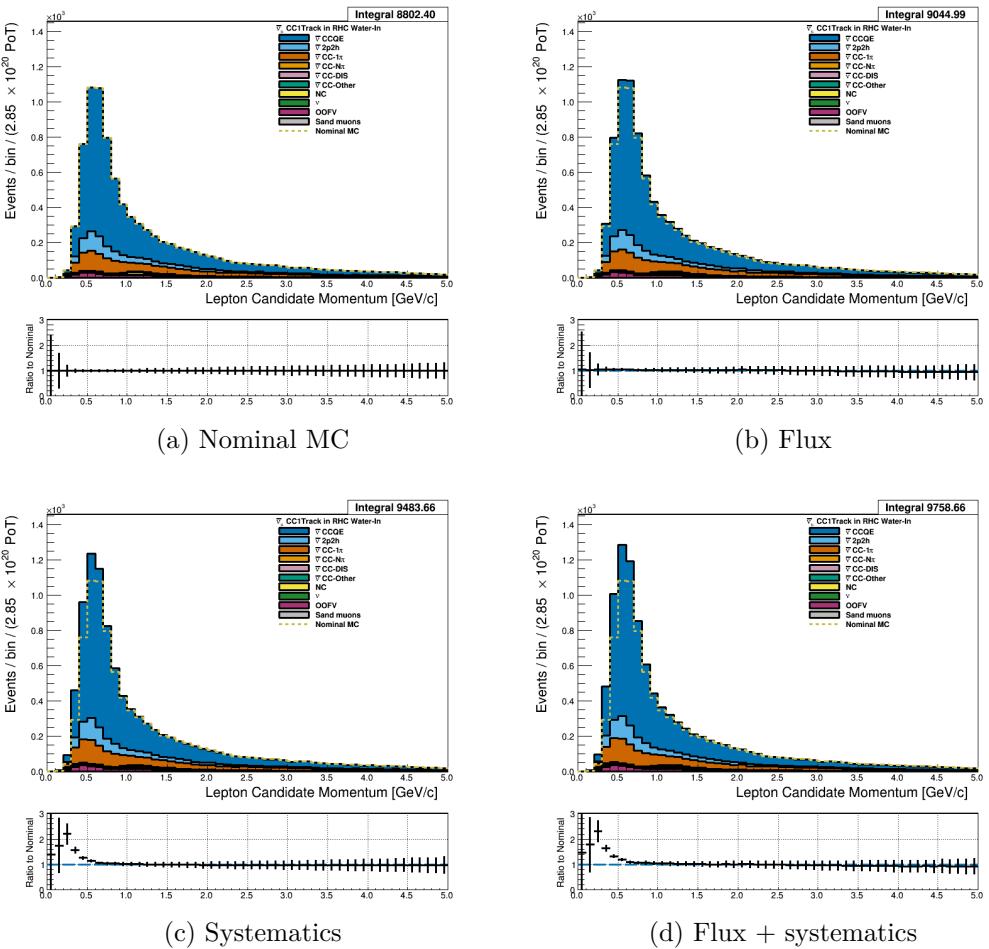


Figure 3.73: Reconstructed lepton candidate momentum separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

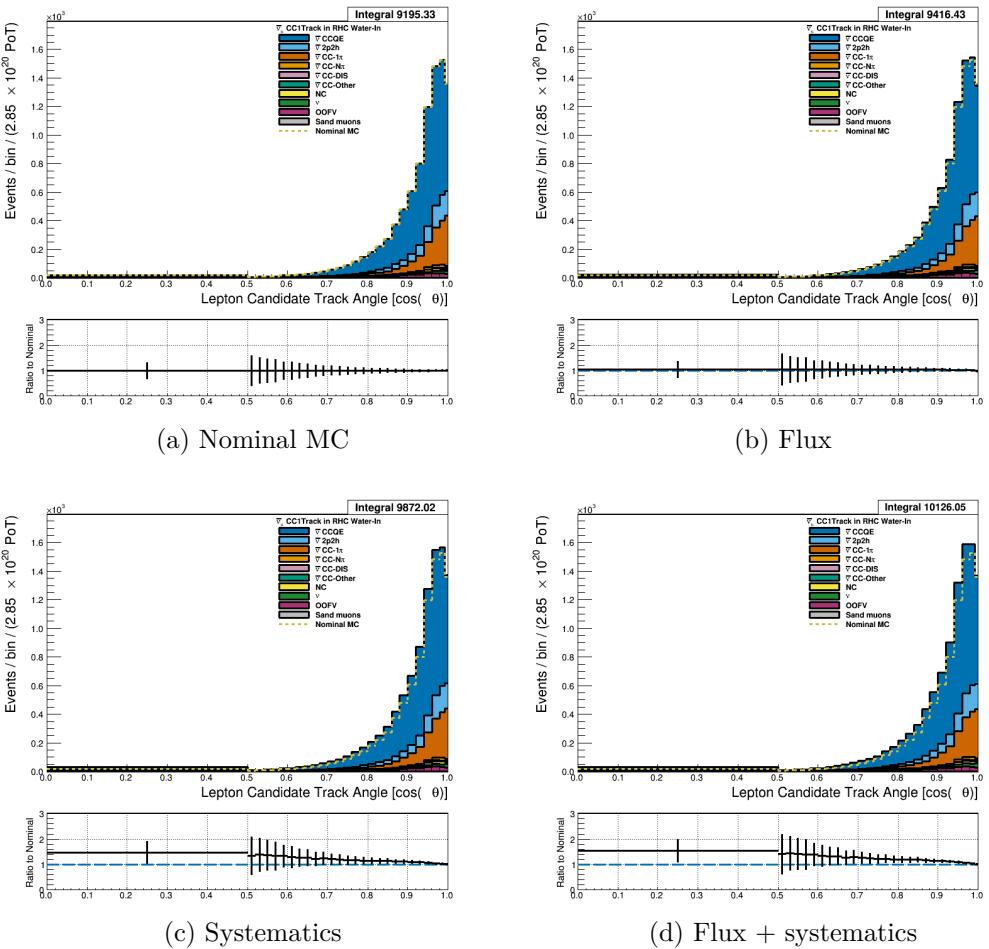


Figure 3.74: Reconstructed lepton candidate $\cos \theta$ separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

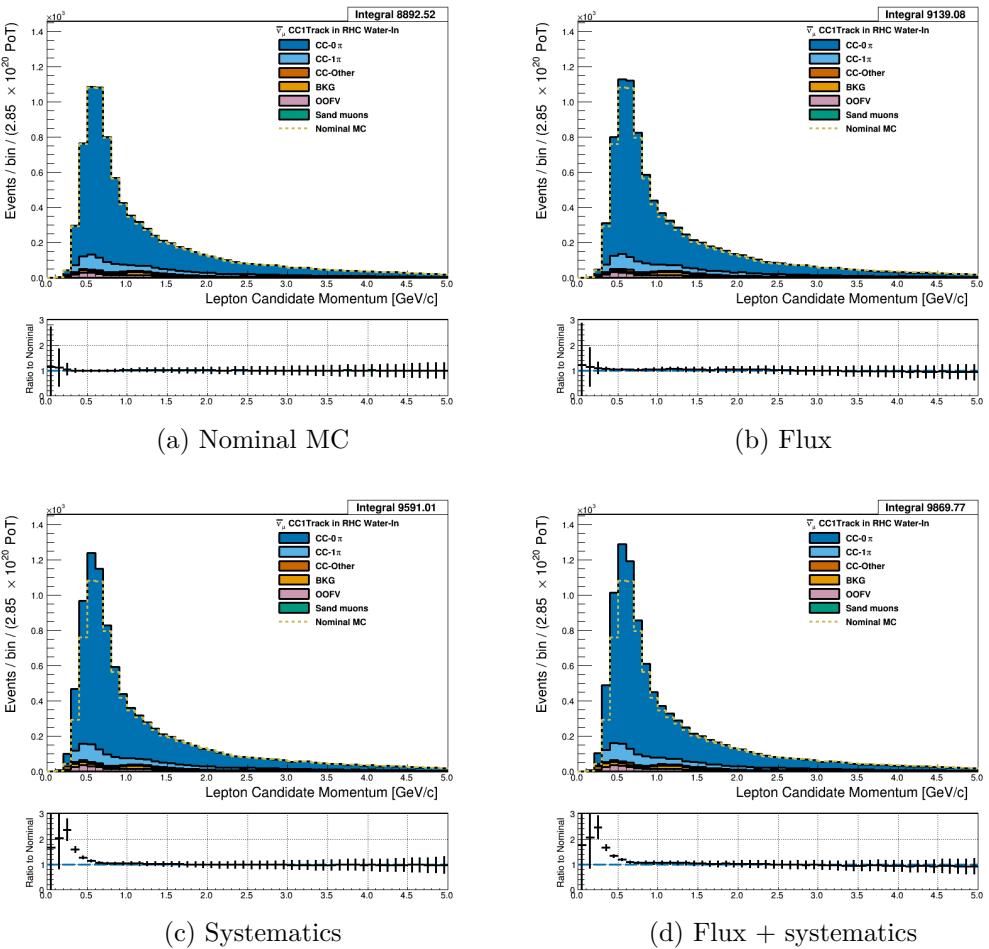


Figure 3.75: Reconstructed lepton candidate momentum separated by topology for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

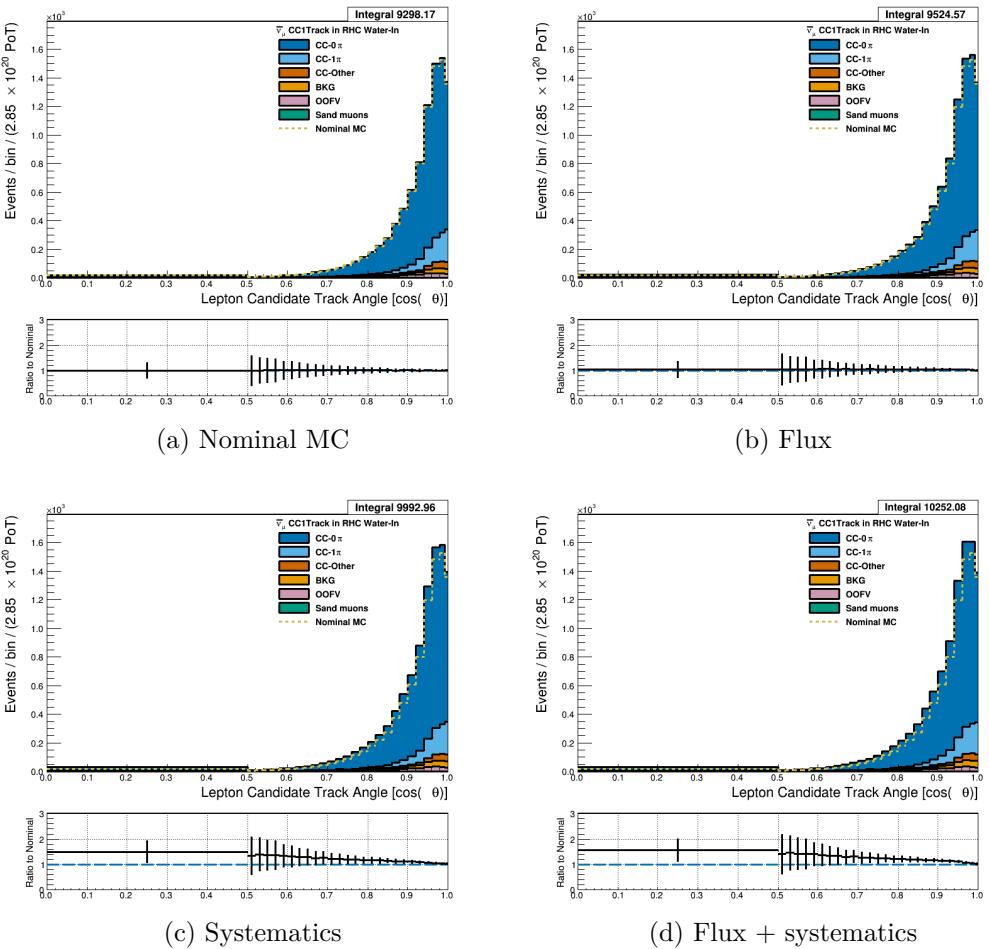


Figure 3.76: Reconstructed lepton candidate $\cos \theta$ separated by topology for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

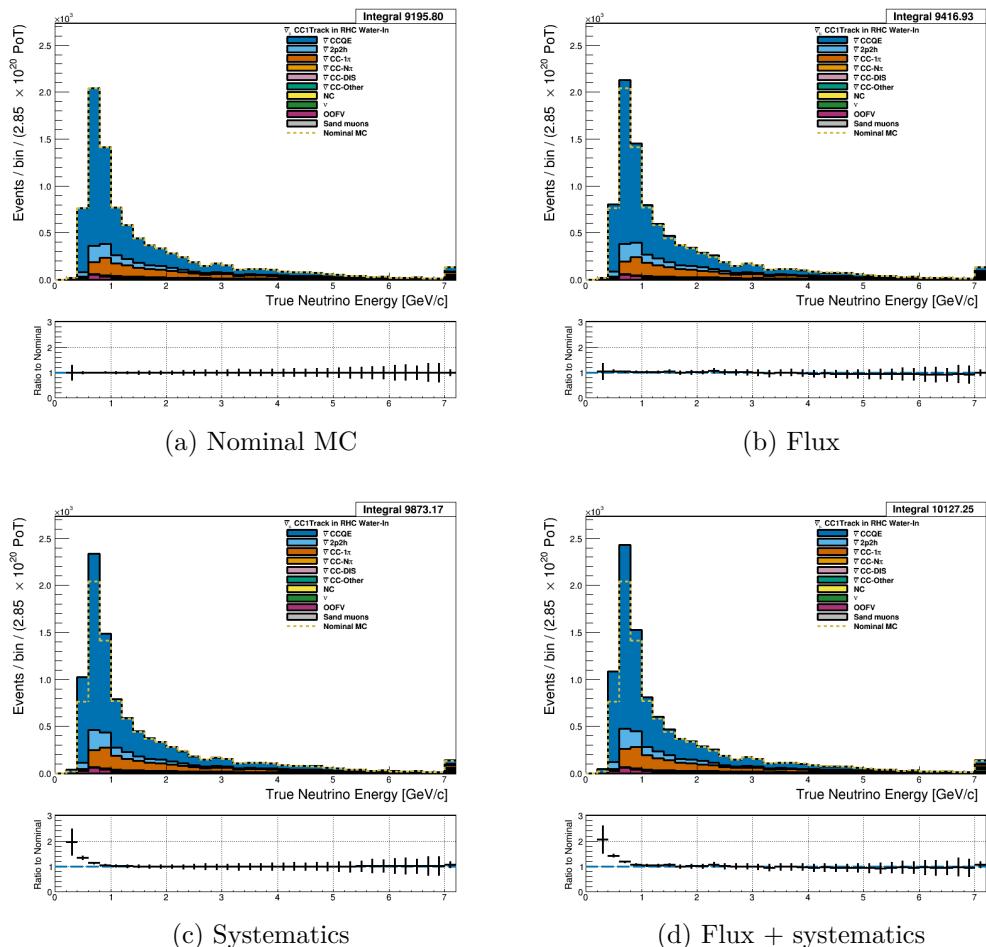


Figure 3.77: True neutrino energy associated with the lepton candidate separated by NEUT model interaction mode for RHC $\bar{\nu}_\mu$ CC Inc. events occurring in the PØD in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.

3.5.2.3 ν_μ Background Selection in RHC Mode: Text

3.5.3 CC N-Tracks (CCnQE Enhanced)

Text

3.5.3.1 ν_μ Selection in FHC Mode: Text

527 **3.5.3.2 $\bar{\nu}_\mu$ Selection in RHC Mode:** Text

528 **3.5.3.3 ν_μ Background Selection in RHC Mode:** Text

529 **3.5.4 Differences Between Water-Out and Water-In Samples**

530 **4 PØD-Only BANFF Parameterization**

531 PØD-only BANFF

532

5 Fitter Validation

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Fitter validation

534

6 Fitter Results

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Fitter results

536

7 Discussion

537

Discussion

538

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572 **Nomenclature**

- 573 BANFF The **beam and near detector task force** is the group responsible for providing near
574 detector constraints on cross section and flux model parameters.
- 575 CC- 0π A **charged current zero pion selection** is an exclusive selection that selects neutrino
576 interaction topologies only one MIP-like particle.
- 577 CC-Inclusive A **charged current event selection** that selects all neutrino interaction topolo-
578 gies with an outgoing charged lepton.
- 579 FD The **far detector** refers to the particle detector in a long baseline neutrino oscilla-
580 tion experiment that is located far away from the neutrino production source where
581 oscillated neutrinos are observed.
- 582 FGD A **fine grain detector** is a detector made of closely spaced, small scintillating bars
583 designed to provide precise resolution of charged particle tracks
- 584 FHC The **forward horn current beam configuration** that focuses positively charged particles
585 into the particle decay pipe. This configuration produces a very pure ν_μ neutrino beam
- 586 HMNT The **highest momentum negatively-charged track** in the bunch
- 587 HMPT The **highest momentum positively-charged track** in the bunch
- 588 MIP A **minimum ionizing particle**
- 589 ND280 The **Near Detector** of T2K which is **280** meters away from the neutrino source.
- 590 ND The **near detector** refers to the particle detector in a long baseline neutrino oscillation
591 experiment that is located close to the neutrino production source before neutrino
592 oscillations occur.

593 CECal The **Central ECal** detector which is a part of the PØD inside ND280

594 PØD The π^0 detector (**pi-Q** detector)

595 PØDule A collection of two active scintillator bar layers inside the PØD

596 RHC The **reverse horn current** beam configuration that focuses negatively charged particles
597 into the particle decay pipe. This configuration produces a $\bar{\nu}_\mu$ enriched neutrino beam
598 with a significant ν_μ contribution.

599 FV The **fiducial volume** of a detector is the region where the detector response is well
600 understood

601 TPC A **time projection chamber** is a device that detects and tracks charged particles with
602 the application of strong electric fields

603 Tracker The region of ND280 consisting of two FGDs and TPCs

604 Global The **Global reconstruction module** responsible for making joined tracks between the
605 subdetectors inside ND280

606 USECal The **Upstream ECal** which is a part of the PØD inside ND280