This section describes the development of and CC-Inclusive selections in both FHC and RHC beam configuration for ()-based analyses. These selections are the continuation of previous works that developed CC-Inclusive selections between the () and TPC1. The first such analyses were T2K-TN-80 and T2K-TN-100 which described the CC-Inclusive event selection and, later, cross-section analysis using ND280 Production 5 software, respectively[?, ?]. These analyzes relied on each sub-detector's reconstruction software and developed a track matching algorithm since the ND280 "Global" reconstruction matching was problematic in Production 5. As the inter-detector matching reconstruction improved in "Global", two cross section analyzes, T2K-TN-258 and T2K-TN-328, were developed that also used the CC-Inclusive selection as pre-selection cuts[?, ?]. The selections described in this technical note also employ the same pre-selection cuts. What follows from here in this section is a layout of the following topic discussions.

The first topic discussed in this section is a description of the Detector (()). The next topic is the event reconstruction using the "Global" reconstruction software. Following that is the pre-selection cut flow. With the pre-selection cuts established, each of the three CC-Inclusive selection's cut flow is described. Concluding this section is a discussion of the three samples in the following order: in FHC mode, in RHC, and in RHC.

0.1 The ()

The (), short for Detector, is a plastic scintillator based tracking calorimeter inside the ND280 basket. The () is constructed as many sandwiches of active and inactive materials designed to fully contain decay photons. The four primary regions inside the () in order of upstream to downstream of the neutrino beam are the upstream ECal (USECal), upstream water target (WT), central WT, and central ECal (CECal). A representation of the entire () can be seen in Figure 1. Each active module, also called a ()ule, consists of two orthogonally oriented sheets of triangular, scintillator-doped plastic bars as shown in Figure 2. The ECal regions are designed to contain decay photons inside the () by alternating the scintillator planes with lead sheets. The WT regions, as compared to the lead sheets in the ECals, alternate a thin brass sheet and water filled bags between the ()ules. A unique feature of the () is that the water can be drained out resulting in two detector configurations: water-in and water-out.

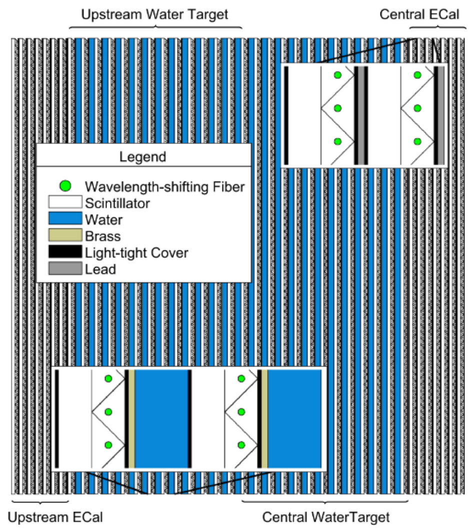


Figure 1: This cartoon illustrates the concept design of the () where the neutrino beam is approaching from the left.

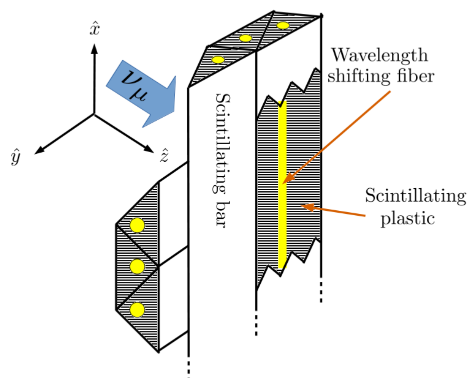


Figure 2: This cartoon illustrates the design of a ()ule with orthogonal layers of scintillating, triangular bars. When a charged particle travels through the bar such as a muon from CC interaction, the scintillation light is captured and wavelength shifted inside a fiber bored in the center of each bar. The wavelength shifted light is later observed by a photon counter.

0.2 Global Reconstruction

The task of the Global reconstruction is to combine ND280 sub-detector reconstruction into an single reconstructed object. It was originally designed to analyze "CCQE-like" events in the Tracker region and has been extended with

Run Period	Horn Current	() 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	79.18
2, 4, 8		Water	3.657	73.47
6b, 6c, 6d, 6e	RHC	Air	3.417	34.92
5c, 7b		Water	2.871	56.48

Table 1: T2K MC and data POT divided by run periods. The bottom four rows are the aggregrated periods grouped by horn current and () status which is how the data analysis is performed.

all of ND280. Global attempts to match and re-fit individual sub-detector objects using a Kalman filter while correcting for energy loss and multiscattering. A vertex associated with the re-fit object is also extracted using a different Kalman filter. A detailed description of the track matching and vertex finding algorithms for Global is described in T2K-TN-46[**?**].

0.3 Data Sets

The data sets used in this analysis are runs 2-8 in both () water-in and water-out (air) modes as shown in Table 1.

0.4 () Selection Cuts

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

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

0.4.1 Pre-Selection Cuts

The pre-selection ("precuts") were initially developed to select CC-Inclusive using the () and TPC sub-detector reconstruction softwares separately[**?**]. They were then used with the Global reconstruction software for the selection in the FHC beam configuration as described in technical note T2K-TN-258[**?**]. The description and flow of the precuts are described here as well since there is an incomplete description of the selection precuts.

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

1. The event has a "good" data quality flag.
   - An event is rejected if any sub-detector or electronics in ND280 reported as "bad" during that bunch.
2. There is at least one (1) track reconstructed in TPC1.
   - There are no restrictions on the number of tracks fully contained in the () or exiting into other sub-detectors.
3. The track in TPC1 must have more than 18 nodes.
   - The TPC reconstruction gathers vertical and horizontal hits into clusters of hits. The charge distribution of the cluster is used to get a vertical (horizontal) position that is more accurate than the individual readout pads. A node is constructed out of each cluster with associated track state information. The set of nodes are used to fit the track helix[**?**].
4. The reconstructed vertex is within the () WT FV.
   - The () FV is defined to include as much as the WT regions as possible. Its X and Y borders are 25 cm away from the ()ule edges while its Z borders intersect the last and first half downstream ()ule in the USECal and CECal, respectively. The enumerated volume edges are shown in table 2. This volume, while used for track-based analyzes in the past, was optimized for and analyzes[**?**].
5. All tracks that enter TPC1 pass the veto cut
   - An event is rejected if any () track enters TPC1 from outside the "corridor" volume. This cut was designed to eliminate broken tracks between the () and TPC1 when the separate sub-detector reconstructions were used[**?**]. In practice, this cut ensures that Global

tracks entering TPC1 away from its X and Y edges. The corridor definition is the same as defined in T2K-TN-208 and shown in Table 2.

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

Table 2: The () WT FV (left) and veto corridor volume (right) in the ND280 coordinate system. The corridor spans from the 5th (8th) to 40th (80th) ()ule (scintillator layer). All the units are given in millimeters.

After passing all the precuts, a single, global track, which is observed in TPC1, is assigned as the "main track" of a selection. The main track for selections is the highest momentum, negatively-charged track (HMNT). Similarly the highest momentum, positively-charged track (HMPT) is assigned the main track for selections.

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

0.4.2 CC-Inclusive in FHC

As discussed in Section 0.4.1 on the preceding page, this selection is the basis for the analysis. This is FHC mode selection and so the lack of a negatively charged track is the final cut for the CC-Inclusive selection.

0.4.3 CC-Inclusive in RHC

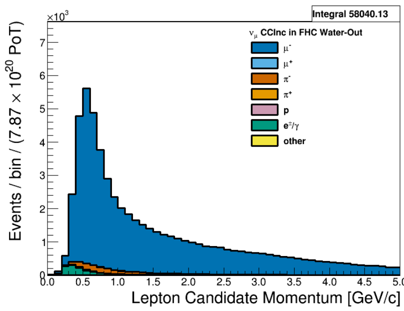
0.5 () Water-Out Samples

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

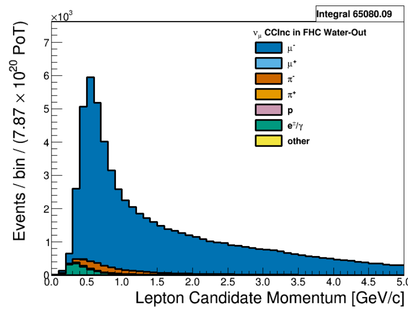
0.5.1 CC-Inclusive

The CC-Inclusive sample cuts are discussed 0.4.1. Since both flux and systematic weights are applied to all MC events in BANFF, it is important to validate the event weights.

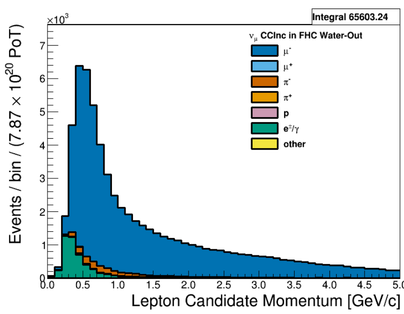
$\boldsymbol{\nu_\mu}$ **FHC**:fig:P0DairFHCnumuCCIncMomTrueParticle,fig:P0DairFHCnumuCCIncAngleTrueParticle,fig:P0 show the momentum and $\cos\theta$ distributions before and after applying different weights.



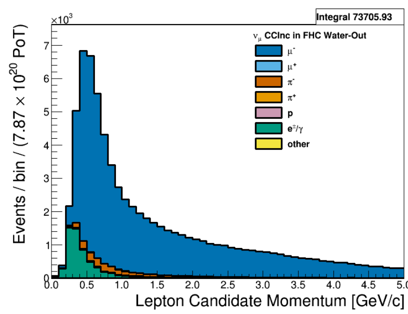
(a) Nominal MC



(b) Flux

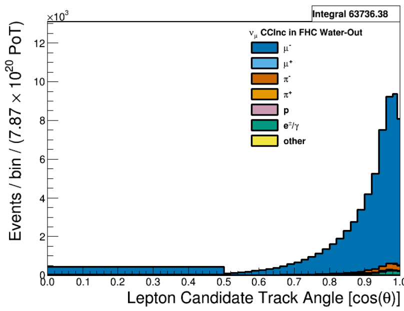


(c) Systematics

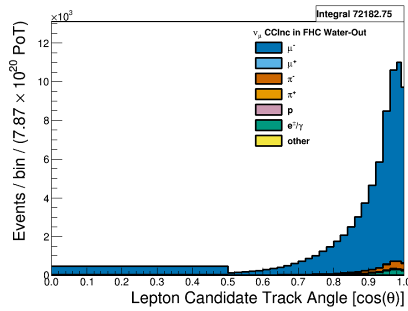


(d) Flux + systematics

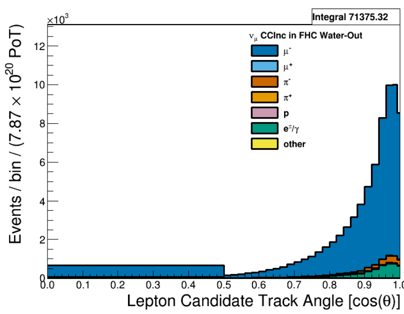
Figure 3: Reconstructed lepton candidate momentum separated by true particle species for FHC CC-Inc. events occurring in the () in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.



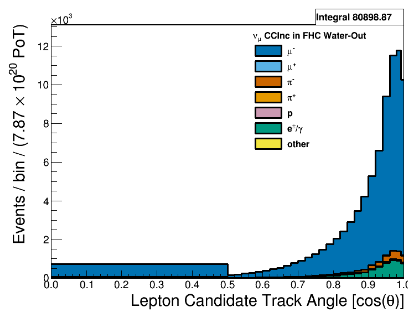
(a) Nominal MC



(b) Flux

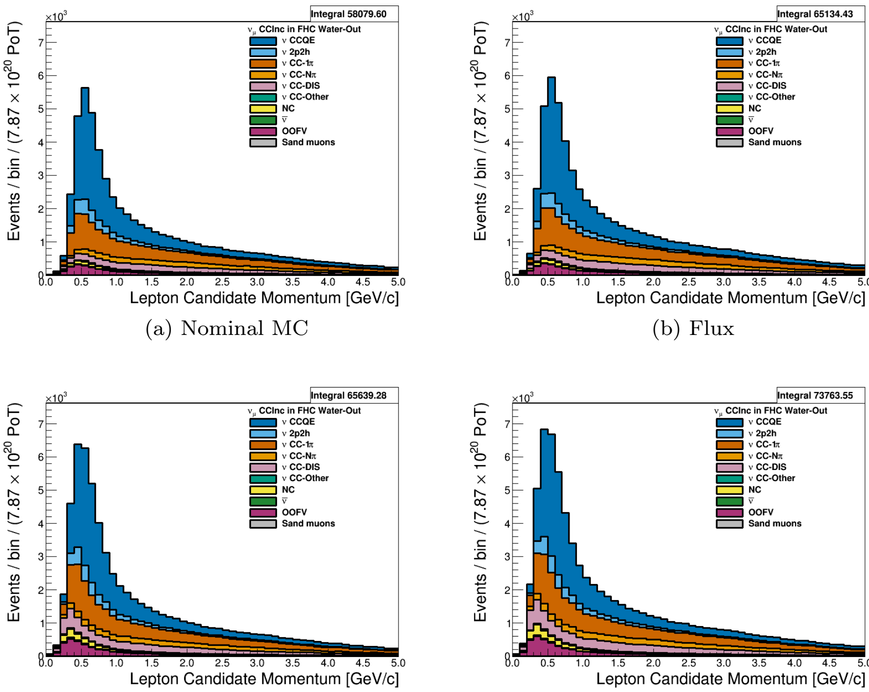


(c) Systematics



(d) Flux + systematics

Figure 4: Reconstructed lepton candidate angle separated by true particle species for FHC CC-Inc. events occurring in the () 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.



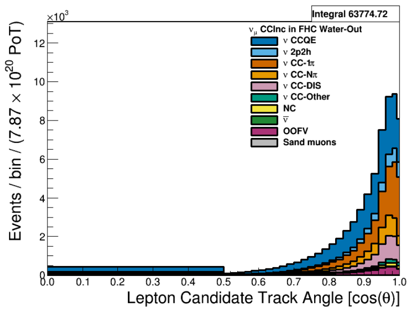
(a) Nominal MC

(b) Flux

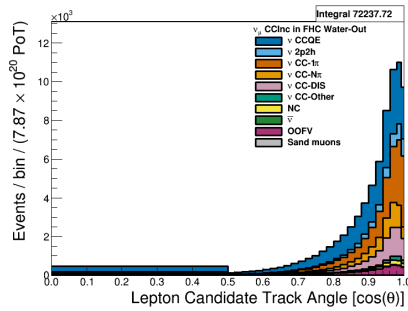
(c) Systematics

(d) Flux + systematics

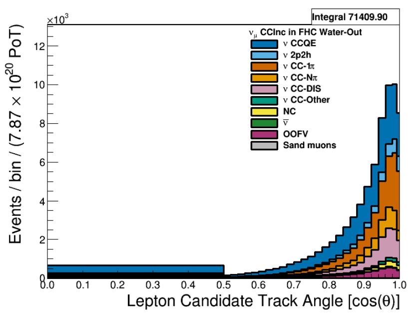
Figure 5: Reconstructed lepton candidate momentum separated by NEUT model interaction mode for FHC CC-Inc. events occurring in the () in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.



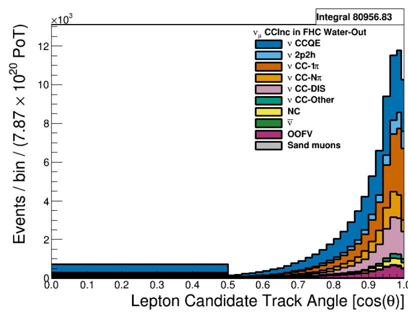
(a) Nominal MC



(b) Flux

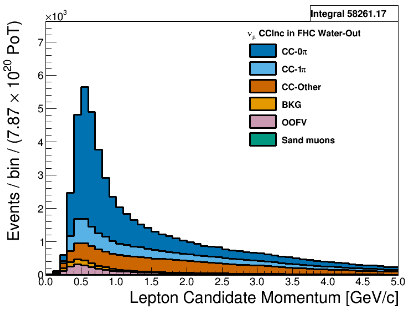


(c) Systematics

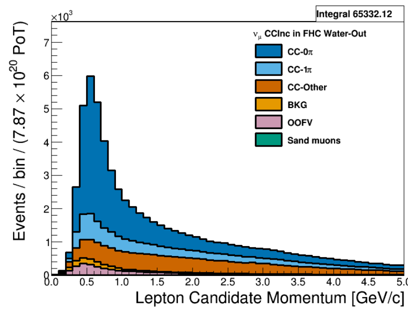


(d) Flux + systematics

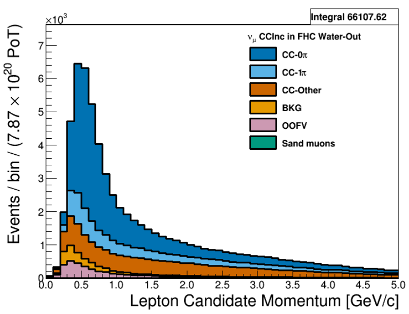
Figure 6: Reconstructed lepton candidate $\cos\theta$ separated by NEUT model interaction mode for FHC CC-Inc. events occurring in the () in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.



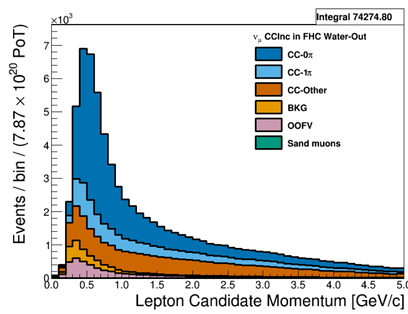
(a) Nominal MC



(b) Flux

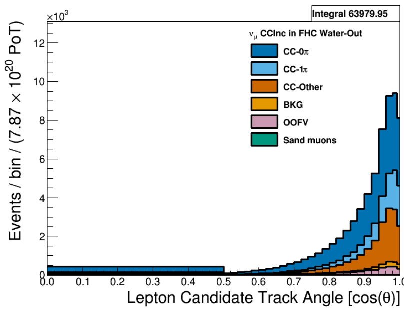


(c) Systematics

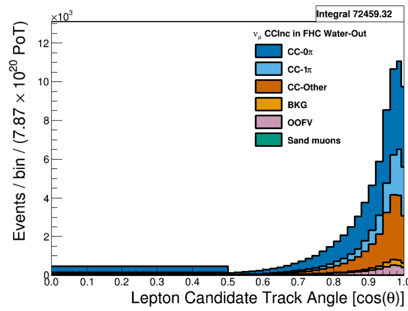


(d) Flux + systematics

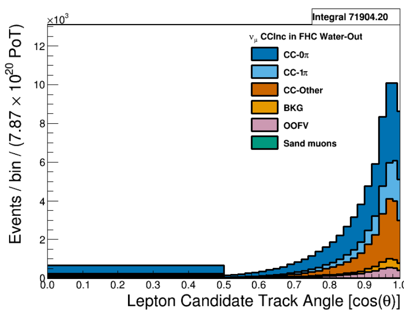
Figure 7: Reconstructed lepton candidate momentum separated by topology for FHC CC-Inc. events occurring in the () in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.



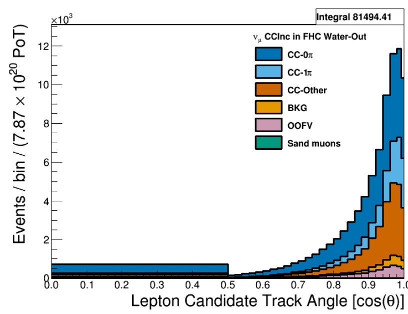
(a) Nominal MC



(b) Flux

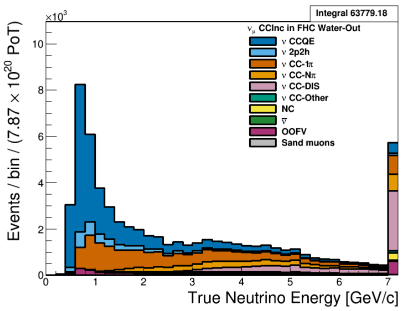


(c) Systematics

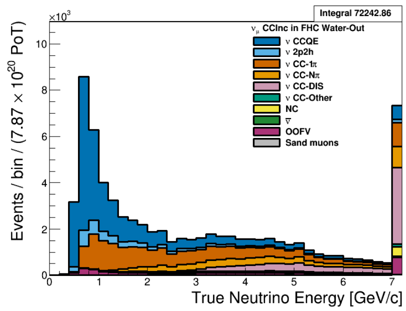


(d) Flux + systematics

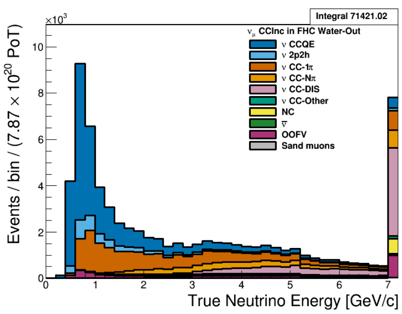
Figure 8: Reconstructed lepton candidate $\cos\theta$ separated by topology for FHC CC-Inc. events occurring in the () in water-out mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.



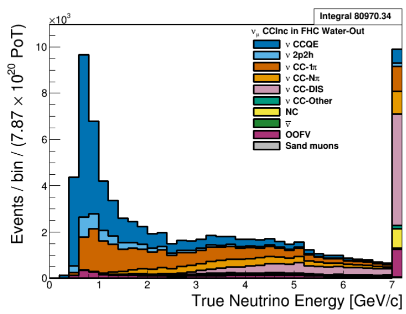
(a) Nominal MC



(b) Flux



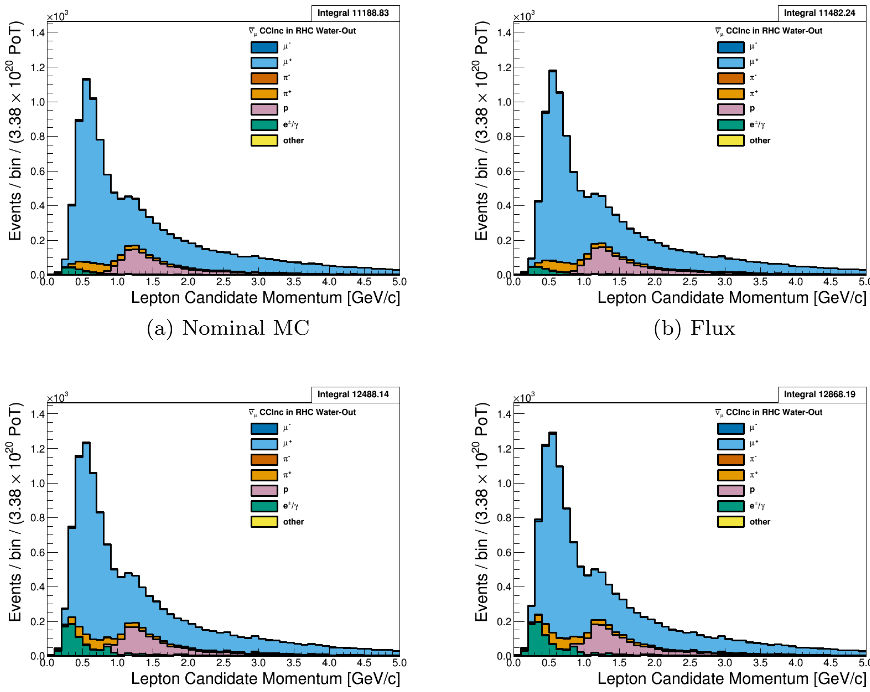
(c) Systematics



(d) Flux + systematics

Figure 9: True neutrino energy associated with the lepton candidate separated by NEUT model interaction mode for FHC CC-Inc. events occurring in the () 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.

RHC:
LOOK FOR ME TOP AIR



(a) Nominal MC

(b) Flux

(c) Systematics

(d) Flux + systematics

Figure 10: Reconstructed lepton candidate momentum separated by true particle species for RHC CC-Inc. events occurring in the () 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.

LOOK FOR ME BOTTOM AIR
RHC:

0.5.2 CC-1 Track (CCQE Enhanced)

0.5.3 CC-N Tracks (CCnQE Enhanced)

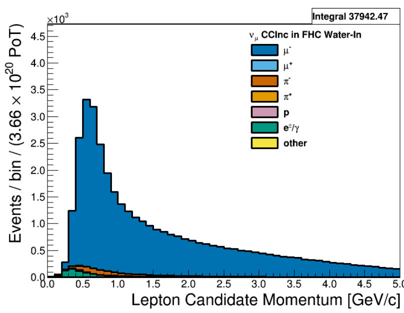
0.6 () Water-In Samples

This section shows the kinematic distributions for the () water-in samples. These samples will demonstrate the similarities between it and water-out modes. First an examination of the CC-Inclusive samples and the effects of the systematic weights will be explored. The samples are then examined as CC 1-track and CC N-tracks.

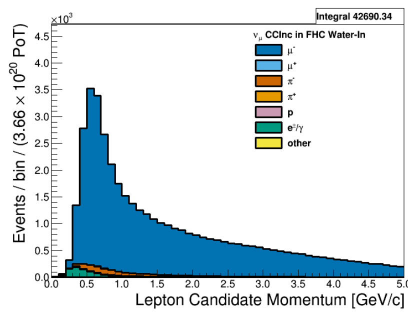
0.6.1 CC-Inclusive

The CC-Inclusive sample cuts are discussed 0.4.1. Since both flux and systematic weights are applied to all MC events in BANFF, it is important to validate the event weights.fig:P0DwaterFHCnumuCCIncMomTrueParticle,fig:P0DwaterFHCnumuCCIncAngleTruePart show the momentum and $\cos\theta$ distributions before and after applying different weights.

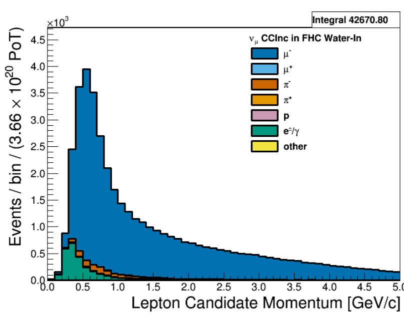
ν_μ FHC:



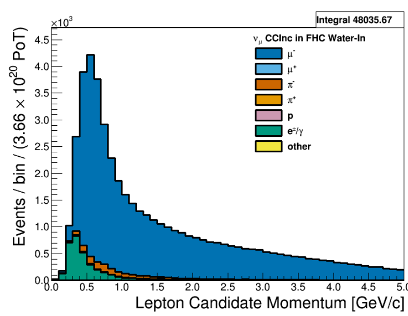
(a) Nominal MC



(b) Flux

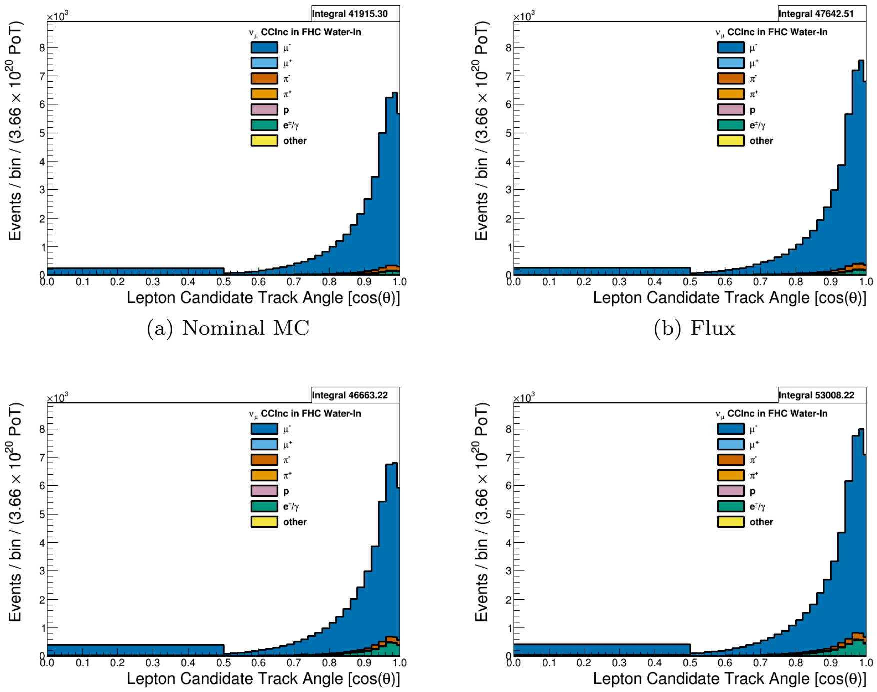


(c) Systematics



(d) Flux + systematics

Figure 11: Reconstructed lepton candidate momentum separated by true particle species for FHC CC-Inc. events occurring in the () 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.



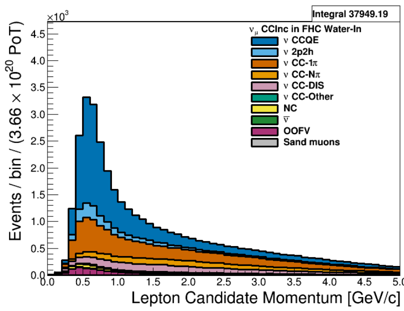
(a) Nominal MC

(b) Flux

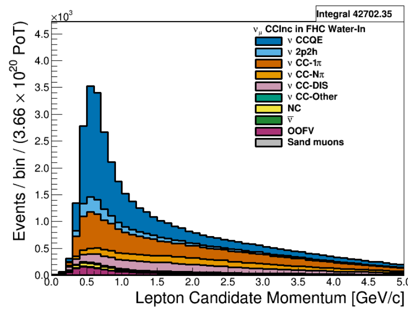
(c) Systematics

(d) Flux + systematics

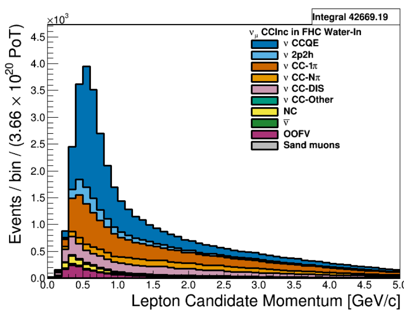
Figure 12: Reconstructed lepton candidate angle separated by true particle species for FHC CC-Inc. events occurring in the () in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.



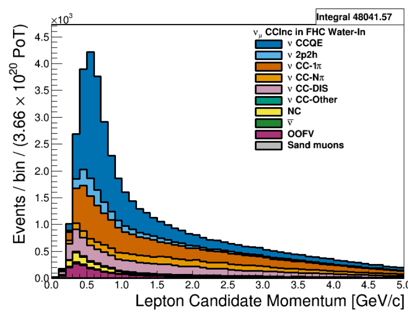
(a) Nominal MC



(b) Flux

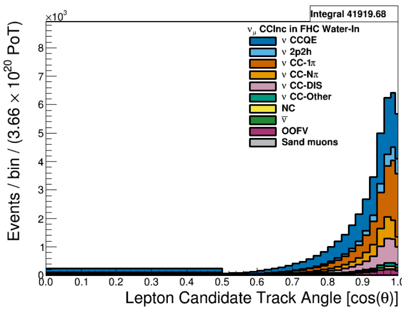


(c) Systematics

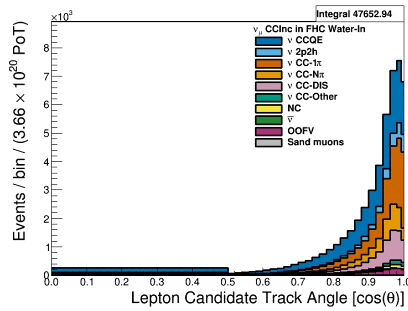


(d) Flux + systematics

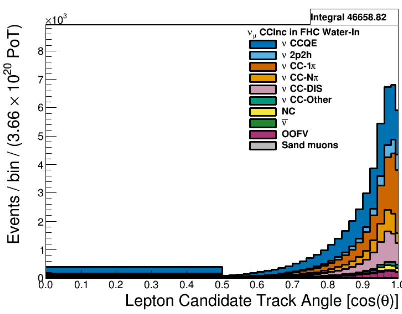
Figure 13: Reconstructed lepton candidate momentum separated by NEUT model interaction mode for FHC CC-Inc. events occurring in the () in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.



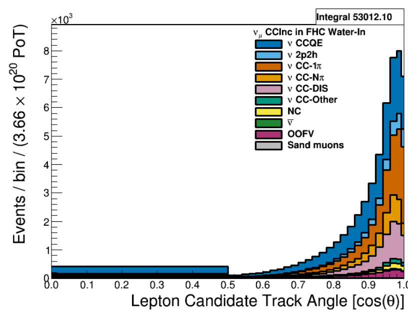
(a) Nominal MC



(b) Flux

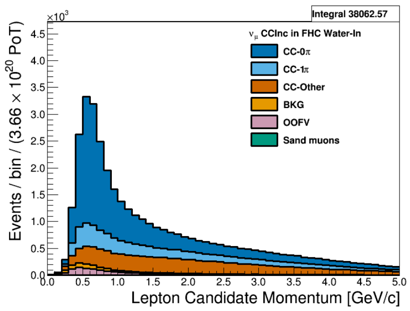


(c) Systematics

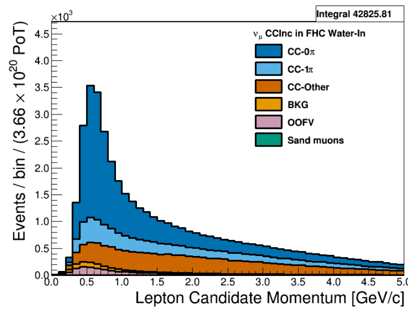


(d) Flux + systematics

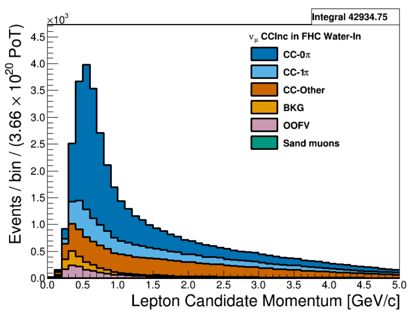
Figure 14: Reconstructed lepton candidate $\cos\theta$ separated by NEUT model interaction mode for FHC CC-Inc. events occurring in the () in water-in mode. (a) The nominal MC prediction without any weights applied. (b) The flux tuning is applied. (c) The systematic weighting is applied. (d) Both flux and systematic weighting is applied.



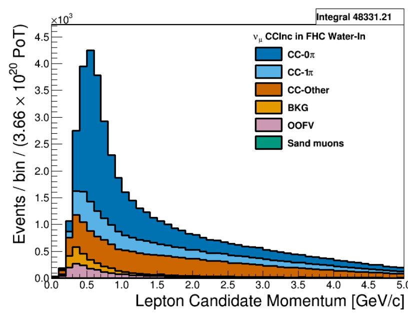
(a) Nominal MC



(b) Flux

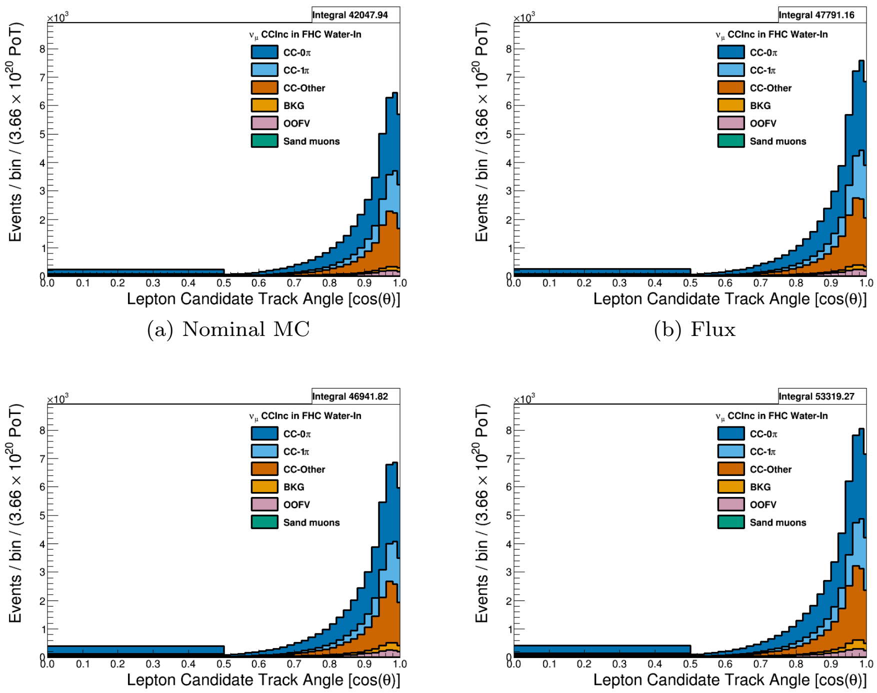


(c) Systematics



(d) Flux + systematics

Figure 15: Reconstructed lepton candidate momentum separated by topology for FHC CC-Inc. events occurring in the () 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.



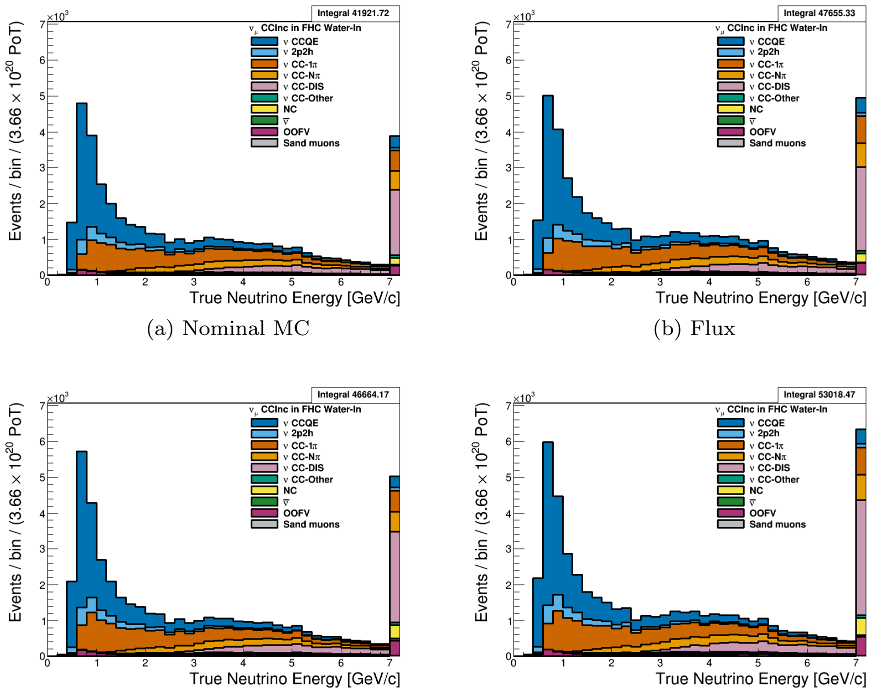
(a) Nominal MC

(b) Flux

(c) Systematics

(d) Flux + systematics

Figure 16: Reconstructed lepton candidate $\cos\theta$ separated by topology for FHC CC-Inc. events occurring in the () 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.



(a) Nominal MC

(b) Flux

(c) Systematics

(d) Flux + systematics

Figure 17: True neutrino energy associated with the lepton candidate separated by NEUT model interaction mode for FHC CC-Inc. events occurring in the () 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.

RHC:
RHC:

0.6.2 CC-1 Track (CCQE Enhanced)

0.6.3 CC-N Tracks (CCnQE Enhanced)

0.6.4 Differences Between Water-Out and Water-In Samples