This is A Tribute To The Best TN of All Time

Hogan, Matthew[1] and Toki, Walter[1]

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[1] *Colorado State University, Fort Collins, USA*

Abstract

This is the abstract

Contents

List of Figures

List of Tables

1 Introduction

1.1 BANFF Treatment of ND Constraint

The primary goal of an oscillation experiment is to measure the parameters in a neutrino mixing matrix. All other parameters, while having some theoretical importance to fundamental physics, are nuisance parameters that must be accounted for. To understand the methodology of BANFF, it is relevant to understand the number of nuisance parameters that go into a ND+FD fit. The BANFF implementation aims to reduce the dimensionality, and hence complexity, of the problem by performing a separate analysis on the nuisance parameters that only the ND can measure. Then that information is propagated to the oscillation analysis for the FD data. Conceptually this approach has computational advantages and should provide the same result with a joint ND+FD analysis. However, information encoded in the ND measurements for shared nuisance parameters is inevitably lost in this "divide-and-conquer" approach.

The BANFF ND-only constraint between 2015 and 2018 is described in TN-220. It uses a frequentist approach to find the best nuisance parameter set to maximize a binned likelihood. The sets of nuisance parameters are

- cross section physics model parameters hereby denoted by $\vec{x}$,
- neutrino flux binned in neutrino energy hereby denoted by $\vec{b}$, and
- detector systematics that affect detector observables hereby denoted by $\vec{d}$.

A priori (prior) knowledge of $\vec{x}$ and $\vec{b}$ are available from external measurements and experiments. The $\vec{d}$ parameters are penalty terms whose effect can be mitigated with control samples.

1.1.1 Constructing a Likelihood

We can define a binned likelihood for the ND280-only constraint with the nuisance parameters as

$$\mathcal{L}\left(\vec{x},\vec{b}\,\middle|\vec{N}^{\text{Data}}_{\text{ND280}}\right)=\mathcal{P}\left(\vec{x},\vec{b},\vec{d}\,\middle|\vec{N}^{\text{Data}}_{\text{ND280}}\right)=\frac{\mathcal{P}\left(\vec{N}^{\text{Data}}_{\text{ND280}}\middle|\,\vec{x},\vec{b},\vec{d}\right)}{\mathcal{P}\left(\vec{N}^{\text{Data}}_{\text{ND280}}\right)}\pi\left(\vec{x}\right)\pi\left(\vec{b}\right)\pi\left(\vec{d}\right), \tag{1.1}$$

where $\vec{N}^{\text{Data}}_{\text{ND280}}$ are the binned data measurements, $\pi\left(\vec{y}=\vec{x},\vec{b},\vec{d}\right)$ are prior distributions which are assumed Gaussian distributions

$$\pi(\vec{y})=\left(\frac{1}{(2\pi)^{k}\det\left(V_{y}\right)}\right)^{\frac{1}{2}}e^{\left(-\frac{1}{2}\Delta\vec{y}\cdot V_{y}^{-1}\cdot\Delta y^{T}\right)}, \tag{1.2}$$

with V_y being the covariance matrix for $\vec{y}$ and $\Delta\vec{y}=\vec{y}-\vec{y}_{\text{Nominal}}$, and $\mathcal{P}\left(\vec{N}^{\text{Data}}_{\text{ND280}}\right)$ is a normalization. We have used Bayes' theorem

$$\mathcal{P}\left(AB\right)=\mathcal{P}\left(B\right)\mathcal{P}\left(A\,|B\,\right) \tag{1.3}$$

to evaluate (1.1) as

$$\mathcal{P}\left(\underbrace{\vec{x},\vec{b},\vec{d}}_{A}\,\middle|\,\underbrace{\vec{N}^{\text{Data}}_{\text{ND280}}}_{B}\right)=\frac{\mathcal{P}\left(\vec{N}^{\text{Data}}_{\text{ND280}},\left(\vec{x},\vec{b},\vec{d}\right)\right)}{\mathcal{P}\left(\vec{N}^{\text{Data}}_{\text{ND280}}\right)} \tag{1.4}$$

which we can further manipulate since the data are independent of the nuisance parameters

$$\mathcal{P}\left(\vec{N}^{\text{Data}}_{\text{ND280}},\left(\vec{x},\vec{b},\vec{d}\right)\right)=\mathcal{P}\left(\underbrace{\left(\vec{x},\vec{b},\vec{d}\right)}_{A},\underbrace{\vec{N}^{\text{Data}}_{\text{ND280}}}_{B}\right)=\pi\left(\vec{x}\right)\pi\left(\vec{b}\right)\pi\left(\vec{d}\right)\mathcal{P}\left(\vec{N}^{\text{Data}}_{\text{ND280}}\middle|\,\vec{x},\vec{b},\vec{d}\right) \tag{1.5}$$

resulting in (1.1). The assumption of a Gaussian prior in (1.2) while not always truly Gaussian, allows for the use of a covariance matrix to describe the uncertainties and correlations in parameters. Once a maximum of the likelihood is found after marginalizing the effects of the systematics $\vec{d}$, the best fit values for $\vec{b}$ and $\vec{x}$ can be propagated to the oscillation analysis.

1.1.2 BANFF Likelihood

In practice maximizing the log-likelihood (LL) is performed instead of maximizing the likelihood function. In addition, multiplying the LL by -2 turns the maximization problem into a minimization one which programs like MINUIT are designed to find. To obtain the best set of parameters $\vec{x}$ and $\vec{b}$ from the ND280 data that minimize the $-2\times$LL, we need to predict how they affect our detector observables. Consider binned samples that select different charged current topologies. A convenient choice of observables for all the samples are the outgoing charged lepton l momentum P_l and angle $\cos\theta_l$ as mesaured in the ND since all the nuisance parameters affect these quantities. We have the pieces needed to define the likelihood function used in ND-only BANFF analysis. For each $(P_l, \cos\theta_l)$ bin $i = 1, 2, \ldots, M-1, M$, the likelihood for the ND-constraint is a ratio (r) of the predicted events $(\vec{N}^p)$ likelihood to the likelihood of the data events $(\vec{N}^d)$

$$\begin{aligned}
\Lambda^r_{\text{ND280}} &= \frac{\mathcal{L}\left(\vec{N}^p\left(\vec{x},\vec{b},\vec{d}\right)\middle|\vec{N}^d\right)}{\mathcal{L}\left(\vec{N}^d\left(\vec{x},\vec{b},\vec{d}\right)\middle|\vec{N}^d\right)} \\
&= \left(\prod_{\vec{y}=\vec{x},\vec{b},\vec{d}} \frac{\pi\left(\vec{y}\right)}{\pi\left(\vec{y}_{\text{Nom}}\right)}\right)\left(\prod_{i=1}^{M}\left(\vec{N}^p_i\right)^{\vec{N}^d_i}\frac{e^{-\vec{N}^p_i}}{\vec{N}^d_i!}\right)\left(\prod_{j=1}^{M}\left(\vec{N}^d_i\right)^{\vec{N}^d_i}\frac{e^{-\vec{N}^d_i}}{\vec{N}^d_i!}\right)^{-1}
\end{aligned}$$

2 PØD Event Selection And Cuts

This section describes the development of ν_μ and $\overline{\nu}_\mu$CC-Inclusive selections in both FHC and RHC beam configuration for PØD-based analyses. These selections are the continuation of previous works that developed ν_μ CC-Inclusive selections between the PØD and TPC1. The first such analyses were T2K-TN-80 and T2K-TN-100 which described the ν_μ CC-Inclusive event selection and, later, cross-section analysis using ND280 Production 5 software, respectively[2, 3]. 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 CC-0π cross section analyzes, T2K-TN-258 and T2K-TN-328, were developed that also used the CC-Inclusive selection as pre-selection cuts[7, 1]. 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 π^0 Detector (PØD). 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: ν_μ in FHC mode, $\overline{\nu}_\mu$ in RHC, and ν_μ in RHC.

2.1 The PØD

The PØD, short for π^0 Detector, is a plastic scintillator based tracking calorimeter inside the ND280 basket. The PØD is constructed as many sandwiches of active and inactive materials designed to fully contain π^0decay photons. The four primary regions inside the PØD 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

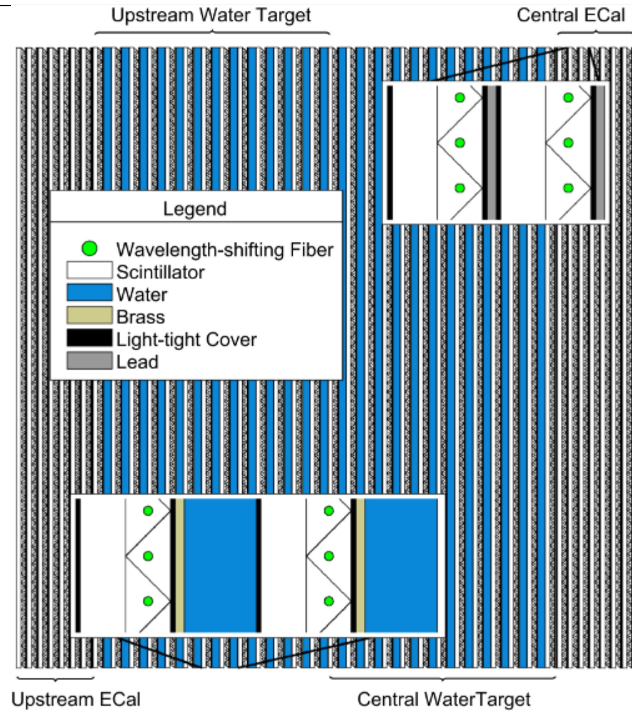


Figure 2.1: This cartoon illustrates the concept design of the PØD where the neutrino beam is approaching from the left.

of the entire PØD can be seen in Figure 2.1. Each active module, also called a PØDule, consists of two orthogonally oriented sheets of triangular, scintillator-doped plastic bars as shown in Figure 2.2. The ECal regions are designed to contain decay photons inside the PØD 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 PØDules. A unique feature of the PØD is that the water can be drained out resulting in two detector configurations: water-in and water-out.

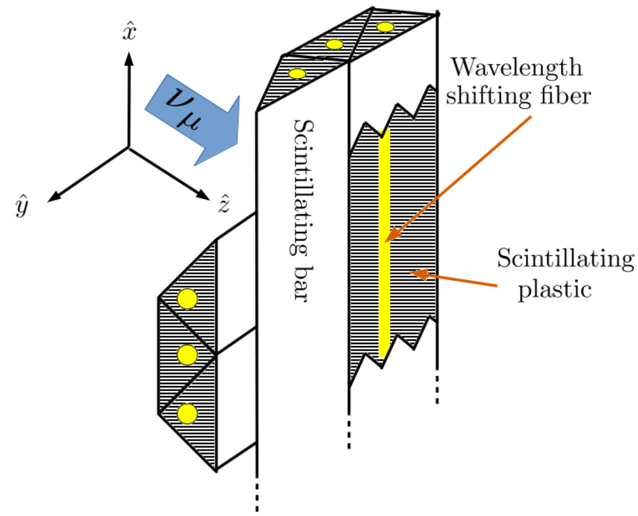


Figure 2.2: This cartoon illustrates the design of a PØDule with orthogonal layers of scintillating, triangular bars. When a charged particle travels through the bar such as a muon from CC interaction, the scintillation light is captured and wavelength shifted inside a fiber bored in the center of each bar. The wavelength shifted light is later observed by a photon counter.

2.2 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 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[6].

2.3 Data Sets

2.4 PØD 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 PØD FV. A MIP is more likely to reach TPC1 from the PØD FV since the PØD 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.

2.4.1 Pre-Selection Cuts

The pre-selection ("precuts") were initially developed to select ν_μCC-Inclusive using the PØD and TPC sub-detector reconstruction softwares separately[2]. They were then used with the Global reconstruction software for the ν_μCC-0π selection in the FHC beam configuration as described in technical note T2K-TN-258[7]. 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 PØD 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[5].

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

    - The PØD FV is defined to include as much as the WT regions as possible. Its X and Y borders are 25 cm away from the PØDule edges while its Z borders intersect the last and first half downstream PØDule in the USECal and CECal, respectively. The enumerated volume edges are shown in Table 2.1. This volume, while used for track-based analyzes in the past, was optimized for π^0 and ν_e analyzes[4].

5. All tracks that enter TPC1 pass the veto cut

    - An event is rejected if any PØD track enters TPC1 from outside the "corridor" volume. This cut was designed to eliminate broken tracks between the PØD and TPC1 when the separate sub-detector reconstructions were used[2]. 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 2.1.

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

Table 2.1: 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.

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 ν_μ selections is the highest momentum, negatively-charged track (HMNT). Similarly the highest momentum, positively-charged track (HMPT) is assigned the main track for $\overline{\nu}_\mu$ 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.

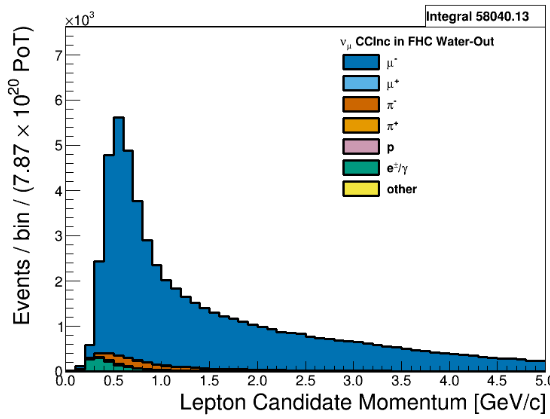
2.4.2 CC-Inclusive in FHC

As discussed in the Section 2.4.1, this selection is the basis for the ν_μ CC-0π PØD+TPC1 analysis. This is FHC mode selection and so the lack of a negatively charged track is the final cut for the CC-Inclusive selection.

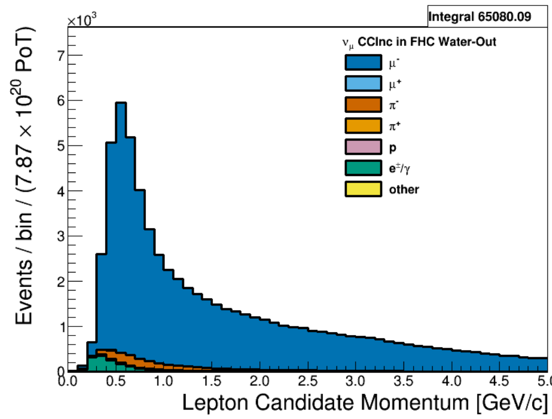
2.4.3 CC-Inclusive in RHC

2.5 PØD Water-Out Selections

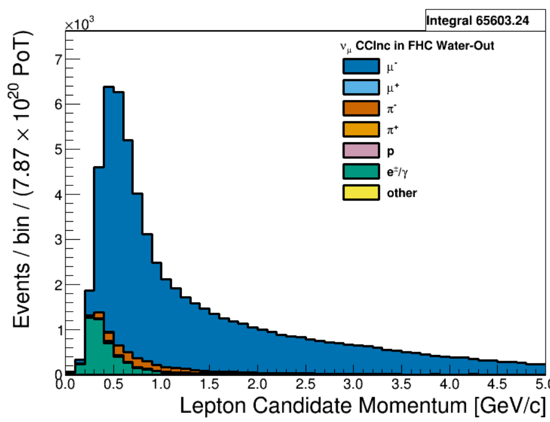
Look for me!!!



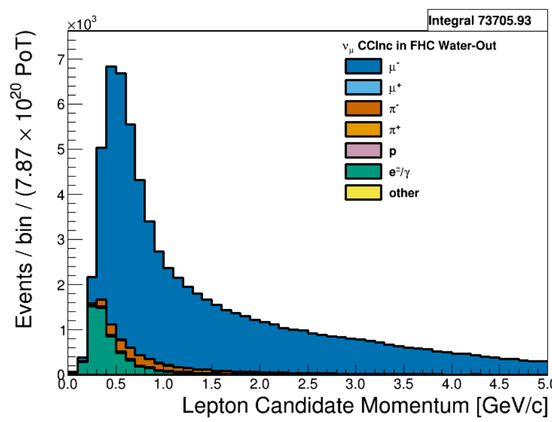
(a) Nominal MC



(b) Flux

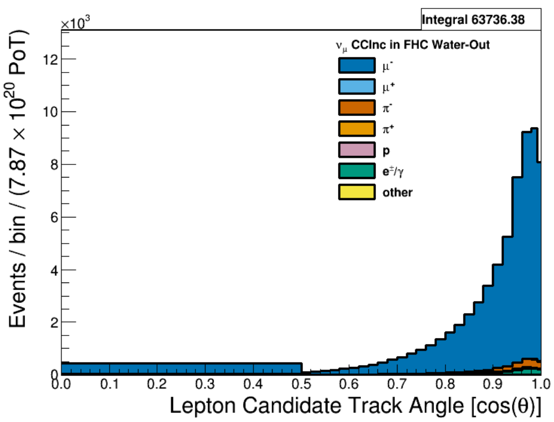


(c) Systematics

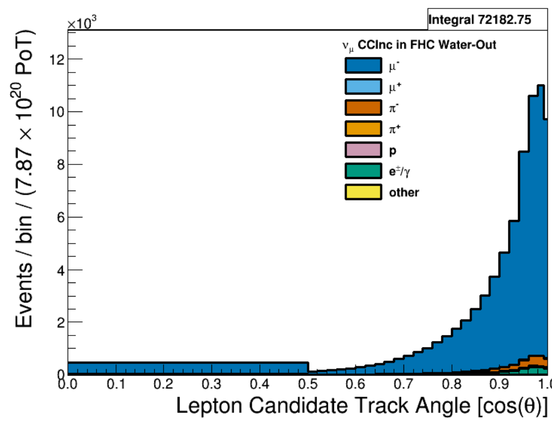


(d) Flux + systematics

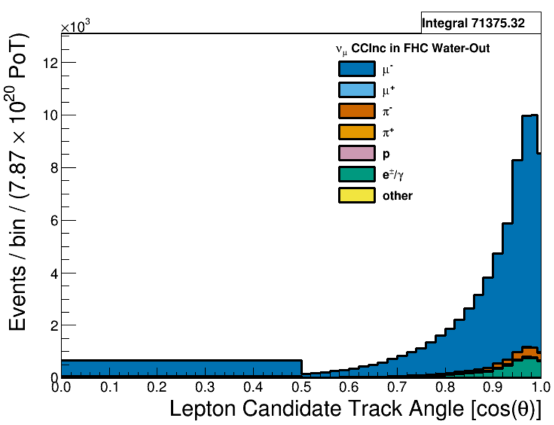
Figure 2.3: Momentum: True Particle



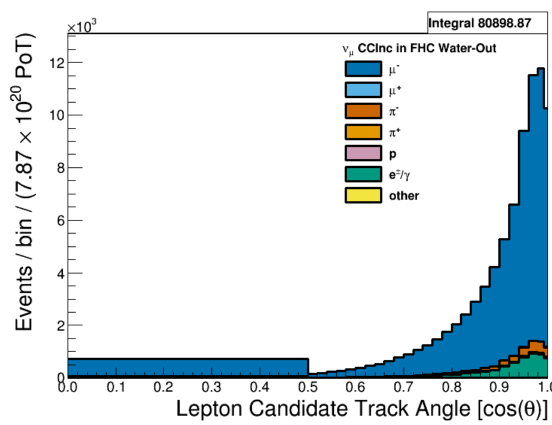
(a) Nominal MC



(b) Flux

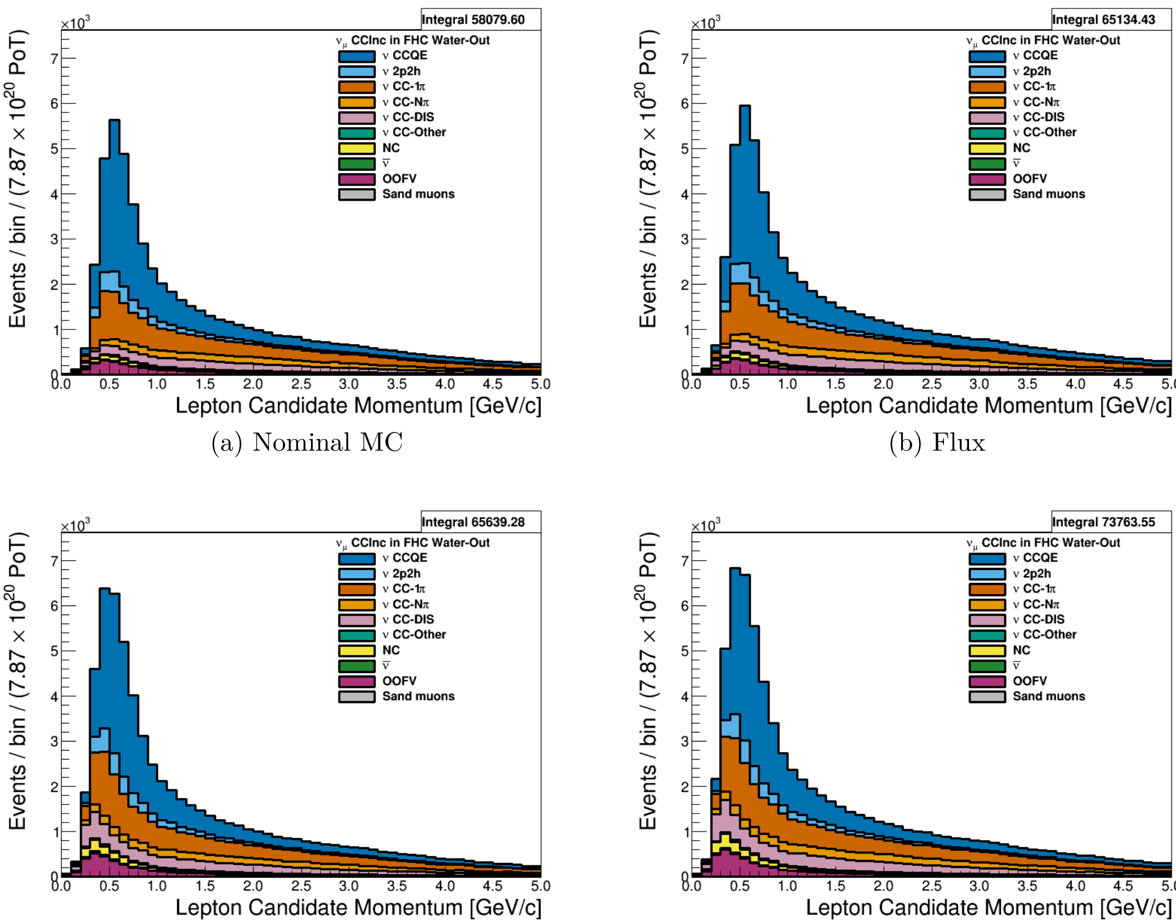


(c) Systematics



(d) Flux + systematics

Figure 2.4: Angle: True Particle



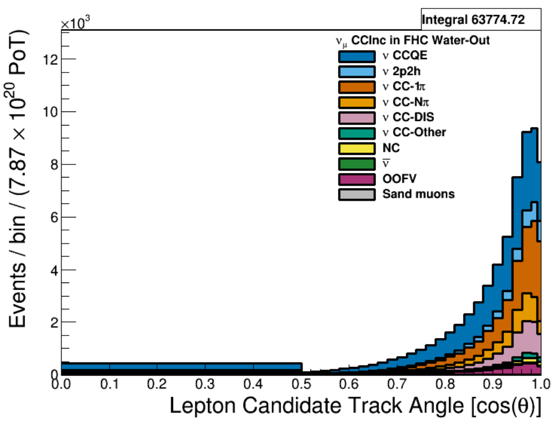
(a) Nominal MC

(b) Flux

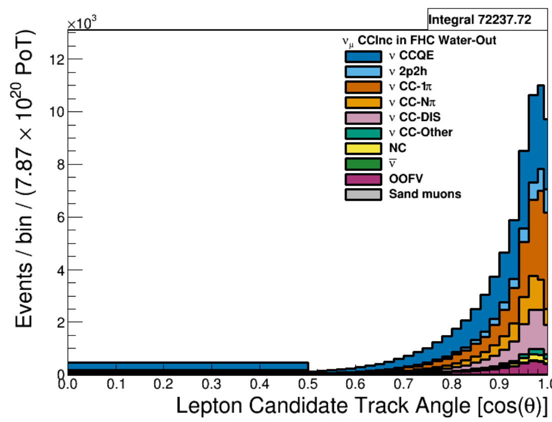
(c) Systematics

(d) Flux + systematics

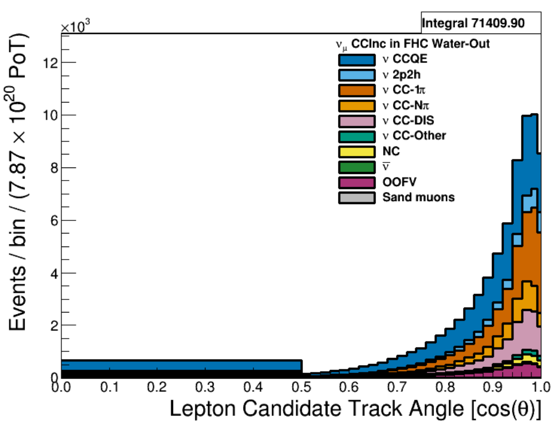
Figure 2.5: Momentum: NEUT Interaction



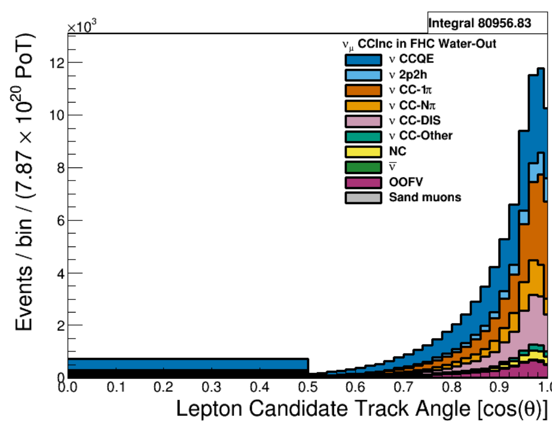
(a) Nominal MC



(b) Flux

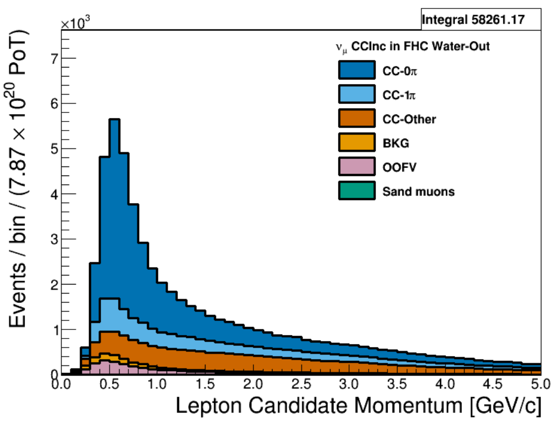


(c) Systematics

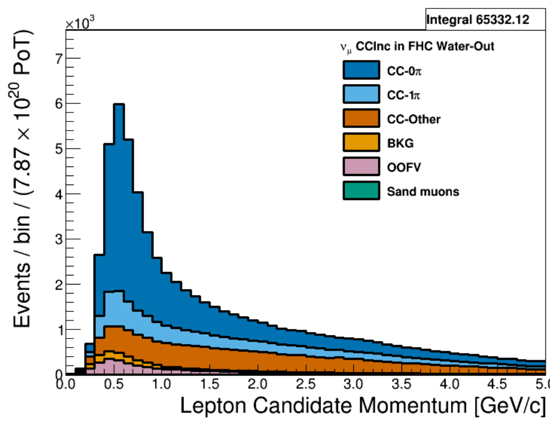


(d) Flux + systematics

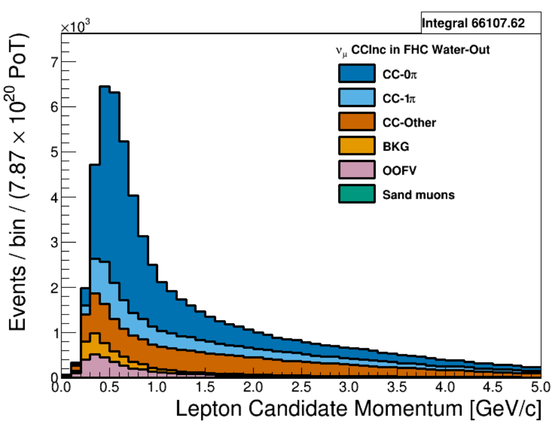
Figure 2.6: Angle: NEUT Interaction



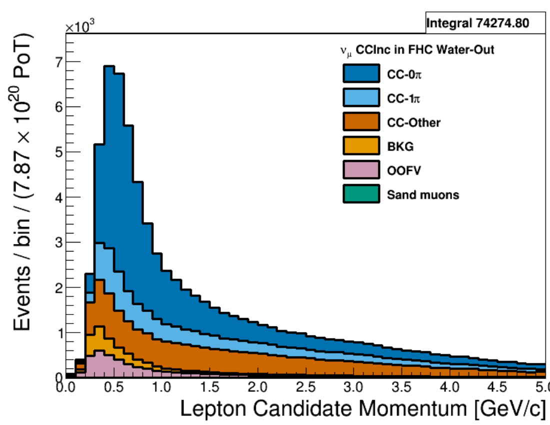
(a) Nominal MC



(b) Flux

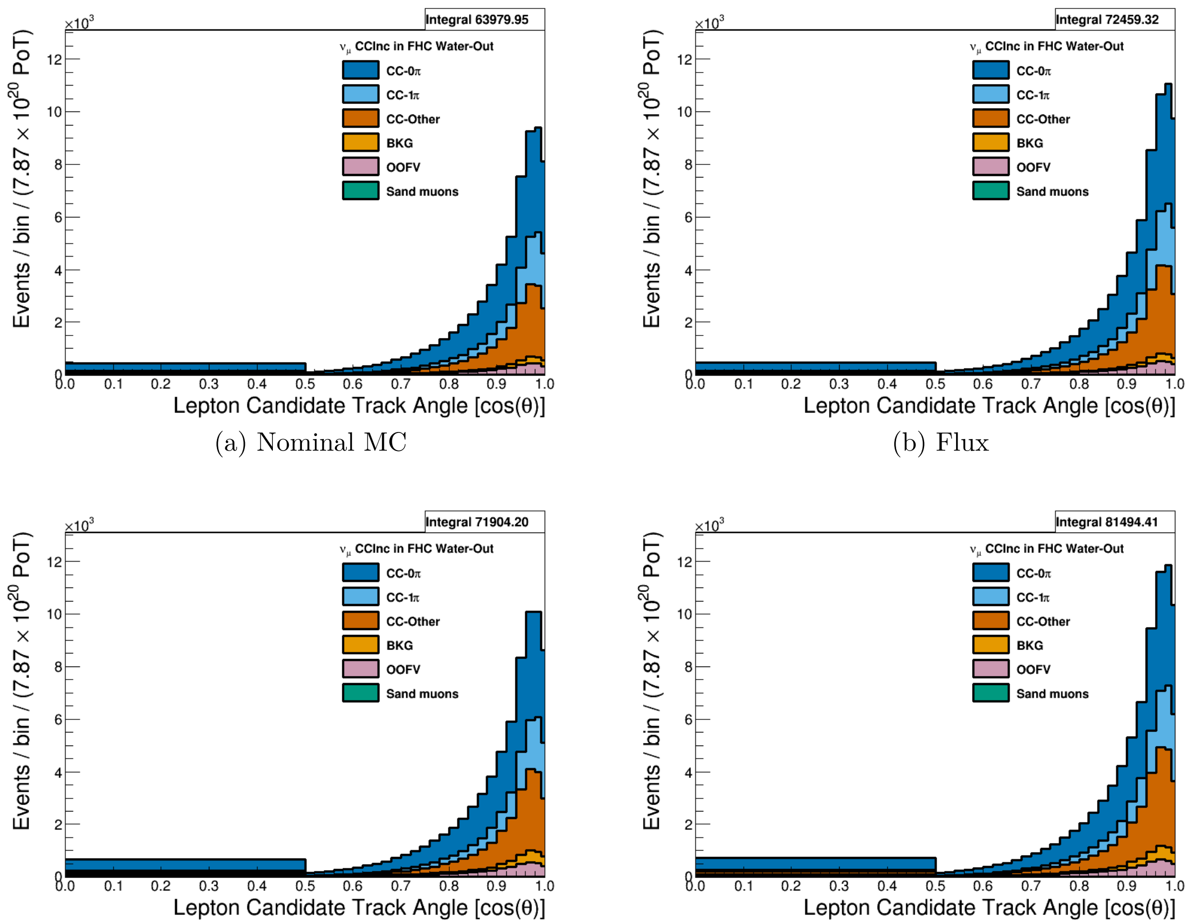


(c) Systematics



(d) Flux + systematics

Figure 2.7: Momentum: True Topology



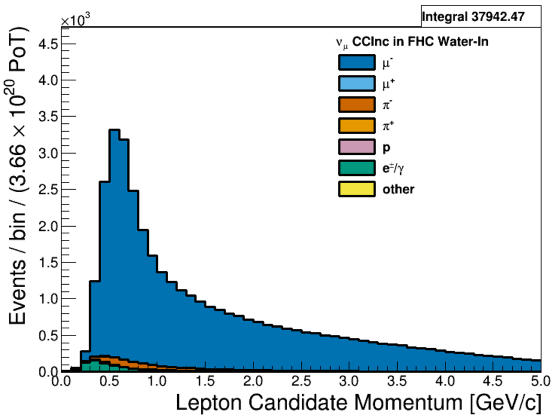
(a) Nominal MC

(b) Flux

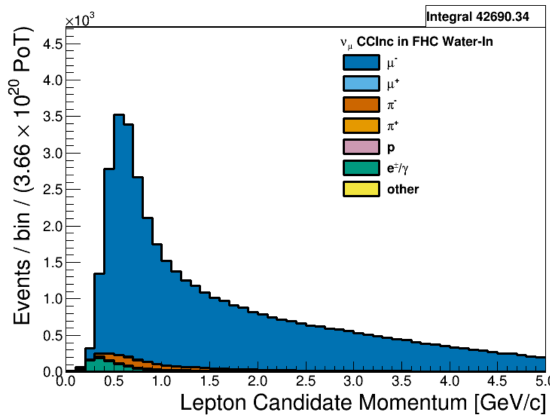
(c) Systematics

(d) Flux + systematics

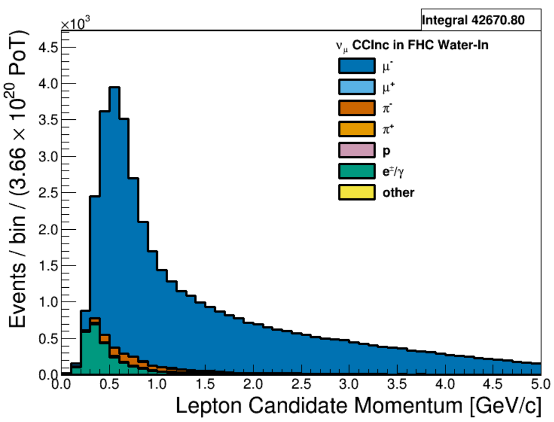
Figure 2.8: Angle: True Topology



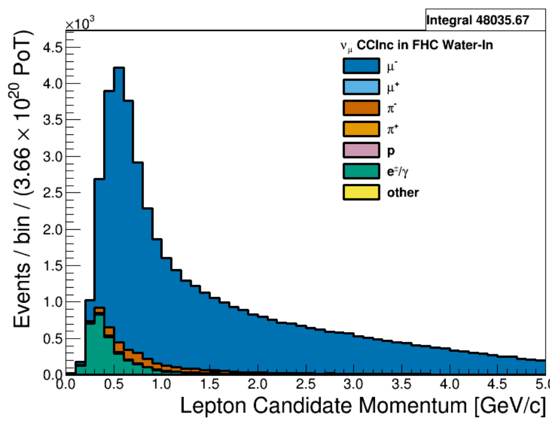
(a) Nominal MC



(b) Flux

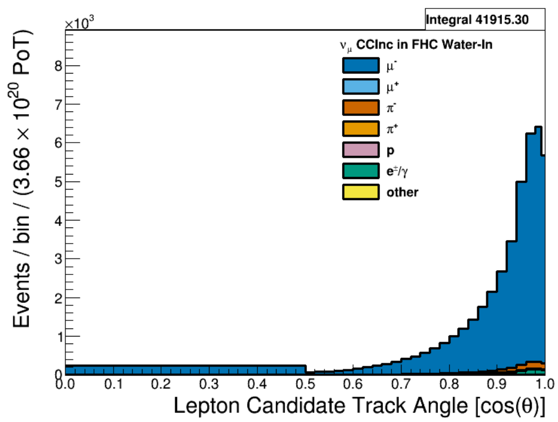


(c) Systematics

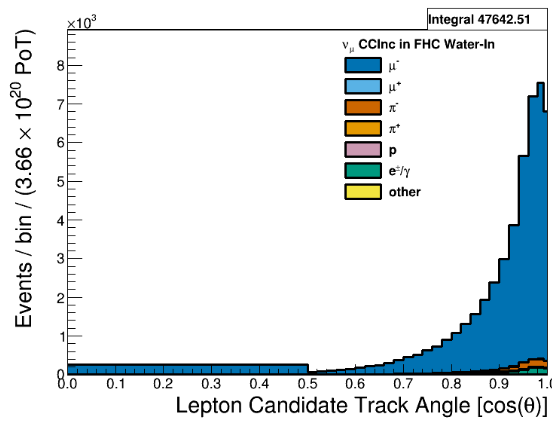


(d) Flux + systematics

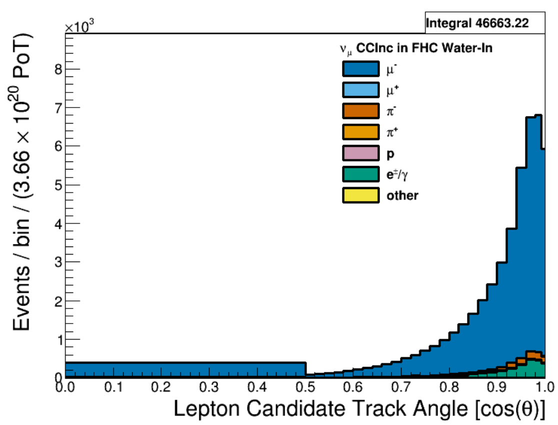
Figure 2.9: Momentum: True Particle



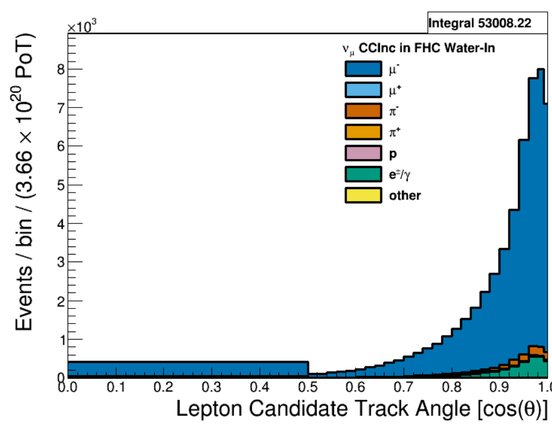
(a) Nominal MC



(b) Flux

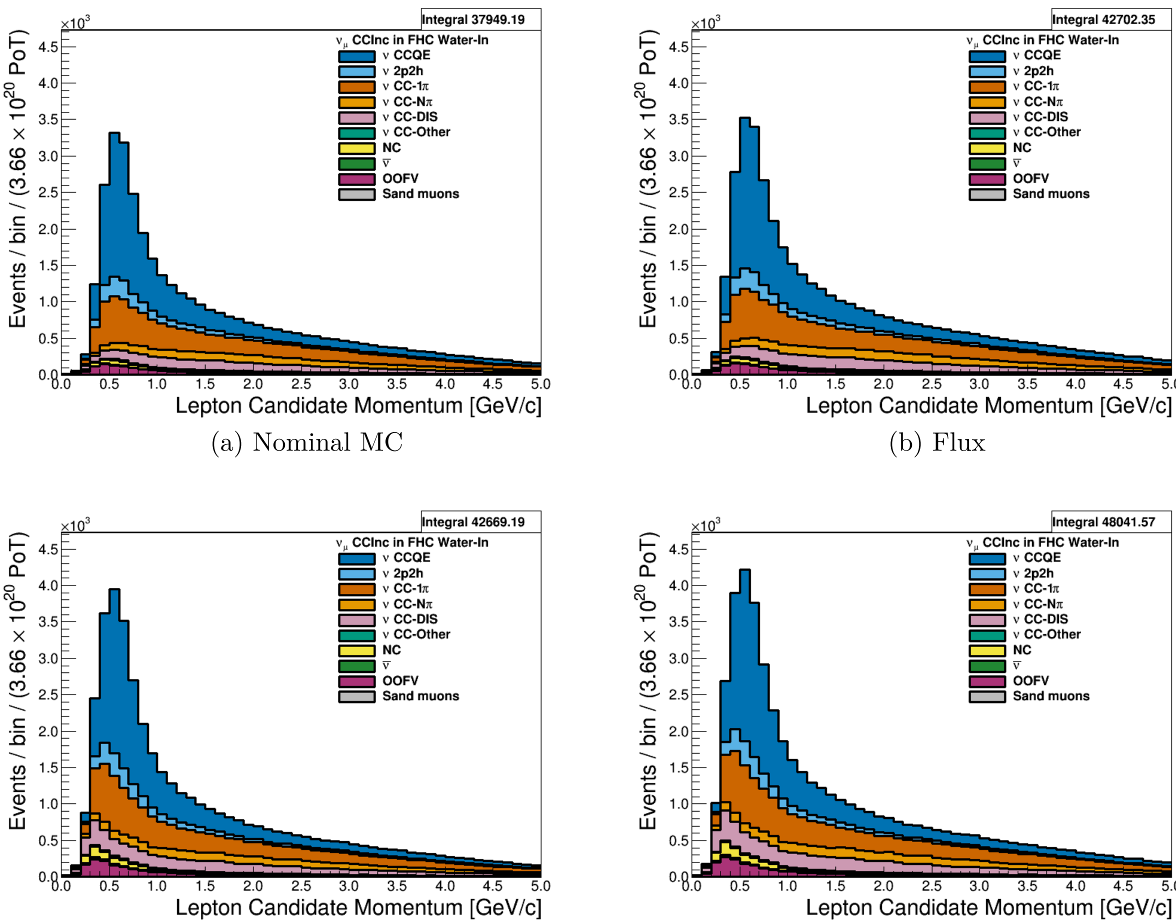


(c) Systematics



(d) Flux + systematics

Figure 2.10: Angle: True Particle



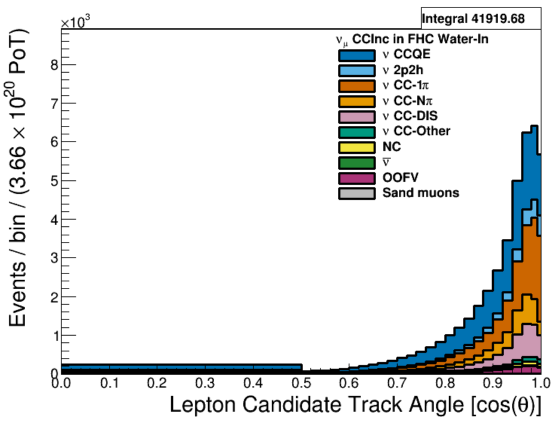
(a) Nominal MC

(b) Flux

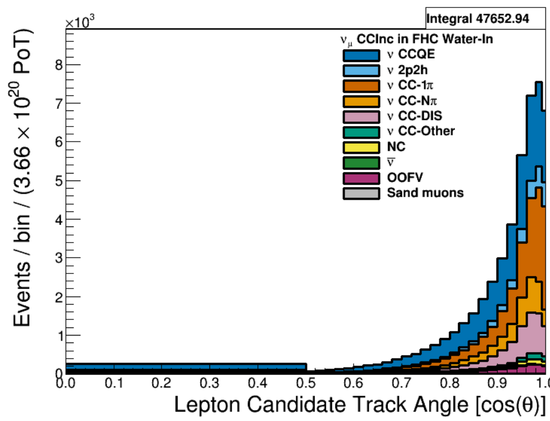
(c) Systematics

(d) Flux + systematics

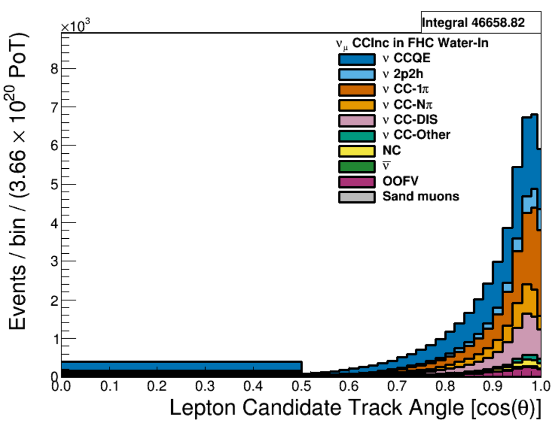
Figure 2.11: Momentum: NEUT Interaction



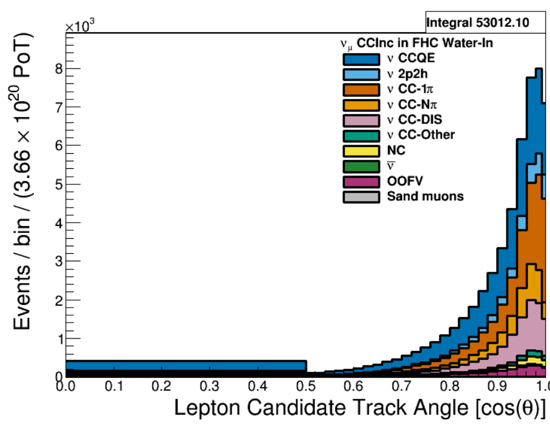
(a) Nominal MC



(b) Flux

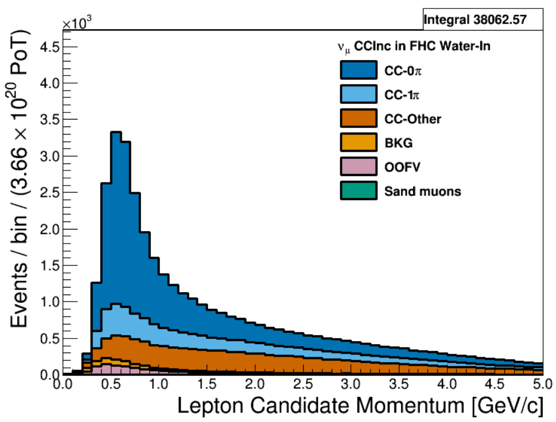


(c) Systematics

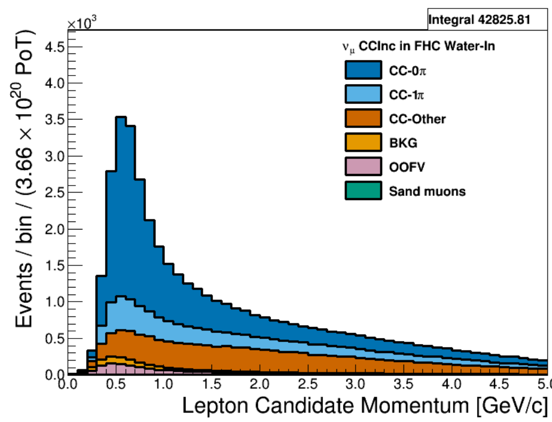


(d) Flux + systematics

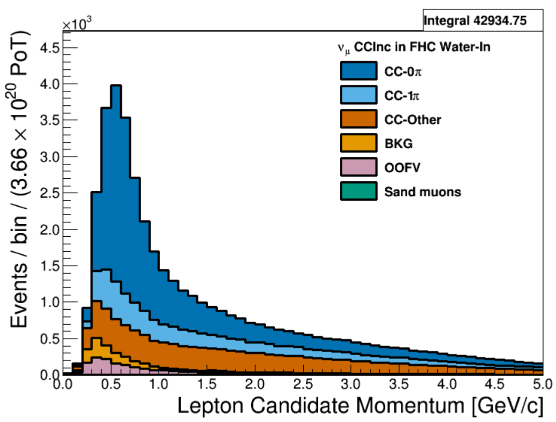
Figure 2.12: Angle: NEUT Interaction



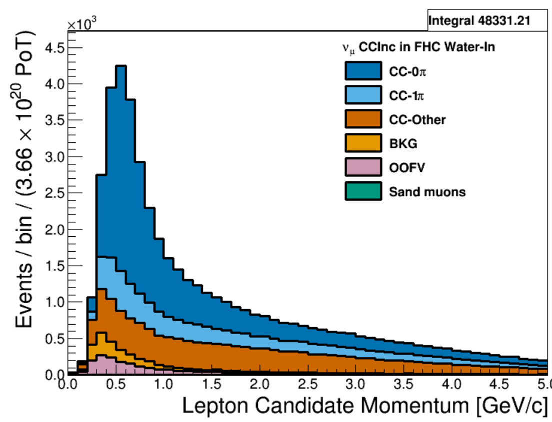
(a) Nominal MC



(b) Flux

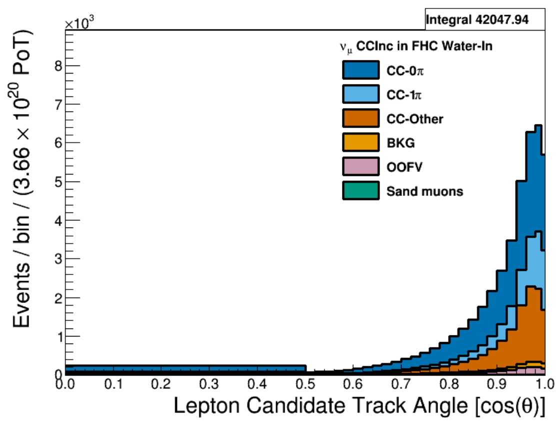


(c) Systematics

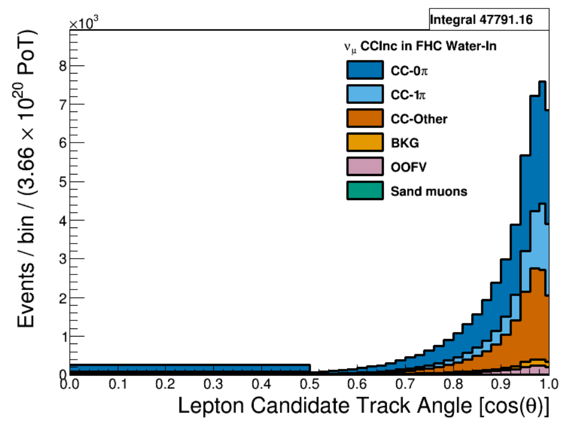


(d) Flux + systematics

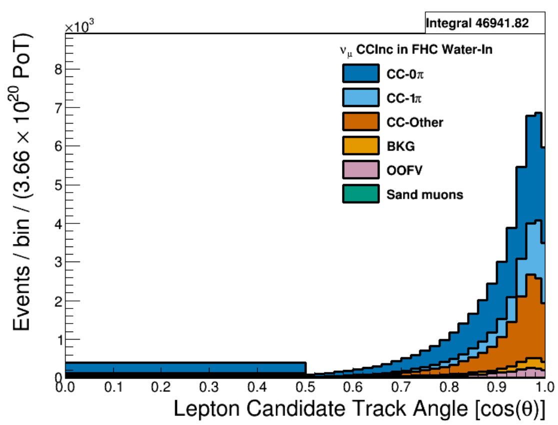
Figure 2.13: Momentum: True Topology



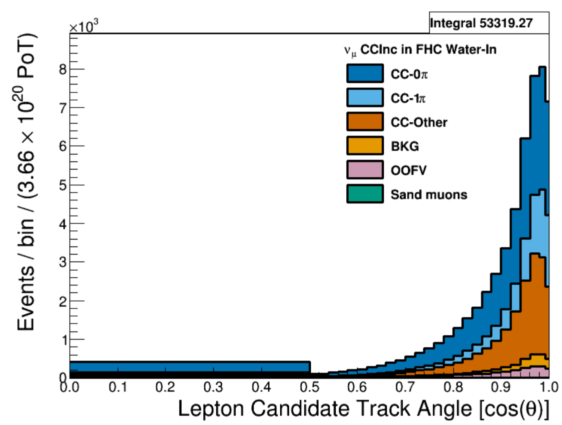
(a) Nominal MC



(b) Flux



(c) Systematics



(d) Flux + systematics

Figure 2.14: Angle: True Topology

2.5.1 CC-Inclusive

2.5.2 CC-1 Track (CCQE Enhanced)

2.5.3 CC-N Tracks (CCnQE Enhanced)

2.6 PØD Water-In Selections

2.6.1 CC-Inclusive

2.6.2 CC-1 Track (CCQE Enhanced)

2.6.3 CC-N Tracks (CCnQE Enhanced)

2.7 Comparison Between Water-Out and Water-In Selections

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Nomenclature

CC-0π A **c**harged **c**urrent zero pion selection is an exclusive selection that selects neutrino interaction topologies only one MIP-like particle.

CC-Inclusive A **c**harged **c**urrent event selection that selects all neutrino interaction topologies with an outgoing charged lepton.

FGD A **f**ine **g**rain **d**etector is a detector made of closely spaced, small scintillating bars designed to provide precise resolution of charged particle tracks

FHC The **f**orward **h**orn **c**urrent beam configuration that focuses positively charged particles into the particle decay pipe. This configuration produces a very pure ν_μ neutrino beam

HMNT The **h**ighest **m**omentum **n**egatively-charged **t**rack in the bunch

HMPT The **h**ighest **m**omentum **p**ositively-charged **t**rack in the bunch

MIP A **m**inimum **i**onizing **p**article

ND280 The **N**ear **D**etector of T2K which is **280** meters away from the neutrino source.

CECal The **C**entral **ECal** detector which is a part of the PØD inside ND280

PØD The π^0 detector (**pi**-**Ø** **d**etector)

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

RHC The **r**everse **h**orn **c**urrent beam configuration that focuses negatively charged particles into the particle decay pipe. This configuration produces a $\overline{\nu}_\mu$ enriched neutrino beam with a significant ν_μ contribution.

FV The **f**iducial **v**olume of a detector is the region where the detector response is well understood

TPC A **t**ime **p**rojection **c**hamber is a device that detects and tracks charged particles with the application of strong electric fields

Tracker The region of ND280 consisting of two FGDs and TPCs

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

USECal The **Up**stream **ECal** which is a part of the PØD inside ND280