Analysis of DUNE Simulation Data of Near Detector to Study the Neutral Current Background

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Abstract

The analyses on charged current and neutral current interactions based on a full simulation, reconstruction, and event selection of the near detector of the Deep Underground Neutrino Experiment (DUNE) are carried out. The neutrino beam mode and antineutrino beam mode are included. DUNE will be able to classify the CC and NC interactions. The determination of NC background in DUNE near detector is needed in order to observe charge-parity (CP) violation in the neutrino sector and resolve the neutrino mass hierarchy. Exact determination and reduction on NC background will allow precise measurements of parameters, namely mixing angles and a CP-violating phase which govern long-baseline neutrino oscillation.

Keywords: CERN summer student research report; DUNE; Near detector; Background analysis.

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1 Introduction

Neutrinos are among the most abundant particles in the universe. Neutrinos may come from different sources, for example, neutrinos from the Sun, Earth's atmosphere by cosmic rays and human-made sources. It has been known that neutrinos are very light. However, it has not been known whether they are completely massless or have small but nonzero masses. In order to answer this question, various experiments have been carried out through international collaborations. Studying neutrinos is challenging, since the only known fundamental forces through which these electrically-neutral leptons interact are the weak force and gravity. Consequently, interactions of neutrinos in a detector are very rare events, so that very large detectors and intense neutrino sources are needed to make experiments feasible. Nevertheless, we have confirmed that the weak interactions of neutrinos are correctly described by the Standard Model (SM) of elementary particle physics [1]. We have the strong convincing evidence that neutrinos do have nonzero masses. This evidence stems from the apparent experimental observation that a neutrino of one type or "flavor" such as a muon neutrino, can metamorphose into a neutrino of another flavor, such as a tau neutrino. This metamorphosis, known as neutrino oscillation, which implies neutrino has mass.

In this report, we briefly review the physics of neutrino mass and oscillation. Next, we discuss on the Deep Underground Neutrino Experiment (DUNE). Then, we explore the neutrino-interaction events in the simulation. We conclude by discussing the future steps to be taken in order to improve the simulation outcomes on reconstructed events.

1.1 Neutrino Oscillation

There are three known flavors of neutrinos: electron neutrino v_e, muon neutrino v_μ, and tau neutrino v_τ. The neutrinos' flavors are defined in terms of leptonic W-boson decay. This decay produces a charged lepton, which may be an electron e, muon μ, or tau τ, and a neutrino with the same flavor. When we send a neutrino on a long travel, the neutrino's flavor state is changed from the initial flavor state. Suppose that this neutrino is produced in the pion decay $\pi \rightarrow \mu + v_\mu$, through virtual W boson, so that at birth it is a muon neutrino. But the muon neutrino v_μ can turn into a electron neutrino v_e as it travels, the existence of the electron e as a product of an interaction implies that during its journey, our neutrino has evolved from a v_μ into a v_e. The last few decades have brought us conclusive evidence that such changes of neutrino flavor indeed happen. The flavor change is referred to as neutrino oscillation, since the probability of flavor change in vacuum has an oscillatory feature [1].

If the neutrinos behave as quarks do, then certain neutrino flavor state v_α is a coherent superposition of mass eigenstates, given by

$$|v_\alpha\rangle = \sum_m U_{\alpha m} |v_m\rangle \,, \tag{1}$$

where the v_m are the mass eigenstates. The coefficients $U_{\alpha m}$ form a matrix U known as the leptonic mixing matrix, or sometimes referred to as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [1]. According to the standard model, extended to include neutrino masses, U is unitary. If there are only 3 neutrino mass eigenstates, then U is a 3×3 complex matrix.

Table 1: Expected POT per year at various primary proton beam momenta [4].

Proton Momentum (GeV/c)	Expected Beam Power (MW)	Expected POT/year
120	1.2	1.1×10^{21}
80	1.07	1.47×10^{21}
60	1.03	1.89×10^{21}

For the case of three mixing, the transformations between basis states is expressed in the form of a complex 3×3 unitary matrix:

$$\begin{pmatrix} v_e \\ v_\mu \\ v_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}. \quad (2)$$

The PMNS matrix in full generality depends on just three mixing angles and a CP-violating phase. The mixing angles and phase are given as $(\theta_{12}, \theta_{23}, \theta_{13})$ and δ_{CP} [4]. This matrix can be parameterized as the product of three two-flavour mixing matrices as follows [5], where $c_{\alpha\beta} = \cos\theta_{\alpha\beta}$ and $s_{\alpha\beta} = \sin\theta_{\alpha\beta}$:

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (3)$$

It is natural to expect that there are CP-violating phases in the leptonic mixing matrix U as in the quark, Cabibbo–Kobayashi–Maskawa (CKM) matrix in the standard-model physics, which these phases could bring CP-violating effects, such as $P(\overline{v}_\mu \to \overline{v}_e) \neq P(v_\mu \to v_e)$ [2]. The experiments that investigate the neutrino oscillation are the T2K Experiment in Japan, Deep Underground Neutrino Experiment (DUNE) and others.

2 Deep Underground Neutrino Experiment (DUNE)

DUNE is a international particle physics experiment which is hosted by the U.S. Department of Energy's Fermi National Acceleratory Laboratory (Fermilab, FNAL). It consists of a DUNE near detector (ND) that will be located on the Fermilab site in Illinois, and a DUNE far detector (FD) to be located in South Dakota. The FD will consist of a modular, liquid argon time-projection chamber (LArTPC). The ND will consist of a highly modular LArTPC, a magnetized gaseous argon time projection chamber (TPC), and a magnetized beam monitor [3]. The ND LArTPC will be made up of 35 independent ArgonCube modules sharing a single cryogenic argon bath, to be located approximately 574 m from the neutrino source for the Long-Baseline Neutrino Facility (LBNF) beam.

A neutrino beam is capable of operating in neutrino mode (forward horn current) and antineutrino mode (reverse horn current). The beam power as a function of proton beam energy from the PIP-II upgrades and the number of protons-on-target per year are depicted in Table 1 [4].

The DUNE experiment is able to measure neutrino interaction rates from which can be extracted the oscillation probabilities for muon (anti)neutrinos to either oscillate to electron (anti)neutrinos or remain the same flavor. Precision measurements of the free parameters of the PMNS matrix, as known in standard three-neutrino formalism can be done through the determination of oscillation probabilities as a function of the neutrino energy. If the measurements of the CP violating phase, δ_{CP} inconsistent with $\sin(\delta_{CP}) = 0$, it would indicate leptonic CP violation [3]. The ND located near the neutrino source, LBNF will measure the unoscillated neutrino interaction rate. It will help in the determination of neutral current interaction background which is important to the neutrino oscillation measurements. On the other hand, the FD will measure the neutrino interaction rate after oscillations. The calculations of oscillation probabilities would be carried out with a comparison of the measurements at the far and near detectors.

2.1 Overview of the Near Detector

The DUNE ND has three primary detector components. It has the capability for two of those components to move off the beam axis to provide extra degree of freedom in the data. This detector has the same target nucleus Ar and basic detection principles as the FD. An illustration of the DUNE ND in the ND cavern is shown in Fig. 1. The LArTPC which constructed using ArgonCube technology is a critical component of the DUNE ND [3]. The detector's charge and light detection systems work together to reconstruct the timing of particle interactions and capture 3D particle trajectories. Its modular design will help scientists to distinguish between multiple neutrino interactions occurred in near detector.

In neutrino physics experiment, the liquid argon is considered because the neutrino–nucleon interaction cross sections are small. The high density of liquid argon increases the likelihood of a particle interacting in a detector. Since argon is a noble element, therefore it has vanishing electronegativity which means that electrons produced by ionizing radiation will not be captured as they drift toward the detector readout. Besides, argon will scintillates when an energetic charged particle passes by. The intensity of scintillator light radiated is proportional to the energy deposited in the argon by the passing particle. Another motivation of using liquid argon is that argon is relatively inexpensive, this allows making large-scale projects economically achievable.

2.2 DUNE Neutrino-Interaction Analysis

Subatomic particles can interact or decay by means of the weak force. There are two classes of weak interactions. The most easily detected class of weak interactions is charged current (CC) interactions. These interactions are mediated by the W^+ and W^- bosons. Exchange of W bosons involves a transfer of electric charge (as well as a transfer of weak isospin, but not weak hypercharge). By contrast, weak neutral current (NC) interactions are mediated by the Z boson. The Z boson is electrically neutral. Exchange of a Z-boson leaves the interacting particles' quantum numbers like charge, flavor, baryon number, lepton number, etc. unaffected except for a transfer of momentum, energy and spin.

Neutrino interactions can be idealized as a three stage process. The first stage of the process is a neutrino hits a nucleus with a complex internal state, including nucleon-nucleon

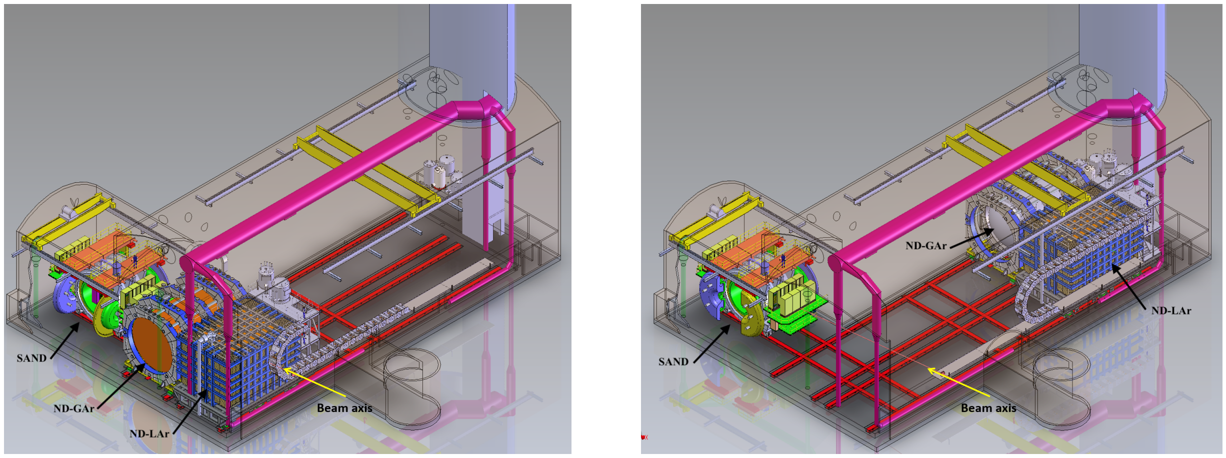

Figure 1: Schematic of the DUNE ND hall shown with component detectors all in the on-axis configuration (left) and with the ND-LAr and ND-GAr in an off-axis configuration (right). The SAND detector is shown in position on the beam axis [3].

interactions. The next stage is where the scattering occurs with one or more of the nucleons, during which the hadronic jets may be ejected. The third stage is the reinteraction of produced hadrons such as mesons and baryons with the remnant nucleus as they escape, which can be described as final-state interactions (FSI). This idealization is a common model used by neutrino event generators. However, the existence of the nucleus influences all three stages in ways that are not completely understood and this makes the simulation process difficult [3].

2.2.1 Background for Experiment

The connection between the observations in the ND and the FD is made using a simulation that convolves models of the neutrino interactions, nuclear effects, neutrino flux, and detector response. One of the issues is that there are backgrounds. One of the backgrounds to a v_e appearance oscillation signal at the FD is coming from the intrinsic v_e content of the neutrino beam. Besides, a significant background to a v_e appearance oscillation signal at the FD is due to the NC events with a π_0 that leads to electromagnetic showers from the produced photons that can mimic v_e charged-current (CC) interactions. The design of the ND complex can be driven by understanding these complicating effects and reducing the uncertainty they generate [3]. The CC interactions of v_e and $\bar{v}_e$ intrinsic to the beam, misidentified v_μ and $\bar{v}_\mu$ CC events, v_τ and $\bar{v}_\tau$ CC events in which the taus' decay into electrons or positrons, and neutral current (NC) backgrounds are in general the backgrounds to v_e appearance in the far detector. NC and v_τ backgrounds are due to higher-energy neutrinos' interactions but they contribute to backgrounds largely at low energy, which are critical for the sensitivity to CP violation [4]. Both the level of these backgrounds, and the identification and detection efficiency vary with energy of neutrino and known poorly. In the near detector, NC events are the main background to CC interaction measurements. The measurement of NC interactions at the near detector helps researchers to understand better on the NC background at the far detector.

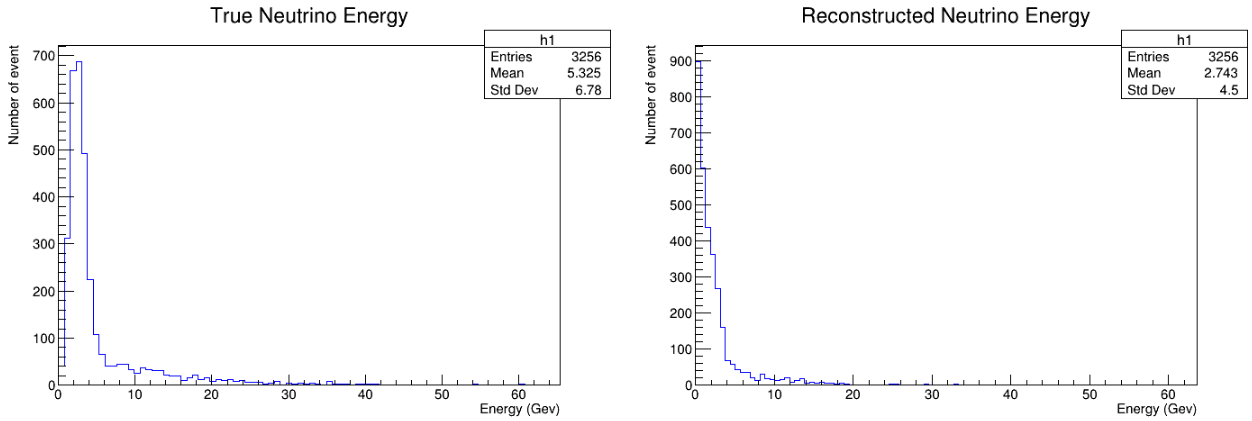

Figure 2: Histogram of true neutrino energy (left) and reconstructed neutrino energy (right).

2.2.2 Data Simulation

The simulated flux, GENIE neutrino interaction generator [6], Geant4 based detector simulation and a parameterized detector response are used to simulate the reconstructed momentum and energy of each final-state particle. Then, the simulated energy deposition of the particles in each interaction is used in the calculation of reconstructed kinematic quantities, for instance, the neutrino energy. The identification of lepton candidates is used to determine the event sample classifications (v_e CC-like, v_μ CC-like, or NC-like) and misidentification rates. Lepton candidates are chosen according to different criteria such as particle kinematics, detector thresholds, and probabilistic estimates of particle fates.

The simple picture on the flow of the simulation[1] process of a neutrino-interaction event with event generator is as follows. First, a random neutrino flavour and energy are generated according to the the DUNE flux model. Then, an interaction mode is chosen randomly. Lastly, simulating the interaction of initial scattering and final-state interaction. All the event configuration information (e.g. run number, near vs far detector, beam mode), truth information (the generated interaction) and reconstructed information (what we saw in the detector) of simulation are stored in Common Analysis Files (CAFs). These CAFs are a DUNE-specific ROOT ntuple with a filename extension, root. With the CAFs, the information like kinetic energy distribution curve of neutrino can be visualized. The Fig. 2 shows the histogram of true neutrino energy (left) and reconstructed neutrino energy (right).

3 Methodology

In this research project, we analyzed the CAFs by using Python interface, PyROOT in SWAN (Service for Web based ANalysis). I accessed the simulation data provided by my supervisor in the CERN cloud (EOS) with SWAN. For this research, we focused on the events that are occurred in the LArTPC, the critical component of DUNE near detector. It is indicated with the label "isFD = 0" in the files (e.g. RHC.*.CAF.root and FHC.*.CAF.root). We analyzed two different types of simulation data. The first case is with neutrino mode (forward horn

[1] Refs. [7, 8, 9] contain the detailed information about simulation.

Table 2: The neutrino interaction modes.

Mode	Name
1	QE (Quasi-elastic)
2	Single Kaon (Kaon production)
3	DIS (Deep inelastic scattering)
4	RES (Resonant)
5	COH (Coherent)
6	Diffractive
7	Nu-e El (Neutrino scattering with atomic electrons)
8	IMD (Inverse muon decay)
9	AMnuGamma (Anomaly-mediated neutrino-gamma interaction)
10	MEC (Meson-exchange current, also known as 2p2h)
11	COHEl
12	IBD (inverse beta decay)
13	GlashowRES (Glashow resonance)
14	IMDAnnihalation

current, FHC) while the second one is with antineutrino mode (reverse horn current, RHC). In order to obtain more accurate finding, we used a total of 3948 and 994 sample files for the analysis of the neutrino mode (FHC) and antineutrino mode (RHC) respectively. For both cases of beam mode, the CC and NC events were studied with the construction of table and plotting of some quantities.

Some tables were made to analyse the CC and NC interactions (each for FHC or RHC beam mode) for the true and reconstructed events with different neutrino interaction modes (from 1 to 14 as shown in Table 2). We obtained the number of events as the entries in the table by choosing some combinations of event selections (Cut) on the simulation data. We wrote some Python codes with PyROOT to extract the information from the files (FHC.*.CAF.root or RHC.*.CAF.root). We also normalized all the number of events with the expected number of POT per year, 1.1×10^{21}.

Besides, we plotted some quantities, for example, the ratio of difference between true proton energy and reconstructed proton energy (eP−eRecoP) to true proton energy (eP). We explored the simulation data to investigate the NC background that were possibly originated from the misidentification of final state particles.

4 Results

In this work, we considered the number of POT in the analysis results. The analysis was basically carried out for two different cases. The first case of analysis is related to simulation with FHC beam mode, while the second case of analysis is related to simulation with RHC beam mode.

For the FHC beam mode, we had about 3.94959×10^{19} of number of POT where was obtained by combining all the FHC files. With the available CAFs that consisted of the label

Table 3: The number of events under different combinations of cuts for different neutrino interaction modes in FHC beam mode. The number of events are normalized with expected number of POT per year.

Mode	isCC == 0 && reco_nc == 0	isCC == 0 && reco_nc == 1	isCC == 1 && reco_nc == 0	isCC == 1 && reco_nc == 1
1	4762.515	15820295.423	29659273.149	20290208.304
2	0.0	0.0	0.0	0.0
3	827340.786	30078931.5	52055042.308	42462027.848
4	300623.323	22916832.875	37538227.779	26735339.52
5	4121.943	693154.833	947155.64	272744.507
6	0.0	0.0	0.0	0.0
7	0.0	0.0	55.702	21361.691
8	0.0	0.0	55.702	5458.789
9	0.0	0.0	0.0	0.0
10	0.0	0.0	8240822.227	4331716.39
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	55.702

"isFHC = 1", we constructed the Table 3. In Table 3, there are four different combinations of event selections. The entries in the Table 3 were the number of selected events after the normalization with the weight of 27.85097. The event selection "isCC == 0" means the event is a true neutral current event, while the event selection "isCC == 1" means it is a true charged current event. On the other hand, the event selection "reco_nc == 0" means the interaction is a reconstructed charged current interaction, while the event selection "reco_nc == 1" means it is a reconstructed neutral current interaction. We have a total of 14 neutrino interaction modes for each combination choice. It can be easily seen that the event selection with the combination of "isCC == 1 && reco_nc == 0" always contained the highest number of events except for some particular interaction modes (e.g. mode 7, 8 and 14). Some neutrino interaction modes are very rare events, so the number of events were appeared to be very small or zero. For example, the number of event is zero for all the combinations of event selections under the neutrino interaction mode 13[2]. This is because it is not relevant for DUNE since it only occurs when the center of mass energy is close to the mass of the W boson. The number of event under the neutrino interaction mode 6[3], is also zero, since in the liquid argon experiment there is no free proton.

Besides, we plotted some histograms in order to analyse the simulation data. Figure 3 shows the distribution of number of events that are associated with proton on the ND FHC samples to describe the level of proton energy reconstruction. It shows how well the reconstruction of events are carried out. Similar results are seen for the RHC samples. The

[2]refers to Table 2.

[3]reaction $v_l + p \to l^- + \pi^+ + p$ or $\overline{v}_l + p \to l^+ + \pi^- + p$, where p means a "free proton" and l means a charged lepton.

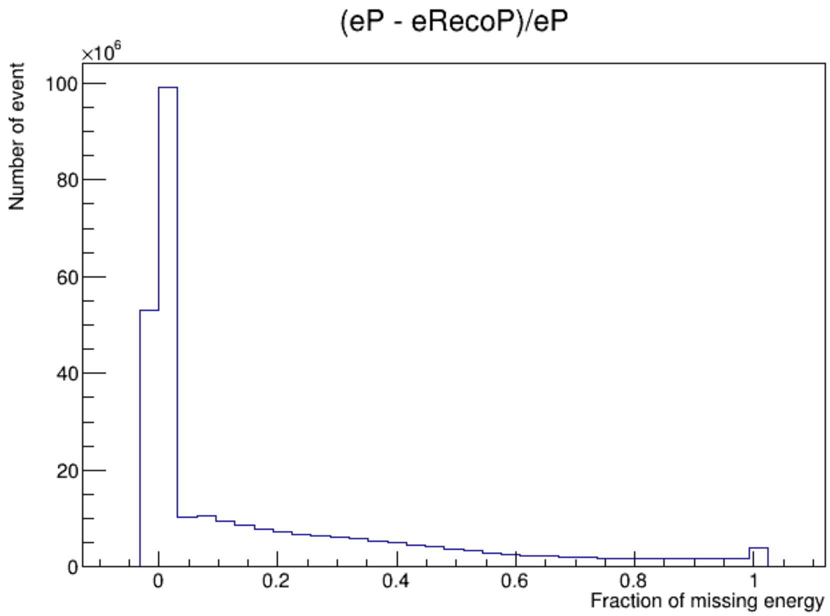

Figure 3: The number of events for the ratio of difference between true proton energy and reconstructed proton energy to true proton energy ND FHC spectrum. The plot is normalized with the expected number of POT per year. Both CC and NC events are considered in this plot.

CC interaction is studied by investigating the difference of true neutrino energy with the sum of the reconstructed energies (e.g. eRecoP + eRecoN + eRecoPip + eRecoPim + eRecoPi0 + eRecoOther)[4] and outgoing true lepton energy (LepE). It is shown in one dimensional histogram from Figure 4. On the other hand, the NC interaction can be studied through the reconstructed energies of outgoing particles (e.g. eRecoP + eRecoN + eRecoPip + eRecoPim + eRecoPi0 + eRecoOther) when the reconstructed energy of charged lepton is not under the consideration. It is represented in one dimensional histogram as depicted in Figure 5.

For the RHC beam mode, we had roughly 9.94657×10^{18} of number of POT where was obtained by combining all the RHC files. With the available CAFs that consisted of the label "isFHC = 0", we constructed a table, Table 4. In Table 4, we have the same four different combinations of event selections as Table 3. The entries in the Table 4 were also the number of selected events after the normalization, but with the weight of 110.59089 in this case. We have also a total of 14 neutrino interaction modes for each combination choice. The constitution of the RHC spectrum in Table 4 is almost similar to Table 3. There is only a tiny difference in the neutrino interaction mode 8 and 14 respectively.

Furthermore, we also carried out the same analysis procedures to study the ND RHC samples. Figure 6 shows the distribution of number of events that are associated with proton. It shows how well the reconstruction of events with protons in the final state are carried out. One dimensional histogram was plotted as shown in Figure 7 to investigate

[4]where the eRecoP is the reconstructed energy of proton, eRecoN is the reconstructed energy of neutron, eRecoPip is the reconstructed energy of π^+, eRecoPim is the reconstructed energy of π^-, eRecoPi0 is the reconstructed energy of π^0 and eRecoOther is the reconstructed energy of other particles.

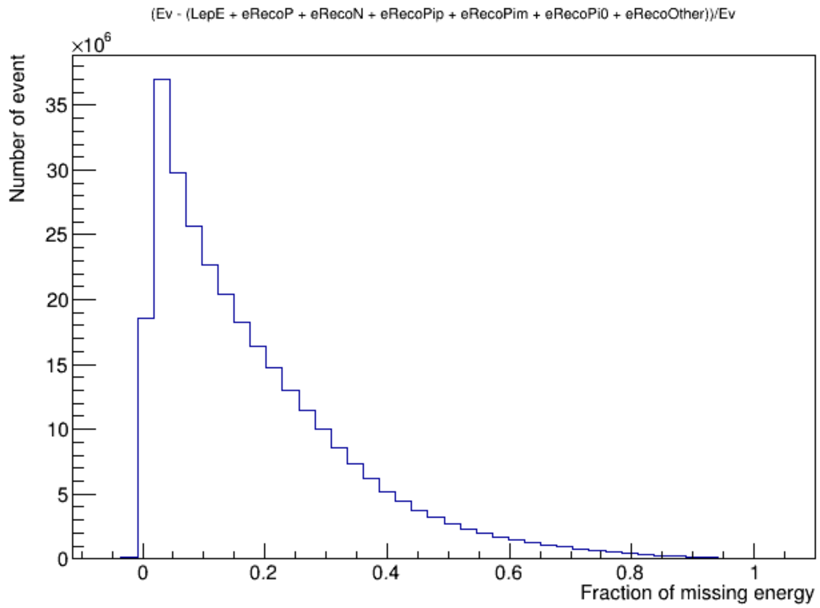

Figure 4: Ratio of difference between the true neutrino energy with the sum of the reconstructed energies of outgoing particles and true lepton energy to true neutrino energy ND FHC spectrum. The reconstructed charged lepton energy (Elep_reco) is not included in this plot, but the true lepton energy either energy of outgoing neutrino or charged lepton in its final state is taking into account. The plot is normalized with the expected number of POT per year. Both CC and NC events are considered in this plot.

Table 4: The number of events under different combinations of cuts for different neutrino interaction modes in RHC beam mode. The number of events are normalized with expected number of POT per year.

Mode	isCC == 0 && reco_nc == 0	isCC == 0 && reco_nc == 1	isCC == 1 && reco_nc == 0	isCC == 1 && reco_nc == 1
1	1437.682	11082755.47	16308506.804	9841372.728
2	0.0	0.0	0.0	0.0
3	515021.776	18697601.805	32013519.121	20743422.683
4	210786.237	15462154.722	23330585.968	13068636.085
5	4865.999	745824.963	983484.787	319054.718
6	0.0	0.0	0.0	0.0
7	0.0	0.0	110.591	21454.633
8	0.0	0.0	0.0	6524.863
9	0.0	0.0	0.0	0.0
10	0.0	0.0	5494708.379	2730931.442
11	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0

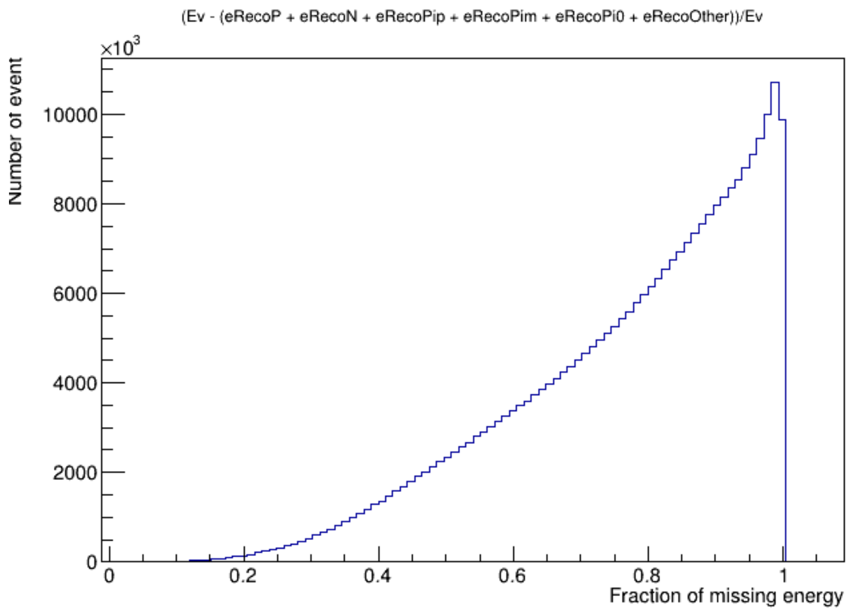

Figure 5: Ratio of difference between true neutrino energy and reconstructed energies of outgoing particles (e.g. eRecoP + eRecoN + eRecoPip + eRecoPim + eRecoPi0 + eRecoOther) to true neutrino energy ND FHC spectrum. The reconstructed energy of charged lepton (Elep_reco) is not under the consideration. The plot is normalized with the expected number of POT per year. Both CC and NC events are considered in this plot.

the CC interaction. On the other hand, the NC interaction can be studied through the reconstructed energies by ignoring the reconstructed charged lepton energy (Elep_reco). It is described by the distribution on one dimensional histogram as depicted in Figure 8.

5 Discussion

In the analyses of CAFs based on true or reconstructed quantities as shown in Table 3 and Table 4, we expected the number of events for the event selections "isCC == 1 && reco_nc == 1" to be very low. However, it is not the case. The number of events for the event selections "isCC == 1 && reco_nc == 1" is quite close to the number of events for the event selections "isCC == 0 && reco_nc == 1". Under the current assumptions of event reconstruction performance in the DUNE ND, 42.3% of the CC events are mis-identified as NC events in FHC and 37.1% in RHC. As a consequence of this, for the events identified as NC events, only 42.5% are true NC events in FHC and 49.6% in RHC. This high mis-identification rate will affect the precision with which NC interactions will be measured in the near detector. Nevertheless, we expect to observe tens of millions of NC events per year in the ND, so we should be able to measure the NC background with a statistical precision much better than 1%. This also means the DUNE ND measurements will likely be limited by systematic uncertainty from the start of the experiment.

The analyses presented here are based on simulation, parameterized reconstruction, and

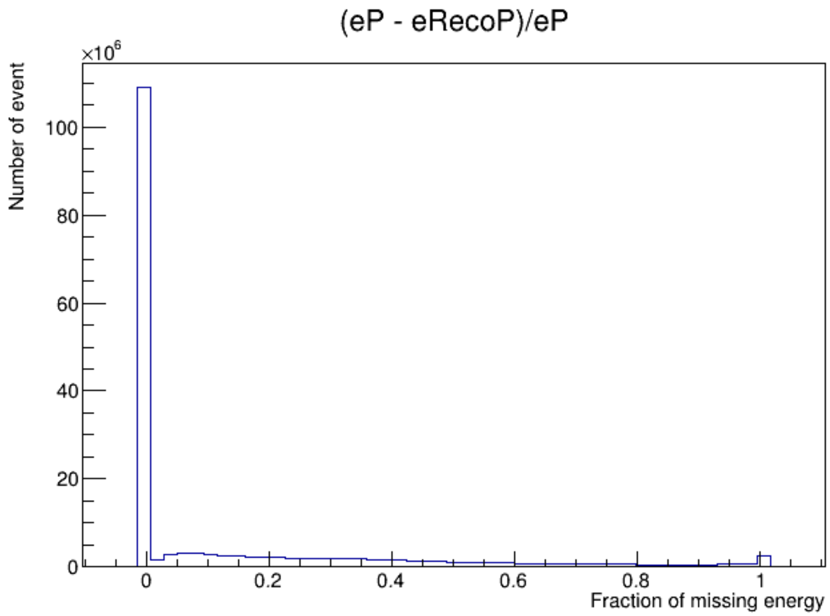

Figure 6: The number of events for the ratio of difference between true proton energy and reconstructed proton energy to true proton energy ND RHC spectrum. The plot is normalized with the expected number of POT per year. Both CC and NC events are considered in this plot.

event selection using a Monte Carlo simulation of the ND of the DUNE. Detailed uncertainties from flux, detector effects and the neutrino interaction model have not been included in this simple analysis. Hence, this analysis can be further improved by including the detailed uncertainties. These studies demonstrate that DUNE will be able to determine the NC background occurred in the near detector, ND, LArTPC. Future improvements are expected when the full potential of the DUNE ND is involved in the analysis. Samples of events from other components of DUNE ND are not explicitly included here, therefore we presume to be able to have better control on the NC background signal in DUNE ND [9].

DUNE will be able to make remarkable contributions in the completion of the standard three flavor mixing picture through precise measurements. Besides, the precise measurements of the three-flavor mixing parameters may also produce inconsistencies that hinted at physics beyond the standard three-flavor model. DUNE can also give some insights to the theoretical works in understanding the relationship between the generational structure of quarks and leptons. The observation of CP-violation in neutrinos would provide some clues towards the understanding of the baryon asymmetry of the universe.

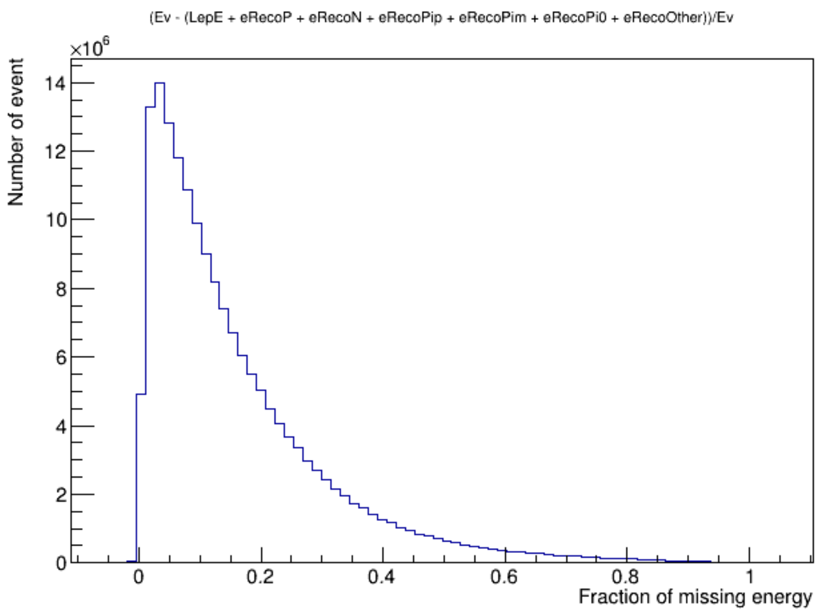

Figure 7: Ratio of difference between the true neutrino energy with the sum of the reconstructed energies of outgoing particles and true lepton energy to true neutrino energy ND RHC spectrum. The reconstructed charged lepton energy (Elep_reco) is not included in this plot, but the true lepton energy either energy of outgoing neutrino or charged lepton in its final state is taking into account. The plot is normalized with the expected number of POT per year. Both CC and NC events are considered in this plot.

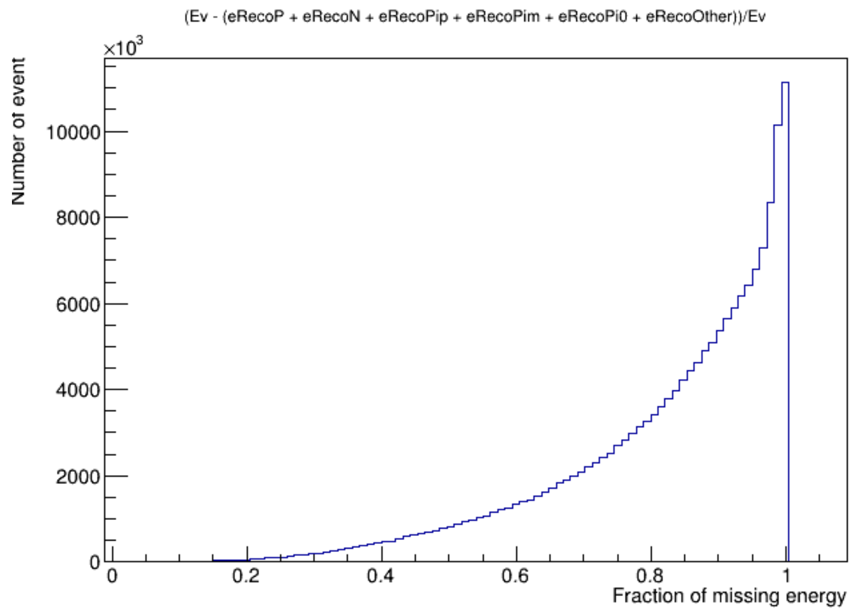

Figure 8: Ratio of difference between true neutrino energy and reconstructed energies of outgoing particles (e.g. eRecoP + eRecoN + eRecoPip + eRecoPim + eRecoPi0 + eRecoOther) to true neutrino energy ND RHC spectrum. The reconstructed energy of charged lepton (Elep_reco) is not under the consideration. The plot is normalized with the expected number of POT per year. Both CC and NC events are considered in this plot.

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