

Research Article

Nuclear Effects and CP Sensitivity at DUNE

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The precise measurement of neutrino-oscillation parameters is one of the highest priorities in neutrino-oscillation physics. To achieve the desired precision, it is necessary to reduce the systematic uncertainties related to neutrino energy reconstruction. An error in energy reconstruction is propagated to all the oscillation parameters; hence, a careful estimation of the neutrino energy is required. To increase the statistics, neutrino-oscillation experiments use heavy nuclear targets like argon ($Z = 18$). The use of these nuclear targets introduces nuclear effects that severely impact the neutrino energy reconstruction which in turn poses influence in the determination of neutrino-oscillation parameters. In this work, we have tried to quantify the presence of nuclear effects on the bounds of the CP phase by DUNE using final state interactions.

1. Introduction

Neutrino-oscillation physics has entered into the era of precision measurement from the past two decades. Significant achievements have been made in the determination of the known neutrino-oscillation parameters, and continuous attempts are being made to estimate the unknown neutrino-oscillation parameters precisely. The neutrino-oscillation parameters governing the three-flavor neutrino-oscillation physics are three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$, a leptonic CP phase δ_{CP} , and two mass-squared differences, Δm_{21}^2 (solar mass splitting) and Δm_{31}^2 (atmospheric mass splitting). Many experiments working in collaboration [1–4] worldwide have led to the precise determination of the abovementioned neutrino-oscillation parameters leaving some ambiguities yet to be resolved. The unknown oscillation parameters in the picture are (1) the octant of θ_{23} whether it lies in the lower octant ($\theta_{23} < \pi/4$) or in the higher octant ($\theta_{23} > \pi/4$); (2) the sign of $|\Delta m_{31}^2|$, i.e., neutrino mass eigenstates m_i ($i = 1, 2, 3$) are arranged in normal order ($m_1 \ll m_2 \ll m_3$) or inverted order ($m_2 \approx m_1 \gg m_3$); and (3) the leptonic δ_{CP} phase which can lie in the entire range $-\pi < 0 < +\pi$. Accurate measurement of the leptonic CP phase can lead to further studies on the origin of leptogenesis [5] and baryon asymmetry of the universe [6]. Determination of the precise value of δ_{CP} is also required

for explaining the phenomenon of sterile neutrinos [7]. The global analysis results as indicated in [8] report current bounds on oscillation parameters which have been performed by several experimental groups.

A defining challenge for neutrino experiments is to determine the incoming neutrino energy since the configuration of the outgoing particles and kinematics of the interaction within the nucleus are completely unknown. In collider experiments, the neutrino beams are generated via secondary decay products which assign a broad range of energies to the neutrinos; hence, their energy reconstruction becomes difficult. Here, the neutrino energy is reconstructed from final state particles that are produced in neutrino-nucleon interactions. The present-day neutrino-oscillation experiments use heavy nuclear targets like argon ($Z = 18$), in order to collect large event statistics. With a nuclear target, where neutrinos interact with Fermi moving nucleons, uncertainties in the initial state particles produced at the primary neutrino-nucleon interaction vertex arise. These nuclear effects are capable enough to change the identities, kinematics, and topologies of the outgoing particles via final state interactions (FSI), thus hiding the information of the particles produced at the initial neutrino-nucleon interaction vertex which gives rise to fake events. Detailed discussion regarding the impact on atmospheric oscillation parameters due to the presence

of FSI in the QE interaction process can be found in [9] and due to fake events stemming from QE and RES processes can be found in [10]. The impact of cross-sectional uncertainties on the CP violation sensitivity can be found in [11]. The impact of missing energy on the measurement of the CP-violating phase in the θ_{23} - δ_{CP} plane has been previously performed in [12]. For further studies on the impact on neutrino-oscillation parameters due to the presence of FSI, one can refer to [13–15].

In this work, we attempt to study the impact of nuclear effects imposed by FSI in the quasi elastic (QE), resonance (RES), and deep inelastic scattering (DIS) interaction processes. Understanding nuclear effects will give us a handle to filter out true events from the fake events in a given neutrino-nucleon interaction which will lead to an accurate measurement of neutrino-oscillation parameters.

2. Neutrino-Oscillation Studies with the Long Baseline Experiment DUNE

The Deep Underground Neutrino Experiment, DUNE [16, 17], an upcoming long baseline neutrino-oscillation experiment, to be set up in the US is aiming for discovering the unknown oscillation parameters and explore new physics. The 1300 km baseline, stretching from the LBNE facility at Fermilab to Sanford Underground Research Facility (SURF) at South Dakota, is ideal for achieving the desired sensitivity for CP violation and mass hierarchy. The far detector will be composed of 40 ktons of liquid argon (nuclear target with $Z = 18$) as detector material which will provide large event statistics. The DUNE-LBNF flux spreads in the energy range of 0.5 to 10 GeV, with average energy peaking at 2.5 GeV. It is composed of QE, resonance, DIS, and coherent neutrino-nucleon interaction processes with resonance being the dominant interaction process in this energy regime. The energy-dependent cross section is different for each interaction process.

To evaluate the sensitivity of LBNE and to optimize the experimental design, it is important to accurately predict the neutrino flux presented in Figure 1(a) produced by the neutrino beam. The corresponding neutrino-oscillation probability is presented in Figure 1(b) for ν_μ disappearance and ν_e appearance channels.

3. Final State Interactions and Nuclear Effects

A neutrino when interacting with a Fermi moving neutron within the nucleus giving a muon and a proton as the final state products is defined as a true charged current quasi elastic (CCQE) process and is represented as $\nu n \rightarrow \mu^- p$. These processes are accompanied by certain other processes in which a pion or a delta resonance is also produced in the initial neutrino-nucleon interaction vertex, e.g., $\nu p \rightarrow \mu^- p \pi^+$ or $\nu p \rightarrow \mu^- \Delta^{++}$, but gets absorbed in the nuclear environment while propagating out of the nucleus via final state interactions. Such particles are not captured by the detector since they are not able to come out from the nucleus and thus lead to missing energy and appear as QE-like events. These events which are not produced as QE but appear as

QE are known as fake-QE events (stuck pion event). These events are counted by the detector as true-QE events though they are not of true-QE origin and thus lead to uncertainties in the QE cross-section measurement. Contrary to the above process, another possibility is the production of a nucleon in the initial neutrino-nucleon QE interaction, which might get rescattered within the nucleus and produce a pion in the final state. Such an event, though having a true-QE origin will be tagged as a QE-like event due to the presence of a pion in the final state. The appearance of such events gives way to uncertainties in the reconstruction of neutrino energy, and the error caused in the energy reconstruction of the neutrino is further propagated to the measurement of neutrino-oscillation parameters. Figure 2 presents migration matrices constructed between true (t) and reconstructed (r) neutrino energies for QE, RES, 2p2h (multinucleon processes), and non-RES interaction processes, using argon as the nuclear target. The migration matrices are computed following the technique mentioned in Ref. [9]. The neutrino-argon interaction events are generated in the energy range of 0.2 to 5 GeV; further, it is binned into 46 equal bins to observe the smearing in the reconstructed neutrino energy for different interaction processes as described above.

Every element $n(E_t, E_r)$ in each of the migration matrices represents the probability that an event which is produced with a certain true energy E_t is observed with some different energy E_r . Any difference in energy between E_t and E_r , produces smearing along the diagonal line, which is evident from Figure 2. If the true and reconstructed neutrino energies are the same, then we will get a diagonal line without any smearing. The non-RES and RES events appear to smear maximally while the 2p2h and QE events smear to a lesser extent as compared to the other two processes. From Figure 2, we can see that the error in energy reconstruction occurring in the various processes cannot be ignored if one has to aim toward reducing the systematic uncertainties in the forthcoming neutrino-oscillation experiments.

4. Simulation and Result

Approximately 2×10^5 events are generated using the DUNE flux for muon disappearance channel with the help of GiBUU (Giessen Boltzmann-Uehling-Uhlenbeck) [18, 19]. The GiBUU model developed as a transport model for various interaction processes induced by the nucleus, nucleon, pion, and electron is based on a coupled set of semiclassical kinetic equations [20]. GiBUU applies a semiclassical approach and models the FSI by solving the Boltzmann-Uehling-Uhlenbeck equations. Recently, the GiBUU code has also included the DIS interaction process successfully [21]. The migration matrices are generated using GiBUU and are inserted in the required format into GLOBES [22–26]. The systematics considered in our work is as follows: signal efficiency is 85% and normalization error and energy calibration error for the signal and background are 5%, 10%, and 2%, respectively. The running time considered is 10 years in neutrino mode with a 35 kton fiducial mass of the detector. The values of oscillation parameters used in

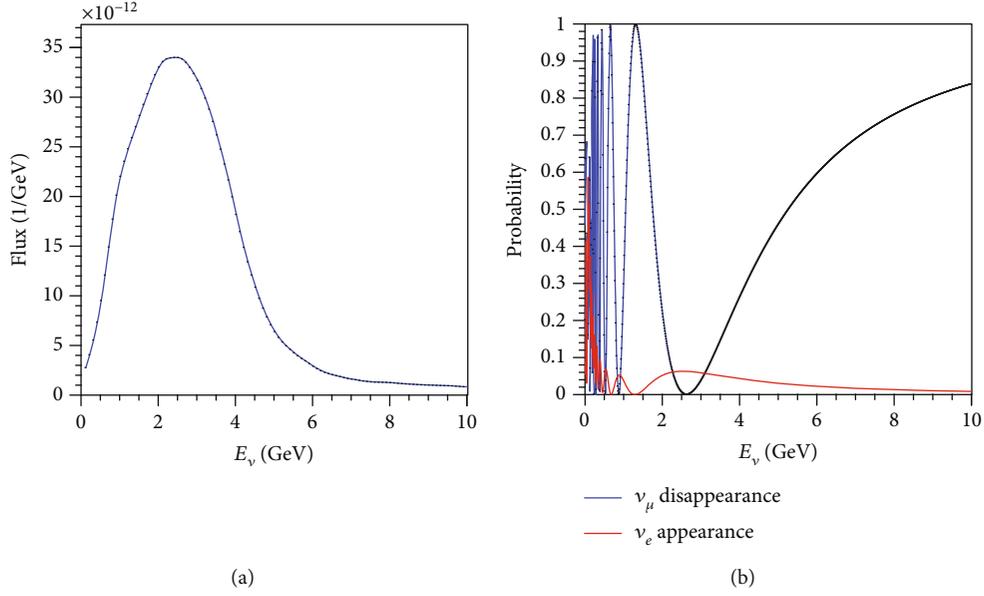


FIGURE 1: Flux distribution in the energy regime 0.1-10 GeV and neutrino-oscillation probability presented in the (a) and (b), respectively.

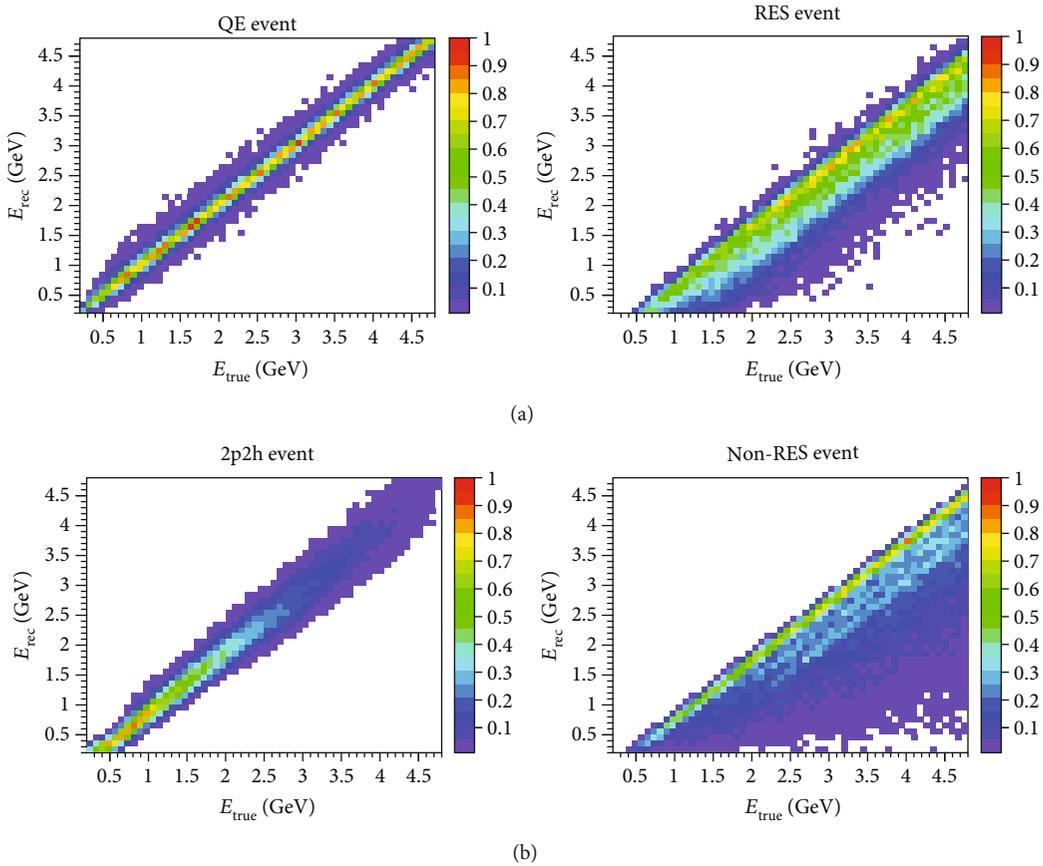


FIGURE 2: Two-dimensional migration matrices for QE, RES, 2p2h and non-RES events (in (a) and (b) as indicated) generated using GiBUU for the argon target.

this work are presented in Table 1 and are motivated from [27, 28]. The value of δ_{CP} considered in this work lies within the present set bounds on δ_{CP} [29].

Here, we consider a parameter α , which helps us to incorporate nuclear effects in our analysis and explore the impact of nuclear effects in two extreme cases, i.e., a case in which we

TABLE 1: True oscillation parameters considered in our work [27, 28].

θ_{12}	33.58°
θ_{13}	8.48°
θ_{23}	45°
δ_{CP}	180°
Δm_{21}^2	$7.50e^{-5} \text{ eV}^2$
Δm_{31}^2	$2.40e^{-3} \text{ eV}^2$

have complete knowledge of nuclear effects and another case in which nuclear effects are completely neglected. It can be considered as a way of including systematic uncertainties; such an approach has been considered previously in [10, 30].

We present the position of the best fit corresponding to values of α taken as 0 and 1, by plugging them in

$$N_i^{\text{rtest}}(\alpha) = \alpha \times N_i^{\text{QE}} + (1 - \alpha) \times N_i^{\text{QE-like}}, \quad (1)$$

$$N_i^{\text{rtest}}(\alpha) = \alpha \times N_i^{\text{QE+RES+DIS}} + (1 - \alpha) \times N_i^{\text{QE-like+RES-like+DIS-like}}, \quad (2)$$

where N is the total number of events. Here, N_i^{QE} in equation (1) represents the pure QE events, i.e., at the initial neutrino-nucleon interaction vertex when the neutrino interacts with the nucleon, the interaction was of QE nature. The products (lepton and a hadron) remain unchanged after traveling through the nucleus, i.e., nature of the initial interaction remains unchanged and is considered as a QE-type interaction, whereas $N_i^{\text{QE-like}}$ are those events which at the initial neutrino-nucleon interaction vertex were not of pure QE origin, but as the products travel inside the nucleus, their initial nature gets modified due to nuclear effects, and at the time of detection, they appear as a QE-type interaction. Similarly, $N_i^{\text{QE+RES+DIS}}$ in equation (2) is the number of events which originates from true-QE, resonance, and DIS interaction processes while $N_i^{\text{QE-like+RES-like+DIS-like}}$ is the number of events which have a contribution from other processes as well.

Two cases arise:

1. When $\alpha = 1$, the second term present in each of equations (1) and (2) does not contribute to the event rate which implies that nuclear effects are completely neglected
2. When $\alpha = 0$, nuclear effects are perfectly known and the contribution arising from the first term of equations (1) and (2) vanishes

In the real scenario, our knowledge of nuclear effects lies between these two extreme cases. To quantify the error on the models defining nuclear effects, the introduction of the parameter α can help us to study the above two extreme cases. “ α ” simply indicates the presence of an error occurring due to insufficient knowledge of nuclear effects. We have also performed the analysis at $\delta_{CP} = 0^\circ$ for the QE + RES + DIS event sample which can be found in the appendix.

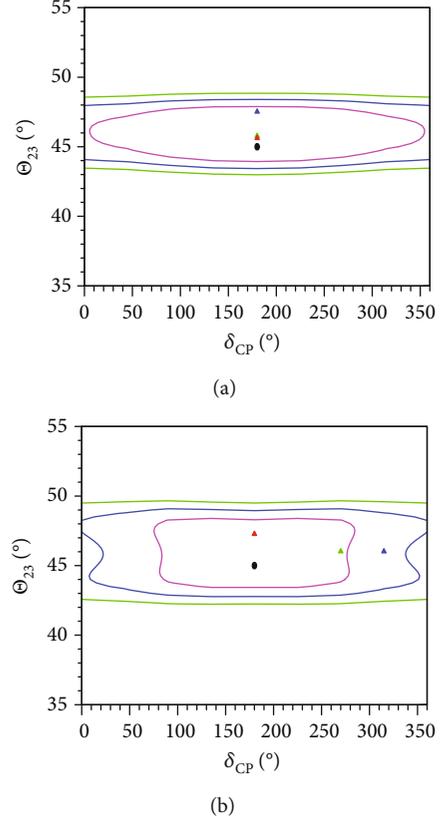


FIGURE 3: Confidence regions in the $(\theta_{23}, \delta_{CP})$ plane, obtained by using the migration matrices of pure QE and QE-like events are shown in (a) and by using the migration matrices of pure QE + RES + DIS and QE + RES + DIS-like events are shown in (b). The circle ($\alpha=1$) shows the true value of the oscillation parameters while the blue ($\alpha=0$), red ($\alpha=0.3$), and green ($\alpha=0.5$) triangles represent the best fit points.

5. Conclusion

Neutrino interactions on a heavy nuclear target (high atomic number, i.e., $A > 12$) are severely affected due to the presence of nuclear effects. We have performed our analysis for the argon target which will be used in DUNE. The study is performed for the QE interaction channel and for a combination of QE, RES, and DIS interaction processes. The impact of FSI on CCQE and CCRes interaction channels has been previously studied on atmospheric oscillation parameters in the Refs. [10, 30]. We have tried to explore the impact of FSI in θ_{23} - δ_{CP} plane in both the cases (i) only QE event and (ii) QE + RES + DIS events.

The positions of the best fit point corresponding to four values of $\alpha \approx 0, 0.3, 0.5$, and 1 for CCQE and CC (QE + RES + DIS) processes are represented in Figures 3(a) and 3(b), respectively. The best fit points for $\alpha = 0.3$, $\alpha = 0.5$, and $\alpha = 1$ are represented by red, green, and blue triangles, respectively. We notice that the deviation of the best fit point from the true input values increases as the value of α increases. In Figure 3(a), we observe a slight shift in the best fit values of oscillation parameters from the true value (θ_{23}), if we increase the value of α from $\alpha = 0$ to $\alpha = 0.5$. The best fit

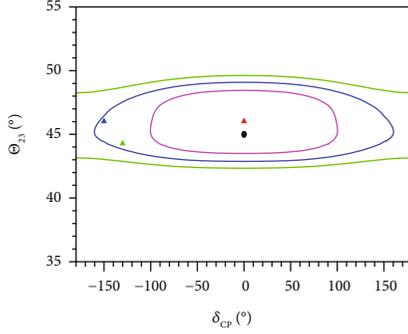


FIGURE 4: Confidence regions in the $(\theta_{23}, \delta_{CP})$ plane, obtained by using the migration matrices of pure QE + RES + DIS and QE + RES + DIS-like events. The circle ($\alpha = 1$) shows the true value of the oscillation parameters while the blue ($\alpha = 0$), red ($\alpha = 0.3$), and green ($\alpha = 0.5$) triangles represent the best fit points.

values of $\alpha = 0.3$ and $\alpha = 0.5$ nearly overlap. This indicates that if the value of α is changed by a small amount (for $\alpha < 0.5$), a slight change is observed in the best fit value of oscillation parameters θ_{23} in the QE case. But as we increase the value of α beyond 0.5, a remarkable change of $\sim 1\sigma$ is observed in the determination of θ_{23} . If we take a data sample where events arising via the QE + RES + DIS channels are taken into consideration, for this situation with $\alpha = 0.3$, we observe a roughly $< 1\sigma$ shift in the value of θ_{23} , whereas if the value of α is increased to 0.5, there is a negligible shift in the true value of θ_{23} but a nearly $\sim 1\sigma$ shift in the value of δ_{CP} is observed. As we increase the value of $\alpha > 0.5$, the shift in the δ_{CP} value increases and gives a shift of roughly 2σ .

Our results show that for an experiment observing QE, RES, and DIS events, with 50% knowledge of FSI, there is a $\approx 1\sigma$ bias in the extracted value of δ_{CP} . If we have complete knowledge of FSI, the bias in the extracted value of δ_{CP} goes beyond 1σ . For an experiment observing only QE-like events, a 1σ bias in the determination of the mixing angle θ_{23} is noted. These results indicate the impact of nuclear effects that may result from uncertainties present in the nuclear models.

In an outlook of the study, we can conclude that the best strategy for third-generation neutrino-oscillation experiments seems to minimize detection thresholds of the employed detectors and to perform an extensive authentication of the accuracy of nuclear models employed in data analysis. Employment of nuclear targets in neutrino-oscillation experiments aids in boosting the event statistics which reduces the statistical error, but we need to pin down the systematic uncertainties arising from the persistent nuclear effects that will bring us a step closer to achieving our goals.

Appendix

Here, we present the confidence regions in the θ_{23} - δ_{CP} plane using the migration matrices of pure QE + RES + DIS and QE + RES + DIS-like events with a different true input value of $\delta_{CP} = 0^\circ$. The positions of the best fit point corresponding to four values of $\alpha \approx 0, 0.3, 0.5$, and 1 for CC (QE + RES + DIS) processes are represented in Figure 4. We notice that the deviation of the best fit point from the true input value

increases as the value of α increases. For this situation with $\alpha = 0.3$, we observe a slight shift in the value of θ_{23} only, whereas if the value of α is increased to 0.5, there is a negligible shift in the true value of θ_{23} , but a nearly $\sim 2\sigma$ shift in the value of δ_{CP} is observed. As we increase the value of $\alpha > 0.5$, the shift in the δ_{CP} value increases and gives a shift of roughly 2σ . The nature of shift of the best fit point is similar to the one illustrated in Figure 3(a). From this, we can say that the impact of nuclear effects is not affected by the choice of the input parameters.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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