Effect of final state interactions on neutrino energy reconstruction at DUNE

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Abstract:
We quantitatively study the percentage of fake events present in CCQE and CCRes interactions and the impact of final state interactions on the neutrino oscillation parameters at DUNE. Resonance interaction will be the most dominant interaction in the oscillation sensitive region of DUNE. The $\nu_\mu$-disappearance Oscillation channel is studied using LAr detector. We find that nuclear effects and detector thresholds play a significant role in CCQE and CCRes interactions and these nuclear effects induce a significant bias in the determination of atmospheric oscillation parameters. The impression of nuclear effects on the determination of $\theta_{23}$ is quantified in this work.

Keywords: Final State interaction, resonance, oscillation physics, fake events.

1 Introduction:
The neutrino nucleon interaction study is vital for any long baseline neutrino experiments. In these experiments the neutrino interacts with a nucleon present in the target nucleus of the detector. As these nucleons are not free hence nuclear effects cannot be ignored while studying the physics related to neutrino nucleon interaction. In neutrino oscillation experiments the neutrino interaction with nuclear targets of the detector provides a quantitative handle to neutrino oscillation physics. Materials with high atomic number are used as detector materials in order to increase the interaction rates. Nuclear effects are highly intertwined in the nuclear targets i.e. nuclear Fermi motion effects, uncertainties from the binding energy, multinuclear correlation and final state interactions of produced hadrons in different interaction channels.

A quantitative understanding with sufficient accuracy of neutrino nucleon interaction cross section is essential for the extraction of neutrino energy and neutrino oscillation parameters from the event rate recorded by the detector. The neutrino beam generated in neutrino oscillation experiments is not monochromatic on the contrary it is sufficiently widespread. According to neutrino experiment selected i.e. NOVA [1], T2K [2], MINOS [3], DUNE [6] etc., the energy of neutrino beam varies from few MeV to several tens of GeV. In this energy region the basic interaction modes are quasi elastic scattering (QE), resonance (Res), deep inelastic scattering (DIS), two body scattering on a pair of correlated nucleons and coherent pion production. Below 1 GeV quasi elastic scattering is the dominant mode of interaction but as we increase in energy resonance and DIS processes overshadow the QE interactions. Superposition of different interaction mechanism in a given neutrino beam complicates the reconstruction of neutrino energy whose precise knowledge is the central element of neutrino oscillation physics [4,5,6,7].

The process of neutrino energy reconstruction is very difficult and entirely different from other leptons. Neutrino energy reconstruction can be performed by two methods: (i) Kinematic method: uses the kinematic information of single outgoing lepton and (ii) Calorimetric Method: Uses the information of all outgoing particles for the construction of neutrino energy.

With the upcoming neutrino experiments the statistical error is getting reduced and that draws our attention towards the systematic errors erupting in neutrino oscillation experiments. The main error in the neutrino energy reconstruction arises due to nuclear effects. The neutrino energy is reconstructed from the final state measurements and further the final state measurements strongly depends on nuclear effects and nuclear properties. The neutrino nucleon interaction products can be significantly modified by the presence of other nucleons inside the nucleus. The initial interaction products can interact with other nucleons on their way and change the particles observed in the detector from those particles which were initially produced. This is known as final state interaction and these interactions give rise to fake events in a particular neutrino nucleon interaction channel. The current uncertainties on nuclear effects including final state interaction is quite high and needs to be addressed in upcoming neutrino oscillation experiments like DUNE, Super-kamiokande and INO.

Pure events in a particular interaction channel will be those events in which the particles detected by the detector are same as they were produced during the initial interaction. If all the events detected by the detector are pure events then the systematic error in energy reconstruction will be reduced to a desirable extent. But in reality a particular neutrino nucleon

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interaction channel events as detected by the detector are a mixture of pure and fake events. Many experiments are trying to reduce mis-reconstruction of neutrino energy by using near detector and implementing some correlation with far detector i.e. T2K Collaboration [8]. Due to the mis-reconstruction of the neutrino energy the quantitative estimation of neutrino oscillation parameters in neutrino oscillation experiment also carries some uncertainties. Number of studies have been conducted to study the impact of nuclear effects on determination of oscillation parameters. The impact of different models for neutrino nucleon cross section determination on oscillation parameters is analysed in different work [9][10][11], whereas few studies are based on quantitating the impact of final state interactions on the estimation of neutrino oscillation parameters [12][13][14]. In this work we have tried to provide a quantitative estimate that final state interactions may induce in the determination of atmospheric neutrino oscillation parameters at DUNE.

2 DUNE flux and Neutrino Oscillation Physics:

The future long baseline neutrino experiment, DUNE [17] (Deep Underground Neutrino Facility) is a broadband neutrino beam experiment. The DUNE LBNF (Long Baseline neutrino Facility) at Fermi Lab will sent intense beam of neutrinos to the near and far detector sites. The neutrinos generated at the LBNF will travel 1300 km to reach the high performance DUNE far detector at Sanford Lab. The DUNE Collaboration with the use of Long Baseline Neutrino Facility and the high performance detectors of DUNE, aims to resolve the puzzles of neutrino with broad sensitivity to neutrino oscillation parameters. For the generation of intense neutrino beam for DUNE, the LBNF will extract a proton beam from the Fermilab Main Injector (MI) and then protons will be smashed to the target where the collisions will generate a beam of charged particles which will decay into neutrinos to generate the neutrino beam aimed at the near and far detectors. The LBNF is designed for initial operation at proton beam power of 1.2 MW which will be subsequently upgraded to proton beam power of 2.4 MW [15].

For this work we have selected an optimized beam flux of 120 GeV [16]. The massive, deep-underground far detector will be a 40 Ktons of liquid argon detector and it will be sensitive for muon neutrino-appearance and muon neutrino-disappearance modes, for proton decay modes and for observation of electron neutrinos from a core-collapse supernova. The Fig. [1] shows the energy distribution of selected neutrino flux and corresponding neutrino oscillation probability at 1300 km for both muon appearance and disappearance channel.

![Fig. 1: Flux distribution for LBNE, normalized in the full energy regime (lower part) and neutrino oscillation probability for $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ channel (upper part).](image-url)
The DUNE neutrino beam peaks around 2.5 GeV and in this energy region resonance production is main mode of neutrino nucleon interaction which mainly results in the production of pions. The dominant contribution comes from single pion production mediated by the $\Delta(1232)$ resonance. The charged current resonance interaction process can be illustrated as:

$$\nu_\mu + p \rightarrow \mu^- + \Delta^{++} \rightarrow \mu^- + p + \pi^+$$
$$\nu_\mu + n \rightarrow \mu^- + \Delta^+ \rightarrow \mu^- + n + \pi^+$$
$$\nu_\mu + n \rightarrow \mu^- + \Delta^+ \rightarrow \mu^- + p + \pi^0$$

The pions emitted in the resonance process can be absorbed or they can interact with other nucleons of the nucleus resulting in an event which gives an impression of different interaction process (fake events). In this work we have estimated the percentage of fake events present in different neutrino nucleons interaction channel and the impact arising from these fake events on the estimation of neutrino oscillation parameters.

3 Nuclear Effects and Final State Interaction:

Along with the large uncertainties on total neutrino cross sections the energy dependance and energy distribution of secondary particles also adds up to the systematic errors. One of the probable reason for this can be presence of bounded nucleon in the target nucleus. The intense neutrino beams in upcoming experiments will greatly increase the statistics and reduce the statistical uncertainty. Now this demands a careful handling to systematic uncertainties in these experiments. One of the main source of systematic uncertainty is the nuclear effects present inside the nucleus. In modern day neutrino experiments complex nuclei are used as neutrino targets. These complex nuclear targets result in non negligible or sizeable nuclear effects. Nuclear effects are taken into consideration by Impulse Approximation [19] or Fermi Gas Model [20] and used by most of the neutrino experiments when simulating neutrino scattering events. Many other independent particle approaches are also developed to include spectral function [21][22][23][24][25] Random Phase Approximation [18][26][27][28][29], a plane-wave impulse approximation (PWIA) where the nucleon-nucleon correlations were included using description of nuclear dynamics, based on nuclear many-body theory [30] and many others. After looking at the experimental results of different neutrino experiments performing in different energy region i.e. MINERvA, MiniBooNE, T2K,NOvA we currently believe that nuclear effects needs to be modelled carefully. The lower energy neutrino experiments like MiniBooNE and MicroBooNE are sensitive to only two type of neutrino interactions i.e. QE and resonance. In these experiments the pion production constitutes the one third of the total neutrino nucleon interaction cross section. As we move towards the higher energy neutrino beam experiments NOvA, MINERvA and ultimately, DUNE the contribution from the pion production to the total cross section increases to the two third [31]. It is thus important to have the pion production channels under good, quantitative control.

Final state interaction is one of the most relevant nuclear effects that gives rise to fake events i.e. the final particles that emerge out from the nucleus at the end of the neutrino nucleon interaction and if detected by the detector are very different from the particles which were formed by the neutrino nucleon interaction at initial stage. In this way the nuclear effects can mask the true type of interaction to a different interaction type (fake), depending on the emerging particles from the nucleus. These fake events are also known as crossed channel events because these events cross the initial interaction channel and give an impression of some other channel as their interaction channel, due to the presence of nuclear effects. Looking at the importance of the good knowledge on pion production channels in high intensity neutrino beam experiments. In this work we have estimated the contribution of nuclear effects (final state interaction) in resonance channel on the estimation of the atmospheric neutrino oscillation parameters at DUNE.

4 Simulation and Results:

In this work we are using GiBUU (Giessen Boltzmann-Uehling-Uhlenbeck) [33] transport model to generate the events, cross section and migration matrices. In GiBUU the final state interactions is modelled by solving Boltzmann-Uehling-Uhlenbeck equations which couples the collision terms and mean field. It does not includes all quantum effects hence it is semi-classical model. It include all the processes e.g. true quasi-elastic, all type of resonances: delta and higher, 2p2h excitations, background pions and deep inelastic scattering. In the begining we have estimated the percentage of fake events in CCQE and CCRRes interaction channels. To get a quantitative handled over this we have generated CCQE and CCRRes events in the absence and presence of FSI. This is achieved by counting the number of initial interaction events i.e at time t=0 in a specific interaction channel i, $N_p(i)$, and the number of those events that remains in the channel after time t = 120 (intranuclear cascade is completed), $N_f(i)$. The
number of crossed channels events or fake events are estimated by subtracting the above two values.

Roughly 2 lacks events are generated using DUNE flux for muon disappearance channel. Fig. [2] and Fig. [3] represents the distribution of true and fake events as a function of neutrino energy when no detector cuts are imposed on the out coming particles. We can see a significant contribution arising from the fake events in both type of interactions. The larger is the contribution from fake events the larger are the nuclear effects on that particular interaction channel. The percentage of fake events produced is also calculated for both the interaction channels i.e. CCQE and CCRes and is illustrated in Table [2].

The detector cuts [40] mentioned in Table [1] are imposed on the outgoing particles to get a realistic picture of fake and true event in a particular interaction channel. Fig. [4] and Fig. [5] represents the distribution of fake and true events with respect to the neutrino energy after detector cuts are applied on the data sample. The percentage contribution of the fake events are shown in Table [3]. This fact must be revised when we will include in our simulation more channels coming from resonances higher than \( \Delta(1232) \).

| Table 1: Threshold kinetic energy cuts for particles |
|-----------------------------------------------|
| Particle Type | p | n | π^+ | π^- | π^0 | μ |
| Threshold kinetic energy (GeV) | 0.05 | 0.05 | 0.1 | 0.1 | 0.1 | 0.03 |

| Table 2: Percentage of fake events without detector cuts |
|---------------------------------------------------------|
| Interaction Type | QE | 43.0 | |
|                  | Res | 67.2 | |

| Table 3: Percentage of fake events with detector cuts |
|-------------------------------------------------------|
| Interaction Type | Percentage of fake events |
|------------------|---------------------------|
| QE               | 51.05                     |
| Res              | 72.4                      |

Fig. 2: Distribution of QE events before (red solid line) and after (blue solid line) FSI as a function of true neutrino energy in the absence of detector cuts.

Fig. 3: Distribution of Res events before (red solid line) and after (blue solid line) FSI as a function of true neutrino energy in the absence of detector cuts.
From the previous plots it is visible that the contribution arising from the fake events to the total events gathered in a charged current neutrino nucleon interaction is more than 50% in both cases. With such a markable contributions arising from the nuclear effects a reanalysis of neutrino oscillation parameters in presence of nuclear effects becomes crucial. As we know that the neutrino oscillation physics depends on the values of neutrino oscillation parameters and the value of these oscillation parameters depends on the precise knowledge of neutrino energy. Due to the presence of nuclear effects a difference between true and reconstructed energy of neutrino becomes sizable and this needs to be pinned down with the knowledge of nuclear effects.

To include the nuclear effects in our work a migration matrix between true and reconstructed energy with a bin size of 0.5 GeV is generated using GiBUU. To quantitate the effects of final state interaction on neutrino oscillation physics the BUU migration matrix and cross sections estimated using GiBUU are included in correct format to the latest version of GLoBES(Global Long Baseline Experiment Simulator)\[32, 34, 36, 37, 38\]. In this work the effects of final state interaction at DUNE oscillation physics has been estimated and for this we use the DUNE neutrino flux and liquid argon far detector of fiducial mass 35 Kt, placed at a baseline of 1300 Km. This work is performed for muon disappearance channel and running time considered here is 5 years in neutrino mode and 5 years in antineutrino mode. The true values of oscillation parameters proposed in this work are $\theta_{23} = 45.0^0$, $\theta_{13} = 34.5^0$, $\theta_{13} = 8.44^0$, $\Delta m^2_{31} = 2.55 \times 10^{-3}$ eV$^2$, $\Delta m^2_{21} = 7.56 \times 10^{-3}$ eV$^2$ and $\delta_{CP} = 0^0$\[39\]. The signal efficiency is 85% for disappearance channel, normalization error of signal and background are 5% and 10% respectively and energy calibration error of signal and background are 2%.

The migration matrix for pure QE and Res events and QE-like and Res-like events are obtained using GiBUU. Resonance like events are those events which at the initial point of neutrino nucleon interaction were not resonance events instead they were something different i.e. QE, DIS or something else, but while leaving the nucleus they appear like if they were produced due to resonance interaction. Let us consider now the case of a charge current neutrino interaction that is not Resonance. Usually, these interactions are discarded from the event sample if another charged particle (for example, a pion) is not observed in the final state. However, there is a certain probability that the produced hadron while passing through the nucleus interacts with other nucleon and produces a pion. In this case, pion will be observed in the final state and consequently this events will be added to the resonance sample. The difference in true and reconstructed neutrino energy arises due to these events.

Estimation of the final state interaction on neutrino oscillation parameters two extreme cases are considered (i)when nuclear effects are completely disregarded and (ii)when nuclear effects are completely known. This condition is achieved by plugging a parameter $\alpha$ to true and like events which eventually adds up to give the total number of events in a particular interaction channel. The parameter $\alpha$ can take any value between 0 and 1. In reality we lie somewhere in between these two situations of complete ignorance and complete knowledge of nuclear effects. Total number of events can be represented as:

$$N^\text{ext}_i(\alpha) = \alpha \times N^\text{QE}_i + (1 - \alpha) \times N^\text{QE-like}_i$$

$$N^\text{ext}_i(\alpha) = \alpha \times N^\text{RES}_i + (1 - \alpha) \times N^\text{Res-like}_i$$

1. When $\alpha = 1$ (nuclear effects are completely disregarded).
2. When $\alpha = 0$ (nuclear effect are perfectly known).
The inclusion of the parameter $\alpha$ can be considered as systematic uncertainty. Similar approach is also considered in [41].

Fig. 6: Confidence regions in the $(\theta_{23}, \Delta m^2_{31})$ plane are obtained using the migration matrices pure QE (black lines) and QE-like (color lines) in the absence of detector cuts. The red triangle($\alpha = 0$), blue triangle($\alpha = 0.5$) shows the best fit point and circle($\alpha = 1$) show the true values of the oscillation parameters.

Fig. 7: Confidence regions in the $(\theta_{23}, \Delta m^2_{31})$ plane are obtained using the migration matrices pure Res (black lines) and Res-like (color lines) in the absence of detector cuts. The red triangle($\alpha = 0$), blue triangle($\alpha = 0.3$) shows the best fit point and circle($\alpha = 1$) show the true values of the oscillation parameters.

A chi square plot between two oscillation parameters $\Delta m^2_{31}$ and $\theta_{23}$ for QE and Res events in absence and presence of detector cuts are shown in Fig. [6], Fig. [7] and Fig. [8], Fig. [9] respectively. The 1, 2, and $3\sigma$ confidence regions in the $(\theta_{23}, \Delta m^2_{31})$ plane are obtained using the migration matrices accounting for (coloured lines) or neglecting (black lines) the effect of final-state interactions, included in the simulated data. The coloured triangle and the black circle show the best fit point and the true values of oscillation parameters respectively.

Fig. 8: Confidence regions in the $(\theta_{23}, \Delta m^2_{31})$ plane are obtained using the migration matrices pure QE (black lines) and QE-like (color lines) in the presence of detector cuts. The red triangle($\alpha = 0$), blue triangle($\alpha = 0.5$) shows the best fit point and circle($\alpha = 1$) show the true values of the oscillation parameters.

Fig. 9: Confidence regions in the $(\theta_{23}, \Delta m^2_{31})$ plane are obtained using the migration matrices pure Res (black lines) and Res-like (color lines) in the presence of detector cuts. The red triangle($\alpha = 0$), blue triangle($\alpha = 0.3$) shows the best fit point and circle($\alpha = 1$) show the true values of the oscillation parameters.
As estimated in Table [1] and Table [2] roughly 50% of the QE events remains QE after final state interaction. A best fit point for $\alpha = 0.5$ is obtained using Equ. [1] is also shown in the Fig. [6] and Fig. [8] which refers to 50% QE and 50% QE-like events. Similarly the mentioned table shows 30% pure Res event after FSI following that a best fit point for $\alpha = 0.3$ is obtained using Equ. [2] and is shown in Fig. [7] and Fig. [9].

5 Conclusion:

In the present work we report an extensive analysis of nuclear effects in neutrino-nucleus interaction at DUNE. For this purpose, GiBUU is used to take into account the nuclear effects. CCQE and CCRes interaction channels are analyzed in this study. Effect of FSI on CCQE interaction channel is also studied in [41]. In neutrino oscillation physics at DUNE resonance interactions plays vital role due to the shape of DUNE flux and in this work we have reported the effects of FSI on CCRes interaction channel too.

The calculations are performed with DUNE flux for liquid Argon detector. We calculated the cross section of detector nuclei in the whole energy range of DUNE flux using CCQE and CCRes channels. For the given target nuclei, we perform an exploratory study of the fake events generated in several reactions. The percentage of fake events increases in resonance events and they increase further when we use the real detector (imposing detector cuts). In a future work, we will improve the work by adding higher resonance and DIS studies to it.

The position of the best fit corresponding to different values of $\alpha \sim 0, 0.5, 1$ for CCQE are shown in the Fig. [6] and Fig. [8] whereas in Fig.[7] and Fig. [9] the best fit corresponding to $\alpha \sim 0, 0.3, 1$ for CCRes are illustrated. As it can be seen in the mentioned figures, the deviation of the best fit from the true input value gets progressively increased with the increase in the value of $\alpha$ or when we move from nuclear effects completely disregarded to nuclear effects completely known. However, according to Fig. [6] for relatively large value of $\alpha \sim 0.5$ the minimum value of $\chi^2$ for CCQE would correspond to a $3 \sigma$ bias in the determination of the mixing angle though according to Fig. [8] it goes beyond the $3 \sigma$ limit when detector cuts are taken into consideration. In Fig. [7] and Fig. [9] the best fit value for $\alpha \sim 0.3$ for CCRes (with and without detector cuts) corresponds to $1 \sigma$ limit in the determination of mixing angles. Therefore, it stands to reason that a successful experiment requires an accurate nuclear model, where the accuracy of the model has been independently verified.

Our results indicate that, for an experiment observing most of Res-like events, a $1 \sigma$ bias in the determination of $\theta_{23}$ and for a experiment observing most of QE-like events roughly a $3 \sigma$ bias in the determination of $\theta_{23}$ could result from errors on the nuclear model. 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.

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