Impact of Transverse Enhancement in Neutrino Oscillation Parameter Measurements in Nova Experiment

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***Abstract* - NOvA is a long baseline neutrino oscillation experiment designed to measure muon neutrino disappearance and electron neutrino appearance using Fermilab's (USA) NuMI beam. Two functionally equivalent detectors are placed Off-Axis from the centre of the NuMI beam, with 810 km oscillation baseline. NOvA is able to make measurements for neutrino mass hierarchy and mixing angles, CP violation phase and can help to improve our understanding about neutrinos. In this work, we study the impact of transverse enhancement in Quasielastic-like processes that occur in neutrino-nucleus scattering at the detector, and its corresponding effect in neutrino oscillation measurements using simulation for NOvA experiment.**

Keywords—Neutrino oscillation; quasielastic; neutrino cross-section; nuclear effects; transverse enhancement .

I. INTRODUCTION

The precise measurement of neutrino energy is the key part of the determination of neutrino oscillation parameters. As the incoming neutrino beams are produced as a secondary decay of primarily produced hadrons, they are quite broad in energy, and hence the neutrino energy needs to be reconstructed on an event-by-event basis. Recent neutrino oscillation experiments use heavy nuclear targets. Nuclear effects arising due to a nuclear target can change the identities, kinematics, and topologies of the outgoing final state particles. Thus nuclear effects hide the true information of the particles produced at the initial neutrino-nucleon vertex. Therefore neutrino interactions with these heavy targets require a careful study of nuclear effects. The presence of uncertainty in the reconstruction of neutrino energy impacts the study of neutrino oscillation parameters as well [1].

In this paper, we study the impact of nuclear effects imposed by Transverse Enhancement (TE) [2] in Quasielastic (QE)-like interactions and their effect on neutrino oscillation parameter measurements. In TEM, nuclear effects coming from Meson Exchange Currents (MEC) are modelled as dependent modifications to the elastic proton and neutrino magnetic form factors. The transverse QE cross-section enhancement comes from MEC. If there are no pions in the final state interactions, the process is considered as a QE cross-section enhancement, and if one or more final state pions are produced it is considered as an inelastic cross-section enhancement.

II. THE NOνA EXPERIMENT

NOνA [3-4], the NuMI Off-axis ν_e Appearance experiment, is a long baseline neutrino oscillation experiment designed to measure $\nu_\mu(\overline{\nu}_\mu)$ disappearance and $\nu_e(\overline{\nu}_e)$ appearance in a $\nu_\mu(\overline{\nu}_\mu)$ beam produced at Fermilab's NuMI (Neutrinos at Main Injector) beam production target. The $\nu_e(\overline{\nu}_e)$ appearance experiment is used to study the neutrino mass hierarchy, the CP violation phase in the neutrino sector and the octant of θ_{23} (whether $\theta_{23}>$ or $< 45^\circ$). The $\nu_\mu(\overline{\nu}_\mu)$ disappearance experiment mainly focuses on the precise measurement on the atmospheric oscillation parameters $|\Delta^2_{32}|$and θ_{23}. NOνA consists of two functionally identical detectors-the 0.3 KTon near detector (ND) is located 100 meters underground at a distance of 1 km from the NuMI beam and the 14 KTon far detector (FD) is placed on the surface at a distance of 810 km from the target near Ash River. The narrow-band beam peaks around 2 GeV. The ND measures the beam before oscillations and the FD is used to measure the oscillated spectrum.

III. QE-LIKE INTERACTIONS

A true charged current (CC) QE process is defined as the scattering of a moving neutrino on a bound neutron within the nucleus releasing a muon and a proton as the final state products and the process is represented as :

$$\nu n \rightarrow \mu^- p \qquad (3)$$

Apart from these processes there are some other processes where the final states will contain events that are not QE. For example, the processes in which a pion or a Δ resonance is produced in the initial neutrino-nucleon interaction vertex e.g. $\nu p \rightarrow \mu^- p \pi^+$or $\nu p \rightarrow \mu^- \Delta^{++}$ and during final state interactions it is absorbed in the nucleus. Therefore, the pion is not captured by the detector in the final state ("stuck pion event") and thus lead to missing energy in the energy reconstruction of the neutrino. Such event is considered as QE-like event even though it is not of true QE origin and gives rise to uncertainties in the QE cross-section measurement. Thus, CC QE-like events are those which are accompanied with 1 muon, 0 mesons and any number of nucleons in the final state. One major contribution to QE-like events comes from the presence of multi-nucleon events in which the incoming neutrino interacts with e.g., 2 nucleons (called 2p-2h events). Contrary to the above process, another possibility arises when a nucleon produced in the initial neutrino-nucleon QE interaction get re-scattered in the nucleus and produces a pion in the final state. Though this event has a true QE origin, it will be disregarded as QE-like event due to the presence of the pion. The appearance of QE-like events produce uncertainties in the neutrino reconstruction energy which further gets propagated to the measurement of neutrino oscillation parameters.

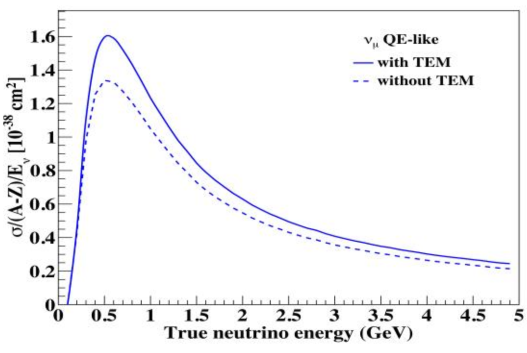
In the stuck pion case, the reconstructed neutrino energy will be lower than the true incident energy as the pion carries away a part of the neutrino energy and is eventually absorbed by the nucleus. The actual value of the reconstructed energy will depend on the energy of the unobserved particles in the final state. For a true QE event, the reconstructed energy will mostly coincide with the incident true energy of the neutrino. But along with it, there exists a certain probability that a non-QE event can be reconstructed with significantly different neutrino energy. This is represented by a migration matrix between true and reconstructed neutrino energies, N(E^{rec},E^{true}). Each element of this matrix represents the probability that an event for a particular true neutrino energy E^{true}can be reconstructed with a different energy E^{rec}. Thus, the final QE-like event sample consists of both QE and non-QE events with no pions in the final state [5]:

$$N(E_j)^{QElike} = M^{QE} \times \sigma_{QE}(E_j) \times P_{\alpha\beta}(E_j) \times \phi(E_j) + M^{non-QE} \times \sigma_{non-QE}(E_j) \times P_{\alpha\beta}(E_j) \times \phi(E_j) \quad (1)$$

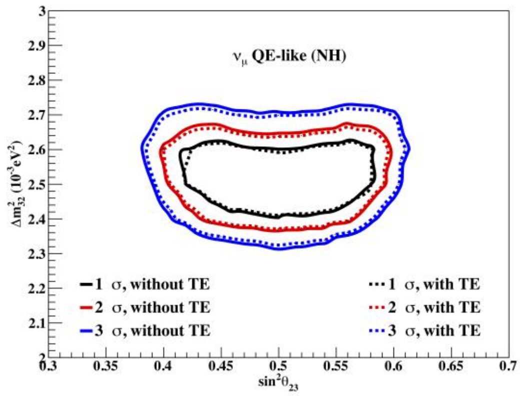
where E_i is the true neutrino energy, $P_{\alpha\beta}$ represents the oscillation probability for the channel $\alpha \rightarrow \beta$ (in this work, we have considered the $\nu_\mu$disappearance experiment), $\phi(E_j)$ stands for the neutrino flux and M is the migration matrix.

As neutrinos are produced in secondary decay of primarily produced hadrons, neutrino beams have a broad energy range. Therefore, the neutrino energy has to be reconstructed on an event-by-event basis. We have used the calorimetric method of neutrino energy reconstruction. In the method, neutrino energy is calculated by adding the energies of all detectable final state particles.

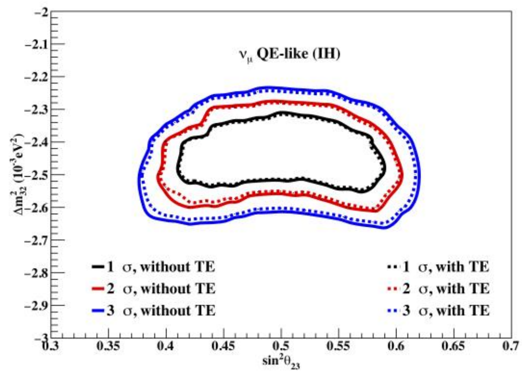
$$E_\nu = E_\mu + E_{hadron} \quad (2)$$



1. Comparison of integrated cross section as a function of true neutrino energy for QE-like interactions with/without TEM.



2. Comparison of 1σ, 2σ and 3σ confidence regions in θ_{23}-Δm^2_{32} plane for QE-like interactions for NH with/without TEM.



3. Comparison of 1σ, 2σ and 3σ confidence regions in θ_{23}-Δm^2_{32} plane for QE-like interactions for IH with/without TEM.

Nuclear effects plays a significant role in neutrino energy reconstruction because incorrect reconstruction energy leads to a major amount of missing energy, the energy which absorbed during FSI.

IV. SIMULATION AND EXPERIMENTAL DETAILS

We have done simulation using software GENIE [6] v3.0.6 (Generates Event for Neutrino Interaction Experiments), and have generated 1 million events using NOνA flux for muon disappearance channel. GENIE is a ROOT [7] based neutrino generator designed using object-oriented methodologies and developed entirely in C++. It is used by researchers world-wide for many neutrino baseline experiments such as MINERvA, MINOS, MicroBooNE, NOνA, and T2K.

In this work, we have considered the contribution from quasielastic, resonance and higher resonances, two particle-two hole, and deep inelastic scattering (DIS) interaction processes. Local Fermi Gas (LFG) is used as a nuclear model to describe the initial state. QE scattering is modelled according to the Llewellyn Smith model [8]. Nieves et al. model [9] is used to model 2p-2h processes. For the DIS process, GENIE uses Bodek and Yang model [10]. Resonance interaction is modelled using the Berger-Sehgal model [11]. To simulate FSI GENIE hN semi-classical intra-nuclear cascade model is used. Extrapolation technique is used to obtain the FD events, where the CC FD events are predicted using CC ND event spectra. TE model (TEM) are included through GENIE, which is the novelty of this work. Chi-square analysis is done using the Feldman-Cousin approach [12]. Migration matrices for QE-like events are generated with GENIE.

IV. RESULTS

In this section, we compute and present the impact of TE model in QE-like cross-section and on the extraction of the neutrino oscillation parameters for both the normal and inverted hierarchies (NH and IH). The ν-carbon integrated cross-section for QE-like sample with (solid blue line) and without (dotted blue line) TE model is shown in Fig. 1. We notice the cross-section with and without TE model overlap in the energy range $\leqslant$ 0.5 GeV, after that the cross-section of QE-like sample with TE model becomes greater than cross-section without TE model. There is a significant difference in the peak of the cross-section due to TE. This incorrect estimation of cross-section of QE-like events will be percolated in incorrect estimation of neutrino energy and further propagates to the neutrino oscillation analysis. The TE model enhances the transverse part of the QE cross-section. In Fig. 2 and Fig. 3, we have plotted the 1σ, 2σ and 3σ confidence regions of QE-like in the θ_{23}-Δm^2_{32} plane, for NH and IH respectively. The solid lines represent the confidence regions without TE and dotted lines represent with TE. The black line is for 1σ, red line for 2σ and blue line for 3σ with/without TE. From both Fig. 2 and Fig. 3 we observe that TEM effect slightly change the neutrino oscillation parameters. Due to increase in cross-section and event distribution, contour area with TE model decreases slightly which implies slight increase in precision in measurement of neutrino oscillation parameters.

V. CONCLUSION

To summarise, in this work, we computed the effects Transverse Enhancement Model (TEM) on neutrino scattering, and observe that it slightly improves the precision of measurement of neutrino oscillation parameters. This impact is more visible in cross-section measurement of QE-like events. We found that the inclusion of nuclear effects in the study of neutrino nucleon interaction is crucial in order to generate a pure QE event sample, and should be included very carefully for precision studies of neutrino oscillation parameters.

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