Systematics due to Energy Reconstruction and Multi-nucleon Effect at NOνA detector

Paramita Deka,[a1] **Jaydip Singh,**[b2] **Neelakshi Sarma,**[c1] **Kalpana Bora,**[d1]

Department of Physics, Gauhati University, Guwahati, Assam, India[1]

Department of Physics, University of Lucknow, Lucknow, India[2]

Paramita Deka

Dr. Kalpana Bora

[a]E-mail: deka.paramita@gmail.com
[b]E-mail:jaydip.singh@gmail.com
[c]nsarma25@gmail.com
[d]E-mail: kalpana@gauhati.ac.in

Introduction

The NUMI Off-Axis ν_e Appearance (NOνA) experiment is a long baseline neutrino oscillation experiment, designed to measure $\nu_e(\bar{\nu}_e)$ appearance probability and $\nu_\mu(\bar{\nu}_\mu)$ disappearance probability. The NOνA target has 50 graphite segments, two identical detectors sited 14 $mrad$ off the beam axis 810 km apart to produce a narrow-band beam around the oscillation maximum region (2 GeV). Its studies are expected to pinpoint neutrino mass hierarchy, CP violation phase, and precise measurement of θ_{23} and Δm^2_{32} [1]. Neutrinos in the beam have energy in range 0.5-3 GeV, where dominant interactions are - quasielastic (QE), resonance (RES), and meson exchange currents (2p2h/MEC) interactions [2].

The neutrino oscillation experiments with heavy nuclear target are inflicted by uncertainties in knowledge of neutrino scattering cross sections- as nuclear effects become important, which are not very well understood. Hence, it becomes important to minimise these uncertainties. At least one way to do this is - cancellation of these effects by considering cross section uncertainties at both ND (Near Detector) and FD (Far Detector). At ND, unoscilated neutrinos are detected, while signal (oscillated) events are observed at FD. These uncertainties in turn may affect the precision measurements of the unknown neutrino parameters, so we need to minimize them.

Main Objectives

- Using simulation, to study the multi-nucleon (MN) effects in neutrino-nucleus scattering cross section at NOνA, in particular the hard scattering 2p2h/MEC effects and long range RPA corrections.
- To pinpoint these effects at ND and FD at NOνA, which would help reduce systematic uncertainties due to those in scattering cross section.
- Future goal - to pinpoint which ν-nucleus scattering model would be best to describe the data of NOνA.

Methodology, Simulation and Experimental Details

- We use GENIE-2_12_8 [3] to generate the ν-nucleus interaction cross sections, using different physics models-QE, RPA, 2p2h/MEC, with Carbon as target.
- It may be noted that in NOνA collaboration papers [4][5], they have used Genie default model and 2p2h process with RPA corrections to describe the preliminary NOνA data.
- The pure Charged Current QE scattering is implemented using the Llewellyn-Smith model (Default) and 2p2h interactions by the model proposed by Valencia group.
- The Nieves model is used to include RPA effects.
- We have neglected matter effects in this work (but would include later), and have done the analysis for the disappearance channel, for both NH and IH. This channel is believed to be mainly suited for θ_{23} and Δm^2_{32} measurements.
- The energy range of 0-5 GeV is used in our analysis.
- We have generated 1 million events for both neutrino and antineutrino at ND and FD.
- For calculating events at FD, folding of ND flux is done with respective oscillation probability.

For a QE event considering the neutron at rest, the neutrino energy can be reconstructed from the kinematic variables of the charged lepton l in the final state as [6]:

$$E_\nu^{QE} = \frac{2(M_n - E_b)E_l - (E_b^2 - 2M_nE_b + \Delta M^2)}{2(M_n - E_b - E_l + p_l\cos\theta_l)} \qquad (1)$$

where $\Delta M^2 = M_n^2 - M_p^2 + m_l^2$, M_n is the free neutron rest mass, E_b= 0.025 GeV is the binding energy for Carbon.

Results

- In Fig. 1, we have plotted the flux of ν (blue) and $\bar{\nu}$ (red) at ND (left panel), and oscillation probability for disappearance channel (right panel)for NOνA setup using latest global fit neutrino oscillation parameter values.
- The ν-nucleus interaction cross sections are shown in Fig. 2.
- Our results of the distribution of events with reconstructed energy of the particles in both ND and FD, for QE, with 2p2h/MEC and RPA effect on and off are shown in Fig. 3 and 4, for both mass hierarchies. Left panel is for neutrino and right panel for antineutrino events.

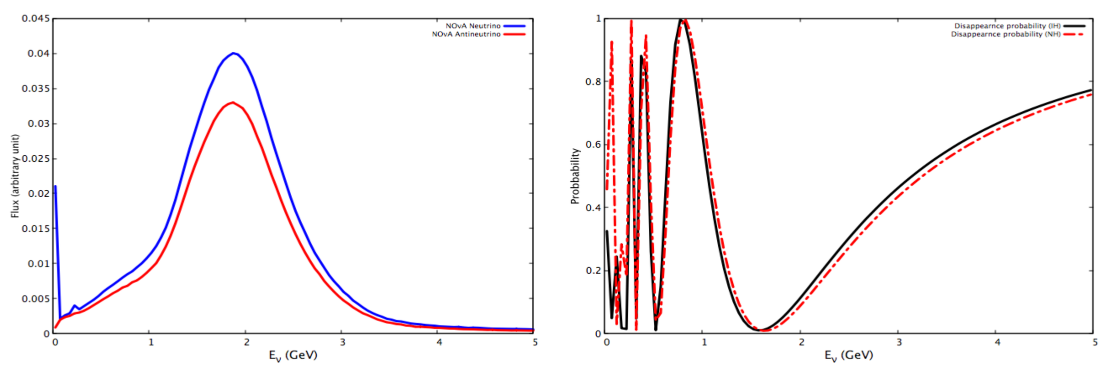

Figure 1: Left: The NOνA flux as a function of neutrino energy used in our work. Right: The neutrino oscillation probability of $\nu_\mu \rightarrow \nu_\mu$ in vacuum at FD.

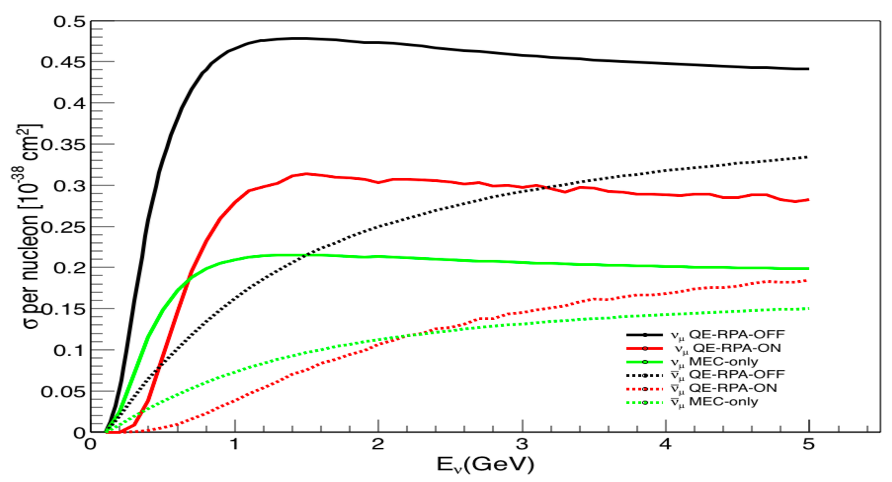

Figure 2: CCQE and CCMEC cross section of ν_μ and $\bar{\nu}_\mu$ with RPA on and off.

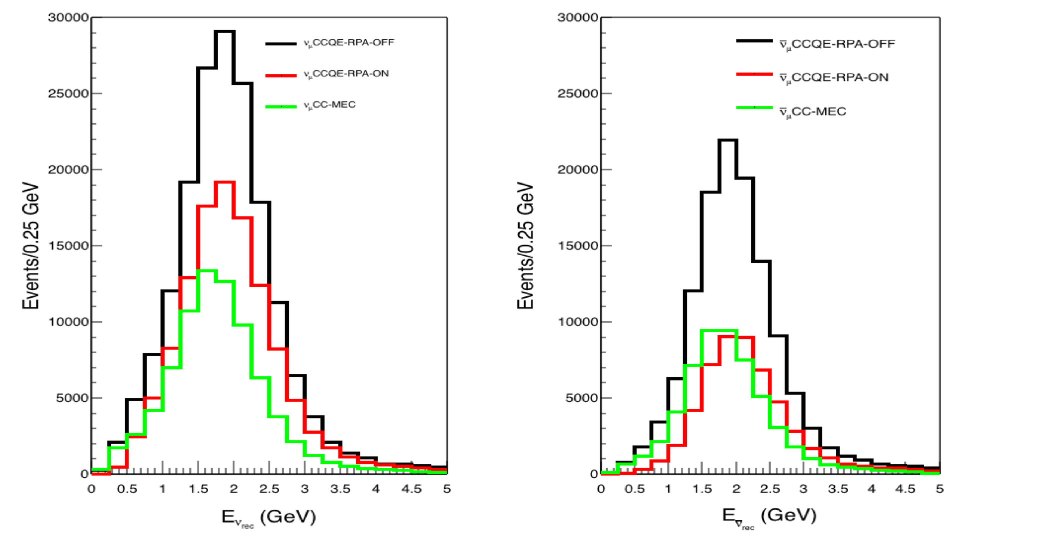

Figure 3: Event distribution as a function of reconstructed energy at ND with RPA on and off.

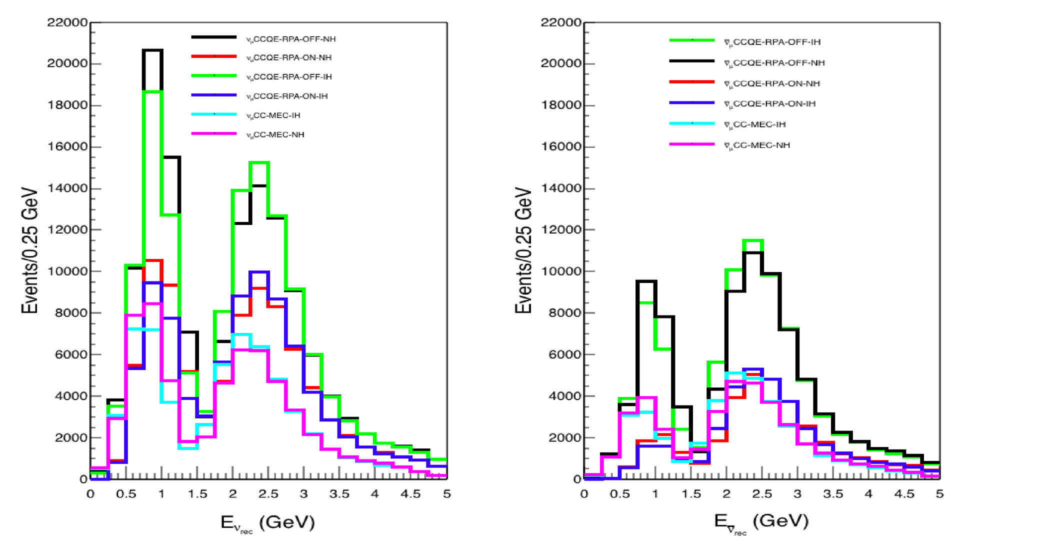

Figure 4: Event distribution as a function of reconstructed energy at FD with RPA off and on.

Discussion

- From Fig. 2, we find that 2p2h/MEC and RPA corrections change the neutrino scattering cross sections in a significant manner.
- From Fig. 3, it is observed that the peak of events at ND with E_{recons} occurs at $E_{recons} \sim 1.9\ GeV$, where the flux also peaks.
- RPA effects decrease the events for both ν and $\bar{\nu}$ CCQE events (at ND), at some values of energy.
- From Fig. 4 (FD), we observe that the highest no events decrease as compared to ND, but there are two peaks in the distribution - in accordance with the oscillation probability.
- It is also observed that the 2p2h/MEC and RPA effects cause significant changes in the event distribution at FD also, for both ν and $\bar{\nu}$.
- Respective changes are also seen with respect to mass hierarchies.
- Due to more flux and cross section, neutrino events are more than antineutrino events.

Summary & Conclusions

To summarise, in this preliminary work, we have

- Through simulation, we studied the effect of 2p2h/MEC and RPA corrections on neutrino scattering cross sections and event distribution for NOνA.
- We did this analysis for both ND and FD, for both the mass hierarchies (NH, IH) and both for neutrino and antineutrino beam fluxes.
- Used kinematic method for energy reconstruction.
- **When more data in future becomes available, we would try to match the data with our predicted results here, to pinpoint which nuclear model is best suitable for NOνA.**

To conclude, we observe that

- The multi-nucleon effects cause significant changes in cross section and events distribution both at ND and FD.
- These studies will be used in future, to reduce the systematic uncertainties due to nuclear effects in neutrino scattering, that are a major source of uncertainties in precision measurement of the neutrino oscillation parameters, specially the mass hierarchy, Octant of atmospheric mixing angle, and CPV phase.

Forthcoming Research

As these are the preliminary results, in future, we aim to do detailed studies on the issues addressed here, to fulfil the objectives listed above. We would include matter effects, do proper FD/ND analysis, and match our predictions of simulation with data.

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