FERMILAB-CONF-23-378-V

Impact of High Energy ν_e ($\bar{\nu}_e$) Events on NOvA Oscillation Sensitivities

Ishwar Singh*[1], Prabhjot Singh†[2], and Brajesh Choudhary‡[1]

[1]Department of Physics and Astrophysics, University of Delhi, India
[2]Queen Mary University of London, London

July 20, 2023

Abstract

NOvA is a two detector, long-baseline neutrino oscillation experiment located at Fermilab, Batavia, IL, USA. It is primarily designed to constraint neutrino oscillation parameters using muon neutrino (anti-neutrino) disappearance data and electron neutrino (anti-neutrino) appearance data. NOvA detects neutrinos from Fermilab's Neutrinos at Main Injector (NuMI) beamline. The unoscillated muon neutrino and beam ν_e events are observed by the NOvA Near Detector (ND), which is 100m underground and at a distance of 1km from the beam source. The Far Detector (FD), situated 809 km away from the ND, is in Ash River, MN, USA, and observes ν_μ and ν_e events after oscillations.

Traditionally, NOvA has used ν_e events in the energy range $1 < E_\nu < 5$ GeV for 3-flavor neutrino oscillation analyses to constraint the neutrino oscillation parameters. In this study we looked at the impact of including high-energy neutrino events with energies up to 12 GeV in the analysis with the aim of constraining the beam electron neutrino/antineutrino background events. Event count predictions after adding this high-energy sample events and latest three flavor oscillation results of the NOvA experiment are presented.

*isingh@fnal.gov
†prabhjot@fnal.gov
‡brajesh@fnal.gov

1 Introduction

The NuMI Off-axis Neutrino Appearance (NOvA) is a world leading long-baseline neutrino oscillation experiment that consists of two functionally equivalent, segmented, mineral oil based scintillator detectors situated 14.6 milli-radians off-axis to the beam direction [1]. The primary goals of the experiment include contraining 3-flavor neutrino oscillation parameters, resolving neutrino mass hierarchy problem, resolving octant degeneracy, and looking for CP-violation in the lepton sector using the data on ν_μ ($\bar{\nu}_\mu$) disappearance and ν_e ($\bar{\nu}_e$) appearance oscillation channels. The Neutrinos at Main Injector (NuMI) beam provides the most intense muon neutrino beam to the experiment. A beam of protons accelerated to 120 GeV energy is extracted from Fermilab's Main Injector and strikes a segmented, fixed graphite target of length approximately 0.96m (interaction length $\approx 1.8\lambda$) which produces a bunch of charged mesons, primarily $\pi^\pm$ and $K^\pm$. A set of two magnetic horns focuses the produced mesons. These horns can be configured to focus either the positively or the negatively charged mesons. The focussed mesons are allowed to decay in a 695m long vacuum pipe to produce the neutrino beams [2].

In the past, NOvA has employed neutrino events observed in the Far Detector with an energy range of $1 < E_\nu < 4$ GeV to constrain the neutrino oscillation parameters [3–5]. This is done because the high energy neutrino event sample is heavily dominated by the beam electron neutrino component. In order to investigate if we could acquire more power to constrain the neutrino oscillation parameters, we included high-energy $\nu_e(\bar{\nu}_e)$ events with energies $4 < E_\nu < 12$ GeV to the analysis in this study. Figure 1 shows the high-energy reconstructed neutrino event distributions. The revised predictions were then employed, rather than the standard 3-flavor predictions, to identify limits on the neutrino oscillation parameters.

2 Revised FD ν_e Predictions

Figure 2 shows revised FD ν_e predictions for the neutrino and the anti-neutrino beams, including high energy ν_e events and existing systematic shifts, generated at the 2020 best fit values [3]. The event counts for the revised FD predictions and the standard 3-flavour neutrino predictions are compared in Table 1. The inclusion of high energy ν_e ($\bar{\nu}_e$) events to FD predictions had a minimal gain in signal events. The majority

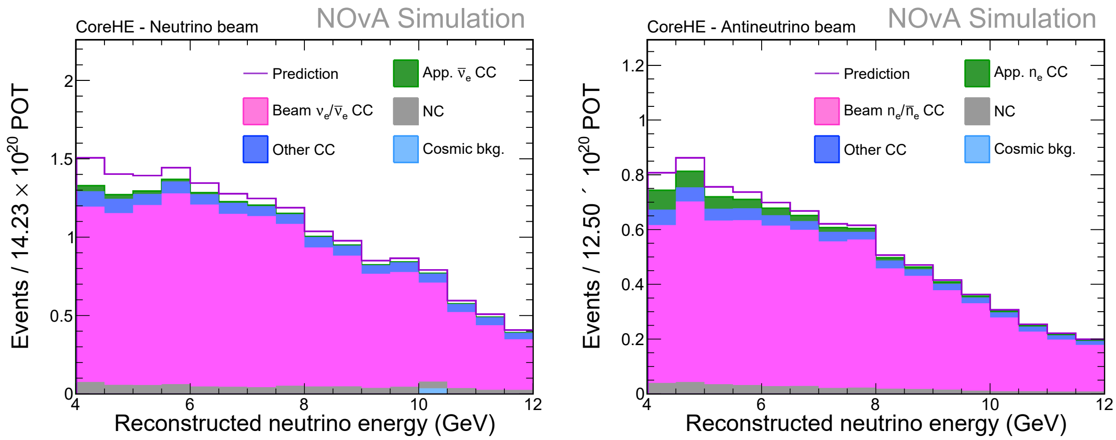

Figure 1: The high-energy reconstructed neutrino energy spectra for the neutrino and the anti-neutrino beam.

of the events contributed to the beam background.

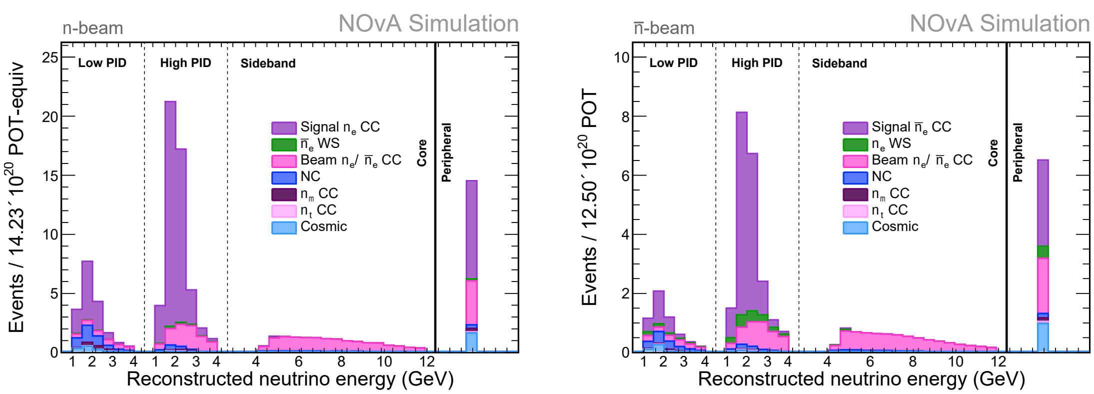

Figure 2: Revised Far Detector 2020 best fit predictions taking into account existing systematic shifts for the neutrino and the anti-neutrino beam.

A joint fit was performed using reconstructed neutrino energy spectra of all the oscillation channels, $\nu_\mu \to \nu_\mu$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$, $\nu_e \to \nu_e$, and $\bar{\nu}_e \to \bar{\nu}_e$, but with the revised FD ν_e ($\bar{\nu}_e$) predictions are shown in figure 2. It was observed that the addition of high energy events to FD predictions had almost no impact on NOvA oscillation sensitivities. The latest NOvA sensitivities are shown in section 3.

		Signal	Beam	Wrong Sign	NC	ν_μ	ν_τ	Cosmic
Neutrino	Revised	59.43	26.76	1.04	6.07	1.69	0.86	3.22
Beam	Standard	59.25	13.91	1.01	5.29	1.36	0.52	3.13
Anti-neutrino	Revised	19.94	12.96	2.38	2.25	0.47	0.49	1.57
Beam	Standard	19.88	6.59	2.30	1.99	0.33	0.32	1.55

Table 1: Comparison of event counts for the revised FD predictions with the standard 3-flavor neutrino predictions.

3 NOvA Latest Oscillation Sensitivities

The latest NOvA oscillation sensitivities were generated for neutrino and anti-neutrino beam exposure of 14.28×10^{20} and 12.50×10^{20} protons-on-target, respectively. The best fit values of the oscillation parameters that lie in the Normal Hierarchy are $\Delta m^2_{32} = (2.41 \pm 0.072) \times 10^{-3}$ eV^2 and $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$. The data also disfavours $\delta_{\rm CP} = \pi/2$ $(3\pi/2)$ at more than 3 (2)σ [3].

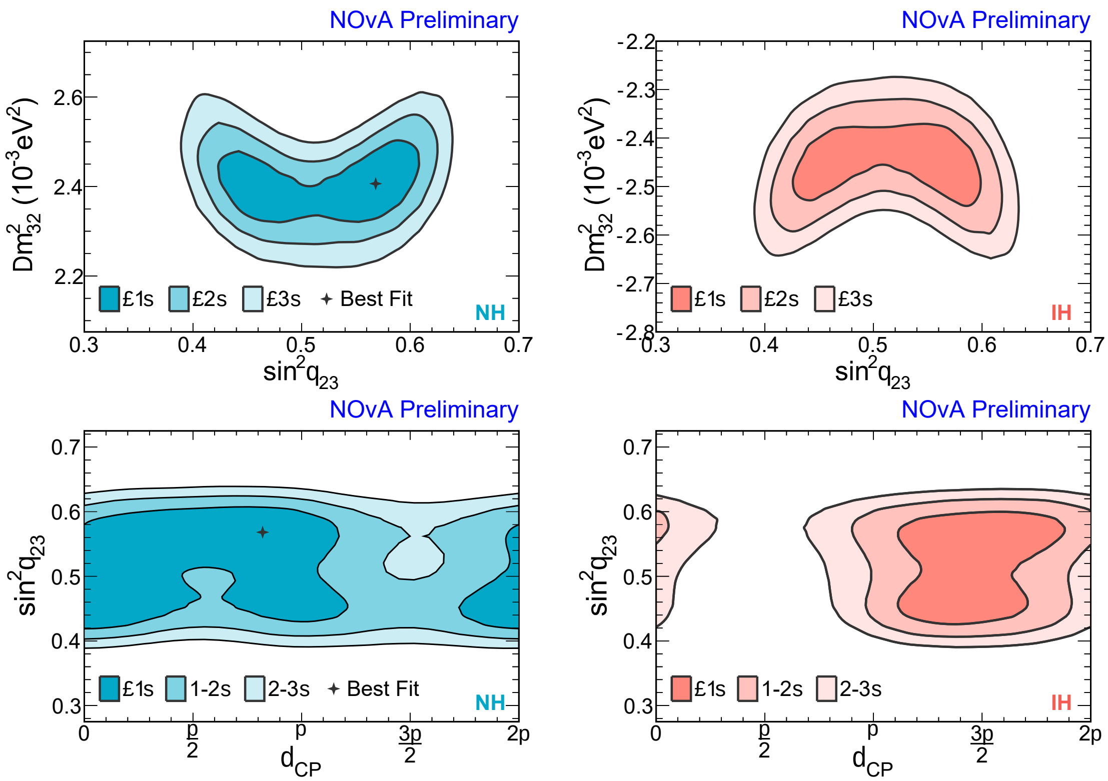

Figure 3: The latest NOvA Δm^2_{32} vs. $\sin^2\theta_{23}$ and $\sin^2\theta_{23}$ vs. $\delta_{\rm CP}$ confidence intervals
.

4 Conclusions

The NOvA oscillation sensitivities were almost completely unaffected by the inclusion of high-energy events to Far Detector ν_e ($\bar{\nu}_e$) predictions. The best fit values of the oscillation parameters that lie in the Normal Hierarchy are $\Delta m^2_{32} = (2.41 \pm 0.072) \times 10^{-3}$ eV^2 and $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$. The data also disfavours $\delta_{\text{CP}} = \pi/2$ ($3\pi/2$) at more than 3 (2)σ.

5 Acknowledgments

This document was prepared by the NOvA collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.I would also like to thank the Council of Scientific & Industrial Research (CSIR), Ministry of Science and Technology, Govt. of India, for providing research fellowship since August 2019. I would like to thank "Indian Institutions - Fermilab Collaboration in neutrino physics" through DST letter No. SR/MF/PS-01/2016-DU/G dated 28.03.2019 under which this collaboration on NOvA experiment has been made possible and work done.

References

1. Ayres DS et al. NOvA: Proposal to Build a 30 Kiloton Off-Axis Detector to Study $\nu_\mu \to \nu_e$ Oscillations in the NuMI Beamline. 2004.
2. Adamson P et al. The NuMI Neutrino Beam. Nucl. Instrum. Meth. A 2016;806:279–306.
3. Acero MA et al. Improved measurement of neutrino oscillation parameters by the NOvA experiment. Phys. Rev. D 2022;106:032004.
4. Acero MA et al. First Measurement of Neutrino Oscillation Parameters using Neutrinos and Antineutrinos by NOvA. Phys. Rev. Lett. 2019;123:151803.
5. Acero MA et al. New constraints on oscillation parameters from ν_e appearance and ν_μ disappearance in the NOvA experiment. Phys. Rev. D 2018;98:032012.