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Latest Three-Flavor Neutrino Oscillation Results from NOvA

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Abstract

NOvA, is a two-detector, long-baseline neutrino oscillation experiment located at Fermilab, Batavia, IL, USA. NOvA was designed primarily to constrain neutrino oscillation parameters by analyzing $\nu_\mu(\bar{\nu}_\mu)$ disappearance and $\nu_e(\bar{\nu}_e)$ appearance data at the far detector. The Neutrinos at Main Injector (NuMI) beamline at Fermilab provides a high purity beam of neutrinos and anti-neutrinos to the experiment. The NOvA experiments consists of two functionally identical, finely granulated liquid tracking calorimeters, both situated 14.6 mrad off-axis to the beam direction. The NOvA near detector, situated 100 meters underground and 1 kilometer from the beam source, detects the un-oscillated $\nu_\mu(\bar{\nu}_\mu)$ and beam $\nu_e(\bar{\nu}_e)$ events. The far detector, located in Ash River, MN, USA, 810 kilometers from the beam source, records the un-oscillated $\nu_\mu(\bar{\nu}_\mu)$ and the oscillated $\nu_e(\bar{\nu}_e)$ events. The most recent measurements of three flavor neutrino oscillation parameters based on an analysis of the data collected from a neutrino-beam exposure of 26.60×10^{20} POT and an anti-neutrino beam exposure of 12.50×10^{20} POT with an additional low energy ν_e sample, will be presented in this talk.

1 Introduction

The NOvA experiment[1] consists of two functionally identical detectors, both situated 14.6 mrad off-axis to the Fermilab's NuMI[2] beam direction. The detectors are made up of PVC extrusion cells, filled with liquid scintillators, arranged in alternating horizontal and vertical planes for 3D reconstruction of the observed events[3]. The experiment observes ν_μ $(\bar{\nu}_\mu)$ disappearance and $\nu_e(\bar{\nu}_e)$ appearance oscillations. The near detector (ND) which situated at a distance of 1km from the beam source at Fermilab, and observes un-oscillated ν_μ $(\bar{\nu}_\mu)$ and beam background events. The far detector (FD) sits on-surface in Ash River, MN, USA at a distance of 810km from the beam source and observes disappeared $\nu_\mu(\bar{\nu}_\mu)$ and appeared $\nu_e(\bar{\nu}_e)$ events. The disappearance channels help in probing the amtospheric mass-squared splitting Δm^2_{32} and the mixing angle θ_{23}. The appearance channels, on the other hand, are sensitive[1] to the mixing angle θ_{13} and the CP-violating phase δ_{CP}. The

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[1]The sensitivity is very mild though. We use reactor constraints on θ_{13} in our joint fits.

asymmetry in $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations, caused by the matter effects experienced by the propagation of neutrinos/anti-neutrinos in the earth might hint towards the mass ordering of neutrinos[1]. The latest measurements of the three flavor neutrino oscillation parameters will be highlighted in this document. Section 2 briefly discusses the strategy used in analysing the data. The spectra of observed and predicted $\bar{\nu}_\mu$ $(\bar{\nu}_\mu) \to \nu_\mu(\bar{\nu}_\mu)$ and $\nu_\mu(\bar{\nu}_\mu) \to \bar{\nu}_e$ $(\bar{\nu}_e)$ events at the far detector are shown in section 3. Finally, the latest constraints on neutrino oscillation parameters will be discussed in section 4.

2 The Oscillation Analysis

A joint fit to the FD data is performed against the simuated number of events at the FD to constrain oscillation parameters. The base FD simulations are corrected using a data-driven technique called extrapolation to construct predicted spectra of $\nu_\mu/\bar{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$ events at the FD. Extrapolation makes use of the high statistics ND ν_μ charged current (CC) events sample to constrain dominant systematic uncertainties such as neutrino cross-sections, neutrino flux, and detector response[4]. The data collected from a neutrino-beam exposure of 26.60×10^{20} POT and an anti-neutrino beam exposure of 12.50×10^{20} POT with an additional low energy ν_e sample was analysed to get improved measurements of the oscillation parameters.

3 Far Detector Data and Predictions

Figures 1 and 2, respectively, show the observed $\nu_\mu(\bar{\nu}_\mu) \to \nu_\mu(\bar{\nu}_\mu)$ and $\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$ events compared against predicted events at the far detector. The observed number of events for all of the oscillation channles are tabulated in table 1.

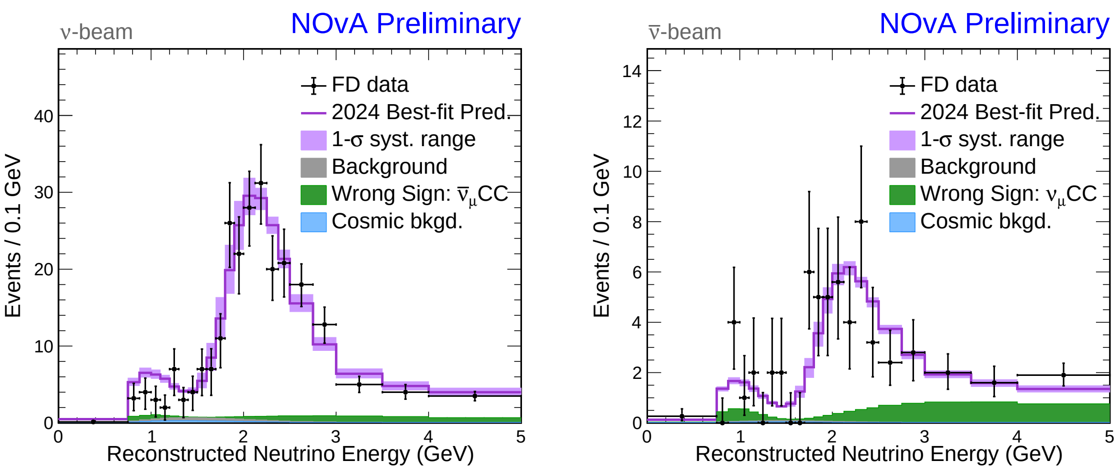


Figure 1: The spectra of observed and predicted $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ events at the far detector overlay with $\pm 1\sigma$ systematic uncertainty bands. The predictions are generated the 2024 best-fit values of the oscillations parameters.

	$\nu_\mu \to \nu_\mu$	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$
Observed FD Data	384	106	181	32
Estimated Background	11.3	1.7	61.7	12.2

Table 1: The observed data and estimated background event counts at the far detector.

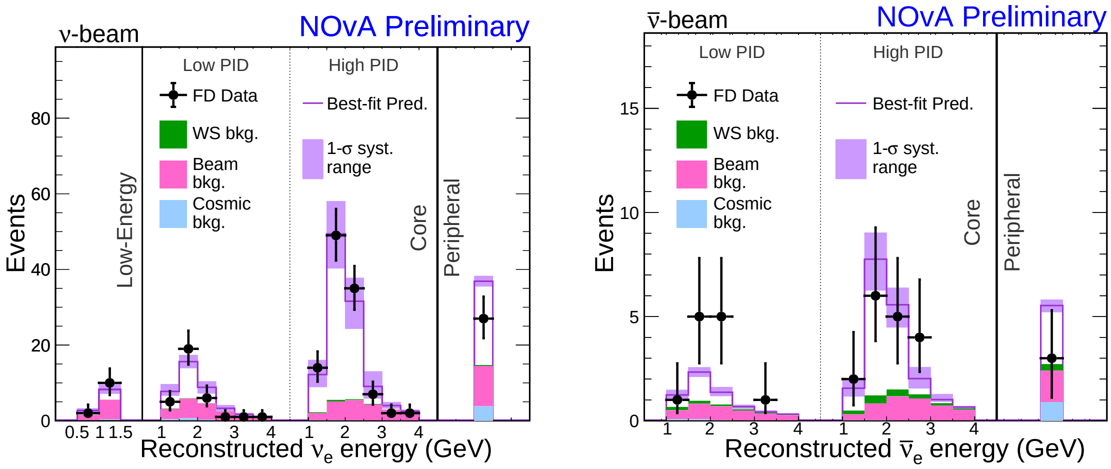


Figure 2: The spectra of observed and predicted $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ events at the far detector in bins of purity, including the low energy ν_e sample, overlay with $\pm 1\sigma$ systematic uncertainty bands. The predictions are generated the 2024 best-fit values of oscillations parameters.

4 Results

Figure 3 shows the 90% confidence limit region of Δm^2_{32} and $\sin^2(\theta_{23})$ measurements at NOvA (the solid filled contour), overlay with measurements from IceCube[5], T2K[6], NOvA+T2K[7, 8] and SK+T2K[9] joint analyses. NOvA's latest $\nu_2 - \nu_3$ sector measurements are consistent with the measurements of the rest of the experiments. The best-fit values of oscillation parameters from the frequentist fit of NOvA data can be found in table 2. The Bayesian 1σ credible intervals of $\sin^2\theta_{23}$ and δ_{CP} measurements at NOvA for both mass orderings are shown in figure 4. NOvA data disfavor $\delta_{CP} = \frac{3\pi}{2}$ in normal mass ordering as opposed to T2K which favors $\delta_{CP} = \frac{3\pi}{2}$ in normal mass ordering. NOvA is consistent with T2K in excluding $\delta_{CP} = \frac{\pi}{2}$ in inverted mass ordering at 1σ level. NOvA data also have a mild preference for normal mass ordering which enhances with 1D and 2D reactor constraints on θ_{13} as shown in figure 5. NOvA has also produced the most precise single experiment measurement of Δm^2_{32} with a precision of 1.4%.

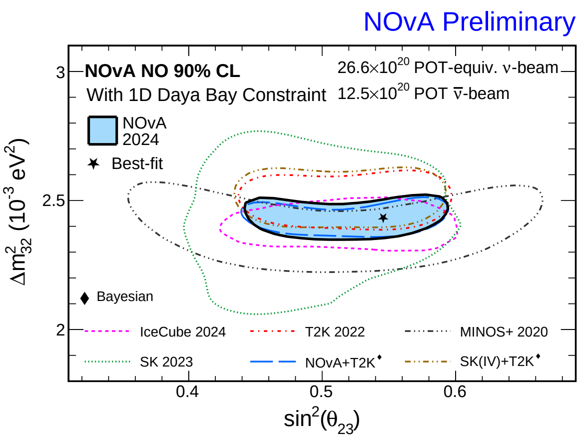
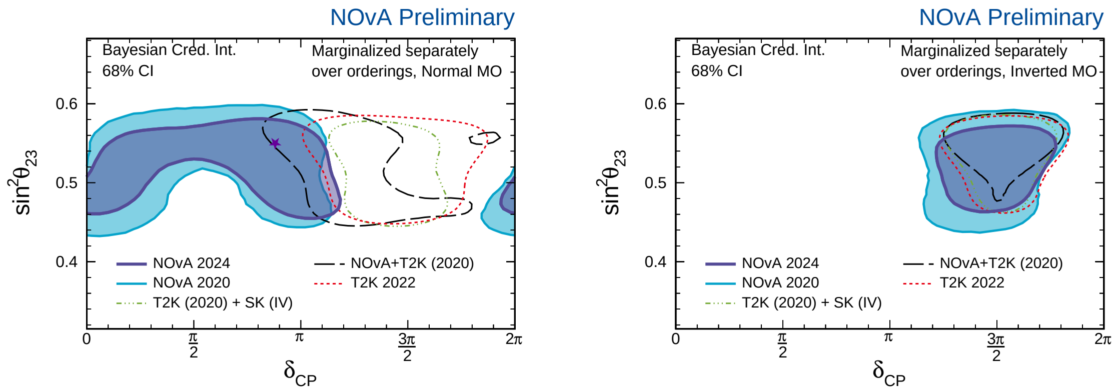


Figure 3: The 90% confidence limit region of Δm^2_{32} and $\sin^2(\theta_{23})$ measurements at NOvA (the solid filled contour), overlay with measurements from other atmospheric and accelerator based experiments.

Parameter	$\sin^2(\theta_{23})$	$\Delta m^2_{32}\ (10^{-3}\,\text{eV}^2)$	$\delta_{\text{CP}}\ (\pi)$
Best-fit	$0.546^{+0.032}_{-0.075}$	$2.439^{+0.035}_{-0.036}$	0.875

Table 2: The best-fit values of oscillation parameters from the frequentist fit of NOvA data with 1D reactor constraints on θ_{13}.



Normal Mass Ordering Inverted Mass Ordering

Figure 4: The Bayesian 1σ credible intervals of $\sin^2\theta_{23}$ and δ_{CP} measurements at NOvA overlay with the contours from other experiments.

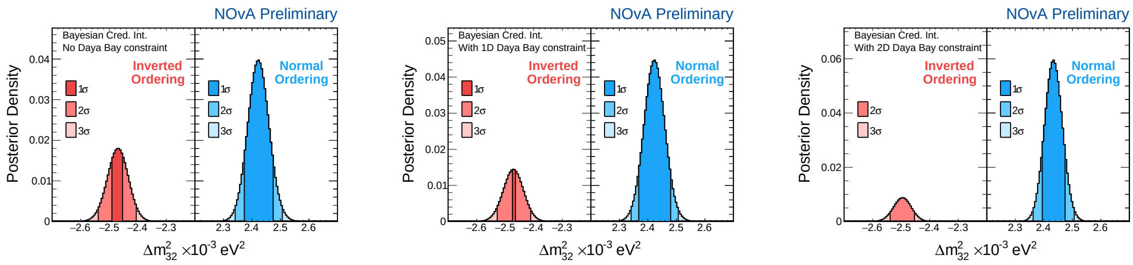


Figure 5: Posterior density distributions of preference to mass orderings from NOvA data without any reactor constraints (left), with 1D reactor constraint (middle), and 2D reactor constraint (right) on θ_{13}.

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