Recent Results of Electron-Neutrino Appearance Measurement at NOvA

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NOvA is a long-baseline accelerator-based neutrino oscillation experiment that is optimized for ν_e measurements. It uses the upgraded NuMI beam from Fermilab and measures electron-neutrino appearance and muon-neutrino disappearance at its Far Detector in Ash River, Minnesota. The ν_e appearance analysis at NOvA aims to resolve the neutrino mass hierarchy problem and to constrain the CP-violating phase. The first measurement of electron-neutrino appearance in NOvA based on its first year's data was produced in 2015, providing solid evidence of ν_e oscillation with the NuMI beam line and some hints on mass-hierarchy and CP. This talk will discuss the second ν_e oscillation analysis at NOvA, which is based on 2 years of data.

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1. Introduction

NOvA is a long-baseline neutrino experiment optimized to observe the oscillation of muon neutrinos to electron-neutrinos. NOvA uses a 14-kt liquid scintillator Far Detector (FD) in Ash River, Minnesota to detect the oscillated NuMI (Neutrinos at the Main Injector) muon neutrino beam produced 810 km away at Fermilab. The NuMI beam has been upgraded to 700 kW. NOvA has the longest baseline in operation, so the matter effect is as large as 30%, which is sensitive to the mass hierarchy determination. NOvA is equipped with a 0.3-kt functionally identical Near Detector (ND) located at Fermilab to measure unoscillated beam neutrinos and estimate backgrounds at the FD. Both detectors are located 14.6 mrad off-axis to receive a narrow-band neutrino energy spectrum near the energy of the $\nu_\mu \to \nu_e$ oscillation maximum range ($\sim$2 GeV), enhancing the $\nu_\mu \to \nu_e$ oscillation signal in the FD while reducing neutral current and beam ν_e backgrounds from high-energy unoscillated beam neutrinos.

NOvA detectors are composed of PVC modules extruded to form long tube-like cells. The FD consists of 344,064 detector cells, and the ND consists of 20,192 cells. Lengths of cells are 16m in FD and 4m in ND. Each cell is filled with liquid scintillator and has a loop of wavelength-shifting fiber routed to an Avalanche Photodiode. The cells are arranged in planes, assembled in alternating vertical and horizontal directions, so the NOvA detectors can serve as both calorimeters and 3-D trackers. The NOvA detectors have low-Z and low-density, each plane is just 0.15 X_0, which is great for e/π^0 separation.

The ν_e appearance analysis at NOvA aims to determine the neutrino mass hierarchy, CP violation and the octant of θ_{23}. Using the first year of neutrino beam data (2.74×10^{20} POT), the NOvA collaboration has published first papers that present its initial results of the ν_e appearance and ν_μ disappearance measurements [1][2]. For the analysis reported in this paper, we use 6.05×10^{20} POT neutrino beam data, which is more than twice as large as the exposure in our first analysis last year.

2. Event selection and Data Analysis

Recently, a convolutional neural network based algorithm has been implemented at NOvA to serve as the primary event identifier for the second analysis. The new particle identification (PID) algorithm is named CVN [3]. It uses pixels as inputs and the output is a variable that describes the probability to be a ν_e CC event with a range $0-1$. In this CVN identifier, convolutional filters are used to automatically extract features from the raw hit map. The output of this neural net is used to classify the event. The statistical power of CVN is equivalent to 30% more exposure than previous PIDs, LID [4] and LEM [5]. In this analysis, an empirical meson exchange current (MEC) model [6] is added in the GENIE event generator [7]. According to the hadronic energy distributions in the ND ν_μ CC Data/MC, this process was found missing in our default simulation in the phase space between the quasi-elastic (QE) and the resonance production (RES) regions, which is also reported by MINERvA [6]. At NOvA, these simulated MEC events are reweighted based on Data/MC comparisons of kinetic variables of ND ν_μ CC events.

We optimize event selection to maximize $FOM = S/\sqrt{S+B}$. According to the far detector MC, the signal efficiency after selection is 73%, and the purity is 76%. After the event selection, we reconstruct the neutrino energy as a function of the electromagnetic energy and hadronic energy. Data and MC of the CVN distribution and the reconstructed neutrino energy in the near detector are shown in Figure 1. We then use the ND data to predict the background energy spectrum in the far detector in 3 PID regions.

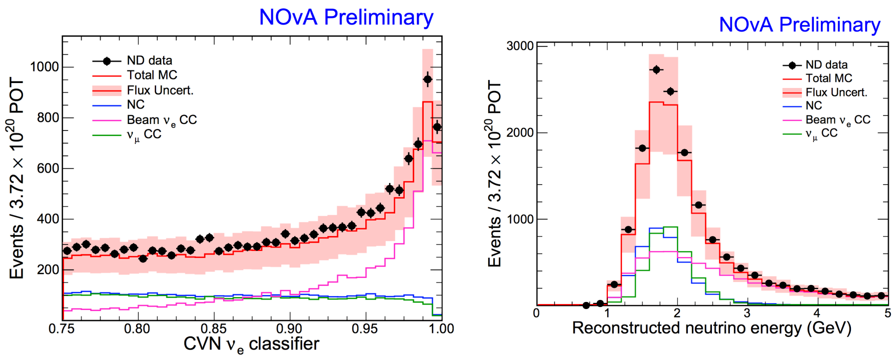

Figure 1: Data and MC of the CVN distribution (left) and the reconstructed neutrino energy (right) in the near detector

For the ν_e CC signal, the consistency between data and MC has been validated based on the ND data and the cosmic ray data, using beam ν_μ CC (replace the muon track with a simulated electron shower) events and electromagnetic showers in cosmic rays. Signal Data/MC difference is found to be less than 1%. Beam ν_e, ν_μ and NC backgrounds are extrapolated differently to the FD. We first reweight kaon and pion components in the flux to match the selected ν_μCC energy spectrum in data, then fix the beam ν_e to the flux-reweighted result (up by 4%), and constrain NC (up by 10%) and ν_μ CC (up by 17%) using Michel electron distributions. After this tuning, the simulated energy spectrum matches the data in all three PID bins.

We predict FD signal+background counts based on the signal MC, the ND data and the cosmic ray data (FD events outside of the beam spill window). The total expected event count depends on oscillation parameters, as shown in Figure 2. Under the assumption of normal mass hierarchy, $\delta_{CP} = 3/2\pi$ and $\sin^2\theta_{23} = 0.5$, we expect to have 36.4 events in total with the CVN selection. When assuming inverted mass hierarchy and $\delta_{CP} = 1/2\pi$, the expected number of events is 19.4. The background prediction in the FD is 8.2 events, varying about %1 for different choices of oscillation parameters. The dominant backgrounds are 3.7 NC events and 3.1 beam ν_e CC events. ν_μ CC, ν_τ CC and cosmic muons take 0.7, 0.1 and 0.5 events, respectively.

This extrapolation eliminates most of the systematic errors. Remaining systematic uncertainties after the extrapolation are evaluated by extrapolating ND data with nominal MC and systematically modified MC samples, with variations to the normalization (POT counting), neutrino cross-sections, calibration, beam simulation, non-linearity in detector responses and other smaller uncertainties. The total systematic errors are about 5% for the signal and about 10% for the background.

3. Results

Before counting and analyzing the FD data in the beam spill window (the signal region), we checked the near-PID sideband, the high-energy sideband and events outside of the beam spill

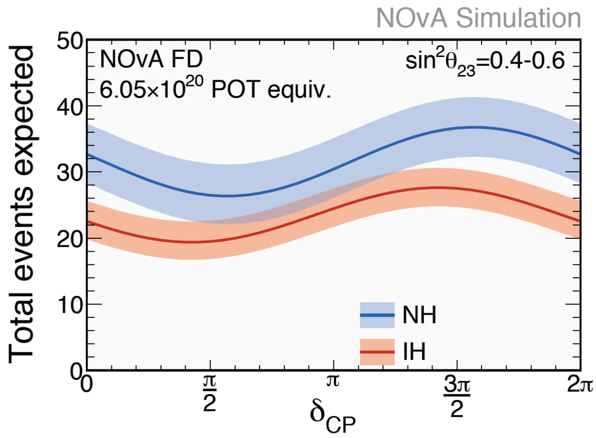

Figure 2: Total number expected event vs. CP phase

window. They all appeared to have good data/MC agreements. Using the CVN selection, we observe 33 ν_e candidates in the FD, and the expected background is 8.2 ± 0.8 events. Using LID and LEM, event selectors in the 2015 analysis, we observe consistent results (LID: 34 events, 12.2 ± 1.2 background expected; LEM: 33 events, 10.3 ± 1.0 background expected).

Energy distributions in the three CVN bins are fit to data to extract oscillation parameters. In this fit, oscillation parameters are constrained as: $\sin^2 2\theta_{13} = 0.086 \pm 0.05$, $\Delta m^2_{21} = 7.53 \pm 0.18 \times 10^{-5}\text{eV}^2$ and $\Delta m^2_{32} = 2.44 \pm 0.06 \times 10^{-3}$ eV^2 for the normal mass hierarchy (NH) and $-2.49 \pm 0.06 \times 10^{-3}$ eV^2 for the inverted mass hierarchy (IH). The systemic uncertainties are included as nuisance parameters in the fit. Figure 3 shows comparisons of the FD data to the best fit prediction for CVN and energy distributions, under the normal hierarchy assumption. The significance of ν_e appearance is greater than 8σ.

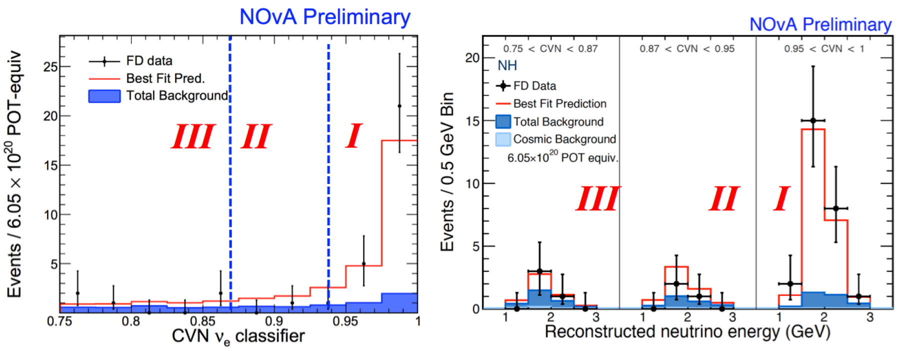

Figure 3: The CVN distribution (left) and the reconstructed energy spectrum (right) of ν_e CC selected events in the far detector. Black points: FD data, red histogram: the best fit prediction, blue shaded histograms: background MC.

The resulting allowed regions of $\sin^2\theta_{23}$ vs. δ_{CP} at 1, 2, and 3σ for each of the hierarchies produced by the fit are shown in Figure 4. The left two plots show contours from the ν_e appearance data and right two plots show contours from the combination of ν_e appearance and ν_μ disappearance data. The global best fit gives us normal hierarchy, $3\pi/2$ CP phase and $\sin^2\theta_{23} = 0.4$. Because the

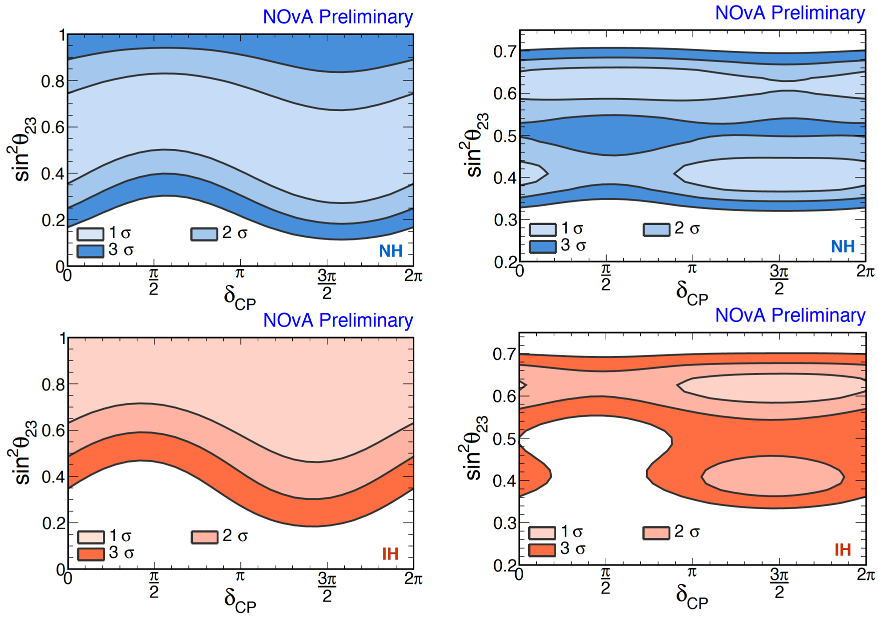

Figure 4: Allowed regions of $\sin^2\theta_{23}$ vs. δ_{CP} at 1, 2, and 3σ: (left) results from ν_e appearance data and (right) results from the combination of ν_e appearance and ν_μ disappearance data.

NOvA ν_μ disappearance analysis found that the mixing is not maximal, both octants are allowed for θ_{23}. If it is the lower octant, NH is preferred and CP is close $3\pi/2$. For the upper octant, both MHs are allowed, and the best fit is around $\pi/2$ for NH, and $3\pi/2$ for IH. $\delta_{CP} \simeq \pi/2$ is rejected for the IH and lower octant.

Figure 5 demonstrates the ambiguity caused by the octant of θ_{23} in our results. The ellipses are all possible results of the ν_e appearances vs. $\bar{\nu}_e$ appearance probabilities in NOvA. For $\theta_{23} < 45^\circ$, the NH and IH ellipses are on the lower left side. For $\theta_{23} > 45^\circ$, the two ellipses are on the upper right side. The result of this analysis ($\nu_\mu \to \nu_e$) is the vertical violet line. One can find that our results prefer (NH, $3\pi/2$ CP) for the lower octant, and prefer (IH, $3\pi/2$) or (NH, $\pi/2$) for the upper octant. This ambiguity can be solved by performing a measurement of $\bar{\nu}_\mu \to \bar{\nu}_e$ (horizontal violet line) using the anti-neutrino beam.

4. Summary

With 6.05×10^{20} of POT NuMI neutrino beam data, we have performed the second ν_e appearance measurement in NOvA. The significance of the ν_e appearance is greater than 8σ, and our data prefers the normal mass hierarchy at a low significance. In our analysis, the inverted mass hierarchy for $\delta_{CP} = \pi/2$ is rejected for lower octant, but we do observe an ambiguity in the mass hierarchy determination caused by the octant of θ_{23}. We plan to run antineutrinos to perform a $\bar{\nu}_e$ appearance analysis in Spring, 2017 to solve these degeneracies.

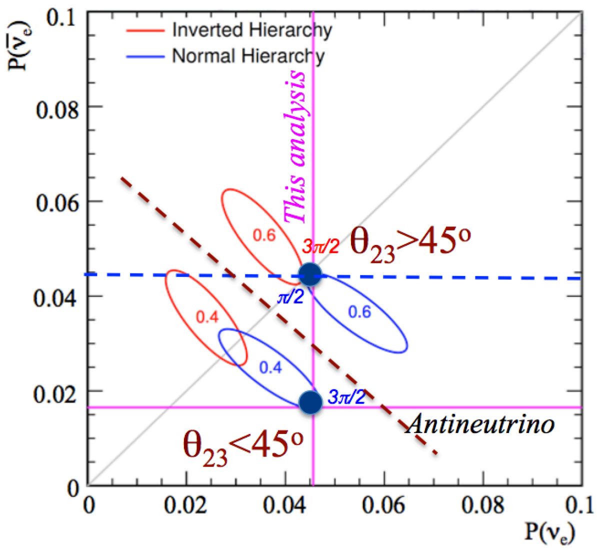

Figure 5: The principle of the NOvA $\nu_e(\bar{\nu}_e)$ appearance measurements. All possible values of probabilities of $\nu_\mu \to \nu_e$ vs. $\bar{\nu}_\mu \to \bar{\nu}_e$ are on the ellipses. The solid blue (red) ellipses correspond to the normal (inverse) hierarchy scenarios, with δ_{CP} varying as one moves around each ellipse.

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