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Results and Prospects from NOvA

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The NOvA experiment at Fermilab uses a beam of neutrinos and two detectors separated by an 810 km baseline to observe muon neutrino disappearance and electron neutrino appearance. These measurements have the potential to reveal the remaining unknowns in neutrino oscillations, namely the mass hierarchy, the θ_{23} octant, and perhaps even hint at the violation of CP in the neutrino sector. In this talk, I will describe the current status of the NOvA experiment, present results and discuss future sensitivities.

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1. Introduction

The NOvA experiment [1] is a long-baseline, neutrino oscillation experiment that studies neutrinos produced by Fermilab's NuMI [2] neutrino beam. NOvA uses two, functionally identical detectors situated 14 mrad off-axis such that the neutrino beam is a narrow-band ν_μ beam peaked around 2 GeV with neutrino energies mainly in the 1-3 GeV range. A 290 ton near detector (ND) sits 100 m underground, 1 km from the beam source at Fermilab and a 14 kton far detector (FD) is 810 km away in Ash River, MN.

This paper presents results from three different oscillation analyses. Initially we report on the standard three-flavor neutrino oscillation analyses; specifically, muon neutrino disappearance and electron neutrino appearance. We begin by describing the results from an exposure equivalent to 6.05×10^{20} protons-on-target (POT) in the FD. The dominant oscillation mode at the NOvA baseline and energy is through the disappearance of ν_μ charged current (CC) events. In this mode, oscillations cause a clear suppression of ν_μ-CC events as a function of energy. This suppression is dependent on the mixing parameters Δm^2_{32} and $sin^2(2\theta_{23})$. The muon neutrino disappearance analysis presented here is published in Ref. [3], which is an update of Ref. [4]. The ν_e appearance channel directly measures the mixing angle θ_{13} which is now well measured and is comparatively large [5]. This channel also depends on θ_{23} and the phase of CP violation, δ_{CP}, which opens the possibility to revealing the θ_{23} octant and a hint at the violation of CP in the neutrino sector. Matter effects make the measurement of the appearance of ν_e-CC events sensitive to a potential determination of the neutrino mass hierarchy. The electron neutrino appearance analysis presented here is published, including a joint analysis with the disappearance data, in Ref. [6]; updated from Ref. [7]. Finally we present the neutral-current (NC) disappearance analysis. This is the first analysis to use the updated exposure equivalent to 8.85×10^{20} POT in the FD. This dataset spans the period February 6, 2014 to February 20, 2017 and is an update of the previous published result in Ref. [8].

2. Muon neutrino disappearance

The initial spectrum and composition of the NuMI neutrino beam is observed in the ND before oscillations can occur. The measured energy spectrum of the ND-selected ν_μ-CC events are used to predict the energy spectrum expectation in the FD. The ν_μ-CC candidate events are selected from NC background by combining input variables in a k-Nearest Neighbour (kNN) classifier that achieves a selection purity of 95% and selection efficiency of 81%. Their energy is estimated by summing the reconstructed energy of the muon and the hadronic recoil system with an overall energy resolution of about 7% for both detectors.

In the absence of oscillations, 473 ± 30 ν_μ-CC events are predicted in the FD. After unblinding the data, we observed 78 candidate events with an expected background of 3.4 NC, 0.23 ν_e-CC, 0.27 ν_τ-CC, and 2.7 cosmic-ray induced events. Figure 1 shows a comparison of the best-fit prediction, in red, for three-flavor oscillations to the observed reconstructed energy spectrum, black dots, of selected events, as well as the prediction assuming maximal mixing, in dashed green. The ratio to the prediction in the absence of oscillations is shown in the lower panel. At the best-fit, 82.4 events are expected and the best-fit has a χ^2/d.o.f = 41.6/17. The largest contributions to the χ^2

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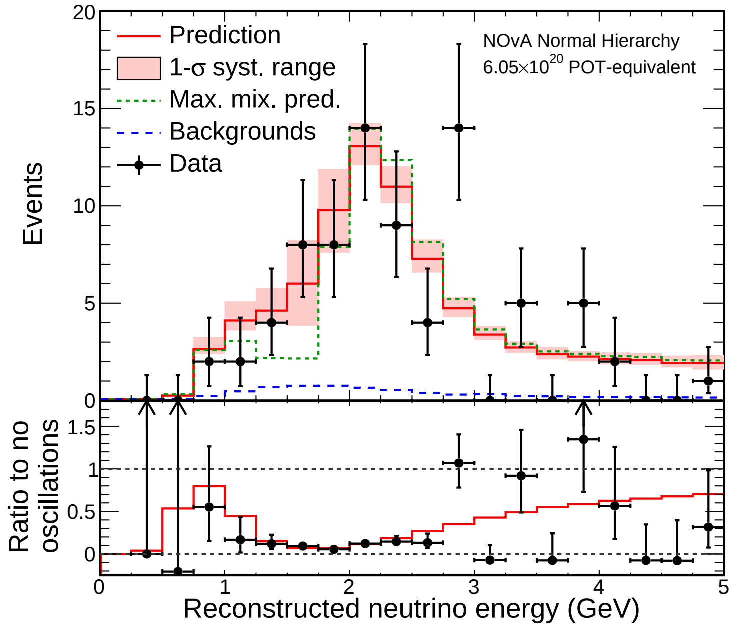

Figure 1: Top: Comparison of the reconstructed energy spectrum of the FD data (black dots) and best-fit prediction (red). The prediction assuming maximal mixing is shown in dashed green. The 1σ systematic uncertainty band is shaded red and combined backgrounds are shown by the dashed line. Bottom: Ratio to no oscillations for data and simulation after background subtraction.

arise mainly from the fluctuations in the tail of the energy spectrum that contain little information about the three-flavor oscillations.

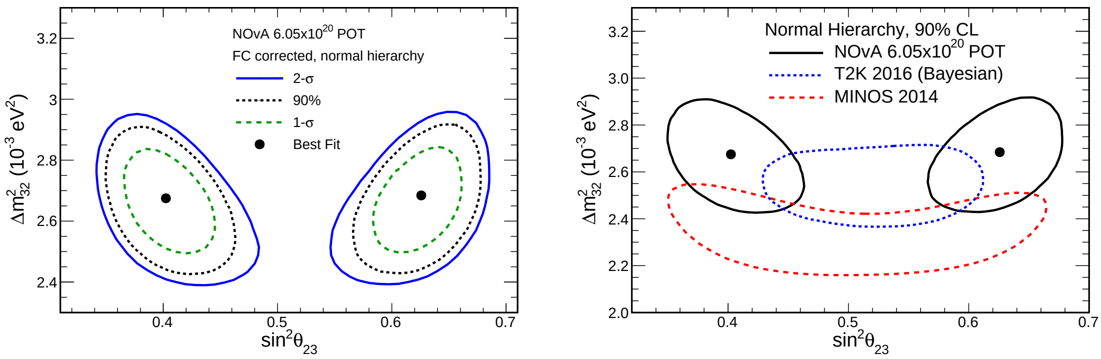

Figure 2: Left: The Feldman-Cousins corrected allowed 1σ (dashed green), 90% (dashed black), and 2σ (solid blue) C.L. regions at the two statistically degenerate best-fit points (black dots) of $sin^2\theta_{23}$ and Δm^2_{32} for the normal hierarchy. Right: NOvA's best-fit (black dots) points and allowed 90% C.L. regions compared to previous results from MINOS [9] and T2K [10] (dashed curves).

The best fit to the data prefers $\Delta m^2_{32} = (2.67 \pm 0.11) \times 10^{-3}\ eV^2$ and $sin^2\theta_{23}$ at the two statistically degenerate values $0.404^{+0.030}_{-0.022}$ in the lower octant and $0.624^{+0.022}_{-0.030}$ in the upper octant, both at the 68% C.L. in the normal hierarchy. The data disfavors maximal mixing, where $sin^2\theta_{23} = 0.5$, at 2.6σ. Figure 2 (left) shows the allowed 1σ, 2σ, and 90% C.L. regions of Δm^2_{32} and $sin^2\theta_{23}$ where the statistical significance of these contours has been determined using the Feldman-Cousins unified approach [11]. Figure 2 (right) depicts the NOvA 90% C.L. contour in comparison to previous results from MINOS [9] and T2K [10]. For a full discussion of the details of the muon neutrino disappearance analysis refer to the publication in Ref. [3].

3. Electron neutrino appearance

The selection of ν_e-like events is performed by an event selection technique based on ideas from the fields of computer vision and deep learning. Calibrated hit maps representing the events are inputs to the Convolutional Visual Network (CVN) algorithm; a deep neural network implementation of a convolutional neural network. Each layer of the network performs convolutions to extract features and draw correlations to identify neutrino flavor. The current iteration of CVN classifies events as NC, ν_μ-CC, ν_e-CC, ν_τ-CC, and cosmic ray interactions. NOvA selects ν_e-CC interactions with 73.5% efficiency and 75.5% purity, representing a gain in the sensitivity of the electron neutrino appearance analysis equivalent to 30% more exposure when compared to the more traditional reconstruction algorithms used in the previously published results [7]. Full details of CVN are given in Ref. [12].

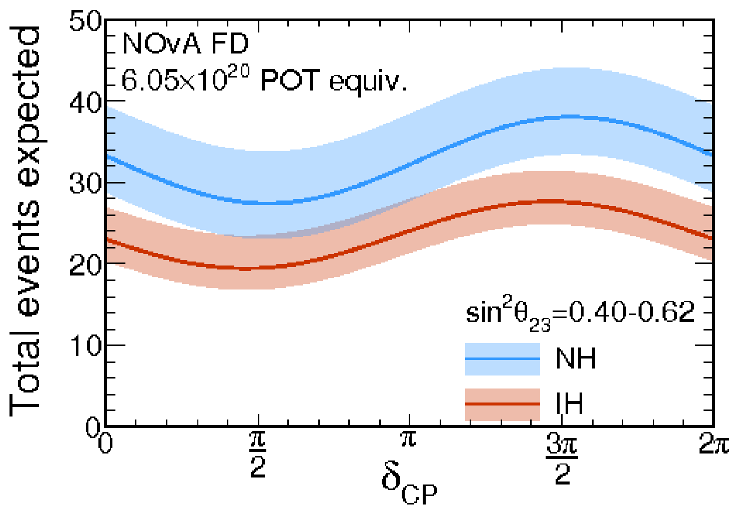

Figure 3: Total number of ν_e-CC events expected at the FD as a function of hierarchy and δ_{CP}. The bands correspond to the range $sin^2\theta_{23} = 0.40$ (lower edge) to 0.62 (upper edge) with the solid line marking maximal marking in the normal hierarchy (blue) and inverted hierarchy (orange).

The selection criteria are chosen to maximize the $\frac{S}{\sqrt{S+B}}$ figure of merit, where S and B are the number of signal and background events, respectively. The ν_e-CC selection selects $\sim$10% more events in ND data than simulation. Data-driven methods are used to estimate the relative sizes of background events; NC, ν_μ-CC, and intrinsic beam ν_e-CC events. The amount of beam ν_e-CC background events is constrained by using the ν_μ-CC selected events. Both the ν_μ and intrinsic ν_e interactions arise from the decays of pions that also produce muons, which in turn decay to produce the majority of the beam ν_e-CC selected events. The ν_μ-CC background component is constrained by fitting the observed number of Michel electrons spectrum in selected events. These considerations lead to a 1% increase over that given by simulation of the intrinsic beam ν_e-CC background rate in the 1 to 3 GeV range in the ND, as well as an increase of 17.7% and 10.4% in the ν_μ-CC and NC background rates, respectively. These corrections account of the 10% discrepancy with simulation and are extrapolated to the FD background spectra in bins of reconstructed energy and the CVN classifier value.

Upon examining the FD data, 33 ν_e-CC candidate events were found, of which 8.2 ± 0.8 (syst.) events are predicted to be background. Figure 3 shows the total number of predicted events at the FD as a function of hierarchy and δ_{CP} for the range $sin^2\theta_{23} = 0.40$ (lower edge) to 0.62 (upper edge). In order to extract oscillation parameters, the ν_e-CC energy spectrum in the three highest bins of the CVN classifier are fit simultaneously with the FD ν_μ-CC energy spectrum. The NOvA ν_μ-CC disappearance result described in Sec. 2 constrains $sin^2\theta_{23}$ around the degenerate best-fit points of 0.404 and 0.624. Systematic uncertainties are included in the fit as nuisance parameters and external data is used to constrain $sin^2 2\theta_{13}$ to 0.085 ± 0.05 [5].

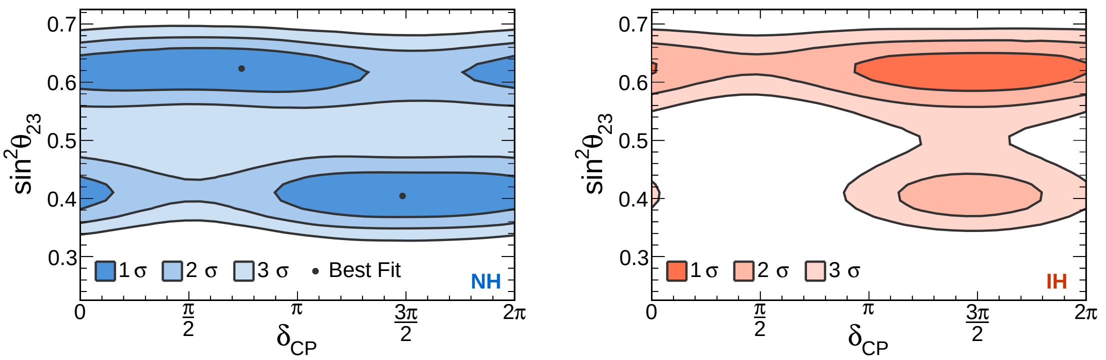

Figure 4: Left: The 1, 2, and 3σ regions of the δ_{CP}, $sin^2\theta_{23}$ parameter space for the normal hierarchy. The color indicates the confidence level at which parameter combinations are allowed. Right: The equivalent contours for the inverted hierarchy case.

Figure 4 shows the regions of $sin^2\theta_{23}$ and δ_{CP} space allowed at various confidence levels for each of the hierarchies. There exist two statistically degenerate best fit points in the normal hierachy, namely $sin^2\theta_{23} = 0.404$, $\delta_{CP} = 1.48\pi$ and $sin^2\theta_{23} = 0.623$, $\delta_{CP} = 0.74\pi$. The best-fit point in the inverted hierarchy is near $\delta_{CP} = 3\pi/2$ and is 0.46σ from the global best-fit points.

Figure 5 shows the significance at which values of δ_{CP} are disfavored for each hierarchy and octant combination. The inverted hierarchy in the lower octant is disfavored at greater than 93% C.L. for all values of δ_{CP}, and excluded at greater than 3σ outside the range $0.97\pi < \delta_{CP} < 1.94\pi$.

4. Neutral-Current disappearance

The energy spectrum of NC events is unaffected by oscillations among active flavors. In the presence of a sterile neutrino state, active to sterile flavor mixing causes an energy-dependent depletion of NC events. As a result NOvA searches for a reducton in the rate of NC events observed at the FD through the NC disappearance analysis. We begin by selecting NC events in the ND and extrapolating to the FD to predict the FD energy spectrum. The ratio of data to simulation in

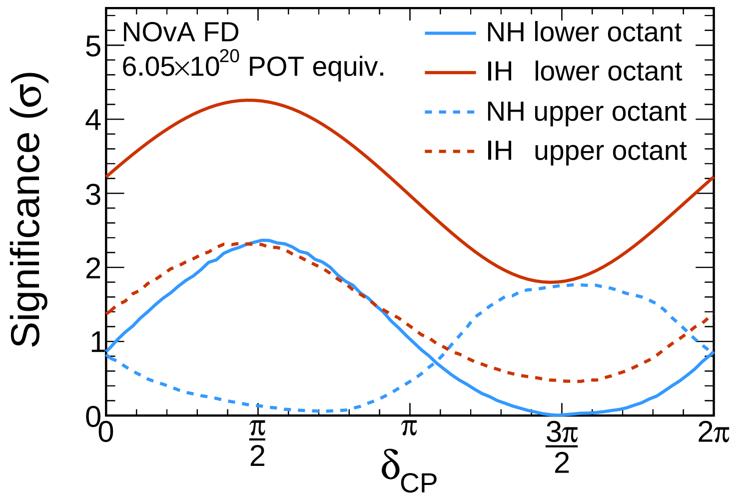

Figure 5: Feldman-Cousins corrected significance as a function of values of δ_{CP} disfavored for normal (blue) or inverted (red) hierarchy, and lower (solid) or upper (dashed) θ_{23} octant. This is after the combination of ν_e appearance and NOvA's latest ν_μ disappearance measurement.

reconstructed energy is used to scale the FD simulated spectrum. The analysis presented here is the first to unblind data from an exposure equivalent to 8.85×10^{20} POT, which represents an increase of 50% more data over the three-flavor oscillation analyses described in Sec. 2 and Sec. 3. This is an updated analysis from the one published in Ref. [8]. As well as the increase in data for this analysis, further upgrades include an improved cosmic rejection boosted-decision tree algorithm, improved cross-section modeling, detector response modeling, and instead of being a rate-only fit this analysis performs a energy spectrum shape-fit.

The NC event selection uses the CVN classifier in a similar fashion to the ν_e-CC appearance analysis. The NC disappearance analysis observes 214 neutral-current candidates at the far detector compared with a prediction of 191.2 ± 13.8 (stat.) $\pm$ 22.0 (syst.) assuming standard three-flavor mixing. Figure 6 shows the observed NC energy spectrum, black dots, compared to the three-flavor NC prediction, blue line, and the various background components. The prediction assumes maximal mixing. No depletion of NC events was observed. Preliminary updated results from the search for sterile neutrinos through neutral-current disappearance show no evidence for $\nu_\mu \rightarrow \nu_s$ transitions.

A energy spectrum shape-fit is performed to measure constraints on the sterile mixing angles θ_{24} and θ_{34} under the assumption of a three active-flavor plus one sterile state oscillation model, namely a 3+1 model. We compare the FD NC rate to unoscillated and oscillated predicted rates that is valid for $0.05 \leq \Delta m^2_{41} \leq 0.5$ eV^2. In this range, the analysis is not sensitive to oscillations affecting the rates in the ND, which are present at larger Δm^2_{41} values. The three-flavor mixing parameters θ_{23}, Δm^2_{32} and δ_{13} are constrained to NOvA's degenerate best fit points. The parameters are fit separately for each three-flavor degenerate solution and we use the least constraining result. External data from solar and reactor experiments constrain $sin^2\theta_{14} < 0.041$ therefore θ_{14} and δ_{14} are assumed to be zero. The fit profiles over the θ_{23}, Δm^2_{32}, and δ_{24} mixing parameters. Figure 7

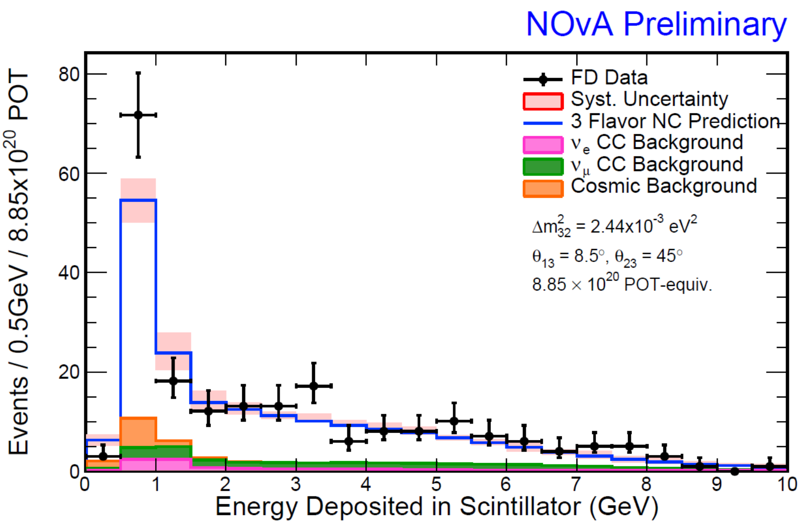

Figure 6: The three-flavor FD energy spectrum for NC selected data (black dots) and predicted NC events (solid blue) with associated systematic uncertainty (shaded band) for the 8.85×10^{20} POT-equivalent exposure. Maximal mixing is assumed for the prediction. The background predictions are broken down into the main components: ν_e-CC (pink), ν_μ-CC and cosmic ray induced backgrounds.

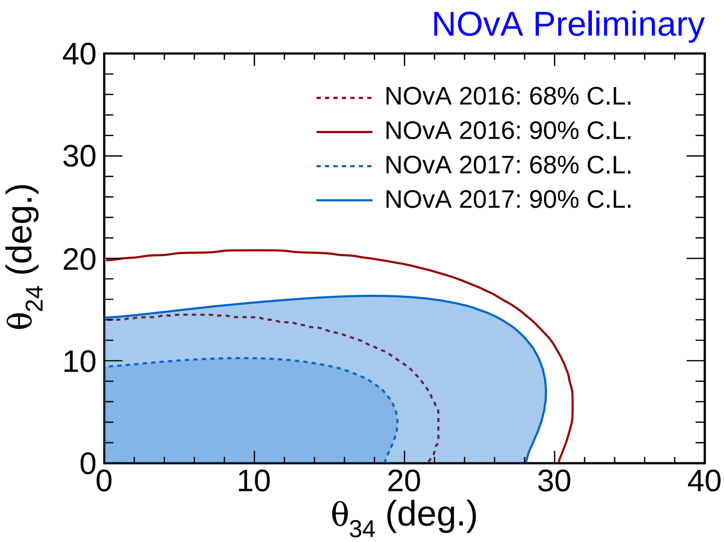

Figure 7: The 68% (dashed) and 90% (solid) nonexcluded regions (shaded) for the mixing angles θ_{24} and θ_{34}. The 8.85×10^{20} POT-equivalent dataset (NOvA 2017) is compared to the previous result (NOvA 2016) that is published in Ref. [8]. The NOvA 2017 analysis performs a shape-fit constrained with NOvA's least constraining three-flavor degenerate solution; normal hierarchy, lower octant. The NOvA 2016 analysis is a rate-only fit assuming maximal mixing.

compares the 68% (dashed) and 90% (solid) C.L. contours in the θ_{24}, θ_{34} space for the previous 2016 analysis, red, and this latest analysis (blue). The shaded regions represent the nonexcluded regions. For the 3+1 model, limits of $\theta_{24} < 16.2°$ and $\theta_{34} < 29.8°$ are obtained at the 90% confidence level. A version with Feldman-Cousins corrections is underway.

5. Summary

The NOvA experiment has a rich physics program. NOvA has observed ν_μ disappearance and ν_e appearance oscillations from the NuMI beam at the Fermilab. Using an exposure equivalent to 6.05×10^{20} POT our data disfavor the maximal mixing scenario with 2.6σ significance when measuring the neutrino mixing angle θ_{23} via muon neutrino disappearance. This measurement gives best-fit oscillation parameters of $\Delta m^2_{32} = (2.67 \pm 0.11) \times 10^{-3}\ eV^2$ and $sin^2\theta_{23}$ at the two statistically degenerate values $0.404^{+0.030}_{-0.022}$ and $0.624^{+0.022}_{0.030}$ (both at the 68% C.L.) in the normal hierarchy. For the same dataset 33 ν_e candidates were observed with a background of 8.2 ± 0.8 (syst.). A joint fit of NOvA's ν_e appearance and ν_μ disappearance data, with external constraints from reactor experiments on $sin^2 2\theta_{13}$, disfavors the hypothesis of inverted mass hierarchy with θ_{23} in the lower octant at greater than 93% C.L. for all values of δ_{CP}. With an exposure equivalent to 8.85×10^{20} POT, an increase of 50% more data, preliminary updated results from the search for sterile neutrinos through neutral-current disappearance show no evidence for $\nu_\mu \rightarrow \nu_s$ transitions. Updated ν_μ-ν_e joint fit and ν_μ-only results with this larger dataset will be released in early 2018 and NOvA's first anti-neutrino results are planned for release later in 2018.

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