New results from NOvA

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Abstract. 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 $\theta_{23}$ octant, and perhaps even hint at the violation of CP in the neutrino sector. This paper describes the current status of the NOvA experiment and present results from two years of data taking, doubling the exposure of our initial results.

1. Introduction

NOvA is a long-baseline, off-axis neutrino oscillation experiment that studies neutrinos produced in the NuMI beam from Fermilab. At 14 mrad off-axis, the neutrino beam is a narrow-band beam, peaked at 2 GeV. NOvA uses two, functionally identical detectors. A near detector (ND) is installed on-site at Fermilab, while a 14 kton far detector (FD) is installed 810 km away in Ash River, MN.

In this paper, we present results from three different oscillation analyses. We first look at the disappearance of $\nu_\mu$ charged current (CC) events, the dominant oscillation mode at the NOvA baseline and energy. In this analysis, oscillations cause a clear suppression of $\nu_\mu$-CC events as a function of energy, a suppression that is dependent on $\Delta m_{32}^2$ and $\sin^2(2\theta_{23})$. The analysis presented here is an update to that published in Reference [1]. Second, we look at the rate of neutral current (NC) events in the FD. Suppression of the NC event rate could be evidence of oscillations involving a sterile neutrino. We fit our data to a 3 active plus 1 sterile model, so we are sensitive to $\Delta m_{31}^2$, $\theta_{34}$, and $\theta_{24}$. Finally, we will look at the appearance of $\nu_e$-CC events, which depends on $\theta_{13}$, $\theta_{23}$, and $\delta_{CP}$. Matter effects make this measurement additionally sensitive to the neutrino mass hierarchy, or mass ordering. With the 810 km baseline, matter effects can give rise to a $\pm 30\%$ change in the appearance probability in NOvA depending on the hierarchy. The appearance analysis is an update to initial results presented in Reference [2].

1.1. Experimental setup

The oscillation results presented here come from an exposure equivalent to $6.05 \times 10^{20}$ protons-on-target in the 14 kton detector. This exposure is more than double that used in the previous publications. The NuMI beam power has steadily ramped up since the beginning of data taking in February, 2014, and we currently run at 560 kW. In fact, the design goal of 700 kW was recently achieved in tests of the accelerator complex.

The NOvA detectors were designed for electron identification. They are made of low-Z materials, are highly segmented, and are made of 65% active material. The FD is 14 kton and
is made up of over 340,000 channels. The FD is installed on the surface, under a modest overburden. It is exposed to 150 kHz of cosmic interactions. The 290 ton ND is installed underground at Fermilab.

The basic unit of the NOvA detectors is a PVC extruded cell, filled with liquid scintillator. Each cell is readout via a wavelength-shifting fiber coupled to an avalanche photodiode. Cells are arrayed side-by-side to form planes, then planes are layered in orthogonal views to form the bulk of the detector. A muon crossing the far end of a cell produces a signal of 40 photoelectrons. Each detector layer corresponds to 17% of a radiation length. The data acquisition system runs without dead time and accepts external triggers for the beam and SNEWS events, but also has internal data driven triggers to collect cosmic ray calibration samples and samples for exotic searches.

**Figure 1.** An illustration of the CVN event identification algorithm. The simulated $\nu_e$-CC event shown at the bottom left is used as input to the network. The array to the right shows the output of a number of different image processing transformation that make up one layer of the network. Three of those outputs are highlighted in the panels above. The output outlined in blue features a dense energy distribution characteristic of an electromagnetic shower extracted from the event.

### 1.2. Event identification

Events are classified based on their topology. A $\nu_\mu$-CC interaction can be identified by the presence of a long, straight track associated with the muon produced in the interaction. A $\nu_e$-CC event, on the other hand, is identified by the presence of a shorter, wider shower associated with the electron produced in the interaction. NC events lack any charged lepton in the final state, and tend to have only diffuse activity resulting from the nuclear recoil system.

The long, straight track from the muon makes $\nu_\mu$-CC events relatively easy to identify. More sophisticated algorithms are needed to isolate NC and $\nu_e$-CC samples with high purity and efficiency. The current analyses feature a new event selection technique based on ideas from the fields of computer vision and deep learning. As illustrated in Figure 1, calibrated hit maps
representing the events are inputs into the algorithm, named the Convolutional Visual Network (CVN). The network applies a series of image processing transformations to the event images to extract abstract features from the event. These extracted features are then used as inputs in a conventional neural network to provide a single event classification variable. Figure 1 shows an array of outputs from the image processing transformations from one layer of the network when a simulated $\nu_e$-CC event is used as input. Three particular outputs are highlighted, showing the features extracted from the event. One of the features is a dense energy deposition characteristic of an electromagnetic shower. That feature is absent when a $\nu_\mu$-CC event is used as input, and instead a different, track-like feature is apparent. Full details of the technique are given in Reference [3], but in brief, the improvement in sensitivity from CVN is equivalent to the gains afforded by 30\% more exposure.

![Figure 2](image-url)

**Figure 2.** Comparisons of the hadronic energy distribution between data and simulation. Each panel shows the distribution for a different range of three-momentum transfer. The black points are the data, while the blue histogram shows the simulated quasi-elastic component, the green shows the resonant component, and the gray shows the deep inelastic component. The reweighted distribution from the meson exchange current process is shown in gold.

1.3. *Improvements to the simulation*

Comparison of the hadronic energy distribution in $\nu_\mu$-CC events in data versus simulation suggests a missing process in the default simulation in the phase space between the quasi-elastic (QE) and $\Delta$ production regions. Figure 2 shows the comparison of the hadronic energy distributions in data and simulation for different ranges of three-momentum transfer. In each panel, the event rate in data exceeds the rate in the simulation coming from QE and resonant (RES) processes. Similar excesses have been reported by the MINERvA experiment [4]. The excess is interpreted as evidence of scattering off substructure within the nucleus.

This process is added to the simulation by enabling an empirical meson exchange current model [5] encoded in the GENIE event generator [6]. The default model is reweighted, primarily to match the observed excess as a function of the three-momentum transfer. The effect of the
addition of this process to the simulation is also shown in Figure 2. The agreement between data and simulation is much improved, but there are still discrepancies in the shape of the hadronic energy distribution. A 50% systematic uncertainty on the normalization of the meson exchange current process is included in the analysis to cover the remaining discrepancy. Even this relatively large systematic uncertainty is mitigated by using the ND measurement to predict the FD, and the dominant systematic errors in the previous analyses, coming from the hadronic energy scale and the QE cross section modeling are greatly reduced. The default GENIE simulation is also modified to reduce the single non-resonant pion production process by 50% [7].

2. Muon-neutrino disappearance

The measured energy spectrum of $\nu_\mu$-CC events selected in the ND are used to predict the energy spectrum of events expected in the FD. To accomplish this extrapolation procedure, first the reconstructed energy distribution of events in the ND is unfolded to a true energy spectrum using the simulated migration matrix. The ratio of the data’s unfolded spectrum to the simulated spectrum in bins of true energy is then used as a scale factor to the simulated true energy spectrum of $\nu_\mu$-CC events selected in the FD. That true energy spectrum is also weighted by the oscillation probability computed for a given set of oscillation parameters. Finally, the true energy spectrum is smeared to a reconstructed energy spectrum, again using the simulated migration matrix.

Figure 3. (Left) The reconstructed energy distribution of $\nu_\mu$-CC events selected in the FD. Black shows the data, while the red histogram shows the spectrum resulting from the best fit to the oscillation hypothesis, corresponding to the non-maximal mixing scenario. The spectrum obtained if the fit is constrained to maximal mixing is show in blue. (Right) The values of $\Delta m^2_{32}$ and $\sin^2(\theta_{23})$ in the normal hierarchy allowed at the 90% C.L. for NOvA in black, compared to previous results from MINOS [8] in red and T2K [9] in blue.

In the case of no oscillations, $473\pm30$ $\nu_\mu$-CC events are expected in the FD; 78 events are observed. Figure 3 shows the observed energy spectrum of those events, along with the result of a fit for three-flavor oscillations. Dominant systematic errors are included in the fit as nuisance parameters. At the best fit, 82 events are expected, including a beam induced background of 3.7 events and 2.9 cosmic induced background events. The $\chi^2/NDF$ of the best fit is 41.6/17. The largest contributions to the $\chi^2$ come from the fluctuations in the data at higher energies, which have no pull in the oscillation fit.

The data prefer $\Delta m^2_{32} = (2.67 \pm 0.12) \times 10^{-3}$ eV$^2$ and $\sin^2(\theta_{23})=0.40^{+0.03}_{-0.02}$ in the lower octant, or $\sin^2(\theta_{23}) = 0.63^{+0.02}_{-0.03}$ in the upper (in the normal hierarchy). The data exclude maximal mixing at 2.5$\sigma$. Figure 3 also shows the spectrum when the fit is constrained to
maximal mixing. Maximal mixing predicts an additional suppression of the event rate between 1-2 GeV that is not observed in the data. The right panel in Figure 3 shows the values of $\Delta m^2_{34}$ and $\sin^2(\theta_{34})$ allowed at the 90% C.L. for NOvA, compared to previous results from MINOS [8] and T2K [9].

3. Neutral current event rate
As in the $\nu_\mu$-CC analysis, the energy spectrum of NC selected events in the ND is used to predict the FD energy spectrum. In the NC case, the ratio of data to simulation in reconstructed energy is used to scale the FD simulated spectrum; no migration matrices are used. In a standard three-flavor oscillation scenario $83.7\pm8.3$ events are expected in the FD with energy between 0.5-4 GeV. Oscillations involving a sterile neutrino would suppress that rate.

When the FD data were inspected, 95 events were observed. The energy spectrum of those events, compared to the prediction, is shown in Figure 4. Using just the total number of events predicted and observed, the sterile mixing angles are limited, with $\theta_{34} < 35^\circ$ and $\theta_{24} < 21^\circ$ at the 90% C.L. for $0.05$ eV$^2 < \Delta m^2_{34} < 0.5$ eV$^2$. While these limits are not yet competitive with the world’s best limits, the excellent purity and efficiency of the NC sample in NOvA promise strong future limits, particularly on the mixing angle $\theta_{34}$.

![Figure 4](image_url)

**Figure 4.** (Left) The reconstructed energy distribution of NC events selected at the FD. Black points show the data, while the red histogram shows the predicted spectrum from a three-flavor oscillation scenario. The blue histogram shows the true NC component, while blue, green and orange histograms show the background components. (Right) The values of $\theta_{24}$ and $\theta_{34}$ allowed at the 90% C.L. for $\Delta m^2_{34} = 0.5$ eV$^2$. Black shows the result of the current analysis, compared to the sensitivity shown in blue, and a previous limit set by MINOS [10] in red.

4. Electron-neutrino appearance
The selection of events for the $\nu_e$ appearance analysis was optimized to favor oscillation parameter measurement, instead of sensitivity to the appearance of signal events above background as in the first analysis. This retuning included both the event classifier cut and the cosmic rejection cuts. The new selection features increased signal efficiency but includes lower purity bins in the analysis. As with all the oscillation analyses, the data selected in the ND are used to predict what one should see in the FD. The $\nu_e$-CC selected sample in the ND is made up of three types of background events, NC, $\nu_\mu$-CC, and intrinsic beam $\nu_e$-CC events. Each one of these background components propagates to the FD differently, so data-driven techniques are used to estimate the relative sizes of each of the components. The amount of beam $\nu_e$-CC background events in the sample is constrained by using the $\nu_\mu$-CC selected events.
These neutrino interactions primarily come from the decays of pions that also produce muons, which in turn decay to produce the majority of the beam $\nu_e$-CC events that are selected. The $\nu_\mu$-CC background component is constrained by fitting the distribution of the number of Michel electrons found in selected events. The $\nu_\mu$-CC events found in the background sample tend to have one more Michel electron than the other event types. These considerations motivate raising the beam $\nu_e$-CC background by 4% over that given by the simulation, while the $\nu_\mu$-CC background level is raised by 17% and the NC background level by 10%.

The backgrounds measured in the ND are extrapolated to the FD in bins of reconstructed energy and the CVN classifier value. As detailed in Table 1, the background predicted in the FD is $8.2^{\pm 0.8}$ events. The signal prediction takes into account discrepancies between the $\nu_\mu$-CC spectrum measured in the ND and the simulation. The total predicted number of signal and background events varies between roughly 20 events to 40 events, depending on the values of the oscillation parameters.

Table 1. The number of background events of each type expected at the FD for the $\nu_e$-CC appearance measurement.

| Total BG | NC | Beam $\nu_e$ | $\nu_\mu$ CC | $\nu_e$ CC | Cosmics |
|----------|----|--------------|---------------|-------------|---------|
| $8.2^{\pm 0.8}$ | 3.7 | 3.1 | 0.7 | 0.1 | 0.5 |

When the FD data were examined, 33 $\nu_e$-CC events were found. The observed number of events, and the predicted number of events as a function of the hierarchy and $\delta_{CP}$ for a range of values of $\theta_{23}$ is shown in the left panel of Figure 5. The energy distribution of the events in the three highest bins of the CVN classifier are fit to extract oscillation parameters. In this fit, external data is used to constrain $\sin^2(2\theta_{13})$ to $0.085^{+0.05}_{-0.05}$ and $\Delta m^2_{32}$ to $(2.44^{+0.06}_{-0.06}) \times 10^{-3}$ eV$^2$ in the normal hierarchy and $(-2.49^{+0.06}_{-0.06}) \times 10^{-3}$ eV$^2$ in the inverted. Systematic uncertainties are included in the fit using nuisance parameters. The right panel of Figure 5 compares the data to the best fit prediction in the normal hierarchy.

The fit was also run with $\Delta m^2_{32}$ and $\sin^2(\theta_{23})$ constrained by the NOvA $\nu_\mu$-CC disappearance result. A version with Feldman-Cousins [11] corrections and a full treatment of the correlations in the systematic uncertainties is underway, but this preliminary combination already further constrains the allowed values of the oscillation parameters. The global best fit prefers the normal hierarchy, $\delta_{CP} = 1.49\pi$, and $\sin^2(\theta_{23}) = 0.40$, but both the hierarchy preference and the octant preference are slight. Both octants and hierarchies are allowed at 1$\sigma$. There is a region of parameter space in the inverted hierarchy, lower octant, around $\delta_{CP} = \pi/2$ that is excluded at the 3$\sigma$ level. Figure 6 shows the values of $\sin^2(\theta_{23})$ and $\delta_{CP}$ allowed at 1, 2, and 3$\sigma$ for each of the hierarchies for both the $\nu_e$ only analysis and the combined analysis.

5. Summary

In summary, NOvA has updated results from three oscillation analyses. In the $\nu_\mu$ disappearance analysis, the data disfavor non-maximal mixing at the 2.5$\sigma$ level. The NC event rate is not suppressed. With no evidence of sterile oscillations, limits are placed on the sterile mixing angles. Additional data promises competitive limits on those mixing angles. Finally, the $\nu_e$ appearance measurement excludes a region of parameter space in the inverted hierarchy, lower octant, around $\delta_{CP} = \pi/2$ at the 3$\sigma$ level. Antineutrino running will help resolve the degeneracies among the octant, hierarchy and $\delta_{CP}$. NOvA has already collected $0.6 \times 10^{20}$ protons-on-target in antineutrino mode and expects to collect more starting Spring 2017.
Figure 5. (Left) The total number of events (signal plus background) expected as a function of $\delta_{CP}$. The normal hierarchy is shown in blue, while the inverted hierarchy is shown in red. The colored shaded regions show the range of values allowed for $\sin^2(\theta_{23}) = 0.4 - 0.6$. The number of events selected in the data is shown in gray. The gray band corresponds to the 1$\sigma$ statistical error. (Right) The reconstructed energy spectrum of $\nu_{e}$-CC selected events in the FD, for three ranges of the CVN event classifier. The black points show the data, while the red histogram shows the spectrum from the best fit. The blue shaded histograms show the background spectrum.

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Figure 6. (Left) The allowed values of $\sin^2(\theta_{23})$ and $\delta_{CP}$ from the fit to the $\nu_e$-CC data. (Right) The allowed values of $\sin^2(\theta_{23})$ and $\delta_{CP}$ from the combination of the $\nu_e$-CC appearance and $\nu_\mu$-CC disappearance data. In each, the top panel shows the allowed region for the normal hierarchy, while the lower panel shows the inverted hierarchy. The different shades of colors correspond to 1$\sigma$, 2$\sigma$, and 3$\sigma$. 