Neutrino Oscillations in the NOvA Experiment

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Analysis of an exposure of 6×10^{20} protons on target of the NuMI muon neutrino beam have produced precision measurements of both disappearance and appearance oscillations, including the first hints that muon to tau neutrino mixing is not maximal.

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1. Overview

The NOvA experiment [1] is a long-baseline neutrino oscillation experiment which uses two similar detectors 810 km apart to study neutrino oscillations at an angle of 14.6 mrad ($0.837°$) from the focusing axis of Fermilab's NuMI [2, 3] neutrino beam. This configuration results in a narrow-band beam of ν_μ peaked between 1–3 GeV, with a L/E right on the first oscillation minimum in the "atmospheric" sector. The off-axis configuration not only reduces uncertainty in the incoming neutrino energy, but also reduces the background of higher-energy neutrinos producing neutral current interactions that might reconstruct as electron neutrinos in the region of interest. However, this does result in a far lower intensity than is available on-axis, mitigated by a large far detector and the fact that the NuMI beam is now routinely operating at its 700 kW design rating. This poster describes the neutrino oscillation analyses of the first 6.05×10^{20} protons-on-target ("pot") of full-detector equivalent exposure of the NOvA detectors in the NuMI beam, as described in [4, 5].

2. Goals

NOvA's primary goal is to observe ν_e appearance in the predominantly ν_μ NuMI beam by comparing the neutrino spectra observed at the near and far detectors. The mixing angle associated with this oscillation (θ_{13}) is now well measured and is comparatively large [6]: thus interesting sub-dominant effects such as the phase of CP violation in the neutrino sector δ_{CP} and the hierarchy of the neutrino mass states could be detected, as well as determining the octant of θ_{23}. The best measurements of these parameters will be obtained by comparing the oscillations observed in a neutrino beam with those seen in an anti-neutrino beam: NuMI has been running as an anti-ν_μ beam since 2016, although analysis of that data is ongoing so this poster uses only ν_μ beam data. Measuring the degree of ν_μ disappearance can tell if θ_{23} is maximal or not and factors into the uncertainties in the ν_e related parameters.

The CP and mass hierarchy effects on oscillations are dependent on the number of electrons in the path of the beam. NOvA has the longest baseline of any accelerator neutrino experiment, thus increasing sensitivity to part of the range of possible parameters. If neutrino mass states are arranged in a "Normal Hierarchy" where the solar doublet of mass eigenstates is larger than the third state, there would be an enhancement of the $\nu_\mu \to \nu_e$ appearance caused by coherent forward scattering of $\nu - e$ on electrons in the earth. The "Inverted Hierarchy" would behave in the opposite fashion. Comparisons to the similar effects seen in the T2K experiment in Japan [7] will allow for more sensitivity than either experiment alone, as T2K and NOvA have beams of different energies and baselines, and possess different systematic errors given the complementary natures of their detectors.

3. The Detectors

The NOvA detectors are constructed to be as similar as possible aside from size: the far detector is 14 kt to maximize statistics at the northernmost point of the baseline in Ash River, MN; while the near detector is close enough to the beam at Fermilab to see a far greater flux, so only needs to be 300 t. Both are constructed out of extruded PVC cells 3.9×6.6 cm in cross section

filled with liquid scintillator, 15.5 m long at the far detector and 3.8 m long at the near detector. Light is piped out of the cell by a length of wavelength shifting fiber looped to the end of each cell and back, allowing avalanche photo-diodes to digitize the light and record when a charged particle has traversed a cell and how much light it created. The cells alternate between vertically and horizontally oriented to allow for a stereo readout. Scintillator itself composes 62% of the mass of the detector, and the low-Z nature of all the components allow for a long radiation length of 35.8 cm. This allows electromagnetic showers from potential neutral current background to be well resolved. Fig. 1 shows how the pattern of scintillator light distributed across the detector can be used to tell apart different kinds of neutrino interactions.

Unlike other neutrino experiments, the NOvA far detector is on the surface with minimal overburden. Its large size means that the cosmic ray rate is 148 kHz, producing a volume of more than 1 GB/s of data. To sort out the rare neutrino interactions, the time of the 10 μs beam spill at Fermilab is sent to the far detector and a window of data surrounding that time is saved. This reduces the cosmic ray background by a factor of 10^5, as in that short time few cosmic rays are coincident in time. These remaining cosmics can be identified as entering events and discarded, while neutrino interactions start well inside the detector volume, for an additional reduction in cosmic background of 10^7 (10^8 for ν_e candidates), for a total reduction of $> 10^{12}$. For non-beam physics, a trigger farm examines the data in real time to save interesting data [8]. For example, a burst of neutrinos from a core-collapse supernova in our galaxy would create an increased rate of 10 MeV positrons via inverse beta decay, if we can trigger on this signature [9]. Given the high rate and good spatial resolution, cosmic ray physics can be also done with both near and far detectors [10].

The NuMI beam was operational as the far detector was constructed and commissioned, with physics data being recorded from February 6, 2014. The modular nature of the detector allowed collecting of neutrino data using the partially built part of the detector. Both detectors were complete in August 2014 with the final commissioning at the far detector finished in November 2014. Scaling the exposure used in this poster by far detector mass, an equivalent of 6.05×10^{20} pot on a full 14 kt was collected before May 2, 2016.

4. Muon Neutrino Disappearance

The NuMI neutrino beam is observed at Fermilab in the near detector before neutrinos have had a chance to oscillate. This establishes the initial spectrum and composition of the beam. Comparing this to the spectrum and composition of the beam 810 km away at the far detector allows the estimation of what values of the neutrino oscillation parameters must be operating on the neutrinos during their journey northwards to change the near to the far spectrum. Assuming no oscillations, the beam at the near (and far) detector is composed of 97.5% (97.8%) ν_μ, 1.8% (1.6%) $\bar{\nu}_\mu$ and 0.7% (0.6%) $\nu_e + \bar{\nu}_e$ between 1-3 GeV. The slight differences are caused by the small differences in kinematic phase space subtended by the two detectors.

As seen in Fig. 1, the different flavors of neutrinos can be easily discerned by the topology of the charged leptons produced in a charge current interaction. However, neutral current interactions are the same regardless of the flavor of the incoming neutrino. Thus, neutral current interactions which are mis-reconstructed as a charged current interaction form the dominant background to a
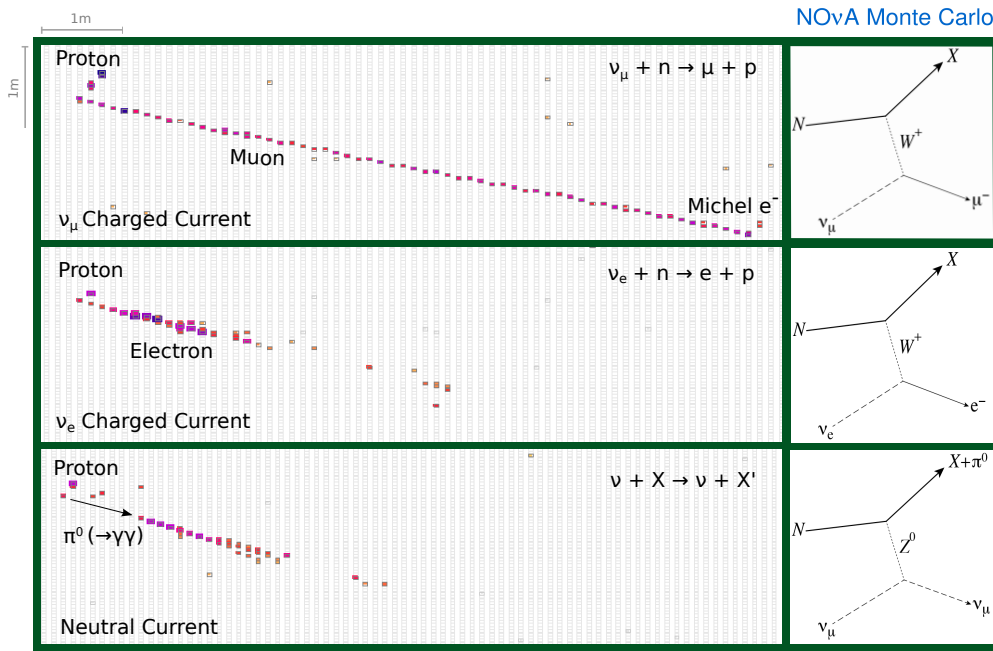
Figure 1: Event displays of simulated neutrino interactions in NOvA. Three different types of neutrino interactions are shown. Each rectangular "pixel" in the displays on the left corresponds to an end-on view of one cell in which passage of a charged particle created some scintillator light. The Feynman diagram of each weak interaction is on the right. In the top interaction, a ν_μ turns a neutron into a proton which recoils (the short stubby track), with the outgoing lepton producing a long straight track indicative of a muon. In the second interaction, a ν_e does produces an electron, which initiates a shorter, fuzzier electromagnetic shower. The third interaction is a neutral current interaction where the neutrino recoils from a proton, producing a neutral pion which rapidly decays into two gamma rays. Note the gap between the interaction vertex and the start of the electromagnetic shower, corresponding to the radiation length of a gamma in the light hydrocarbons which compose the NOvA detector.

flavor-based analysis. While the off-axis nature of the experiment greatly reduces the number of neutral current interactions which produce something that looks like a ~ 2 GeV charged current interaction, each neutrino candidate is examined by a collection of tracking algorithms (see [4] for details), with events matching ν_μ charged current interactions being kinematically reconstructed and plotted as a function of energy as shown in the left of Fig. 2. Performing the same reconstruction on Monte Carlo data shows it to be 62% efficient at retaining true ν_μ charged current interactions, with an overall energy resolution of 7%.

There are 78 ν_μ candidate events in the far detector selected by this process. If there were no oscillations, a projection of the flux seen in the near detector would result in 473 ± 30 such events. Of those 78 events, it is estimated that there are backgrounds of 3.4 neutral current, 0.23 ν_e, 0.27 ν_τ, and 2.7 cosmic-ray-induced events (the blue line in Fig. 2's spectrum). Neutrino oscillations are fit to the resulting spectra, producing a best fit (the red line) 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 $0.624^{+0.022}_{-0.030}$ (at 68% c.l.) in the normal hierarchy. For the inverted hierarchy, $\Delta m^2_{32} = (-2.72 \pm 0.11) \times 10^{-3}$ eV^2 and $\sin^2 \theta_{23} =$
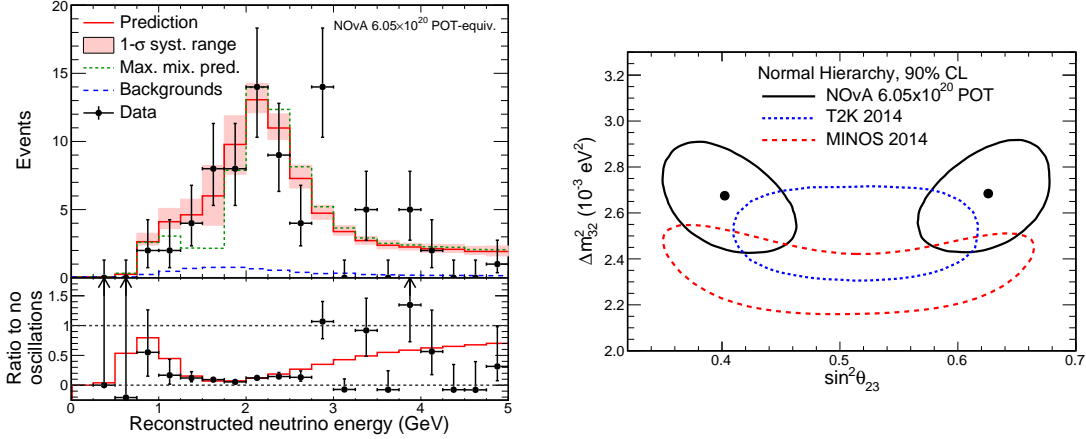
Figure 2: **Left:** A reconstructed ν_μ energy spectrum of data in the nova far detector (black dots with statistical errors) compared to the best oscillation fit prediction with systematic errors (red). Backgrounds are the small blue dashed line, and the prediction at maximal mixing the green dashed line. The ratio of observed data to the unoscillated ν_μ spectrum derived from the near detector is the bottom part of the graph. **Right:** 90% allowed contours on the oscillation parameters: these results are the black lines, other experiments the dashed lines. Note the separation of the NOvA data from $\sin^2\theta_{23}$=0.5. Plots from [4].

$0.398^{+0.030}_{-0.022}$ or $0.618^{+0.022}_{-0.030}$ (again at 68% c.l.). This analysis is mostly insensitive to different values of Δ_{CP}, so potential variations therein have been taken as a systematic error. The resulting allowed region is shown on the right of Fig. 2.

Of particular interest is the fact that if $\sin^2\theta_{23} = 0.5$ ("maximal mixing"), then there are too many ν_μ surviving at this L/E corresponding to the first oscillation minimum, even more than can be accounted for by background events or by the smearing of bins by the detector's energy resolution. This is shown by the difference between green and red lines in the spectrum, and results in the separation of the two 90% allowed regions in the right of Fig. 2 not approaching the middle ($\sin^2\theta_{23} = 0.5$) of the plot. Maximal mixing is disfavored by the data at 2.6σ. For a full discussion of the details of the fitting and systematic errors please see [4].

## 5. Electron Neutrino Appearance

While the dominant oscillation effect at this energy and baseline is the muon neutrino disappearance discussed above, recent work by many experiments (summarized in [6]) has shown that some ν_μ appear as ν_e, governed by the mixing angle θ_{13}. NOvA was designed to measure this process, and thus has some sensitivity to sub-dominant oscillation terms involving the neutrino mass hierarchy, CP-violating phase δ_{CP}, and the octant of θ_{23}. Counting the ν_e-like events and separating them from the other two categories shown in Fig. 1 is handled by a Convolutional Visual Network (CVN) as discussed in [11]. This improves the sensitivity of the result by 30% over traditional reconstruction algorithms, and results in 73.5% efficiency and 75.5% purity of ν_e events in the final sample (as determined from Monte Carlo studies), while rejecting 97.6% of the neutral current and 99.0% of the ν_μ charged current beam backgrounds. Thousands of ν_e candidates are selected in high-flux present at the near detector, where the baseline is too short for any oscillation signal to be

present. This results in a map of the backgrounds to be expected at the far detector (see the left part of Fig. 3). After reconstruction, 33 ν_e candidates are found at the far detector, of which 8.2±0.8 correspond to the expected background in the absence of ν_e appearance oscillations (the right part of Fig. 3). For complete details see [5].
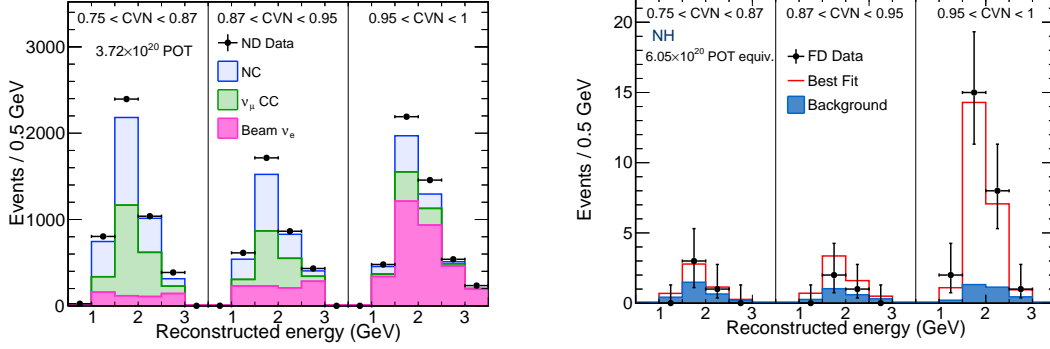
Figure 3: Left: Reconstructed ν_e candidates energy spectrum of data in the nova near detector (black dots with statistical errors) compared to estimated sources of backgrounds for three different ranges of signal purity. No oscillations are present at the short baseline of the near detector, all selected events are thus backgrounds. **Right:** The same for the far detector, with all backgrounds (as extrapolated from the near detector data) lumped together, showing the surplus of ν_e-like events caused by appearance oscillations. Plots from [5].

To obtain oscillation parameters, these data are fit simultaneously with the ν_μ data discussed previously, taking the precise value of θ_{13} and its uncertainty from reactor experiments [6] as a given. The inverted mass hierarchy predicts too few ν_e events appearing at the far detector (see the left part of Fig. 4), so if θ_{23} is in the lower octant, is disfavored at all values of δ_{CP} by at least 93% c.l. Other combinations of hierarchy and octant are more consistent with the data (see the right half of Fig. 4).
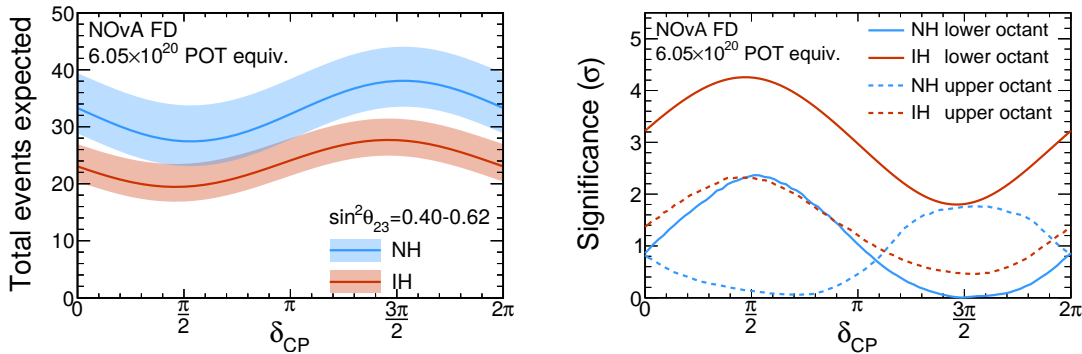
Figure 4: Left: The number of ν_e candidates expected at the NOvA far detector as a function of δ_{CP} for the normal (blue) and inverted (red) mass hierarchies. The shaded bands correspond to the uncertainty on θ_{23}. **Right:** The significance at which each of the four possible combinations of mass hierarchy and θ_{23} octant are disfavored as a function of δ_{CP}. Plots from [5].

6. Summary

The NOvA experiment observes both ν_μ disappearance and ν_e appearance oscillations in the primarily ν_μ NuMI beam. Analysis of both these modes using the first 6.05×10^{20} protons on target exposure have helped refine our knowledge of oscillation parameters. Muon neutrino disappearance points to non-maximal mixing with 2.6σ significance and best-fit oscillation parameters of of $\Delta m_{32}^2 = (+2.67 \pm 0.11) \times 10^{-3}$ eV^2 and $\sin^2 \theta_{23}$ at the two statistically degenerate values $0.404^{+0.030}_{-0.022}$ and $0.624^{+0.022}_{-0.030}$ (at 68% c.l.) in the normal hierarchy. Electron neutrino appearance oscillations allow the testing of the four possible permutations of θ_{23} octants mass hierarchies as a function of δ_{CP} given the θ_{13} constraints from reactor experiments and NOvA's own θ_{23} measurements, disfavoring the lower θ_{23} octant by at least 93% c.l. at all values of δ_{CP} in the case of the inverted hierarchy.

A comparison of an exposure of 9×10^{20} pot neutrino exposure (this data is in the can) with a similar amount of anti-neutrino data (the data being taken since 2016) is planned for the summer of 2018.

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