PROCEEDINGS OF SCIENCE

The NOvA Experiment

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NOvA is a long-baseline accelerator neutrino experiment that studies neutrino oscillation phenomena governed by the atmospheric mass squared splitting. NOvA has the potential to resolve the neutrino mass hierarchy and the octant of θ_{23} at the 3σ level. The NOvA collaboration is expected to release its first oscillation results this year (2015).

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1. Introduction

Although the past two decades have seen unprecedented advancement in the field of neutrino physics, many fundamental questions remain about the nature of neutrinos. Is there CP violation in the lepton sector? What is the neutrino mass ordering? Is θ_{23} maximal, and if not, then what is the octant of θ_{23}? The NOvA experiment is capable of probing these questions by studying the transition of muon neutrinos (antineutrinos) to the other neutrino (antineutrinos) flavors along a baseline of 810 km at an energy near 2 GeV.

The experiment uses two functionally identical detectors to measure the transition rate. The first detector, referred to as the near detector (ND) is 0.3 kt and is located less than 1 km from the production target at Fermilab. The ND is used to measure the neutrino energy spectrum before the neutrinos have oscillated. The second detector, referred to as the far detector (FD), is 14 kt and located at Ash River, Minnesota a distance of 810 km from the production target. The FD is used to measure the effect of oscillation on the neutrino energy spectrum. Because the detectors are functionally identically, systematic effects from flux, cross-section, and detector efficiencies are greatly reduced when comparing the event yields in the two detectors.

2. Beam

The neutrino beam is created in the NuMI facility [1] by colliding 120 GeV protons from the Fermilab Main Injector with a graphite target. The collision products are focused by two magnetic horns and directed down a 0.68 km decay pipe where the resulting decays produce the neutrino beam. The polarity of the horns can be reversed to run in a neutrino-enhanced or an antineutrino-enhanced beam. The NOvA detectors are located at a 14 mrad off-axis angle which results in a narrow-band neutrino energy spectrum that is peaked near 2 GeV. The resulting NuMI energy spectra for various off-axis angles is shown in Fig. 1. The narrow band beam operation reduces the neutral-current (NC) backgrounds to the identification of ν_e charged-current (CC) and ν_μ CC events.

The NUMI design goal is run at a 700 kW beam power with 6×10^{20} protons on target (POT) being delivered to NOvA each year. The nominal plan is to accumulate 18×10^{20} POT in neutrino mode and 18×10^{20} POT in antineutrino mode. To date, 6×10^{20} POT in neutrino mode have been delivered to NOvA. However, about half of the beam data was collected with a variable-fraction of the final FD mass as the FD was being assembled.

3. Detectors

The NOvA detectors are liquid scintillator tracking calorimeters. The FD is composed of extruded PVC cells that are 4 cm x 6 cm x 15.6 m. The cells are grouped into 15.6 m x 15.6 m x 6 cm planes with the cells in an individual plane running parallel to each other. The FD is composed of 896 planes that are layered so that the orientation of cells in each successive plane are rotated by 90^o. The cells are filled with a liquid scintillator that is composed of mineral oil and a pseudocumene scintillant. In order to collect the light that is produced in the scintillator, a single wavelength shifting fiber runs down the length of the cell. The fiber wraps around at one end of

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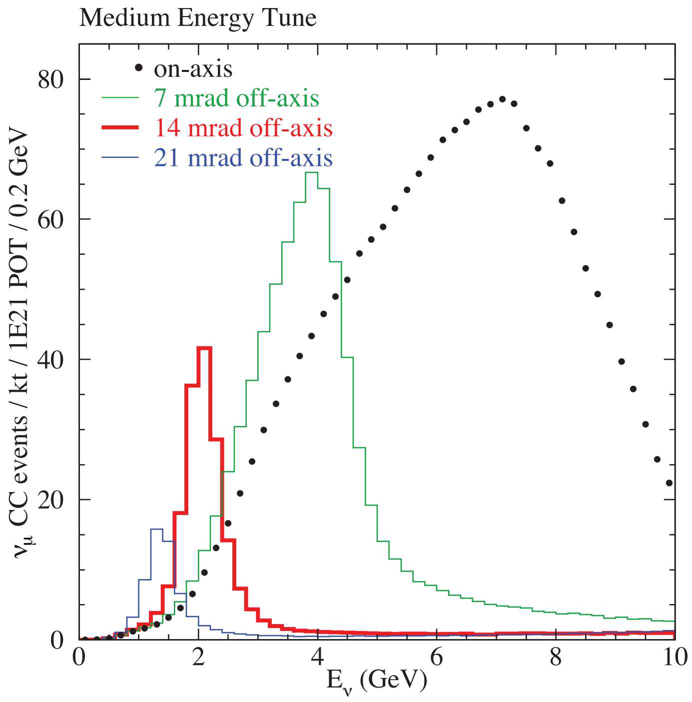

Figure 1: The neutrino spectra (flux times cross-section) for various angles. The NOvA detectors are located at 14 mrad which corresponds to a peak neutrino energy that is located near the first oscillation maximum.

the cell and is readout by both ends by a single APD pixel. The FD is 77% active by mass with a radiation length of 38 cm which corresponds to a distance of 6 planes along the beam direction and a distance of 10 cells transverse to the beam direction.

The ND is based on the same design as the FD, but is smaller than FD. The planes are 4.1 m x 4.1 m x 6 cm, and there are only 206 planes. In order to range out muons, the end of the ND contains ten 10-cm wide steel planes that are interspersed with active scintillator planes.

4. Event Selection

The survival probability for muon neutrinos is determined by comparing the energy dependent event yield for ν_μ-CC interactions in the FD with respect to the ND. The ν_μ-CC events are selected by identifying contained neutrino interactions that have a reconstructed muon track. The muon track is identified by using a kNN algorithm that uses information about the the track length, scattering, dE/dx, and fraction of the track hits (in number of planes) without overlapping hadronic activity. The performance of the ν_μ-CC selector is shown in Fig. 2. The events with a kNN value greater than 0.75 are selected which results in a 15 to 1 signal to background ratio. The ν_μ-CC events are further separated into quasielastic and non-quasielastic events by another kNN algorithm. The kNN algorithm has been trained separately based on the number of reconstructed tracks in the event. The performance of the quasielastic classifier is shown in Fig. 3. The events are separated by quasielastic and non-quasielastic topologies to increase the sensitivity of the final fit to the reconstruction energy spectrum. The quasielastic events have a 4% energy resolution while the non-quasielastic have a 6% energy resolution.

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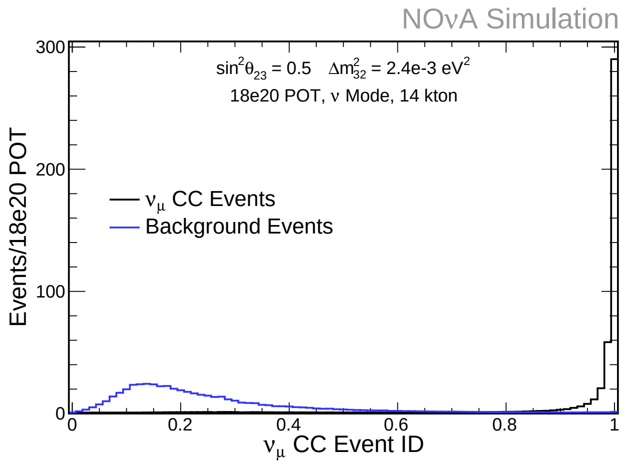

Figure 2: The kNN output of the ν_μ-CC selector. Values near 0 are background-like, and values near 1 are signal-like.

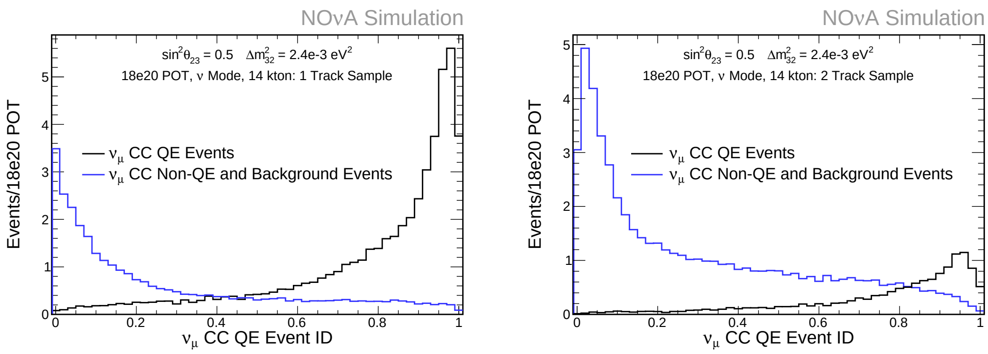

Figure 3: The kNN output for the quasielastic classifier for ν_μ-CC events. Values near 0 are non-quasielastic-like, and values near 1 are quasielastic-like. The figure on the left is for events with one reconstructed track, and the figure on the right is for events with two reconstructed track. If more than two tracks are present in the event, then it is considered non-quasielastic.

The appearance probability for electron neutrinos is determined by selecting ν_e-CC events. These events are identified by finding contained neutrino interactions that have an electron. The electron is identified by using a multivariate technique that looks for a cluster of hits that are consistent with a electromagnetic shower from an electron. Two ν_e-CC selectors are used to test for consistency among the methods. The performance of the ν_e-CC selectors are shown in Fig. 4. Both ν_e-CC selectors which result in a 2 to 1 signal to background ratio.

5. Physics Sensitivity

The expected reconstructed energy distributions of selected FD ν_μ-CC events collected over the final beam exposure of 18×10^{20} POT of neutrino running and 18×10^{20} POT of antineutrino running are shown in Fig. 5 for the selected quasielastic events and in Fig. 6 for the selected non-quasielastic events. Based on these expected energy distributions the sensitivity to θ_{23} and Δm^2_{32} is shown in Fig. 7.

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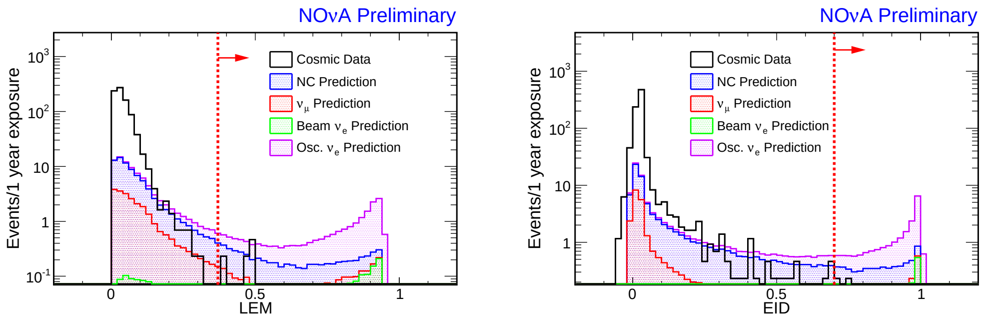

Figure 4: The output of the two ν_e-CC selectors, referred to as LEM and EID. Values near 0 are background-like, and values near 1 are signal-like. The vertical dashed red lines indicate the corresponding cut values for each selector.

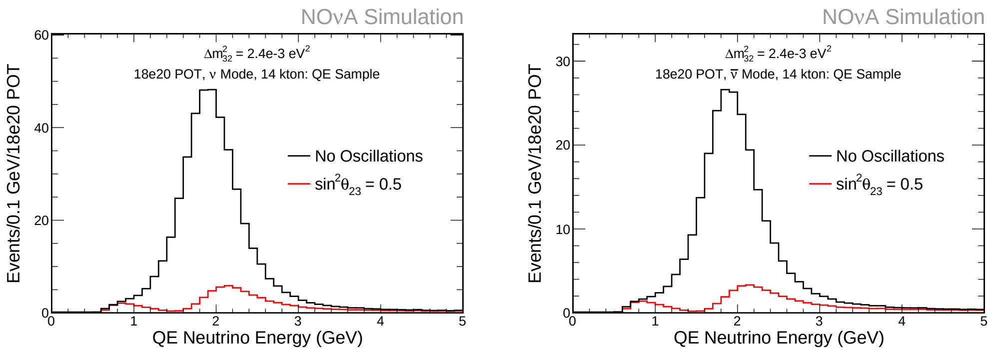

Figure 5: The simulated reconstructed energy distribution for selected quasielastic events. The plot on the left (right) is for events collected with a neutrino-enhanced (antineutrino-enhanced) beam.

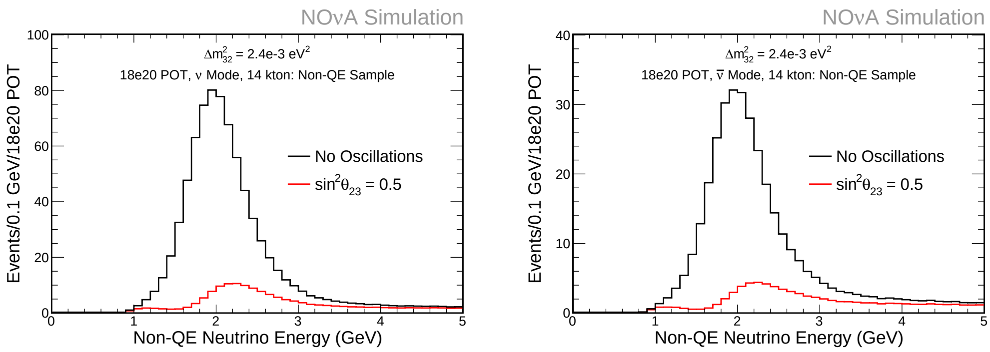

Figure 6: The simulated reconstructed energy distribution for selected non-quasielastic events. The plot on the left (right) is for events collected with a neutrino-enhanced (antineutrino-enhanced) beam.

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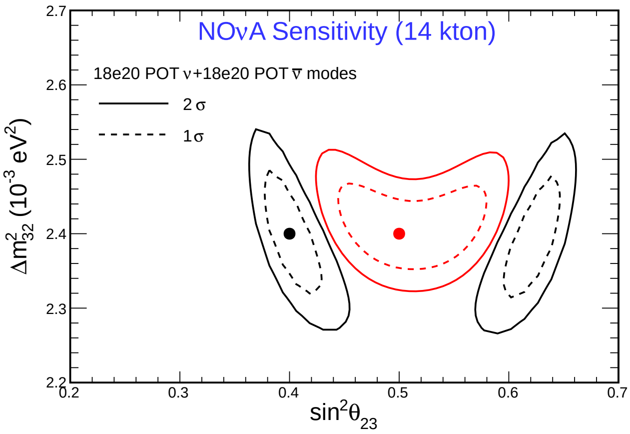

Figure 7: The NOvA sensitivity to θ_{23} and Δm^2_{32} using the expected final NOvA data sample. The black (red) contours are the sensitivity if the values of θ_{23} and Δm^2_{32} are given by the black (red) dot.

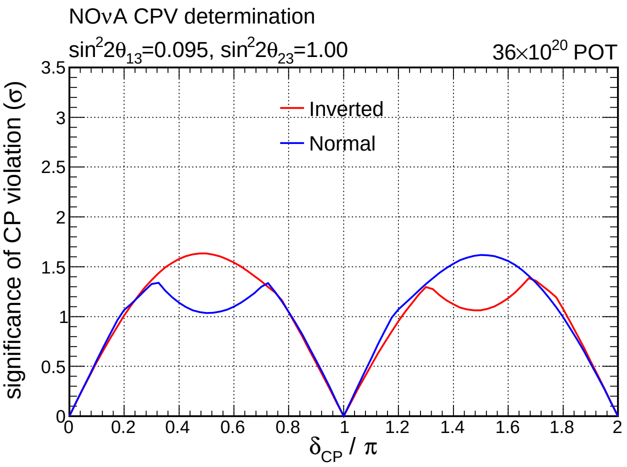

Figure 8: The NOvA sensitivity to δ_{CP} using the expected final NOvA data sample. The plot shows the significance to which no CP violation can be ruled out as a function of the true value of δ_{CP}.

Using the value of θ_{23} and Δm^2_{32} measured in the ν_μ-CC analysis, the ν_e-CC appearance analysis will place constraints on δ_{CP}, the mass hierarchy, and the octant of θ_{23}. The potential constraints are shown in Fig. 8, Fig. 9, and Fig. 10.

6. Summary

To date, 6×10^{20} POT have be delivered to NOvA with a neutrino beam. The nominal plan is for NOvA to accumulate a total of 18×10^{20} POT in neutrino mode and 18×10^{20} POT in antineutrino mode. With the total data set, NOvA will make precision measurements of θ_{23} and Δm^2_{32}. Depending on the value of θ_{23} and δ_{CP}, NOvA has the potential to resolve the neutrino mass hierarchy and the octant of θ_{23} at the 3σ level.

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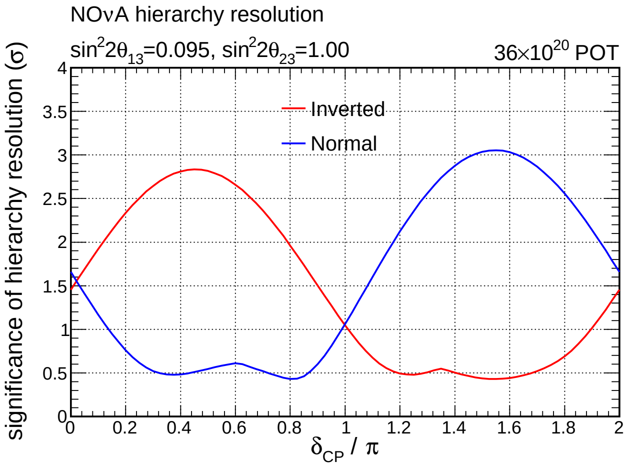

Figure 9: The NOvA sensitivity to mass hierarchy using the expected final NOvA data sample. The plot shows the significance to which the hierarchy can be resolved as a function of the true value of δ_{CP}.

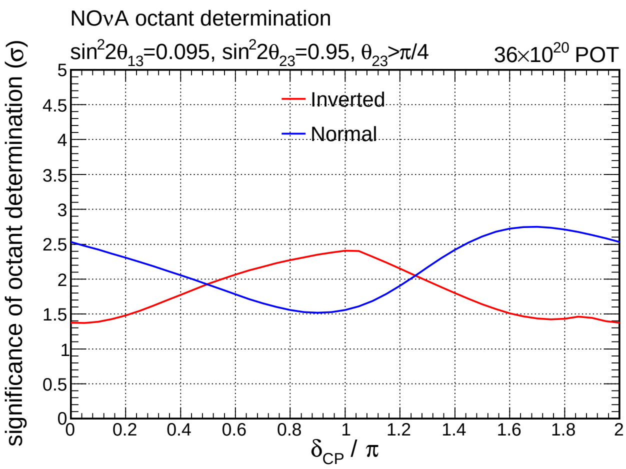

Figure 10: The NOvA sensitivity to the octant of θ_{23} using the expected final NOvA data sample. The plot shows the significance to which the octant can be resolved as a function of the true value of δ_{CP} assuming $\sin^2(2\theta_{23}) = 0.95$. If $\sin^2(2\theta_{23})$ is greater than 0.95 the sensitivity degrades as θ_{23} becomes closer to maximal.

References

[1] K. Anderson *et al.*, *The NuMI Facility Technical Design Report* ,FERMILAB-DESIGN-1998-01 (1998).

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