PROCEEDINGS OF SCIENCE

Details of the NOvA 3-flavor oscillation analysis

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NOvA is a world-leading long-baseline neutrino oscillation experiment. Its fine granularity allows the detection and identification of particle interactions in the detectors, notably muon and electron neutrino interactions. NOvA can measure the electron neutrino and antineutrino appearance rates, as well as the muon neutrino and antineutrino disappearance rates, in order to constrain the neutrino oscillations parameters, the neutrino mass hierarchy and the CP-violating phase δ_{CP}. NOvA's latest results combine both neutrino data (8.85×10^{20} POT) and antineutrino data (12.33×10^{20} POT). A 4.4σ evidence for $\overline{\nu}_e$ appearance in a $\overline{\nu}_\mu$ beam was measured. In addition, NOvA favors the Normal Hierarchy (1.9σ) and prefers the Upper Octant for θ_{23} (1.6σ).

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1. The NOvA experiment

The NOvA experiment uses the 700 kW NuMI beam at Fermilab to send muon neutrinos to two functionally identical detectors, located slightly off the beam axis (2 GeV energy peak). The Near Detector is located underground in Fermilab, while the much larger 14 kton Far Detector sits on the surface, 810 km further away, in Minnesota. They share the same experimental design in order to largely reduce the flux and cross-section systematics uncertainties. They are composed of 6.6 cm × 3.9 cm plastic cells filled with liquid scintillator. The light produced by charged particles traveling through the detector is collected by wavelength shifting fibers and read out by avalanche photodiodes. This high granularity design allows NOvA to detect neutrino interactions, to identify individual particle tracks and to measure their energies.

2. Details of the NOvA 3-flavor oscillation analysis

NOvA's 2019 oscillation results combine 8.85×10^{20} POT of muon neutrino beam and 12.33×10^{20} POT of muon antineutrino beam, which represents 78 % more antineutrino data compared to the 2018 analysis. NOvA performs a joint ν_e appearance ν_μ disappearance analysis combining neutrino and antineutrino data. Studying both neutrino and antineutrino oscillations helps solve degeneracies between the oscillation parameters that NOvA aims to constrain, namely Δm^2_{32}, $\sin^2\theta_{23}$ and δ_{CP}.

2.1 Principle

These oscillation parameters can be constrained by comparing the ν_e and ν_μ neutrino energy spectra recorded at the Far Detector with predictions made by extrapolating the ND ν_μ energy spectrum recorded at the Near Detector. This extrapolation technique greatly cancels the flux and cross-section systematics uncertainties. It uses both simulation (detector acceptance, reconstruction efficiency, etc.) and data-driven techniques to further reduce systematics uncertainties. Notably, NOvA can measure the small fraction of beam ν_e in the Near Detector to constrain the beam background expected at the Far Detector.

2.2 Event selection and reconstruction

The first step of the analysis is to reconstruct and identify the neutrino interactions in both detectors. Before looking for neutrino event candidates, quality, containment and fiducial cuts are applied and cosmic backgrounds are rejected with timing cuts and Boosted Decision Trees trained for that purpose. The ν_μ and ν_e Charged Current interactions are then identified with a dedicated Convolutional Neural Network [1]. Finally, muon tracks are identified with a k-Nearest-Neighbors algorithm while electron tracks are identified with another dedicated CNN [2].

2.3 Near Detector neutrino energy spectra

Once a ν_μ CC interaction is identified the neutrino energy is measured by summing the muon energy and the hadronic energy. The former is a function of the track length and offers a 3 % energy resolution, while the latter is a function of the calorimetric energy, providing a 30 % energy resolution. The resulting spectra measured in the ND are presented in Figure 1 for both neutrino and antineutrino data. After area normalization, the data is in very good agreement with the prediction and well within the shape only systematics uncertainties. The wrong sign background originates from the failure of the magnetic horns to focus the right charged hadrons, thus producing antineutrino in a neutrino beam, and conversely. This fraction is estimated to be 3 % of the neutrino events and 11 % of the antineutrino events. This high statistics Near Detector ν_μ spectrum can then be used to predict the surviving ν_μ spectrum and the appearing ν_e spectrum in the Far Detector. In practice, the ND ν_μ spectrum is split into 4 quartiles depending on their energy resolution (driven by the hadronic fraction), ranging from 6 % to 12 %. Each quartile is normalized and oscillated independently in order to improve the analysis sensitivity.

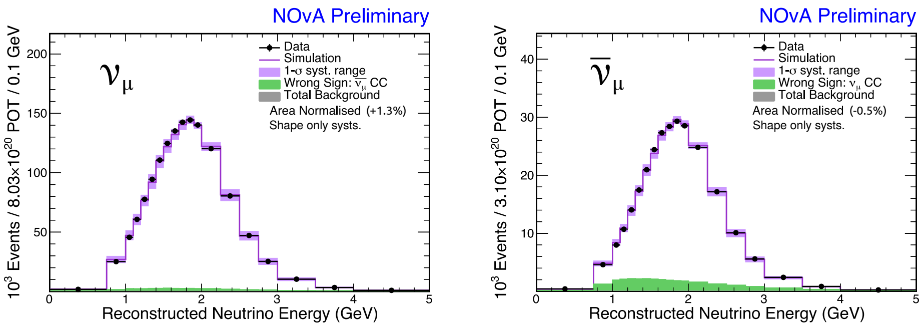


Figure 1: Reconstructed muon neutrino (left) and muon antineutrino (right) energy spectra in the Near Detector.

No ν_e appearance is expected in the Near Detector, so measuring the ν_e energy spectrum provides a powerful estimate of the backgrounds for the appearance analysis. The ν_e energy is a function of the electromagnetic and the hadronic energies, which are both reconstructed calorimetrically. Since the energy resolution is more modest and the statistics available is lower, less information can be extracted from the spectrum shape in the Far Detector. It is here more important to separate actual ν_e CC interactions from the various backgrounds. This is why splitting the sample into a high and a low purity sample also helps improve the analysis sensitivity. In addition, NOvA can use data-driven techniques to further constrain the different ν_e backgrounds: the number of observed Michel electrons helps constrain the NC and CC fractions, contained ν_μ's constrain the π flux and thus the low energy beam ν_e event rate, uncontained ν_μ's constrain the K flux and thus the high energy beam ν_e event rate. These background decomposition techniques help us adjust and improve our data and Monte-Carlo agreement, as illustrated by the ND ν_e energy spectra in Figure 2. This also means NOvA is able to extrapolate each background individually.

2.4 Far Detector neutrino energy spectra and event counts

The same selection and reconstruction techniques are applied for the neutrino candidates at the Far Detector. The data and best fit predictions are presented in Figure 3.

The sensitivity to Δm^2_{32} and θ_{23} in the disappearance analysis comes from the oscillated ν_μ spectra shapes. The final fit is therefore performed in four quartiles split by energy resolution. The ν_μ and $\overline{\nu}_\mu$ spectra shown here combine all quartiles for convenience. The statistics available in the appearance analysis is much lower. An extra "peripheral" sample, composed of events failing

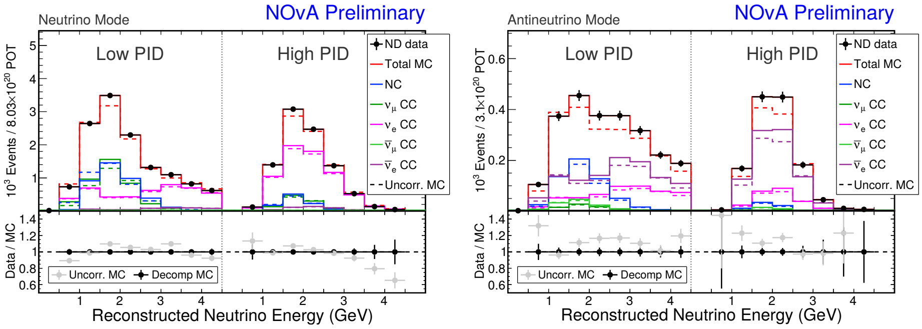
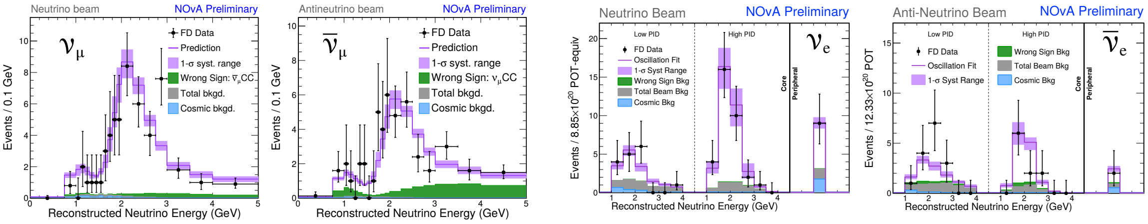


Figure 2: Reconstructed electron neutrino (left) and electron antineutrino (right) energy spectra in the Near Detector. Data-driven techniques help constrain the different background contributions and improve the data/Monte-Carlo agreement.



Obs. ν_μ candidates	113
Best fit prediction	123.9
Total background	4.2
Beam bkg	2.1
Cosmic bkg	2.1
No oscillations	730

Obs. $\bar{\nu}_\mu$ candidates	102
Best fit prediction	96.2
Total background	2.2
bkg	1.4
bkg	0.8
No oscillations	476

Obs. ν_e candidates	58
Best fit prediction	59.3
Total background	15.0
Beam bkg	11.1
Cosmic bkg	3.3
Wrong sign	0.7

Obs. $\bar{\nu}_e$ candidates	27
Best fit prediction	26.8
Total background	10.3
Beam bkg	7.0
Cosmic bkg	1.1
Wrong sign	2.2

Figure 3: The reconstructed energy spectra as well as the best fit prediction and event counts are presented for the disappearing ν_μ channel (left), the disappearing $\overline{\nu}_\mu$ channel (middle left), the appearing ν_e channel (middle right) and the appearing $\overline{\nu}_e$ channel (right).

preliminary cuts (such as containment cuts) but possessing a very high electron CNN score, is included in the analysis in order to increase the statistics and therefore improve the sensitivity. NOvA observed 27 $\overline{\nu}_e$ candidate events with 10.3 predicted background events. This represents a 4.4σ excess, which is the first evidence of $\overline{\nu}_e$ appearance in a $\overline{\nu}_\mu$ beam over a long baseline.

2.5 Fit and confidence interval estimation

The best fit prediction shown in the FD spectra above is obtained by performing a joint neutrino and antineutrino appearance and disappearance fit. The 3 parameters of interest Δm^2_{32}, $\sin^2\theta_{23}$ and δ_{CP} are unconstrained while 53 other terms like other oscillation parameters and systematics uncertainties are with Gaussian penalty terms. NOvA's main uncertainties are the detector calibration, the neutrino cross-sections, the muon energy scale and the uncertainty related to the neutron interaction, which was introduced along with the antineutrino data. The best fit point is determined by minimizing a Poisson negative log-likelihood. Because of the low statistics and the existence of physical boundaries (θ_{23} maximum mixing, δ_{CP} is cyclical, the mass hierarchy is a binary parameter), NOvA follows the Feldman-Cousins unified approach [3] for confidence interval estimation.

For a given point in the oscillation parameter space, many pseudo-experiments are generated and fitted in order to build empirical $\Delta\chi^2$ distributions. The fraction of pseudo-experiments with a $\Delta\chi^2$ larger than data at that particular point of parameters space is used to derive a p-value which can then be translated into a significance. By repeating this procedure over the parameter space, it is possible to build 2-dimensional confidence contours constraining the oscillation parameters. This frequentist approach is very computationally expensive but can be extremely parallelized on supercomputers in order to greatly speed up the procedure: in doing so, NOvA reached 1 million concurrent threads on NERSC machines.

2.6 NOvA 2019 3-flavor oscillation results

The best fit point lies in the Normal Hierarchy ($\Delta m^2_{32} = +2.48 \times 10^{-3}$ eV^2/c^4) and in the Upper Octant ($\sin^2\theta_{23} = 0.56$) with $\delta_{CP} = 0$ [4]. The confidence contours for Δm^2_{32} vs. $\sin^2\theta_{23}$ and $\sin^2\theta_{23}$ vs. δ_{CP} are shown for both Hierarchy hypotheses in Figure 4. The Normal Hierarchy is favored at the 1.9σ level (CL$_S = 0.091$). The maximum mixing of θ_{23} is disfavored at the 1.2σ level, while the Upper Octant is preferred at the 1.6σ level.

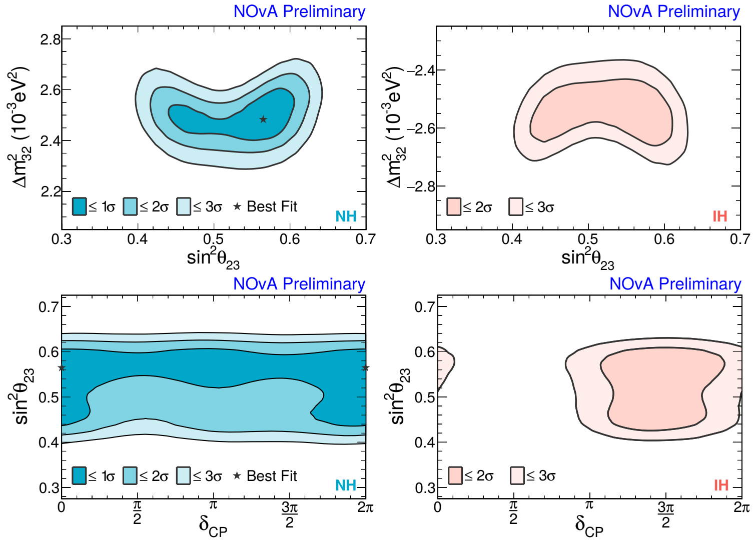


Figure 4: Confidence contours for Δm^2_{32} vs. $\sin^2\theta_{23}$ and $\sin^2\theta_{23}$ vs. δ_{CP} in the Normal and Inverted hierarchies.

References

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