PROCEEDINGS OF SCIENCE

Neutrino Oscillation Results from the NOvA Experiment

Erica Smith, for the NOvA Collaboration[a,*]

[a] *Indiana University,*
Bloomington, IN, USA

E-mail: ess3@iu.edu

The NOvA experiment is a long-baseline accelerator-based neutrino oscillation experiment that uses the upgraded NuMI beam from Fermilab to measure electron-neutrino appearance and muon-neutrino disappearance between the Near Detector, located at Fermilab, and the Far Detector, located at Ash River, Minnesota. NOvA's primary physics goals include precision measurements of oscillation parameters, such as θ_{23} and the atmospheric mass-squared splitting, along with probes of the mass hierarchy and of the CP-violating phase. This talk will cover NOvA's most recent three-flavor oscillation results, based on a neutrino beam exposure of 13.6E20 protons-on-target and an anti-neutrino beam exposure of 12.5E20 protons-on-target.

**** Particles and Nuclei International Conference - PANIC2021 ****
**** 5 - 10 September, 2021 ****
**** Online ****

[*] Speaker

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PoS(PANIC2021)289

1. Overview

Neutrinos are fundamental particles that are electrically neutral and have small but nonzero mass. There are three flavors of neutrinos: electron, muon, and tau. Neutrinos created as one flavor may be detected in another flavor; this phenomenon is called neutrino oscillation and occurs because flavor states are a linear superposition of neutrino mass states. Several parameters govern oscillation probability: the mixing angles θ_{ij}, which control flavor mixing; the squared differences between neutrino mass states, Δm^2_{ij}; a CP-violating parameter δ_{CP}, which will be non-zero if neutrinos and antineutrinos behave differently; neutrino energy; and flight distance. Long-baseline neutrino oscillation experiments set the last two parameters with their experimental setup; the others are measurable quantities.

2. 3 Flavor Oscillation Physics Goals for NOvA

By convention we denote the mass eigenstate containing the largest fraction of ν_e as ν_1. The scenario in which ν_1 is lightest is called the normal hierarchy, and the one in which ν_3 is lightest is the inverted hierarchy. Neutrino oscillation experiments have measured the mass squared differences Δm^2_{21} and Δm^2_{32}, but have not yet determined which mass state is the lightest.

Measuring θ_{23} allows us to investigate a possible ν_μ - ν_τ asymmetry; that is, whether the ν_μ or ν_τ flavor state contributes more to the mass states, or if they contribute equally. The case in which they contribute equally, i.e. $\theta_{23} = 45°$, is called "maximal mixing." If we see an asymmetry, we can determine whether θ_{23} is in the upper octant ($> 45°$) or lower octant ($< 45°$).

Neutrinos may be a source of CP-violation in the lepton sector; this would be indicated by differences in oscillation behavior between neutrinos and antineutrinos and would be reflected by a δ_{CP} value other than 0 or π.

Long-baseline neutrino oscillation experiments can answer these questions by comparing neutrino spectra before and after oscillation. Making these comparisons allows us to make precision measurements of θ_{23} and Δm^2_{32} and to probe the mass hierarchy and CP-violating phase.

3. NOvA (NuMI Off-Axis ν_e Appearance)

NOvA [1] is a long-baseline neutrino oscillation experiment that uses the NuMI beam provided by Fermilab. NOvA has two functionally-equivalent detectors; the 290 ton Near Detector (ND) is located 1 km away from the neutrino source, 100 m underground at Fermilab, and the 14 kiloton Far Detector (FD) is 810 km away from the source, on the surface in Ash River, Minnesota. The detectors are 14.6 mrad off beam axis, producing a neutrino energy spectrum that peaks near 2 GeV; this distance and energy was chosen to maximize the oscillation probability for the electron neutrino appearance channel.

The NuMI (Neutrinos from the Main Injector) beam is produced by accelerating 120 GeV protons which strike a carbon target to produce charged pions and kaons. Positively and negatively charged pions decay into muon neutrinos and antineutrinos, respectively. The charged particles are focused with magnetic horns, allowing the selection of neutrinos or antineutrinos. This analysis includes data taken through March 2020 and contains 13.6×10^{20} POT in neutrino mode and 12.5×10^{20} POT in antneutrino mode.

The NOvA detectors are fine-grained, low-Z, highly-active tracking calorimeters. The detectors are composed of 4-cm by 6-cm PVC cells filled with organic scintillator. Cells are arranged in planes, which alternate horizontal and vertical orientations, enabling three-dimensional event reconstruction.

4. 3 Flavor Oscillation Analysis

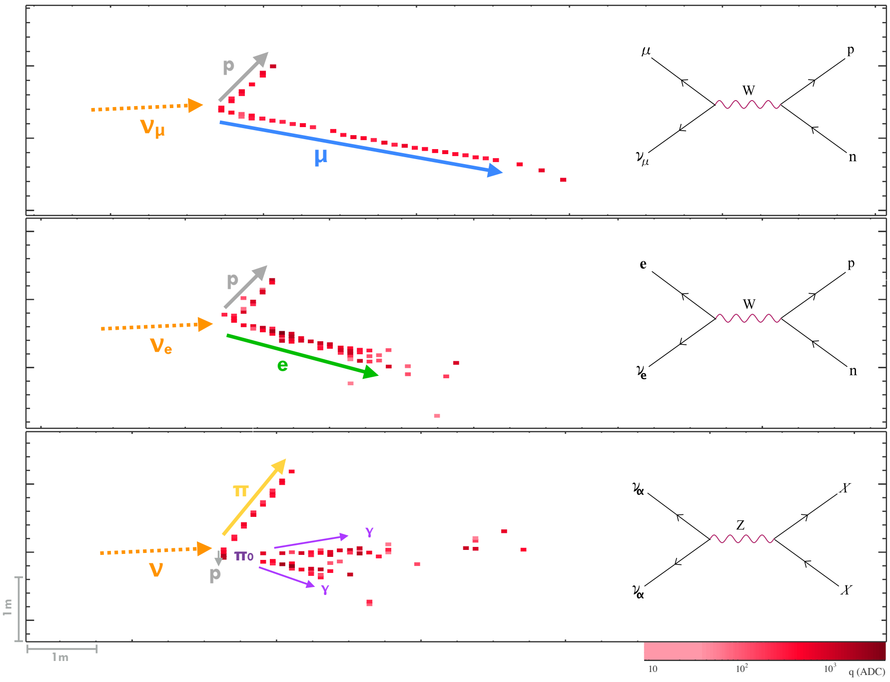

Figure 1: Sample events selected from Near Detector data. Each pixel corresponds to one cell. Top: ν_μ charged current event. The identifying feature is the long, low dE/dx track indicative of a minimally ionizing muon. Middle: ν_e charged current event. The distinguishing feature is the shorter, broader electromagnetic shower. Bottom: Neutral current event. The neutrino is the outgoing lepton in neutral current events so the hadronic component is the only signature. In this event, a neutral pion is produced which decays into two photons. The distinguishing feature between this interaction and a ν_e interaction is the gap between the interaction vertex and the shower.

Sample events from ND data are shown in Fig. 1. We use a convolutional neural network in the image recognition style to select events. Loose preselection and containment cuts are first applied to remove obvious backgrounds, and a first pass of cosmic rejection is used to catch cosmics that pass containment cuts. We additionally require a well-reconstructed muon track for muon neutrino interactions. Relative to this preselection, the event ID selects muon neutrino events with ~90% efficiency and rejects 99% of backgrounds, and selects electron neutrino events with ~80% efficiency and rejects 80% of backgrounds.

PoS(PANIC2021)289

Muon neutrinos selected at the ND are used to predict the energy spectra at the FD for both unoscillated muon neutrinos and oscillated electron neutrinos. Electron neutrinos selected at the ND are either electron neutrinos intrinsic in the beam or other backgrounds that mimic the electron neutrino signature. This sample constrains backgrounds for electron neutrino appearance at the FD.

At the FD, we observe 211 muon neutrinos in neutrino mode and 105 muon antineutrinos in antineutrino mode. The dip in the spectrum due to oscillation is strongly pronounced in Fig. 2(a,b) due to the promixity of θ_{23} to maximal mixing. Selected ν_e events are separated into three bins, shown in Fig. 2(c,d): low and high event ID bins to contain backgrounds largely in one bin, and a peripheral bin to include events that fail the event selection but pass stringent additional checks. In neutrino mode, we see 82 events, with a background of 27. In antineutrino mode, we see 33 events with a background of ~ 14, $> 4\sigma$ evidence of $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam.

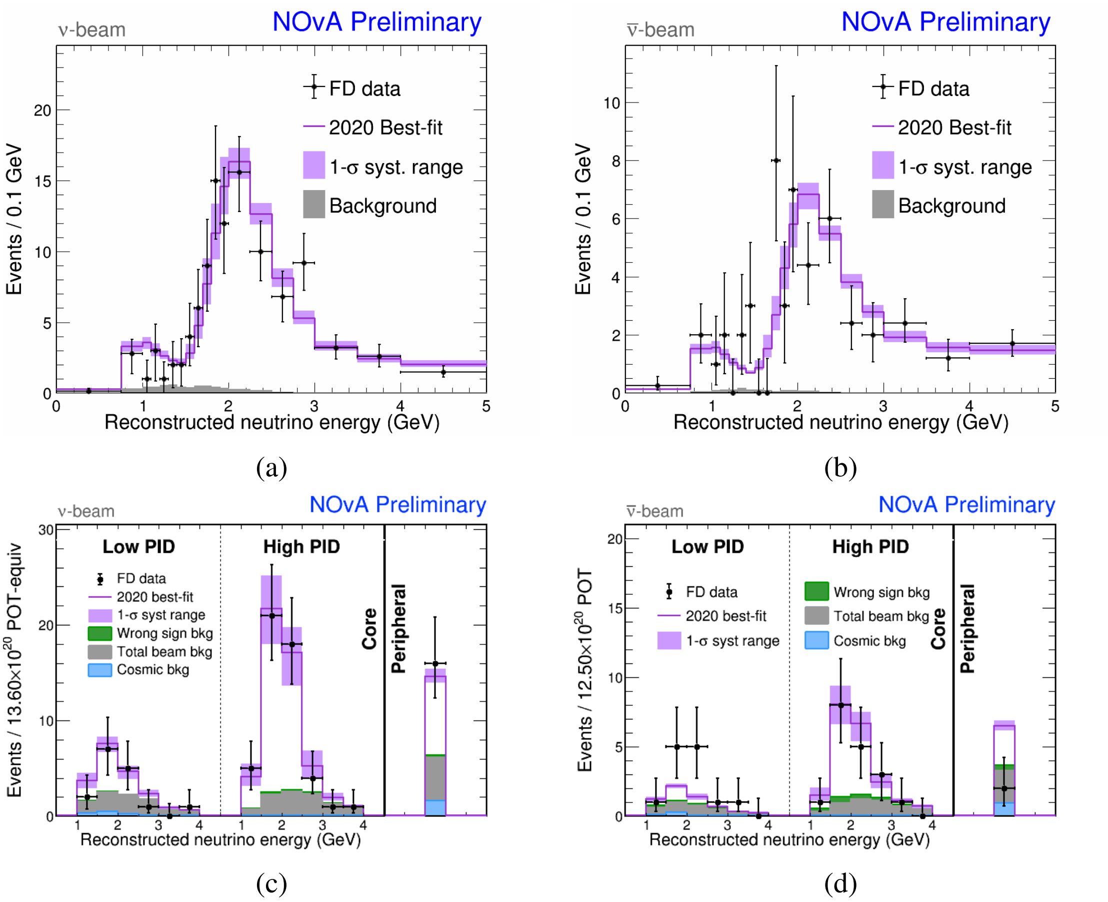

Figure 2: Energy spectra of selected (a) muon neutrino, (b) muon antineutrino, (c) electron neutrino, and (d) electron antineutrino events in the Far Detector. Data is in black and simulation in purple, drawn with a 1σ systematic range. Total background in (a) and (b) is gray; backgrounds in (c) and (d) are factored into wrong sign contamination (green), beam backgrounds (gray), and cosmics (blue).

We fit the ν_μ and ν_e FD energy spectra simultaneously to determine the oscillation parameters. We see good agreement with other long-baseline and atmospheric neutrino oscillation experiments, shown in Fig. 3. We do not see a strong asymmetry in event rate between neutrino and antineutrino

PoS(PANIC2021)289

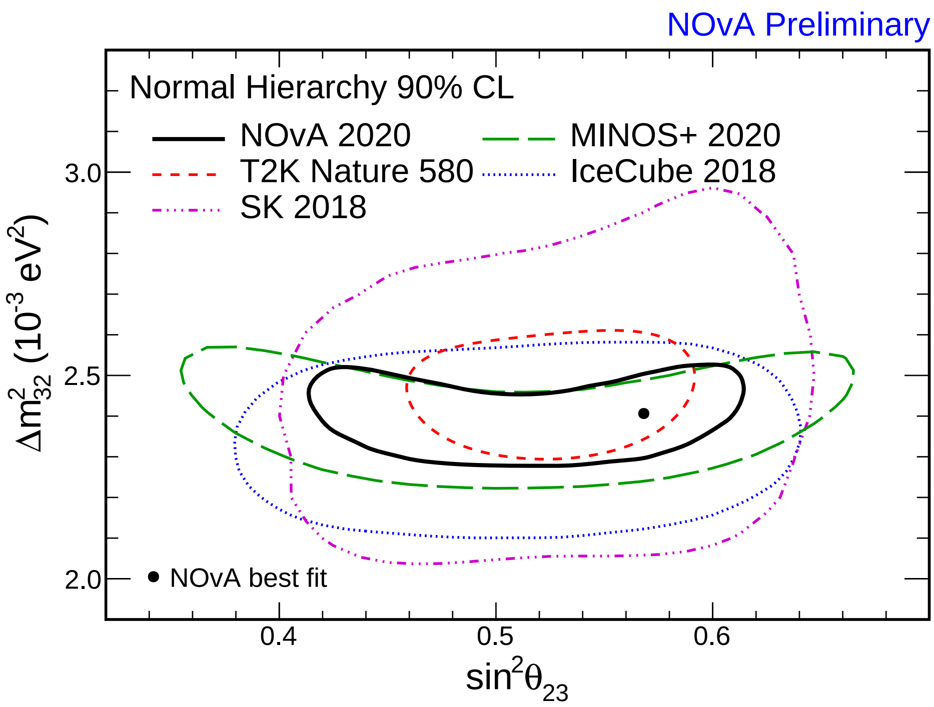

Figure 3: NOvA 90% confidence level contour with systematics and Feldman-Cousins corrections applied, compared to that of other long-baseline and atmospheric neutrino oscillation experiments [2–5]. Results are consistent across all experiments. The NOvA best fit values are $\Delta m^2_{32} = (2.41 \pm 0.072) \times 10^{-3}$ eV^2 and $\sin^2\theta_{23} 0.57^{+0.04}_{-0.03}$.

modes. We have a slight preference for the normal hierarchy and upper octant, exclude $\delta_{CP} = \pi/2$ in the inverted hierarchy at $> 3\sigma$, and disfavor $\delta_{CP} = 3\pi/2$ in the normal hierarchy at $\sim 2\sigma$.

References

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