FERMILAB-CONF-16-127-ND

FIRST NEUTRINO OSCILLATION RESULTS FROM NOνA

M. J. Frank[a b]
University of Virginia, Charlottesville, VA 22904, USA

Abstract. The NOνA experiment aims to study the mixing behavior of neutrinos and anti-neutrinos using the Fermilab NuMI neutrino beam. The experiment collects data at two detectors, one near the neutrino production target at Fermilab; the other 810 km away. The detectors are 14 mrad off the beam axis, which results in an almost monoenergetic beam of 2 GeV neutrinos. The construction of the 14 kT Far Detector and 300 T Near Detector finished in 2014. Since then, NOνA has collected data and we will discuss the first data analyses using 2.74×10^{20} POT searching for muon neutrino disappearance and electron neutrino appearance in the Far Detector.

1 Introduction

The acronym NOνA stands for NuMI Off-Axis ν_e-Appearance, which summarizes our experiment [1]. The NuMI (Neutrinos at the Main Injector) facility provides the muon neutrino (ν_μ) source [2]. These neutrinos travel north through the earth to the Far Detector (FD) which is located 14 mrad off the beam axis where we expect an almost monoenergetic beam of 2 GeV neutrinos. During their 810 km journey to the FD, the neutrinos oscillate in their flavor states and we measure the disappearance rate of muon neutrinos (ν_μ) and appearance rate of electron neutrinos (ν_e). From this we can measure the transition probabilities $P(\nu_\mu \to \nu_\mu)$ and $P(\nu_\mu \to \nu_e)$ which are functions of the oscillation parameters [3]. From the measurement of $P(\nu_\mu \to \nu_\mu)$ we can extract information about the mixing angle θ_{23} and the neutrino mass difference Δm^2_{32}. From the measurement of $P(\nu_\mu \to \nu_e)$ we can extract information about the mixing angle θ_{13} and θ_{23}, the CP-violating phase angle δ_{CP}, and the neutrino mass hierarchy.

2 Neutrino Detection

The neutrino interaction cross section is very low, so we require a large detector mass. When an electron neutrino interacts with the detector an electron is produced that will in turn produce an electromagnetic (EM) shower. We therefore designed a "fully active" detector using low Z materials. We use PVC extrusions filled with liquid scintillator, which provides a radiation length of approximately 40 cm and a Molière radius of 11 cm. Each of the extrusions contains one wavelength-shifting fiber that is read out by an avalanche photo-diode (APD). This detection technique is optimized to differentiate EM showers from hadronic showers as will be shown later.

[a] On behalf of the NOνA collaboration.
[b] E-mail: mjf8u@virginia.edu

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy

3 The Experiment

The neutrinos are created in the NuMI facility by colliding 120 GeV protons on a graphite target, which results in π^+ particles that are allowed to decay into μ^+ and ν_μ. The μ^+ particles are stopped by muon absorbers and the muon neutrinos travel onward to the Near Detector (ND). The NuMI beam line is operating routinely with a beam power of 420 kW and is being upgraded to increase to a final power of 700 kW.

The ND is located 105 m underground and 14 mrad off the beam axis. It has a mass of approximately 300 tons and a size of 4 m by 4 m by 15 m. The FD is located on the surface a distance of 810 km away and also 14 mrad off the beam axis. Its construction was completed in 2014 and it has a mass of over 14,000 tons and a size of 15 m by 15 m by 60 m.

Figure 1 shows the simulated signatures of different particle interactions in the ND. It shows that we are able to differentiate EM showers (center) from hadronic showers (bottom). With this particle identification we can measure $P(\nu_\mu \to \nu_\mu)$ and $P(\nu_\mu \to \nu_e)$ by looking for a deficit of ν_μ events and an excess of ν_e events, respectively. We can then extract nature's parameters based on the standard oscillation equations [3] as explained above using a baseline of 810 km and a neutrino energy of 2 GeV.

Figure 2 shows what NOνA can achieve by combining three years of neutrino running with three years of anti-neutrino running. If nature's parameters reside at the starred point, we would have optimal sensitivity for the neutrino mass hierarchy and δ_{CP}.

4 Muon Neutrino Disappearance Analysis

The ν_μ disappearance analysis to measure $P(\nu_\mu \to \nu_\mu)$ proceeds by first identifying ν_μ charged-current events together with their energies in both the ND and FD. From the measured ND neutrino energy spectrum, we can extrapolate the expected FD energy spectrum as explained in Figure 3. We can then extract the oscillation parameters ($\sin^2(\theta_{23})$ and Δm^2_{32}) by comparing the extrapolated energy spectrum to the one we measure in the FD. Figure 4 shows the FD ν_μ energy spectrum and Figure 5 shows the extracted oscillation parameters in a two-dimensional contour. For the normal mass hierarchy, we measured the individual oscillation parameters to be:

$$\begin{aligned} \Delta m^2_{32} &= 2.37^{+0.16}_{-0.15} \\ \sin^2\theta_{23} &= 0.51 \pm 0.10 \end{aligned}$$

The official NOνA ν_μ disappearance results are described in more detail elsewhere [6].

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy

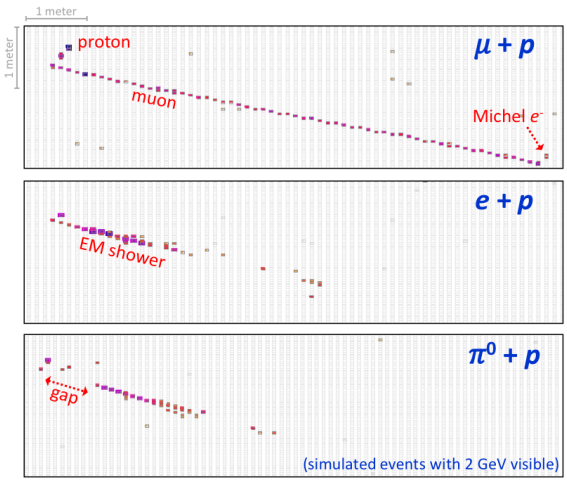

Figure 1: Simulated ND event with a visible energy of 2 GeV. The top event shows a ν_μ charged-current interaction with the characteristically long muon track and short proton track with large energy deposition. The middle event shows a ν_e charged-current interaction that demonstrates the long EM shower in our "fully active" detector. The bottom event shows a hadronic interaction where the majority of the π^0 momentum is carried by one of the two decay photons, which in turn produces a displaced EM shower.

5 Electron Neutrino Analysis

The ν_e appearance analysis to measure $P(\nu_\mu \to \nu_e)$ proceeds by first identifying ν_e charged-current events. We then predict the beam backgrounds using ND events and finally interpret the FD event excess as ν_e appearance. The ν_e signature has been explained in Figure 1, so the task is to identify all such events in the FD. The largest background comes from the cosmic rays passing through the FD at a rate of 10^5 Hz because of the detector's proximity to the earth's surface. We therefore only look at events that are in time with a beam spill onto the NuMI target, which reduces our cosmic ray background events by a factor of 10^5. Additionally, we reduce our background by three additional orders of magnitude by applying event-topology-based requirements on our events. Finally, we use two techniques to identify electron showers. The Likelihood Identification (LID) technique tests event shower $\frac{dE}{dx}$ profiles against probability density functions for different particle hypotheses. The Library Event Matching (LEM) technique tests the entire event topology against a large library of simulated electron neutrino signal and background events. Figure 6 shows the energies of the six identified LID ν_e candidates and eleven LEM ν_e candidates. If we compare this result to the reactor measurement of $\sin^2(2\theta_{13})$ [7–9] (we use the weighted average $\sin^2(2\theta_{13}) = 0.086$), we can

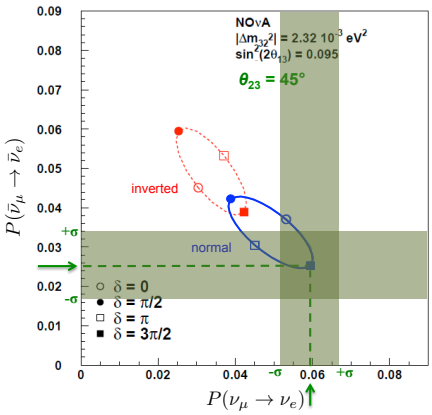

Figure 2: This plot shows the transition probabilities $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ for different values of $\delta_{\rm CP}$ for the normal (solid blue oval) and inverted (dashed red oval) mass hierarchies. If we measure the probabilities indicated by the green arrows we could resolve the mass hierarchy and set limits on $\delta_{\rm CP}$ at different confidence levels. The 1σ range is indicated by the green shaded region.

produce the exclusion significances shown in Figure 7. The official NOνA ν_e appearance results are described in more detail elsewhere [10].

Acknowledgments

I wish to thank the organizers of the 17$^{\rm th}$ Lomonosov Conference on Elementary Particle Physics for a most enlightening and entertaining conference, my NOνA colleagues, and Fermilab. Fermilab is operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

[1] D. S. Ayres *et al.*, FERMILAB-DESIGN-2007-01 (2007).
[2] J. K. Anderson *et al.*, FERMILAB-DESIGN-1998-01 (1998).
[3] K. A. Olive *et al.* (Particle Data Group), Chin. Phys. C, 38, 090001 (2014).
[4] P. Adamason *et al.*, Phys. Rev. Lett. 112, 191801 (2014).
[5] K. Abe *et al.*, Phys. Rev. D 91, 072010 (2015).
[6] P. Adamson, arXiv:1601.05037 (2016).
[7] F. P. An *et al.*, Phys. Rev. Lett. 115, 111802 (2015).
[8] S. H. Seo, arXiv:1410.7987 (2014).
[9] Y. Abe *et al.*, JHEP 1410 86 (2014).
[10] P. Adamson, arXiv:1601.05022 (2016).

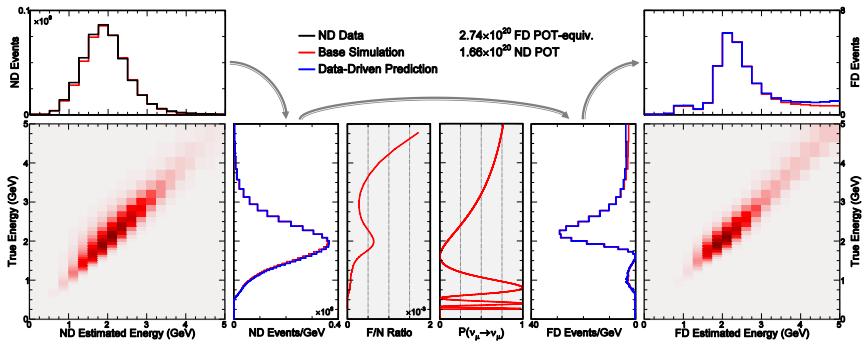

Figure 3: This diagram explains how we predict the number of neutrino events in the FD using a data-driven extrapolation technique. We start with the ND neutrino energy spectrum and estimate the true energy distribution. Next, we multiply by the expected far/near event ratio and oscillation probability. As a final step we convert the extrapolated true energy spectrum to the reconstructed energy spectrum that we measure in the FD.

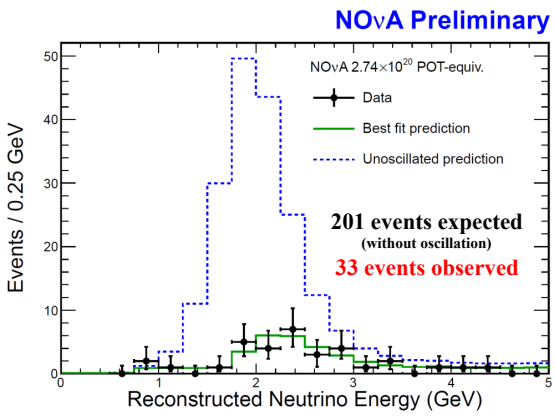

Figure 4: This plot shows the FD ν_μ energy spectrum. The black points show the measured FD data, the green line shows the best fit to the data from which we extract our oscillation parameters. For illustration, the prediction if there were no neutrino oscillations is shown as the blue dotted line. Without neutrino oscillations, we would have expected 201 ν_μ events, but we observe only 33 events, which is unambiguous confirmation of neutrino oscillations.

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy

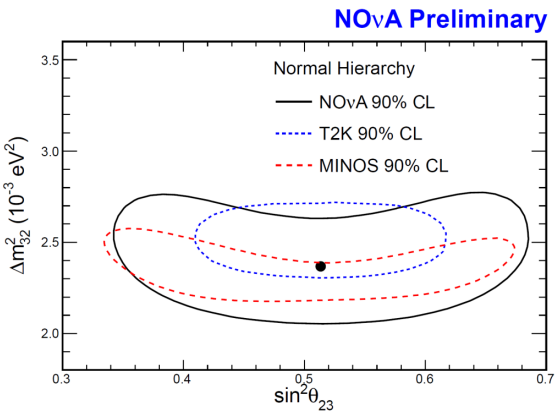

Figure 5: This plot shows the 90% C.L. contours of the normal mass hierarchy oscillation parameters ($\sin^2(\theta_{23})$ and Δm^2_{32}) extracted from the data in Figure 4. For comparison, the MINOS [4] and T2K [5] results are superimposed showing that our first results are in good agreement.

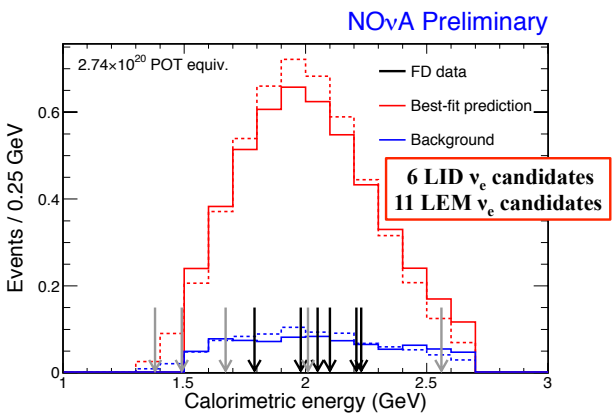

Figure 6: This plot shows the FD ν_e energy spectrum. The black arrows indicate the ν_e candidates identified by both the LID and LEM technique, while the grey arrows indicate the ν_e candidates identified by LEM only. The red lines indicate the best-fit spectrum to the LID (solid) and LEM (dashed) candidate events. The blue lines indicate the estimated background for LID (solid) and LEM (dashed).

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy

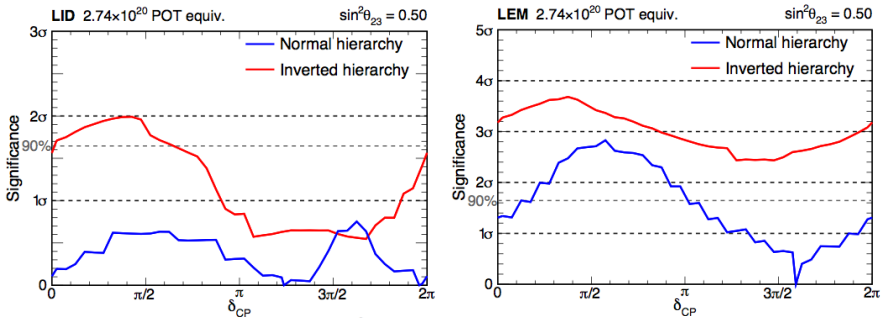

Figure 7: The plots above show the exclusion significance for different values of δ_{CP} for both the normal (blue) and inverted (red) neutrino mass hierarchies. The left plot shows the result using the 6 LID ν_e candidates and the right plot shows the result when we use the 11 LEM ν_e candidates instead.

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy