Current MINOS Oscillation Results and Status of the NOνA Experiment

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The MINOS experiment collected 3.36×10^{20} protons-on-target from May 2005 through July 2007 from Fermilab's NuMI beam. The data are consistent with $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillation with parameters $|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% CL) and $\sin^2 2\theta > 0.90$ (90% CL). An independent analysis of the first 2.46×10^{20} protons-on-target reveals no indication of sterile neutrino oscillation. A search for ν_e appearance is ongoing. The NOνA experiment is optimized for the detection of ν_e appearance off-axis from an upgraded NuMI beam and will be capable of an order-of-magnitude greater precision in $\nu_\mu \rightarrow \nu_\tau$ oscillation parameters.

1. Introduction

A variety of experiments have demonstrated clear evidence of ν_e and ν_μ neutrino disappearance [1–8] consistent with the hypothesis of unitary three flavor neutrino oscillation [9]. The Main Injector Neutrino Oscillation Search (MINOS) has published evidence for energy-dependent ν_μ disappearance from the beam produced at Fermilab's Neutrinos at the Main Injector (NuMI) facility with a significance of 5.2σ using one year of data corresponding to 1.27×10^{20} protons-on-target (POT) [8]. In its first two years of operation, MINOS has collected 3.36×10^{20} POT and has made significant improvements in both systematic uncertainty determination and simulation. Though the MINOS experiment is designed primarily for sensitivity to ν_μ disappearance as measured by the relative rate of ν_μ charged-current (CC) interactions far and near to the neutrino source, additional analyses of the data sample have been undertaken to search for ν_e appearance, and to search for sterile neutrinos via neutral-current (NC) disappearance.

The next-generation NuMI Off-axis ν_e Appearance (NOνA) experiment is based on similar technology as MINOS, but situated off-axis to an upgraded NuMI beam at a 10% longer baseline. With six years of data, NOνA will have an order-of-magnitude greater sensitivity to the oscillation parameter $\sin^2\theta_{13}$ than MINOS, as well as an order-of-magnitude greater precision to the $\nu_\mu \rightarrow \nu_\tau$ oscillation parameters.

In this paper, we present an overview of the most current MINOS neutrino oscillation analyses including an update of ν_μ CC disappearance in the MINOS detectors [10], a search for sterile neutrinos [11], and an ongoing search for ν_e appearance. We also present an overview of the NOνA experiment and its current development.

2. The NuMI Neutrino Beam

The NuMI facility, described in detail in Ref. [12], is located at Fermilab in Batavia, IL, and sends a beam of primarily ν_μ through the earth to intersect the MINOS far detector in Soudan, MN, 735 km away. NuMI is a conventional two-horn-focused neutrino beam with a 675 m long decay tunnel. The horn current and position of the hadron production target relative to the horns can be configured to produce different ν_μ energy spectra. The beam with target and horns configured in the low energy (LE-10) position is comprised of 92.9% ν_μ, 5.8% $\overline{\nu}_\mu$, and 1.3% $\nu_e + \overline{\nu}_e$. NuMI is supplied a 10μs spill averaging 2.4×10^{13} POT every 2.2 seconds over the first two years of running (Runs I & II), which has been increased to an average 3.0×10^{13} POT per spill more recently. Data is more recently accumulated at a rate about 10^{18} POTs per day. The delivered beam power is 275 kW, which will be upgraded to 700 kW and routinely run in the medium energy (ME) horn/target position for NOνA data-

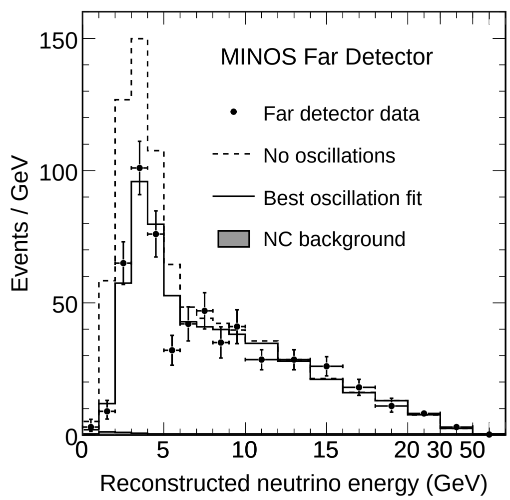

Figure 1. Comparison of the FD data (points, with statistical uncertainties) from the low- and high-energy configurations with the predictions for the energy spectra with and without the effect of oscillations. The estimated neutral-current (NC) background is indicated.

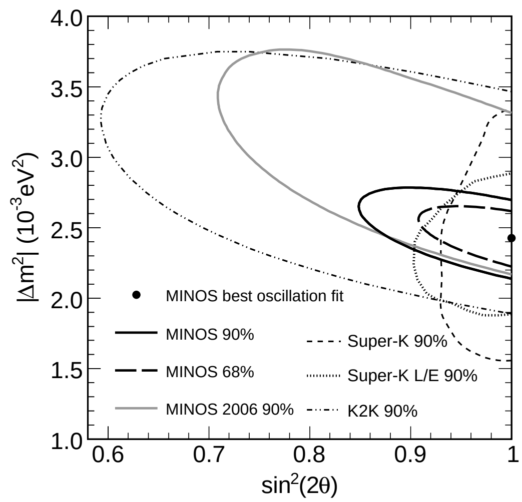

Figure 2. Contours for the oscillation fit to the data in Fig. 1, including systematic errors. Also shown are contours from previous experiments [1, 4] and MINOS's previous result [8].

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3. MINOS

MINOS, described in detail in Ref. [13], consists of two octagonal detectors: a 0.98 kt near detector (ND) of dimension $3.8 \times 4.8 \times 15$ m located 1.04 km from the NuMI target, and a 5.4 kt far detector (FD) of dimension $8 \times 8 \times 30$ m located 735 km from the target. Both are functionally-identical segmented, magnetized calorimeters that permit particle tracking. Each detector is built from alternating orthogonal layers of scintillating strips oriented ± 45 degrees from vertical, interspersed with 2.54 cm thick steel planes.

Using two detectors is crucial to making oscillation measurements in both MINOS and NOνA. The NuMI neutrino energy spectra are measured at both the ND and FD. The ND spectrum is extrapolated to the FD as an expected unoscillated spectrum, canceling common sources of possible systematic uncertainty which would be present if the ND spectrum were not utilized. Oscillation parameters may be extracted from differences between the observed and the extrapolated unoscillated spectra. Complications do arise in extrapolating the ND spectrum since the ND sees a line-source neutrino beam at high flux (i.e. there are an average 18 ν interactions in the ND per spill) while the FD sees a point-source beam with $O(10^6)$ reduction in flux. Timing and topology are used to separate events in each spill in the ND and beam events are well identified in time with the NuMI spill trigger at the FD.

Events identified as ν_μ CC typically have a long muon track and some hadronic activity at the vertex. NC events are typically short and diffuse due to hadronic showering through inactive steel layers. Events identified as ν_e CC are typically short with energy deposition consistent with a characteristic electromagnetic shower profile. More precise details for the specific event selection techniques and analyses may be found in Refs. [10,11].

The analysis of ν_μ CC event disappearance yields a significant observation of energy-dependent depletion consistent with the hypothesis of neutrino oscillation. The observed energy spectrum shown in Fig. 1 is compared to the $\nu_\mu \to \nu_\tau$ oscillation hypothesis, using the survival probability:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267\Delta m^2 L/E), \quad (1)$$

where L (km) is the distance traveled and E (GeV) is the neutrino energy. Pure decay [14] and pure decoherence [15] hypotheses are disfavored relative to oscillation by 3.7σ and 5.7σ, respectively. The oscillation parameters derived are $|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% CL) and $\sin^2 2\theta > 0.90$ (90% CL) with $\chi^2/ndf = 90/97$. The uncertainty in the result is statistics dominated, however the fit includes the three largest systematic uncertainties included as nuisance parameters: 10.3% absolute hadronic energy scale, 4% normalization, and 50% NC contamination. Contours for the oscillation fit are shown in Fig. 2.

An independent analysis to search for evidence of sterile neutrino oscillation via disappearance of NC events at the MINOS FD conducted on the first 2.46×10^{20} POT collected reveals no indication of the existence of sterile neutrinos. Performing a fit to the selected FD NC spectrum shown in Fig. 3 using a simple 4-neutrino model of neutrinos (3 active + 1 sterile) with oscillation occurring at one value of Δm^2, with survival and oscillation probabilities given by

$$P(\nu_\mu \to \nu_\mu) = 1 - \alpha_\mu \sin^2(1.267\Delta m^2 L/E) \quad (2)$$

and

$$P(\nu_\mu \to \nu_s) = \alpha_\mu \sin^2(1.267\Delta m^2 L/E), \quad (3)$$

yields a sterile fraction,

$$f_s = P(\nu_\mu \to \nu_s)/\left[1 - P(\nu_\mu \to \nu_\mu)\right] = 0.28^{+0.25}_{-0.28}, \quad (4)$$

or less than 0.68 (90% CL).

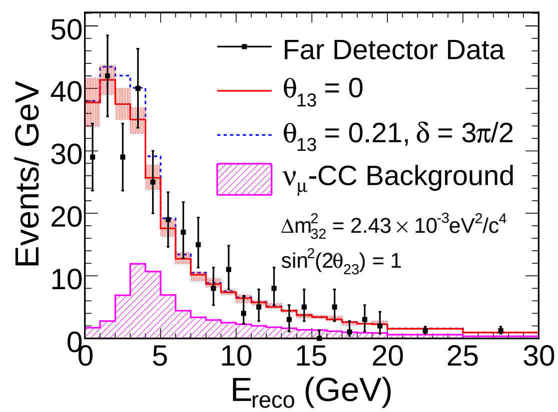

Figure 3. Spectrum of observed NC-like events in the FD with predictions for two extreme $\nu_\mu \to \nu_e$ oscillation hypotheses. The filled regions in each bin indicate the systematic uncertainty in the predicted rates.

An analysis of the first two years of MINOS data is also underway to search for ν_e appearance, signaling sub-dominant $\nu_\mu \to \nu_e$ oscillation. Projected sensitivity shown in Fig. 4 to the oscillation parameter $\sin^2 2\theta_{13}$ is expected to be slightly better than the 90% CL limit from the CHOOZ experiment [16]. Results are expected in early 2009.

4. NOνA

Significant improvement in sensitivity to $\nu_\mu \to \nu_e$ oscillation will be possible with planned improvements to the NuMI beam and the construction of two new detectors for the NOνA experiment [17]. NOνA is optimized for the detection of $\nu_\mu \to \nu_e$ oscillation with several differences relative to MINOS, including (1) upgrades to the NuMI beam to 700kW (also known as ANU), (2) detectors located off-axis to increase NC background discrimination, (3) a 10% longer baseline with the FD located 810 km away from the target in Ash River, MN inside Voyaguer's National Park, (4) inexpensive components comprising a

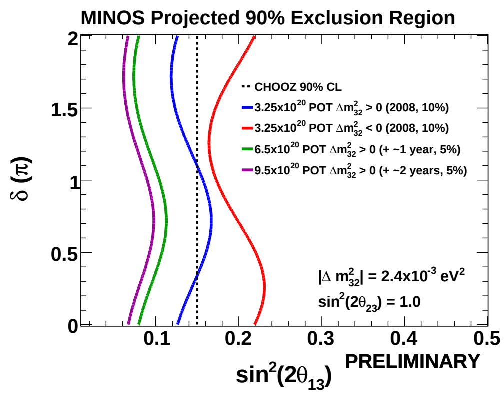

Figure 4. Values of δ_{CP} and $\sin^2 2\theta_{13}$ excluded at the 90% confidence level if we observe only the predicted number of background events for an exposure of 3.25×10^{20} POT with 10% systematic error and $6.5 \times 10^{20}$and 9.5×10^{20} POT with 5% systematic error.

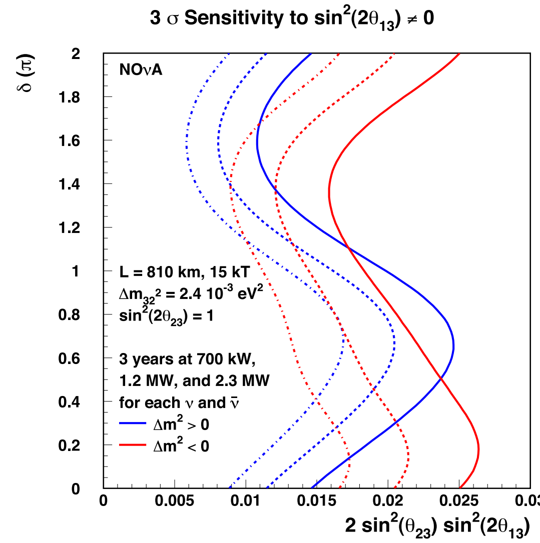

Figure 5. Expected sensitivity to $\sin^2 2\theta_{13}$ at the 3σ level in the NOνA experiment with 3 years of neutrino and 3 years of anti-neutrino data.

70% active detector volume with a planned 15 kt FD total mass.

The NOνA FD will be composed of 385,000 cells of extruded PVC plastic, with each cell 3.9 cm wide, 6.6 cm deep, and 15.7 m long, filled with 3.3 million gallons (12.5 million liters) of liquid scintillator. The liquid scintillator makes up 70% of the total detector mass, thus it is a totally active tracking calorimeter optimized for identification of ν_e interactions. Energy deposition signals are read out by 13,000 km of 0.7 mm diameter optical wavelength-shifting fiber using 12,000 avalanche-photodiodes (APDs). A 222 ton ND will be constructed with similar components. The NOνA detectors are similar in design to the active element of the MINOS detectors, with the substitution of geometric differences, liquid scintillator used instead of plastic scintillator, and APDs used instead of photomultiplier tubes. Unlike MINOS, the NOνA FD is located in a surface building recessed only 12 m below the surface and covered with 15 cm of barite and layers of concrete. Secondary containment of the detector is provided by a solid granite foundation. Assuming 3 years of neutrino plus 3 years of anti-neutrino beam delivered by NuMI, NOνA will have an order-of-magnitude greater sensitivity to the oscillation parameter $\sin^2 2\theta_{13}$ as shown in Fig. 5, as well as an order-of-magnitude more precise determination of the dominant ν_μ oscillation parameters Δm^2_{23} and $\sin^2 2\theta_{23}$, shown in Fig. 6 for several test points. If the value of $\sin^2 2\theta_{13}$ is sufficiently large, NOνA will also have significant sensitivity to the CP-violating parameter δ. With the varying densities of earth seen along the NuMI beam's path to the FD, NOνA is also particularly sensitive to matter effects on the oscillation probabilities, yielding a unique potential method of determining the neutrino mass hierarchy.

The NOνA project has seen some very significant milestones since its first workshop in 2002. In particular, the FY2008 federal budget which caused hardship across most of high-energy physics in the U.S. specifically provided zero funds and stopped on-budget work on the project. Despite this setback, NOνA was recom-

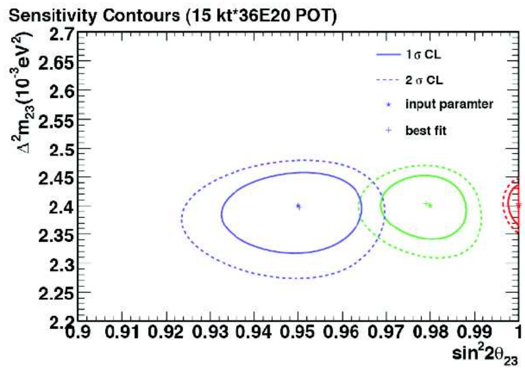

Figure 6. Expected sensitivity contours for 1σ and 2σ for example test points in $\sin^2 2\theta_{23}$ and Δm^2_{23} characteristic of ν_μ disappearance in the NOνA experiment with 3 years of neutrino and 3 years of anti-neutrino data.

mended for CD-2 approval in April 2008, granted in September. A supplemental emergency spending bill passed by the U.S. Congress in July provided US$9M to continue necessary work on the project until a FY2009 budget is passed. As of this writing, no FY2009 budget has been put forward, but activities have continued as scheduled and there is cautious optimism that NOνA will continue.

5. Summary and Prospects

Using the NuMI neutrino beam sent from Fermilab to the Soudan Mine 735 km away in northeast Minnesota, the MINOS experiment is now making precise measurements of ν_μ disappearance consistent with neutrino oscillation seen previously in atmospheric neutrinos. Recent progress has been made constraining the possibility of ν_μ oscillation to sterile neutrinos in a neutral-current disappearance analysis, as well as progress to further limit the oscillation parameter θ_{13} via the search for ν_e appearance in the present NuMI beam. NOνA is a next-generation totally-active two-detector long-baseline neutrino oscillation experiment which will operate off-axis from an upgraded 700kW NuMI neutrino beam, with a near detector at Fermilab and far detector 810 km away in northern Minnesota at Ash River. NOνA is optimized for the detection of $\nu_\mu \to \nu_e$ oscillation. NOνA will have an order-of-magnitude greater sensitivity to the observation of $\nu_\mu \to \nu_e$ oscillation, and will be able to make an order-of-magnitude more precise measurement of the ν_μ disappearance oscillation parameters. Despite funding setbacks, NOνA is continuing with cautious optimism.

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