Current MINOS neutrino oscillation results

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Alec Habig, for the MINOS collaboration
University of Minnesota Duluth, Physics Department, 10 University Dr., Duluth, MN 55812, USA
E-mail: ahabig@umn.edu

Abstract. The MINOS experiment is now making precise measurements of the $\nu_\mu$ disappearance oscillations seen in atmospheric neutrinos, tests possible disappearance to sterile $\nu$ by measuring the neutral current flux, and has extended our reach towards the so far unseen $\theta_{13}$ by looking for $\nu_e$ appearance in the $\nu_\mu$ beam. It does so by using the intense, well-understood NuMI neutrino beam created at Fermilab and observing it 735 km away at the Soudan Mine in Northeast Minnesota. High-statistics studies of the neutrino interactions themselves and the cosmic rays seen by the MINOS detectors have also been made. Results from MINOS’ first three years of operations will be presented.

1. Introduction
The MINOS experiment uses two magnetized steel/scintillator calorimeters [1] to investigate the neutrino oscillations previously observed using atmospheric neutrinos [2, 3]. This long-baseline experiment observes the intense and well-understood NuMI beam both near its source at Fermilab with a 0.98 kton “near detector”, and again 735 km to the northwest in the Soudan Mine Underground Lab with the 5.4 kton “far detector”. This before and after comparison of the neutrinos as seen in the similar detectors greatly reduces the systematic errors associated with comparing the differences in the observed neutrino spectra to various neutrino oscillation scenarios, allowing for a more accurate probe of the physics of neutrino propagation. The NuMI beam is composed of 92.9% $\nu_\mu$, 5.8% $\bar{\nu}_\mu$, 1.2% $\nu_e$ and 0.1% $\bar{\nu}_e$. The bulk of the data come from the “low energy” beam configuration, peaked at several GeV (see the red line in Fig. 1). This paper summarizes the status of several analyses of the neutrino data acquired over the two year time period starting with the beginning of NuMI operations in May of 2005 and ending during the summer shutdown in June 2007, an integrated exposure of over $3 \times 10^{20}$ protons on target (“pot”) with a neutrino yield on order of one neutrino per proton. The intrinsic divergence of the beam results in a neutrino flux at the far detector which is a factor of $10^6$ lower than that at the near detector.

2. Oscillation Analyses
2.1. $\nu_\mu$ Disappearance Oscillations
The design goal of the MINOS experiment is to use quasi-elastic $\nu_\mu$ interactions to make a precision measurement of mixing. A $\nu_\mu$ of energy $E_\nu [GeV]$ observed after traveling some distance $L [km]$ has a probability of being detected as a $\nu_\mu$ given by $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L / E)$, where $\Delta m^2 [eV^2]$ is the mass difference between $\nu_2$ and $\nu_3$ and $\sin^2(2\theta)$ is the mixing amplitude. The oscillation minima at the 735 km baseline is less than the $\tau$ production threshold, so the oscillatory signature is that of $\nu_\mu$ disappearance.

An exposure of $3.36 \times 10^{20}$ pot has been analyzed [4], selecting 848 events as $\nu_\mu$ with good purity. The observed, unoscillated near detector signal is used to calculate an expectation of $1065 \pm 60$ far detector...
events, including a small background of 2.3 external $\mu$, 5.9 neutral current ("NC") induced showers, and 1.5 $\tau$ decays, and are shown with the observed data in Fig. 1. Systematic errors (dominated by relative normalization, NC background, and overall hadronic energy scale) are still smaller than statistical errors, so the measurement will improve as data from the current run is added.

![Reconstructed neutrino energy (GeV)](image1)

**Figure 1.** The MINOS far detector $\nu_{\mu}$ spectrum [4]. The data (points with statistical errors) show a significant deficit from the null hypothesis (red line), but well-match a $\nu_\mu \leftrightarrow \nu_\tau$ oscillation scenario (black line), with best fit mass splitting $|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2$ (68% cl) and mixing angle $\sin^2(2\theta) > 0.90$ (90% cl).

![Allowed region in oscillation parameter space](image2)

**Figure 2.** The allowed region in oscillation parameter space for the data in Fig. 1, at 90% (solid black) and 68% (dashed black) confidence levels. Two Super-K atmospheric analyses are shown in red [3] and blue [2], and the K2K long baseline experiment results produce the grey contour [5].

2.2. Anti-neutrinos
The magnetized nature of the MINOS detectors allows the event-by-event determination of the charge sign of muons, and thus the identification of the parent neutrino or anti-neutrino. Selection of wrong-sign muons in the $\nu_\mu$ beam tests if $\bar{\nu}_\mu$ oscillate in the same fashion as $\nu_\mu$ in Sec. 2.1, and if some fraction $\alpha$ of disappearing $\nu_\mu$ reappear as $\bar{\nu}_\mu$ – both tests of CPT conservation. Given that only 6.4% of the neutrino events in a $3.2 \times 10^{20}$ pot far detector exposure are due to anti-neutrinos, the relative backgrounds are higher and statistics lower. 42 $\bar{\nu}_\mu$ events are seen while $64.6 \pm 8.0_{\text{stat}} \pm 3.9_{\text{syst}}$ are expected in the no-oscillation case, and $58.3 \pm 7.6_{\text{stat}} \pm 3.6_{\text{syst}}$ if CPT is conserved given the observed $\nu_\mu$ oscillation parameters. This places a 90%cl upper limit on $\alpha < 0.026$, and the anti-neutrino oscillation parameters are consistent with the neutrino parameters given these low statistics. The next year of NuMI beam running will be optimized to produce anti-neutrinos to better understand anti-neutrinos.

2.3. Sterile Neutrinos
Another possible explanation of the $\nu_\mu$ disappearance is oscillation into sterile neutrinos which experience no interactions. This would suppress the rate of NC events in the far detector compared to the traditional explanation of sub-threshold $\nu_\tau$, since $\nu_\tau$ still undergo NC interactions. Thus, NC showers have been selected from an exposure of $3.18 \times 10^{20}$ pot, following the analysis outlined in [6].
The ratio of observed to expected NC events in the far detector is $R = 1.04 \pm 0.08_{\text{stat}} \pm 0.07_{\text{syst}} - 0.10_{\nu_e}$, resulting in a limit on the fraction of $\nu_s$ participation of $f_s < 0.51$ at 90%cl.

2.4. The Search for $\nu_e$ Appearance

MINOS was designed to be a good muon calorimeter for $\nu_\mu$ disappearance, but is coarse for resolution of $\sim$GeV electromagnetic showers. It retains sensitivity to the $\sim$2% $\nu_e$ appearance signal which a $\theta_{13}$ near the CHOOZ limit [7] would create, and the first $3.14 \times 10^{20}$ pot of MINOS data have been examined [8] by a neural network to select electromagnetic shower candidates. When applied to Monte Carlo data this is 41% efficient while rejecting $>92\%$ of NC showers (the dominant background) and $>99\%$ of $\nu_\mu$ charged current (“CC”) interactions (high-y hadronic showers). Given the small expected signal and large uncertainties in hadronic shower modeling, data-driven methods are used to better estimate the background. At the near detector no oscillation has yet occurred, so with the exception of the well-modeled inherent beam $\nu_e$, all events selected must be examples of such background events. This yields an expected background of 26.6 (18.2 NC, 5.1 CC, and 2.2 beam $\nu_e$) at the far detector, while 35 $\nu_e$ like events are seen, a 1.5 $\sigma$ excess (including 7.3% statistical and 19% systematic errors) (Fig. 3). If fit for oscillations, this is just below the CHOOZ limit and consistent within errors with no $\nu_e$ appearance.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{The spectrum of potential $\nu_e$ interactions in the MINOS far detector, with statistical plus systematic error bars [8]. The 1.5$\sigma$ excess is consistent with both the expected large background (red) and a $\sin^2(2\theta_{13})$ comparable to the CHOOZ limit [7] (purple).}
\end{figure}

3. Conclusions

MINOS has measured neutrino oscillation parameters in the “atmospheric” $\nu_2 \leftrightarrow \nu_3$ sector with high precision, favoring standard $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. Further statistics will be of great interest to investigate the possibility of $\nu_e$ appearance just under the CHOOZ limit.

Acknowledgments

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