A Brief Review of MINOS neutrino oscillation results

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The MINOS long-baseline experiment is using the NuMI neutrino beam to make precise measurements of neutrino flavor oscillations in the “atmospheric” neutrino sector. MINOS observes the $\nu_\mu$ disappearance oscillations seen in atmospheric neutrinos, tests possible disappearance to sterile $\nu$ by measuring the neutral current flux, and extends our reach towards the so far unseen $\theta_{13}$ by looking for $\nu_e$ appearance in this $\nu_\mu$ beam. The magnetized MINOS detectors also allow tests of CPT conservation by discriminating between neutrinos and anti-neutrinos on an event-by-event basis. The intense, well-understood NuMI neutrino beam created at Fermilab is observed 735km 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. MINOS started taking beam data in May of 2005 and is now nearing the end of its five-year run. This paper reviews results published based on the first several years of data.

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1. Introduction

One possible implication of non-zero neutrino mass is that as neutrinos propagate, mixing occurs between mass eigenstates ($\nu_1, \nu_2, \nu_3$) and the flavor eigenstates ($\nu_e, \nu_\mu, \nu_\tau$) involved in the weak interactions governing neutrino production and detection. The mass and flavor eigenstates are related by a unitary matrix $U_{PMNS}$ expressed in terms of three mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$) and a CP-violating phase $\delta$ [1,2]. Experimental evidence points towards this occurring via disappearance of $\nu_e$ in solar neutrinos [3,4] and $\bar{\nu}_e$ in reactor neutrinos [5], as well as $\nu_\mu$ disappearance in atmospheric neutrinos produced by cosmic rays [6,8] and accelerators [9].

The goal of the Main Injector Neutrino Oscillation Search (“MINOS”) long-baseline experiment is to precisely measure the oscillation parameters involved in the atmospheric-sector oscillations. It does this by observing the intense and well-understood NuMI beam over a known baseline using with two similar magnetized...
steel/scintillator calorimeters: 1 km from its source at Fermilab with a 0.98 kton “near detector”, then again 735 km to the northwest in the Soudan Mine Underground Lab using the 5.4 kton “far detector”. Such a before-and-after comparison of the neutrinos greatly reduces systematic errors associated with comparing differences in the observed neutrino spectra to various neutrino oscillation scenarios, allowing for a more accurate probe of the physics of neutrino propagation. Details of the detector designs, calibrations, and performance can be found in [10].

The NuMI beam [11] is generated by 120 GeV protons hitting a carbon target. The resulting charged pions are focused by two electromagnetic horns and sent down a 675 m decay pipe, producing a beam of 92.9% $\nu_\mu$, 5.8% $\bar{\nu}_\mu$, 1.2% $\nu_e$ and 0.1% $\bar{\nu}_e$. Changing the pion-focusing horn positions and currents creates very different neutrino spectra. The bulk of the data come from the “low energy” beam configuration, peaked at several GeV (see the dashed line in Fig. 1). Short exposures in other beam configurations observed by the high-statistics near detector provide good crosschecks to the beam modeling process and also help to reduce systematic errors.

This paper summarizes the results 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. An additional $4 \times 10^{20}$ pot is on tape, representing beam from October 2007 through June 2009. The beam focusing was reversed to favor anti-neutrino production upon resumption of data taking in September of 2009, and was switched back to normal neutrino mode in March 2010 after collecting $1.8 \times 10^{20}$ pot.

MINOS analyses are done “blind”. That is, small subsets of the data are examined immediately to develop the algorithms and cuts which extract the physics results from the data, but the bulk of the dataset is left alone till the data analysis methods have been settled on. Detailed comparisons of variables used in cuts are made between simulated Monte Carlo data and real data, to be sure that detector quirks and parameter distributions are well modeled and understood. Once the simulations and analysis techniques are close to final and uncertainties, systematic errors and expected sensitivities calculated, “sidebands” (parameters similar to but not actually the ones used to produce the final answer) are revealed and compared to expectations. Only once everything is as well understood as possible is the “box opened” and the mature analysis unleashed on the full dataset to produce the final physics results. This process helps to ensure that the development of the analysis doesn’t inadvertently (consciously or otherwise) converge on a fluctuation in the data, skewing the final results or their significances. Extensions to the analyses presented below to the newer, as yet unanalyzed data are in progress, and as new improvements are being made to the methods, the new analyses are also using this
blinding procedure.

2. Oscillation Analyses

MINOS was intended to observe Charged Current (“CC”) quasi-elastic $\nu_\mu$ interactions to make a precision measurement of $\Delta m_{32}^2$. Its calorimeters are designed to measure the $\mu$ produced in $\nu_\mu$ CC interactions, and are magnetized to provide momentum and charge discrimination on an event by event basis, as well as the standard calorimetric method of establishing particle energies via $dE/dx$. By using far and near detectors which are as similar as possible, uncertainties in the energy scale between measurements of the neutrino spectrum before and after traveling the 735 km baseline are minimized. Small differences between detectors in light collection and electronics were cross-calibrated in a beam test at CERN using the “calibration detector” [12] which observed the same particles with both sets of electronics [13].

Since the oscillation minima at this baseline is less than the $\tau$ production threshold energy, the oscillatory signature is that of $\nu_\mu$ disappearance rather than $\nu_\tau$ appearance, an analysis described in Sec. 2.1. MINOS’ magnetic fields allow discrimination between $\nu_\mu$ and $\bar{\nu}_\mu$ and provide a chance to test CPT conservation by seeing if neutrinos and anti-neutrinos have the same oscillation parameters (Sec. 2.2). Although the calorimetry is coarser than one might like for such a measurement, electromagnetic showers can still be resolved. This allows further study of possible $\nu_\mu$ disappearance to sterile $\nu$ states by observation of Neutral Current (“NC”) interactions (Sec. 2.3), and sensitivity to sub-dominant $\nu_\mu \leftrightarrow \nu_e$ transitions by looking for $\nu_e$ appearance oscillations (Sec. 2.4).

2.1. $\nu_\mu$ Disappearance Oscillations

Since $\theta_{23} \gg \theta_{13}$ and $\theta_{12}$, when considering the atmospheric neutrino sector the full neutrino mixing matrices reduce to a simpler two-flavor equation. A $\nu_\mu$ of energy $E_\nu[GeV]$ observed after traveling some distance $L[km]$ from its production point has a probability of being detected as a $\nu_\mu$ given by

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23}) \sin^2 \left( 1.27 \frac{\Delta m_{32}^2 L}{E} \right),$$

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.

An exposure of $3.36 \times 10^{20}$ pot in MINOS has been analyzed [14], selecting 848 far detector events as $\nu_\mu$ with good purity. The observed (unoscillated) near detector signal is used to calculate a null hypothesis expectation of $1065 \pm 60$ far detector events, including a small background estimated to be composed of 2.3 external $\mu$, 5.9 NC induced showers, and 1.5 $\tau$ decays. The resulting spectra is shown with the observed data in Fig. 1. Comparing the observed data to expectations modified by Eq. 1 result in best fit oscillation parameters of $|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2$. 


Fig. 1. The MINOS far detector $\bar{\nu}_\mu$ spectrum \[14\]. The data (points with statistical errors) show a significant deficit from the null hypothesis (dashed line), but well-match a $\nu_\mu \leftrightarrow \nu_\tau$ oscillation scenario (solid 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).

(68% cl) and $\sin^2(2\theta) > 0.90$ (90% cl). Systematic errors in $\Delta m^2$ are dominated by uncertainties in the hadronic energy scale ($\pm 10.3\%$ absolute and $\pm 3.3\%$ relative between near and far detectors) and the relative normalization between detectors ($\pm 4\%$). The background of NC showers mis-reconstructed as $\nu_\mu$ quasi-elastic interactions ($\pm 50\%$) dominates in $\sin^2 2\theta_{23}$. These systematics ($\pm 0.108 \times 10^{-3} \text{eV}^2$ in $\Delta m^2$ and $\pm 0.018$ in $\sin^2 2\theta_{23}$) are still smaller than the statistical ($\pm 0.19 \times 10^{-3} \text{eV}^2$ in $\Delta m^2$ and $\pm 0.09$ in $\sin^2 2\theta_{23}$) errors, so the measurement will improve as data from the remaining $\sim \frac{3}{4}$ of the MINOS exposure are added.

### 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 undergoing the quasi-elastic interaction that produced them. Selection of wrong-sign muons in the $\nu_\mu$ beam tests if $\bar{\nu}_\mu$ oscillate in the same fashion as $\nu_\mu$ in Eq. \[1\] is $\theta_{23} = \theta_{23}$ and $\Delta \tilde{m}_{23}^2 = \Delta m_{23}^2$? Furthermore, could some fraction $\alpha$ of disappearing $\nu_\mu$ reappear as $\bar{\nu}_\mu$? These are both tests of CPT conservation,
Fig. 2. The resulting 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 [7] and blue [6], and the K2K long baseline experiment results produce the gray contour [9].

and with its magnetic field MINOS is the only experiment capable of testing this.

Anti-neutrinos in the NuMI beam come primarily from $\pi^+$ which travel directly down the center of the focusing horns and thus avoid being de-focused, leaving little kinematic phase space for these pions. Combined with the lower cross-sections for anti-neutrinos compared to neutrinos, only 6.4% of the neutrino interactions in a $3.2 \times 10^{20}$ pot far detector exposure are due to anti-neutrinos, making the relative backgrounds are higher, the statistics lower, and the spectrum harder (Fig. 3).

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, or $58.3 \pm 7.6_{\text{stat}} \pm 3.6_{\text{syst}}$ if CPT is conserved given the observed $\nu_\mu$ oscillation parameters [15]. This places a 90%cl upper limit of $\alpha < 0.026$, and the anti-neutrino oscillation parameters are consistent with the neutrino parameters given these low statistics, excluding $5.0 < \Delta m^2_{32} < 81 \text{eV}^2$ at 90%cl for maximal mixing.
To increase the anti-neutrino dataset by an order of magnitude, the polarity of the focusing horns in the NuMI beam was reversed to focus $\pi^+$ rather than the usual $\pi^-$ for an exposure of $1.8 \times 10^{20}$ pot of anti-neutrino production. The statistics available in this set of data would make a reasonable measurement of $\bar{\theta}_{23}$ and $\Delta \bar{m}^2_{32}$ (Fig.4).

2.3. Sterile Neutrinos

Another possible explanation of $\nu_\mu$ disappearance is oscillation into sterile neutrinos ("$\nu_s$") which experience no interactions and thus would disappear. This would also suppress the rate of NC events in the far detector compared to the traditional explanation of oscillation to sub-threshold $\nu_\tau$, since those $\nu_\tau$ still undergo NC interactions but $\nu_s$ would not.

To test this hypothesis, NC showers have been selected from an exposure of $3.18 \times 10^{20}$ pot [16]. A NC interaction produces no outgoing leptons, but simply a hadronic shower. Any $\pi^0$ produced in that shower decays rapidly to a pair of gamma
Fig. 4. Sensitivity contours comparing the oscillation parameters available using just the anti-neutrinos from the neutrino beam, as described in the text but including all available data ($7.2 \times 10^{20}$ pot, the black line) to that obtainable using a $7.2 \times 10^{20}$ pot exposure of dedicated anti-neutrino beam (red contour). This red contour is comparable in scope to that of the K2K experiment’s neutrino results (the gray line in Fig. 2).

rays, which produce diffuse electromagnetic showers that can be reliably separated from the long $\mu$ tracks used in Sec. 2.1. 388 events are selected, 141 of them of less than 3 GeV, with an estimated 17 non-NC interactions (primarily very short track $\nu_\mu$ CC interactions) creeping in as background in this low energy region of interest for oscillation physics. The resulting spectrum of these NC events (Fig. 5) is not depressed compared with the expectations of NC interactions from standard $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. The ratio of observed to expected NC events in the far detector is $R = 0.99 \pm 0.09_{\text{stat}} \pm 0.07_{\text{syst}} - 0.08_{\nu_\mu}$ in the energy region of 0-3 GeV where $\nu_\mu$ are disappearing. While the addition of a fourth neutrino eigenstate results in several new ways things could oscillate, fits to all those models place limits on $\theta_{24}$ and $\theta_{34}$ on being half (or less) than $\theta_{23}$, showing that sterile neutrinos are not a dominant player in $\nu_\mu$ disappearance. Another way to state this is as a limit on the fraction...
of $\nu_s$ participation of $f_s < 0.51$ at 90%cl.

![Figure 5](image)

Fig. 5. The MINOS far detector neutral current spectrum [16]. The data (points with statistical errors) track the predicted spectrum (red hashed boxes) and do not show the deficit at lower energies expected from an scenario which involves the NuMI $\nu_\mu$ changing to something which does not undergo such interactions, either a sterile neutrino or by decaying away entirely. The dashed line is the prediction for showers should there be $\nu_e$ appearance at the CHOOZ limit, as they would be included in this data selection. The gray shaded region is the expected background, primarily composed of mis-reconstructed charged current events.

2.4. The Search for $\nu_e$ Appearance

The CHOOZ experiment [17] sets an upper limit of $\sin^2(2\theta_{13}) < 0.15$ on the mixing amplitude governing the transmutation of NuMI $\nu_\mu$ into $\nu_e$. MINOS was designed to be a good muon calorimeter for $\nu_\mu$ disappearance, but is coarse for resolution of $\sim$GeV electromagnetic showers, each 2.54 cm steel+1.0 cm plastic thick plane being 1.4 radiation lengths thick, and each 4.1 cm wide scintillator strip being 1.1 Molière radii. However, the experiment retains sensitivity to the $\sim 2\%$ $\nu_e$ appearance signal which a $\theta_{13}$ near the CHOOZ limit [17] would create, and the first $3.14 \times 10^{20}$ pot of MINOS data have been examined [18] by a neural network to select electromagnetic shower candidates, which are more compact when produced by an electron from a CC $\nu_e$ interaction than from a NC-induced $\pi^0$. When applied to Monte Carlo data this is 41% efficient at keeping $\nu_e$ events while rejecting $>92\%$ of NC showers (the dominant background) and $>99\%$ of $\nu_\mu$ charged current (“CC”) interactions (high-y collisions which put much more energy into the hadronic debris than the outgoing $\mu$ lepton).
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. The two classes of backgrounds have different production kinematics so extrapolate to the Far Detector slightly differently, thus two techniques are used to deconvolve the background. The first takes obvious $\nu_\mu$ interactions and subtracts the hits from the muon track, resulting in a sample of CC-induced showering events to study. The second compares data from beam running with the focusing horn on or off. The very different neutrino spectra which result allow fitting for the two background components. Both methods give comparable results and produce the background at the far detector shown as the red line in Fig. 6. 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. 6). If fit for oscillations, this is just below the CHOOZ limit and consistent within errors with no $\nu_e$ appearance.

![Fig. 6. The spectrum of potential $\nu_e$ interactions in the MINOS far detector, with statistical plus systematic error bars. 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 (purple).](image)

There is somewhat more than twice the exposure used for this analysis already
on tape. In addition to decreasing the statistical error on the data points, the systematic error bars include a large statistical component due to the small data subsets used in the data-driven background estimation. Thus, an analysis of the additional data available is expected to substantially reduce the systematic error bars as well. Projections of the sensitivity of this new dataset suggest that the slight excess observed in this current analysis will either be shown to be more significant (if it is really $\nu_e$ appearance) or to be revealed as merely a background fluctuation.

2.5. Alternate Hypotheses

Two other hypotheses have been presented (and not thoroughly ruled out by previous observations) to explain the $\nu_\mu$ disappearance outside the standard oscillations model. The first is quantum decoherence of the neutrino’s wave packet [20], in which the survival probability equivalent to Eq. 1 varies as $[1 - \exp(-m^2L^2/E)]$ (Eq. 5 of [20]) rather than $\sin^2(1.27L/E)$. The best fit to this function is shown in Fig. 7 as the dashed line, and a comparison of $\chi^2$ to the data and the standard $\nu_\mu \leftrightarrow \nu_\tau$ disfavors the decoherence hypothesis at the $5.7\sigma$ level.

The second alternate hypothesis is that neutrinos decay [19], producing a survival probability which varies as $[\sin^2 \theta + \cos^2 \theta \exp(-\alpha L^2/E)]^2$ (Eq. 13 of [19]). Again, this shape does not match the data in Fig. 7 as well as standard oscillations, and is disfavored at $3.7\sigma$. However, this result is for pure neutrino decay, which is also disfavored by Super-K [6]. If there were oscillations and neutrino decay happening at the same time [21], the waters are muddier, see Eq. 17 of [16]. In order to get a better handle on this problem, MINOS makes use of NC events as well as the CC spectral shape [16], since a decayed neutrino will not produce a NC event while a $\nu_\tau$ will. Doing this improves the rejection of the pure decay hypothesis to 5.4 $\sigma$, and places a limit on the ratio of neutrino mass eigenstate $m_3$’s lifetime to mass of $\tau_3/m_3 > 2.1 \times 10^{-12}$ s/eV (Fig. 8).

2.6. Atmospheric Neutrinos

In addition to the NuMI beam, the MINOS far detector is bathed in the same flux of cosmic-ray induced atmospheric neutrinos which provided the first measurements of neutrino oscillations [22]. However, MINOS being an order of magnitude smaller than Super-Kamiokande, the atmospheric neutrino interaction rate is several per week rather than dozens per day, limiting the statistical significance of such measurements. Nevertheless, analyses of such neutrinos are consistent with the oscillation parameters established in the beam neutrinos [24] and provide the first direct observations of anti-neutrinos from cosmic rays [25].

3. Non-Oscillation analyses

This review is of MINOS’ neutrino oscillation results, so other work using these detectors will not be discussed in depth. However, studies using cosmic rays have
Fig. 7. The ratio of the MINOS far detector data from Fig. 1 to the no-oscillation null hypothesis, from [14]. Superimposed are the best fit expectations of three $\nu_\mu$ disappearance models: standard $\nu_\mu \leftrightarrow \nu_\tau$ (thick solid line), which fits the data the best; pure neutrino decay [19] (thin solid line), which is disfavored at the 3.7 $\sigma$ level; and quantum decoherence [20] (dashed line), which is disfavored by this data at 5.7 $\sigma$.

grown out of the need to calibrate the MINOS detectors, and speak to the depth of understanding of these detectors. Cosmic ray analyses include the first direct measurement of the charge ratio of cosmic ray muons at TeV energies [25] and probe the meson production in cosmic ray primary interactions by watching the variation in the underground muon rate vary with stratospheric conditions [26], a competition between secondary mesons decaying to produce the observed cosmic ray muon and re-interacting in the atmosphere. This effect is also of use to atmospheric physicists, who turn the problem around to use the cosmic rays to study unusual events in the stratosphere itself [27].

Studies of neutrino interactions themselves are also a large topic of work, as the near detector observes $O(10^4)$ neutrino interactions per day of operations, by far the largest statistics sample in the world. The resulting improved knowledge of neutrino interaction physics feeds directly back to reducing the systematic errors
Fig. 8. MINOS’ 90%cl allowed region for the neutrino mass/lifetime ration $\alpha$ compared to the oscillation mixing angle $\theta$ [10]. The best-fit is for no decay (infinite lifetime), with an upper limit of $\tau_3/m_3 > 2.1 \times 10^{-12} \text{s/eV}$.

in the oscillation analyses [28]. Looking at MiniBOONE neutrinos in MINOS and vice-versa helps to understand the off-axis components of neutrino beams [29]. Using beam neutrinos in different ways has also yielded interesting results on the velocity of neutrinos (comparing arrival times at near and far detectors) [30] and has been used to test for violation of Lorentz Invariance in the neutrino sector [31].

4. 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 with $|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2$ (68% cl) and $\sin^2(2\theta) > 0.90$ (90% cl). Quantum decoherence as an explanation for the $\nu_\mu$ disappearance is disfavored at the 5.7$\sigma$ level. Measurements of the total active neutrino flux using neutral current interactions help to disfavor pure $\nu_\mu \leftrightarrow \nu_\tau$ oscillations by 5.4$\sigma$, place a limit on the ratio of neutrino mass eigenstate $m_3$’s lifetime to mass of $\tau_3/m_3 > 2.1 \times 10^{-12} \text{s/eV}$, and limit the participation of sterile neutrinos in a sub-dominant mode to a fraction $f_s < 0.51$ at 90%cl. Examination of the limited set of anti-neutrino data have shown no evidence for different oscillation parameters for anti-neutrinos, and limit the fraction $\alpha$ of $\nu_\mu$ disappearing to $\bar{\nu}_\mu$ to $\alpha < 0.026$ at 90%cl.

These results come from an exposure of roughly 1/3 the eventual complete MINOS dataset, so the final precision of the measurements will be greater than those reviewed here. This is especially true in the cases of $\nu_e$ appearance, where the
data-driven background estimations methods will benefit greatly from additional statistics, and in the measurements of $\bar{\nu}_\mu$, which will take advantage of dedicated anti-neutrino beam running.

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