Oscillation results from MINOS

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Abstract. MINOS has previously presented antineutrino disappearance results based on its first exposure in dedicated antineutrino beam mode corresponding to 1.7×10^{20} PoT of accumulated data. Here we present an updated antineutrino disappearance result obtained using 70% more antineutrino data. The best fit antineutrino oscillation parameters, \( \Delta m^2_{23} = 2.62^{+0.31}_{-0.28} \times 10^{-3} \text{eV}^2 \) and \( \sin^2(2\theta_{23}) = 0.95^{+0.10}_{-0.11} \text{(stat)} + 0.01 \text{(syst)} \) are now in good agreement with those obtained for neutrinos. New results on electron neutrino disappearance extracted using an improved analysis technique and 15% more data are also presented. We obtain 90% confidence limits for normal (inverted) mass hierarchy of \( \sin^2(2\theta_{13}) < 0.12 \) (\( \sin^2(2\theta_{13}) < 0.20 \)).

1. Introduction
The MINOS experiment at Fermilab combines the high-intensity NuMI beam at Fermilab with two neutrino detectors, one at Fermilab (Near Detector), and one 735 km away in Soudan Minnesota (Far Detector), to explore neutrino oscillation phenomena. Both MINOS detectors are magnetized tracking calorimeters composed of 2.54 cm thick planes of iron and 1 cm thick planes of scintillator.

MINOS has made the most precise determination to date of the neutrino squared mass difference, \( \Delta m^2_{23} = (2.32^{+0.12}_{-0.08}) \times 10^{-3} \text{eV}^2 \) and constrains the mixing, \( \sin^2(2\theta_{23}) > 0.90 \) (90% C.L.) [1]. The magnetized MINOS detectors can distinguish event-by-event muon neutrino charged-current (\( \nu_\mu \text{CC} \)) from muon antineutrino charged-current (\( \bar{\nu}_\mu \text{CC} \)) interactions by measuring the sign of the charged-muon track. This MINOS feature, which is unique among accelerator long-baseline experiments, allows MINOS to obtain a tagged sample of antineutrinos and to directly constrain antineutrino oscillation parameters.

This paper presents MINOS’ new constraints on antineutrino mass and mixing parameters based on a larger antineutrino data sample. Also, as presented below, MINOS now has the tightest constraint on the unknown mixing angle, \( \theta_{13} \), obtained by searching for \( \nu_e \) appearance at the Far Detector.

2. Antineutrino disappearance
To obtain a large sample of antineutrino interactions, the NuMI beamline is reconfigured by reversing current in both focusing horns (RHC mode). Analysis of the first MINOS RHC beam mode exposure (Run IV, corresponding to 1.7×10^{20} PoT of accumulated data) found a surprising difference in best fit \( \Delta m^2_{23} = (3.36^{+0.46}_{-0.40}) \times 10^{-3} \text{eV}^2 \) [2] from the neutrino counterpart, which was \( \Delta m^2_{23} = 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{eV}^2 \) [1]. Figure 1 shows the allowed antineutrino oscillation parameter space from this measurement (red curve) compared with the MINOS measured neutrino parameter space (grey shaded region). The result presented below uses the Run IV
data sample combined with 70% more accumulated data in RHC obtained this past year (Run VII). The combined total exposure in dedicated antineutrino running mode is $2.95 \times 10^{20}$ PoT.

Muon neutrino (antineutrino) charged-current events, $\nu_\mu (\bar{\nu}_\mu) N \rightarrow \mu^- (\mu^+) + X$, are identified in the MINOS detectors by the presence of an isolated $\mu^- (\mu^+)$ track. The incident $\nu_\mu (\bar{\nu}_\mu)$ energy is reconstructed from the muon track energy combined with the energy detected at the hadronic vertex which is typically a shower of hadronic particles whose energy is measured through calorimetry. Muon energy is measured by range for contained tracks or from curvature in the toroidal magnetic field for exiting tracks. Muon charge is measured for each event from the bend direction in the magnetic field, (focusing for positive tracks, defocusing for negative tracks in RHC beam mode). As in previous MINOS oscillation analyses [1, 2] the measured Near Detector energy spectrum is used to predict the Far Detector spectrum by applying a beam transfer matrix which incorporates beamline geometry and particle production and decay kinematics.

For the combined result, several improvements were made to the analysis. In particular, an alternative method for measuring shower energy is employed that uses a KNN multivariant discriminator obtained by comparing detailed shower topological parameters to Monte Carlo samples [3]. This method is identical to that used in the neutrino disappearance analysis [1]. Adapting the same technique to the antineutrino sample reduces the possibility that a different analysis method introduces a difference in the extracted oscillation parameters. The use of this new technique, which has better resolution at low energy, gives a 10% improvement in oscillation parameter sensitivity. The effect of this change on the measured oscillation parameters was studied using the Run IV sample and found to be small (less than 1σ shift of the parameters).

The second change is in the selected Near Detector data sample. We remove events which pass near to or through the difficult to model coil hole region. This remedies a long-standing problem with modeling events which fail the track fitting. The result is a significant improvement in Monte Carlo modeling of the Near Detector sample. The effect of this change on extracted oscillation parameters is also small.

For the full combined data samples (Run IV + Run VII) we expect 273 events at the Far Detector for the null oscillation hypothesis. We observed 193 events and exclude the null hypothesis at 7.3σ. The measured Far Detector spectrum is shown in Fig. 1 (left) along with the ratio to the no oscillation predicted spectrum (middle plot). We find best fit oscillations parameters of $\Delta m^2_{32} = 2.62^{+0.31}_{-0.28} \times 10^{-3}$ eV$^2$ and $\sin^2(2\theta_{23}) > 0.75$ at 90% confidence level, which are in good agreement with the measured neutrino parameters. Assuming identical underlying oscillation parameters, antineutrino and neutrino measurements are consistent at the 42% confidence level, while this was only 2% for the Run IV data set alone.

Figure 1 shows a comparison of contours for antineutrino oscillation parameter measurements. The new combined Run IV+VII result from MINOS (blue curve) can be compared with Run IV alone (red curve) and Run VII alone (grey curve) contours. Both individual antineutrino samples are likely experimental outcomes assuming the underlying parameters are those of the combined best fit, and given the statistical uncertainties which dominate the measurements. The MINOS neutrino result is also shown (shaded region) for comparison along with the recent antineutrino constraint from Super-K [4]. The MINOS result uniquely uses tagged antineutrinos and provides the tightest constraints on the atmospheric mass splittings for both neutrinos and antineutrinos.

### 3. Electron neutrino appearance

MINOS has previously searched for appearance of electron neutrinos at the Far Detector using a sample of $7.4 \times 10^{20}$ PoT of accumulated neutrino mode data, and obtained tight constraints [5] on the unknown mixing angle $\theta_{13}$. Recently, as discussed below, a more sensitive analysis technique has been applied to a larger data sample of $8.2 \times 10^{20}$ PoT and new constraints have
Figure 1. (left) Observed Far Detector energy spectrum for the combined RHC data sample. Curves show the best fit prediction (blue) and the null oscillation hypothesis (red). The shaded band shows the size of the systematic uncertainty in each energy bin. (middle) Ratio of observed spectrum to null oscillations expectation. The curve shows the best fit oscillation hypothesis. (right) Comparison of 90% confidence allowed regions for neutrino and antineutrino oscillation parameters. The shaded contour shows the MINOS allowed neutrino region [1]. The dashed curve shows the MINOS antineutrino contour from the first RHC beam exposure (Run IV) and the solid curve shows the updated result from the full RHC beam sample.

been obtained. More details can be found in Ref [6].

A key component in MINOS’ electron neutrino appearance analysis is separation of signal from the main backgrounds which arise from neutral-current interactions, muon neutrino induced charged-current interactions at high inelasticity, and beam $\nu_e$ sources. A new technique, LEM (Library Event Matching), has been employed here which compares each event against a library of 20 million signal and 30 million background events and classifies it based on information from the 50 best matches. The estimated 15% improved sensitivity of the LEM technique [6] over the previous ANN discriminator [5] arises from use of strip-level pattern and pulse height information for event discrimination.

The background composition is measured at the Near Detector by fitting the charged-current $\nu_e$-like event sample to each component in three beam configurations (nominal, horn-off, and high energy mode). Each of these configurations has different background compositions. The components are separately extrapolated to the Far Detector to obtain the $\nu_e$ oscillation appearance background. The measured visible energy for the charged-current $\nu_e$-like sample at the Far Detector along with the background prediction are shown in Fig. 2. The best fit signal is shown as the hatched region.

We observe 62 candidate events at the Far Detector with expected background contributions of 34.1 neutral-current, 6.7 muon neutrino induced charged-current, 6.4 beam $\nu_e$, and 2.2 tau neutrino induced charged-current interactions. The expected signal at the Far Detector for $\theta_{13} = 0$ is 49.6±7.0 (stat)±2.7 (syst). We obtain best fit parameters of $\sin^2(2\theta_{13}) = 0.041\pm0.047$ for $\delta=0$, $\theta_{23} = \pi/4$, and normal hierarchy. Figure 2 shows the best fit and allowed region contours for normal (inverted) mass hierarchy. We exclude $\sin^2(2\theta_{13}) > 0.12$ ($\sin^2(2\theta_{13}) > 0.20$) at 90% confidence (for $2\sin^2(\theta_{23})=1$, $\delta=0$, and $|\Delta m^2_{32}| = 2.32\times10^{-3}\text{eV}^2$) and $\sin^2(2\theta_{13}) = 0$ at 89% CL.
Figure 2. (left) Measured visible energy for the charged-current $\nu_e$-like sample at the Far Detector. The red curve shows the predicted background as described in the text. The shaded region shows the signal at the best fit value of $\sin^2(2\theta_{13}) = 0.041$ for $\delta = 0$ and normal hierarchy. (right) Best fit curve along with 68% and 90% contour allowed regions for normal (top right) and inverted (bottom right) mass hierarchy. The dashed line is the CHOOZ 90% C.L. upper limit [7].

4. Conclusion
MINOS has obtained direct constraints on antineutrino oscillation parameters using the NuMI antineutrino-enhanced beam and a charged-sign tagged event sample. The oscillation parameters obtained are in good agreement with the corresponding parameters for neutrinos, also measured precisely in MINOS. MINOS also performed a sensitive search for $\nu_e$ appearance which provides important constraints on the unknown mixing angle $\theta_{13}$.

Acknowledgments
This work was supported by the US DOE; the UK STFC; the US NSF; the State and University of Minnesota; the University of Athens, Greece; and Brazil’s FAPESP and CNPq. We are grateful to the Minnesota Department of Natural Resources, the crew of the Soudan Underground Laboratory, and the personnel of Fermilab for their contributions to this effort.

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