Neutrino and Antineutrino Oscillation Parameters Measured by the MINOS Atmospheric and Beam Data

M. M. MEDEIROS[1], C. F. CASTROMONTE[1], R. A. GOMES[1], J. DEJONG[2] A. HABIG[3] S. WOJCICKI[4] FOR THE MINOS COLLABORATION.

[1] *Federal University of Goias*
[2] *University of Oxford*
[3] *University of Minnesota*
[4] *Stanford University*

medeiros@fnal.gov

Abstract: The functionally identical and magnetized MINOS detectors are used to collect atmospheric neutrino data as well as data from the NuMI neutrino beam. The atmospheric data taken by the Far Detector, located underground at a depth of 2070 meters-water-equivalent and at 735 km from the neutrino production target, is combined with beam data from both Near and Far Detectors to measure the neutrino and antineutrino mixing parameters. The complete MINOS data set is analyzed under two possible scenarios: assuming neutrinos and antineutrinos have different oscillation parameters; and assuming these parameters are identical. We report the world-leading measurement of the neutrino and antineutrino mass splitting parameter along with the most precise comparison to date of neutrino and antineutrino oscillation parameters.

Keywords: neutrino, antineutrino, oscillation parameters

1 Introduction

The most successful hypothesis that explains neutrino disappearance is the mechanism of neutrino oscillations first suggested by Pontecorvo and Maki, Nakagawa and Sakata [1–3]. In this model, the neutrino is a wave packet that propagates in its mass eigenstate and interacts in its flavor eigenstate. The oscillations arise from the mixing of mass and flavor eigenstates, which are connected by a unitary rotation matrix, the so called PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix [4]:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle ,$$

where $|\nu_\alpha\rangle$ represents the flavor eigenstates, $|\nu_i\rangle$ represents the mass eigenstates and U is the PMNS matrix.

Evidence for oscillating neutrinos has been measured by many experiments and accounts for the only physics beyond the Standard Model yet observed. Among these experiments, MINOS has been playing an important role in measuring neutrino oscillations.

2 The MINOS Experiment

MINOS is a long-baseline experiment designed to study muon neutrino oscillations. A neutrino beam (NuMI beam) is produced at the Fermi National Accelerator Laboratory (Fermilab) by striking 120 GeV protons onto a graphite target. The resulting charged pions and kaons are focused by magnetic horns into a decay pipe, where they decay into muon neutrinos and other particles. The beam then passes through a hadron absorber and rock, so neutrinos remain while the other particles are blocked. We can either produce a ν_μ-dominated beam or a $\overline{\nu}_\mu$-enhanced beam by focusing positive or negative pions and kaons, respectively.

After the beam is produced, we measure its event and energy spectra in the Near Detector at Fermilab, one kilometer away from the target, and later in the Far Detector, which is 735 kilometers away from the beam production, located in the Soudan Mine, Minnesota. Both detectors are steel-scintillator tracking calorimeters consisting of steel planes with segmented plastic scintillator strips mounted on them. The planes are perpendicular to the beam direction and the scintillator strips are oriented at 45° from the vertical, but perpendicular to each other in consecutive planes for tri-dimensional event reconstruction.

The detectors are functionally identical, allowing detector related systematic uncertainties to be largely canceled. Furthermore, they are magnetized giving us the ability to separate the interactions from neutrinos and antineutrinos on an event-by-event basis.

The Far Detector is also used to study atmospheric neutrinos and antineutrinos, which are created by interactions of cosmic ray particles with the nuclei in the Earth's atmosphere. At the depth of the detector, 2070 m water-equivalent, the flux of cosmic ray muons is reduced by a factor of 10^6 relative to the surface [5]. Furthermore, a scintillator veto shield is placed above the Far Detector to enhance the rejection of cosmic ray muon background, yielding a clean sample of atmospheric neutrino signal events.

The MINOS experiment has been taking data since 2005[1] and has published several analyses of neutrinos from the NuMI beam and of atmospheric neutrinos, separately [5, 9–17]. For the first time, MINOS has carried out a combination of its beam and atmospheric neutrino and antineutrino data sets. We used the complete MINOS data set accumulated over nine years of operations: 10.71×10^{20} protons on target (POT) in the ν_μ-dominated beam, 3.36×10^{20} in

1. When the Near Detector started operations. However the Far Detector started in 2003.

the $\bar{\nu}_\mu$-enhanced beam and 37.88 kiloton-years of atmospheric data.

3 Data Analysis

The muon neutrinos and antineutrinos are recorded by the detectors through their charged current (CC) interactions:

$$\nu_\mu(\bar{\nu}_\mu) + N \rightarrow \mu^-(\mu^+) + X.$$

The events are characterized by a long track left by the muons and by a diffuse shower due to the hadronic activity (X). The main background is neutral current (NC) interactions that can exhibit a track-like topology, even though they generate only hadronic showers. These are a small percentage of the total number of NC events occurring in the detectors [6].

Events with vertex contained inside the fiducial volume of the detectors are the contained-vertex muon sample and those which vertex is outside the fiducial volume are neutrino-induced rock-muons. We use in this analysis both samples and obtain the muon momentum from the track range for muons that stop in the detector and from the track curvature for through-going muons. The hadronic shower energy is estimated by a k-Nearest-Neighbor classification algorithm (kNN) taking into account the calorimetric energy deposited and the topology of the shower [7], for the beam data. For the atmospheric data, the true shower energy is estimated by the addition of the calorimetric energy deposits in each scintillator strip [5]. The reconstructed neutrino energy is determined by the sum of the muon and shower energy measurements.

The muon neutrino oscillations that occur in the MINOS experiment are well described by an effective two-flavor model with a single mixing angle θ. The muon neutrino (and antineutrino) survival probability is given by [8]:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.267|\Delta m^2|(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})}\right),$$

where L is the distance travelled by the neutrino in kilometers, E is its energy in GeV and $\sin^2 2\theta$ and $|\Delta m^2|$ (in eV^2) are the oscillation parameters[2].

We perform a maximum likelihood fit to the data in order to obtain the oscillation parameters. In the fit we assume separate oscillation parameters for neutrinos ($|\Delta m^2|$, $\sin^2 2\theta$) and antineutrinos ($|\Delta\overline{m}^2|$, $\sin^2 2\overline{\theta}$) and include the major systematic uncertainties related to the beam data and to the atmospheric data as nuisance parameters. We minimize the likelihood with respect to all parameters and calculate the likelihood surface in the parameter space by using a grid search method. From the resulting four-dimensional likelihood surface we can calculate the two-dimensional profiles for neutrinos and antineutrinos.

Two different scenarios are considered: the case when neutrinos and antineutrinos having identical oscillation parameters ($|\Delta m^2| = |\Delta\overline{m}^2|$ and $\sin^2 2\theta = \sin^2 2\overline{\theta}$: a two-parameter fit)), and the case when their parameters are different ($|\Delta m^2| \neq |\Delta\overline{m}^2|$ and $\sin^2 2\theta \neq \sin^2 2\overline{\theta}$: a four-parameter fit). Therefore we are able to test CPT (charge-parity-time reversal) symmetry violation.

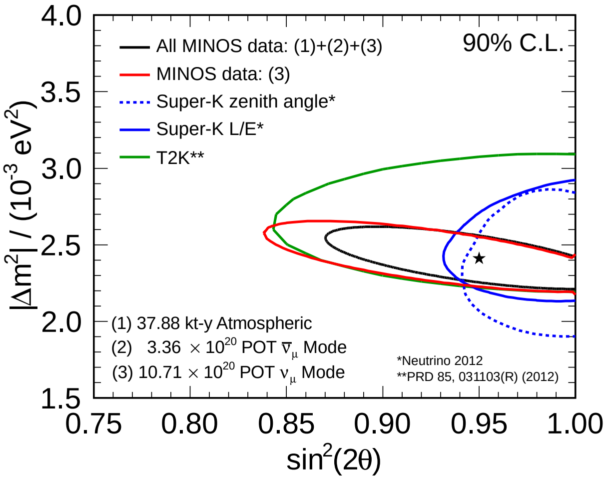

Figure 2: The 90% confidence level contours for the neutrino oscillation parameters from MINOS and other experiments are shown. We compare contours from a two parameter fit performed on MINOS beam data set only and MINOS combined beam and atmospheric data sets with the published Super-Kamiokande and T2K neutrino contours. The best fit point from the MINOS combined analysis is indicated by the star.

4 Results

The energy spectra for each data set of the beam and atmospheric samples used in the analysis is shown in Figure 1. The data are well described by the oscillation model, as expected.

The 90% confidence level (C.L.) contour obtained for the neutrino oscillation parameters using the two-parameter fit is shown in Figure 2. We compare this with the contour we would have obtained by using beam neutrinos only and with results from other experiments. The best fit to the data is $|\Delta m^2| = 2.41^{+0.09}_{-0.10} \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 0.950^{+0.035}_{-0.036}$ (>0.89 at 90% C.L.).

The best fit for antineutrino oscillation parameters is obtained by a 4-parameter fit: $|\Delta\overline{m}^2| = 2.50^{+0.23}_{-0.25} \times 10^{-3}$ eV^2 and $\sin^2 2\overline{\theta} = 0.97^{+0.03}_{-0.08}$ (>0.83 at 90% C.L.). In Figure 3 we compare the contour from our measurement of the antineutrino oscillation parameters using all antineutrino data with the contour from our measurement of the neutrino parameters in which the neutrino and antineutrino oscillation parameters are fitted separately, and the contour from our measurement of the neutrino parameters in which the neutrino and antineutrino oscillation parameters are fixed to the same value (the last one is the same contour -in black- shown in Figure 2).

The difference between the antineutrino and neutrino mass splittings is measured to be $|\Delta\overline{m}^2| - |\Delta m^2| = 0.12^{+0.24}_{-0.26} \times 10^{-3}$ eV^2, as can be seen in Figure 4. The good agreement between the oscillation parameters indicates that the MI-

2. We quote the neutrino parameters without bars and the antineutrino parameters with the bars.

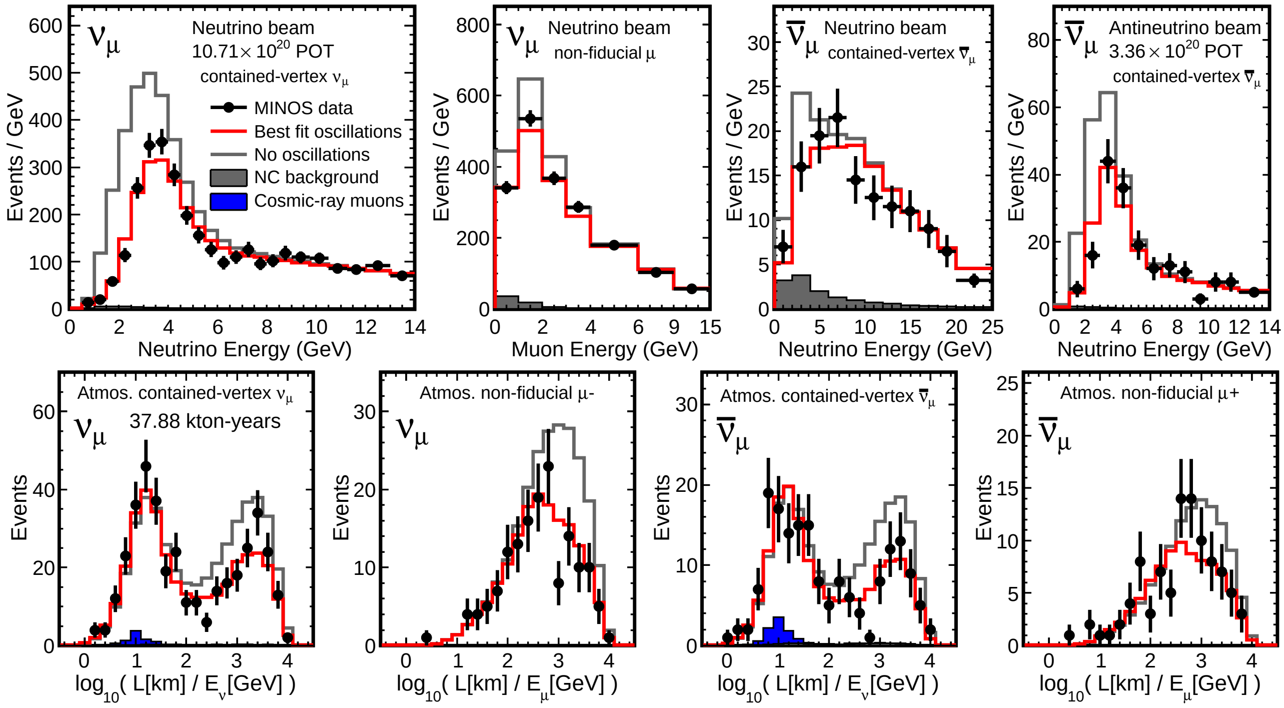

Figure 1: This multi-panel plot shows the event spectra for the primary beam and atmospheric event samples used in the analysis. The grey histograms show the predictions in the absence of oscillations; the red histograms show the best fit obtained from the two-parameter oscillation analysis; the blue and dark grey histograms show the main sources of background in the analysis; and the points with errors show the observed data.

NOS data is consistent with neutrinos and antineutrinos having the same oscillation parameters.

5 Conclusion

For the first time, MINOS has carried out a measurement by combining beam and atmospheric neutrinos and antineutrinos and using its complete data set accumulated over nine years of operation. The combined analysis has yielded the world's most precise measurement of the mass splitting parameter for both muon neutrinos and antineutrinos. Furthermore, no evidences was found for CPT violation, since the neutrino and antineutrino oscillation parameters have very good agreement. This is also the most precise comparison ever made between neutrino and antineutrino oscillation parameters.

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References

[1] B. Pontecorvo, J.Exptl. Theoret. Phys. 33, 549 (1957)., Sov. Phys. JETP 6, 429 (1958).
[2] B. Pontecorvo, J.Exptl. Theoret. Phys. 34, 247 (1958)., Sov. Phys. JETP 7, 172 (1958).
[3] Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. (1962), 28:870.
[4] B. Kaiser, Neutrino Oscillation Physics, 2012.
[5] P. Adamson et al. MINOS Collaboration , Phys. Rev. D 86, 052007 (2012).
[6] P. Adamson et al. MINOS Collaboration , Accepted in Phys. Rev. Lett., arXiv:hep-ex/1304.6335 (2013).
[7] C. Backhouse, Ph.D. Thesis,, University of Oxford (2011).
[8] J. Evans, Measuring Antineutrino Oscillations with the MINOS Experiment, Ph.D. Thesis, University of Oxford (2008).
[9] P. Adamson et al. MINOS Collaboration , Phys. Rev. D 73, 072002 (2006).
[10] D. G. Michael et al. MINOS Collaboration, Phys. Rev. Lett. 97, 191801 (2006).
[11] P. Adamson et al. MINOS Collaboration, Phys. Rev. D 75, 092003 (2007).
[12] P. Adamson et al. MINOS Collaboration, Phys. Rev. D 77, 072002 (2008).
[13] P. Adamson et al. MINOS Collaboration, Phys. Rev. Lett. 101, 131802 (2008).
[14] P. Adamson et al. MINOS Collaboration, Phys. Rev. Lett. 106, 181801 (2011).
[15] P. Adamson et al. MINOS Collaboration, Phys. Rev. Lett. 107, 021801 (2011).
[16] P. Adamson et al. MINOS Collaboration, Phys. Rev. D 84, 071103(R) (2011).
[17] P. Adamson et al. MINOS Collaboration, Phys. Rev. Lett. 108, 191801 (2012).

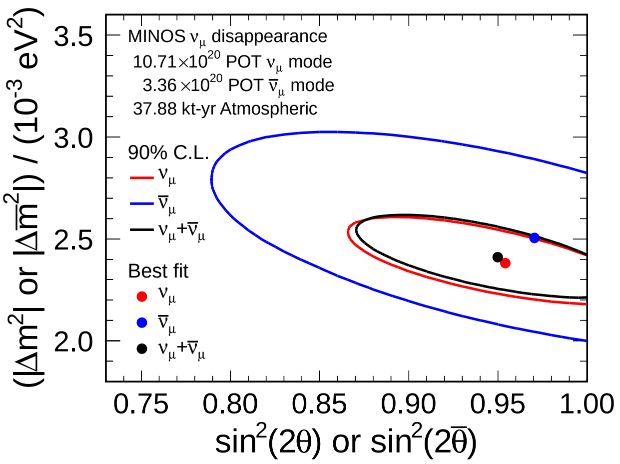

Figure 3: The 90% confidence level contours for the antineutrino oscillation parameters using all antineutrino data (blue), the contour from our measurement of the neutrino parameters using all neutrino data (red), and the contour from our measurement of the neutrino parameters using all neutrino and antineutrino data (black).

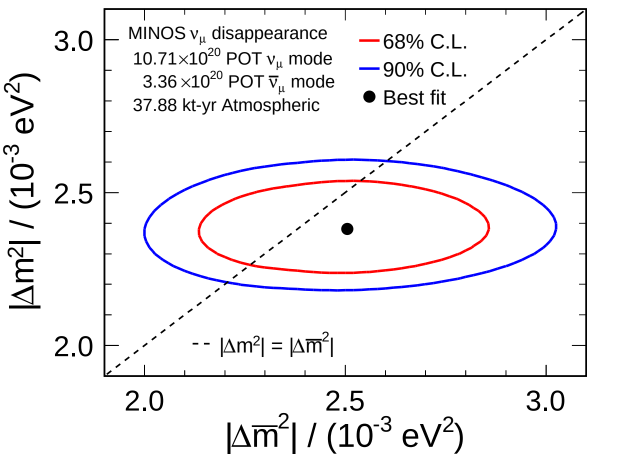

Figure 4: Confidence limits obtained for the oscillation parameters $|\Delta m^2|$ and $|\Delta\overline{m}^2|$, representing the mass splittings for neutrinos and antineutrinos, respectively. At each point in parameter space, the negative log-likelihood function has been minimized with respect to the mixing parameters $\sin^2 2\theta$ and $\sin^2 2\overline{\theta}$. The 68% and 90% contours are indicated by the red and blue curves, respectively. The diagonal dashed line indicates the case when $|\Delta m^2| = |\Delta\overline{m}^2|$.