Combined Analysis of \( \nu(\mu) \) Disappearance and \( \nu(\mu) \rightarrow \nu(e) \) Appearance in MINOS Using Accelerator and Atmospheric Neutrinos

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Combined Analysis of $\nu_\mu$ Disappearance and $\nu_\mu \rightarrow \nu_e$ Appearance in MINOS Using Accelerator and Atmospheric Neutrinos


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We report on a new analysis of neutrino oscillations in MINOS using the complete set of accelerator and atmospheric data. The analysis combines the $\nu_\mu$ disappearance and $\nu_e$ appearance data using the three-flavor...
formalism. We measure $|\Delta m^2_{32}| = [2.28 - 2.46] \times 10^{-3}$ eV$^2$ (68% C.L.) and $\sin^2 \theta_{23} = 0.35 - 0.65$ (90% C.L.) in the normal hierarchy, and $|\Delta m^2_{32}| = [2.32 - 2.53] \times 10^{-3}$ eV$^2$ (68% C.L.) and $\sin^2 \theta_{23} = 0.34 - 0.67$ (90% C.L.) in the inverted hierarchy. The data also constrain $\delta_{CP}$, the $\theta_{23}$ octant degeneracy and the mass hierarchy; we disfavor 36% (11%) of this three-parameter space at 68% (90%) C.L.

The study of neutrino oscillations has entered a precision era in which the experimental data can be used to probe the three-flavor framework of mixing between the neutrino flavor eigenstates ($\nu_e, \nu_\mu, \nu_\tau$) and mass eigenstates ($\nu_1, \nu_2, \nu_3$). In the standard theory, neutrino mixing is described by the unitary PMNS matrix [1], parametrized by three angles $\theta_{12}, \theta_{23}, \theta_{13}$, and a phase $\delta_{CP}$. The oscillation probabilities additionally depend on the two mass-squared differences $\Delta m^2_{21}$ and $\Delta m^2_{31}$, where $\Delta m^2_{ij} \approx m^2_i - m^2_j$. The current generation of experiments has measured all three mixing angles and the mass-squared differences using accelerator, atmospheric, reactor, and solar neutrinos [2]. Most recently, the smallest mixing angle, $\theta_{13}$, has been measured precisely by reactor neutrino experiments [3–5]. However, the picture is not yet complete. The value of $\delta_{CP}$, which determines the level of CP violation in the lepton sector, has not yet been measured. It is also not known whether the neutrino mass hierarchy is normal ($\Delta m^2_{32} > 0$) or inverted ($\Delta m^2_{32} < 0$), whether $\sin^2 2\theta_{23}$ is maximal, or if not, whether the mixing angle $\theta_{23}$ lies in the lower ($\theta_{23} < \pi/4$) or higher ($\theta_{23} > \pi/4$) octant. These unknowns, which are essential to a complete understanding of neutrino mass and mixing, can be probed by long-baseline neutrino experiments.

The MINOS long-baseline experiment [6] has published measurements of oscillations using accelerator and atmospheric neutrinos and antineutrinos. The oscillations observed by MINOS are driven by the larger mass-squared difference $\Delta m^2_{32}$; hence, many features of the data can be described by an effective two-flavor model with a single mass-squared difference $\Delta m^2$ and mixing angle $\theta$. In this approximation, the $\nu_\mu$ and $\bar{\nu}_\mu$ survival probabilities are

$$ P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E_\nu} \right) ,$$

where $L_\nu$ is the neutrino propagation distance and $E_\nu$ is the neutrino energy. A previous two-flavor analysis of $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance using the combined accelerator and atmospheric data from MINOS yielded $|\Delta m^2| = 2.41^{+0.31}_{-0.19} \times 10^{-3}$ eV$^2$ and $\sin^2 2\theta = 0.950^{+0.035}_{-0.036}$ [7]. The statistical weight of the data now enables MINOS to constrain the full three-flavor model of $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance. The uncertainty on $\Delta m^2$ is approaching the size of the smaller mass-squared difference, $\Delta m^2_{21}$, which is neglected in the two-flavor model. Moreover, the precise knowledge of $\theta_{13}$ enables an analysis of the data based on the full set of mixing parameters. In this Letter we present the three-flavor analysis of the combined MINOS data.

In the three-flavor framework, the oscillations are driven by two mass-squared differences $\Delta m^2_{32}$ and $\Delta m^2_{31}$, where $\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{12}$. The interference between the resulting two oscillation frequencies leads to terms in the oscillation probabilities that depend on all the mixing parameters. The leading-order $\nu_\mu$ and $\bar{\nu}_\mu$ survival probabilities in vacuum take the same form as the two-flavor approximation in Eq. (1), with the effective parameters given by [8]:

$$ \sin^2 2\theta = 4 \sin^2 \theta_{23} \cos^2 \theta_{13} (1 - \sin^2 \theta_{23} \cos^2 \theta_{13}) , $$

$$ \Delta m^2 = \Delta m^2_{32} + \Delta m^2_{31} \sin^2 \theta_{12} + \Delta m^2_{21} \cos \delta_{CP} \sin \theta_{13} \tan \theta_{23} \sin 2\theta_{12} . $$

The exact symmetries of the two-flavor model under $\theta \to \pi/2 - \theta$ and $\Delta m^2 \to - \Delta m^2$ lead to approximate degeneracies in the octant of $\theta_{23}$ and mass hierarchy in the three-flavor formalism.

For neutrinos traveling through matter, the propagation eigenstates are modified by the MSW effect [9]. In this case, the mixing angle $\theta_{13}$ is replaced by a modified version, $\theta_M$, given by [10]

$$ \sin^2 2\theta_M = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + (A - \cos 2\theta_{13})^2} . $$

The size of the matter effect is determined by the parameter $A = \pm 2\sqrt{2}G_F n_e E_\nu / \Delta m^2_{31}$, where $G_F$ is the Fermi weak coupling constant, $n_e$ is the density of electrons, and the sign of $A$ is positive (negative) for neutrinos (antineutrinos). Equation (3) shows that $\sin^2 2\theta_M$ is maximal at $A = \cos 2\theta_{13}$. This condition leads to the resonant enhancement of $\nu_\mu \leftrightarrow \nu_\mu$ oscillations, which can significantly alter the magnitude of $\nu_\mu$ disappearance. The effect is present for neutrinos in the normal hierarchy and for antineutrinos in the inverted hierarchy. An MSW resonance is predicted to occur in multi-GeV, upward-going atmospheric neutrinos, which travel through Earth’s mantle [11]. MINOS is the first experiment to probe this resonance by measuring $\nu_\mu$ and $\bar{\nu}_\mu$ interactions separately with atmospheric neutrinos, yielding sensitivity to the mass hierarchy and $\theta_{23}$ octant.

MINOS [12] has previously reported measurements of $\nu_e$ and $\bar{\nu}_e$ appearance in accelerator $\nu_\mu$ and $\bar{\nu}_\mu$ beams. Measurements of $\nu_\mu \to \nu_e$ appearance in accelerator neutrinos have also been published by T2K [13]. Both results are based on three-flavor analyses. For accelerator neutrinos, the $\nu_\mu \to \nu_e$ appearance probability in matter, expanded to second order in $a \equiv \Delta m^2_{21} / \Delta m^2_{31}$ ($\approx 0.03$), is given by [14]:
\[ P(\nu_\mu \to \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2 \Delta (1 - A)}{(1 - A)^2} \]
\[ + \alpha \bar{J} \cos(\Delta \pm \delta_{\text{CP}}) \frac{\sin \Delta A \sin (1 - A)}{A} \]
\[ + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 \Delta A}{A^2}. \quad (4) \]

In this expression, \( \bar{J} \equiv \cos \theta_{13} \sin 2\theta_{13} \sin \theta_{12} \sin \theta_{23} \), \( \Delta \equiv \Delta m_{31}^2 L_{\text{en}} / 4 E_\nu \), and the plus (minus) sign applies to neutrinos (antineutrinos). The first term in Eq. (4) is proportional to \( \sin^2 \theta_{23} \) and breaks the \( \theta_{23} \) octant degeneracy. In addition, the dependence on \( A \) is sensitive to the mass hierarchy and the second term in the expansion is sensitive to CP violation. In this Letter, we strengthen the constraints on \( \delta_{\text{CP}} \), the \( \theta_{23} \) octant, and the mass hierarchy obtained from the MINOS disappearance data [12] by combining the complete MINOS disappearance and appearance data and by exploiting the improved precision on \( \theta_{13} \) from reactor experiments.

In the MINOS experiment, the accelerator neutrinos are produced by the NuMI facility [15], located at the Fermi National Accelerator Laboratory. The complete MINOS accelerator neutrino data set comprises exposures of 10.71 \( \times 10^{20} \) protons on target using a \( \nu_\mu \)-dominated beam and 3.36 \( \times 10^{20} \) protons on target using a \( \bar{\nu}_\mu \)-enhanced beam [7]. These data were acquired in the “low energy” NuMI beam configuration [15], where the neutrino event energy peaks at 3 GeV. The spectrum and composition of the beam are measured using two steel-scintillator tracking detectors with toroidal magnetic fields. The Near and Far detectors are located 1.04 and 735 km downstream of the production target, respectively. The 5.4 kton Far Detector is installed 705 m (2070 m water equivalent) underground in the Soudan Underground Laboratory and is equipped with a scintillator veto shield for rejection of cosmic-ray muons. These features have enabled MINOS to collect 37.88 kton-y of atmospheric neutrino data [16].

The oscillation analysis uses charged-current (CC) interactions of both muon and electron neutrinos. These events are distinguished from neutral-current (NC) backgrounds by the presence of a muon track or electromagnetic shower, respectively. The events also typically contain shower activity from the hadronic recoil system. The selection of accelerator \( \nu_\mu \) CC and \( \bar{\nu}_\mu \) CC events is based on a multivariate k-nearest-neighbor classification algorithm using a set of input variables characterizing the topology and energy deposition of muon tracks [17]. The selected events are separated into contained-vertex neutrinos, with reconstructed interaction positions inside the fiducial volume of the detectors, and non-fiducial muons, in which the neutrino interactions occur outside the fiducial volume or in the surrounding rock. The contained-vertex events are further divided into candidate \( \nu_\mu \) and \( \bar{\nu}_\mu \) interactions based on the curvature of their muon tracks. In the oscillation fit, the events are binned as a function of reconstructed neutrino energy. For contained-vertex events, this is taken as the sum of the muon and hadronic shower energy measurements; for nonfiducial muons, the muon energy alone is used as the neutrino energy estimator. To improve the sensitivity to oscillations, the contained-vertex \( \nu_\mu \) events from the \( \nu_\mu \)-dominated beam are also binned according to their calculated energy resolution [18–20]. The predicted energy spectra in the Far Detector are derived from the observed data in the Near Detector using a beam transfer matrix [21].

The selection of accelerator \( \nu_e \) CC and \( \bar{\nu}_e \) CC events is based on a library-event-matching algorithm that performs hit-by-hit comparisons of contained-vertex shower-like events with a large library of simulated neutrino interactions [22–24]. The events are required to have reconstructed energies in the range 1–8 GeV, where most of the \( \nu_e \) and \( \bar{\nu}_e \) appearance is predicted to occur. The 50 best-matching events from the library are used to calculate a set of classification variables that are combined into a single discriminant using an artificial neural network. The selection does not discriminate between \( \nu_e \) and \( \bar{\nu}_e \) interactions. The selected events are binned as a function of the reconstructed energy and library-event-matching discriminant. The background contributions from NC, \( \nu_\mu \) CC, and \( \bar{\nu}_\mu \) CC interactions, and intrinsic \( \nu_e \) CC and \( \bar{\nu}_e \) CC interactions from the beam, are determined using samples of Near Detector data collected in different beam configurations. The backgrounds in the Far Detector are calculated from these Near Detector components [25]. The rates of appearance in the Far Detector are derived from the \( \nu_\mu \) CC and \( \bar{\nu}_\mu \) CC spectra measured in the Near Detector [12].

Atmospheric neutrinos are separated from the cosmic-ray muon background using selection criteria that identify either a contained-vertex interaction or an upward-going or horizontal muon track [26,27]. For contained-vertex events, the background is further reduced by checking for associated energy deposits in the veto shield. The event selection yields samples of contained-vertex and nonfiducial muons, which are each separated into candidate \( \nu_\mu \) CC and \( \bar{\nu}_\mu \) CC interactions. These samples of muons are binned as a function of \( \log_{10}(E) \) and \( \cos \theta_z \), where \( E \) is the reconstructed energy of the event in GeV and \( \theta_z \) is the zenith angle of the muon track. This two-dimensional binning scheme enhances the sensitivity to the MSW resonance. The results remain in close agreement with the two-flavor analysis of \( \nu_\mu \) and \( \bar{\nu}_\mu \) disappearance, in which these data were binned as a function of \( \log_{10}(L/E) \) [7]. A sample of contained-vertex showers is also selected from the data, composed mainly of NC, \( \nu_e \) CC, and \( \bar{\nu}_e \) CC interactions. These events are grouped into a single bin, since they have negligible sensitivity to oscillations but constrain the overall flux normalization. The predicted event rates in each selected sample are calculated from a Monte Carlo simulation of atmospheric neutrino interactions in the Far Detector [16,28]. The cosmic-ray muon backgrounds are obtained from the observed data by reweighting the events tagged by the veto shield according to the measured shield inefficiency [26].
For all the data samples, the predicted event spectra in the Far Detector are reweighted to account for oscillations, and the backgrounds from $\nu_e$ and $\bar{\nu}_e$ appearance are included. The oscillation probabilities are calculated directly from neutrinos, a constant electron density of $(3.36 \times 10^{20}$ POT $\nu_e$)-enhanced beam $37.88$ kton-yr atmospheric neutrinos, and the backgrounds from the Far Detector are reweighted to account for oscillations, $(\Delta a)$ maximum likelihood fit to the data. The parameters yield similar oscillation results. The impact of these two parameters is evaluated by shifting them in the fit according to their uncertainties; the resulting shifts in the fitted values of $\delta_{CP}$ for each hierarchy. The horizontal dotted lines indicate the 68% and 90% C.L.

The oscillation parameters are determined by applying a maximum likelihood fit to the data. The parameters $\Delta m^2_{32}$, $\sin^2 \theta_{23}$, $\sin^2 \theta_{13}$ and $\delta_{CP}$ are varied in the fit. The mixing angle $\theta_{13}$ is subject to an external constraint of $\sin^2 \theta_{13} = 0.0242 \pm 0.0025$, based on a weighted average of the published results from the Daya Bay [31], RENO [4], and Double Chooz [5] reactor experiments. This constraint is incorporated into the fit by adding a Gaussian penalty term to the likelihood function. The fit uses fixed values of $\Delta m^2_{32} = 7.54 \times 10^{-5}$ eV$^2$ and $\sin^2 \theta_{12} = 0.307$ [32]. The effect of these two parameters is evaluated by shifting them in the fit according to their uncertainties; the resulting shifts in the fitted values of $\Delta m^2_{32}$ and $\sin^2 \theta_{23}$ are found to be negligibly small. The likelihood function contains 32 nuisance parameters, with accompanying penalty terms, that account for the major systematic uncertainties in the simulation of the data [16,23,33]. The fit proceeds by summing the separate likelihood contributions from the $\nu_\mu$ disappearance [7] and $\nu_e$ appearance [12] data sets, taking their systematic parameters to be uncorrelated.

Figure 1 shows the 2D confidence limits on $\Delta m^2_{32}$ and $\sin^2 \theta_{23}$, obtained by maximizing the likelihood function at each point in this parameter space with respect to $\sin^2 \theta_{13}$.

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Figure 1 shows the 2D confidence limits on $\Delta m^2_{32}$ and $\sin^2 \theta_{23}$, obtained by maximizing the likelihood function at each point in this parameter space with respect to $\sin^2 \theta_{13}$.
In summary, we have presented the first combined analysis of $\nu_\mu$ disappearance and $\nu_e$ appearance data by a long-baseline neutrino experiment. The results are based on the complete set of MINOS accelerator and atmospheric neutrino data. A combined analysis of these data sets yields precision measurements of $\Delta m^2_{32}$ and $\sin^2 \theta_{23}$, along with new constraints on the three-parameter space defined by $\delta_{CP}$, the $\theta_{23}$ octant, and the mass hierarchy.

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