Results and prospects from MINOS and MINOS+

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Abstract. We present the latest results from the MINOS long-baseline neutrino oscillation experiment. New results are reported on a three-flavor combined analysis of beam and atmospheric neutrino data using ν_μ and $\overline{\nu}_\mu$ disappearance and ν_e and $\overline{\nu}_e$ appearance channels. We also show preliminary results on a sterile neutrino search with MINOS and indicate future plans for MINOS+.

1. Introduction

The MINOS experiment [1] consists of two magnetized tracking calorimeters placed in the path of the NuMI beam generated at Fermilab. A 0.98 kton Near Detector (ND) is deployed 1.04 km from the beam target and measures the composition of the NuMI beam at short distances. Situated 735 km from the beam target, the 5.4 kton Far Detector (FD) is located in the Soudan Mine in Minnesota at a depth of 705 m. The latter is used to observe neutrinos from the NuMI beam at a substantially longer distance; it also records the interactions of neutrinos produced by cosmic rays in the Earth's atmosphere. The MINOS Far Detector has been operating since 2005. It has accumulated data from 15.6×10^{20} Protons-on-Target (PoT) delivered to the NuMI beam while also collecting 37.88 kton-years of atmospheric neutrino data.

Different types of neutrino interactions can be studied by selecting for specific event topologies with multivariate techniques. Charged Current (CC) neutrino interactions are characterized by the associated charged lepton. For muon-neutrino interactions, we select for long tracks, typical of the high energy muons produced. Electron-neutrinos are identified by a dominant electromagnetic shower produced by the electron. Neutral Current (NC) interactions are often dominated by a hadronic shower with an ionization profile which is distinct from the electromagnetic showers in the detector.

2. Neutrino oscillation

The main purpose of the MINOS experiment is to study the dependence of the neutrino flavor content with time. One such time dependence is the neutrino oscillation phenomenon which derives from the mismatch of neutrino interaction and propagation eigenstates. The frequency of neutrino oscillations is governed by the difference in the square of their masses. Two distinct oscillation frequencies have been observed, in agreement with the three neutrino species known.

A peculiarity of the observed frequencies is that they differ by a factor of ~ 30. Because of this large discrepancy, most experiments are unable to observe both of these frequencies simultaneously. As a result, neutrino oscillations have been studied mostly in a two-flavor approximation. In some ways, this is an advantage as it allows experiments to probe different parameters independently, however it also introduces extra symmetries which appear as parameter degeneracies.

Two important degeneracies are the mass hierarchy and the octant of the effective mixing angle. Both of these degeneracies are broken in a three-flavor framework, yet they remain unresolved experimentally at the present time. The resolution of these degeneracies is a top priority for the upcoming experiments and it can be achieved by three different approaches. Firstly, one can probe three-flavor specific effects that break these degeneracies but are suppressed by the mass splitting ratio. Secondly, matter effects may reduce the effective mass splitting ratio, enhancing the degeneracy breaking terms. Thirdly, one can observe different oscillation channels in order to compare effective mixing angles and frequencies. This report makes use of all three approaches to present the first three-flavor oscillation results of the MINOS experiment.

3. Three-flavor oscillation analysis

The analysis presented here is an extension of the two-flavor results previously published [2]. It comprises the full MINOS data set including 10.71×10^{20} PoT with the ν_μ-dominated beam, 3.36×10^{20} PoT with the $\overline{\nu}_\mu$-enhanced beam, and 37.88 kton-years of atmospheric neutrino data. The samples of ν_μ and $\overline{\nu}_\mu$ selected events used here are the same as were used in the two-flavor analysis. We look for the disappearance of ν_μ and $\overline{\nu}_\mu$ in these samples as a function of the neutrino energy and as a function of the cosine of the zenith angle in the case of atmospheric neutrinos. In addition, we include the latest MINOS ν_e and $\overline{\nu}_e$ appearance results [3].

The appearance and disappearance channels are analyzed separately to form four-dimensional log-likelihood surfaces in the $(\Delta m^2_{32}, \sin^2\theta_{23}, \sin^2\theta_{13}, \delta_{CP})$ parameter space, while profiling over the systematic uncertainties associated with each sample. The remaining oscillation parameters are fixed to values from a global fit [4], namely $\Delta m^2_{21} = 7.54 \times 10^{-5}$ eV^2 and $\sin^2\theta_{12} = 0.307$. The resulting 4-D surfaces are combined and subject to the external constraint $\sin^2\theta_{13} = 0.0242 \pm 0.0025$ as derived from an average of recent reactor neutrino experiments [5].

We find the best fit values and allowed ranges given in Table 1. The data marginally prefer an inverted hierarchy and a lower octant solution. Figure 1 shows the contour and profile plots as a function of Δm^2_{32} and $\sin^2\theta_{23}$ from the combined fit to ν_μ disappearance and ν_e appearance data. Figure 2 shows the profiled log-likelihood distribution as a function of δ_{CP} for each of the four combinations of hierarchy and θ_{23} octant. The data disfavor the normal hierarchy and higher octant combination at >81% C.L. for all values of δ_{CP}.

	Parameter	Best-fit	Confidence limits
Normal hierarchy	$\Delta m^2_{32}/10^{-3}$ eV^2	2.37	2.28 – 2.46 (68% C.L.)
	$\sin^2\theta_{23}$	0.41	0.35 – 0.65 (90% C.L.)
Inverted hierarchy	$\Delta m^2_{32}/10^{-3}$ eV^2	2.41	2.32 – 2.53 (68% C.L.)
	$\sin^2\theta_{23}$	0.41	0.34 – 0.67 (90% C.L.)

Preference for inverted hierarchy: $-2\Delta \log L = 0.23$
Preference for lower octant: $-2\Delta \log L = 0.09$
Exclusion of maximal mixing: $-2\Delta \log L = 1.54 \Rightarrow$ (79% C.L.)

Table 1. The best fit values and confidence limits on the Δm^2_{32} and $\sin^2\theta_{23}$ parameters, calculated separately for the normal and inverted hierarchy.

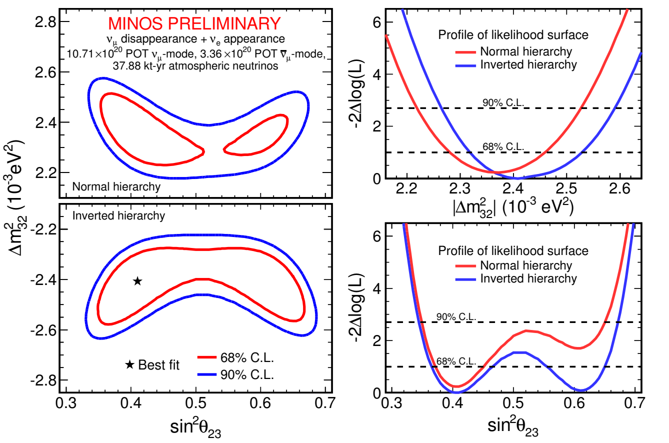

Figure 1. Contour and profile plots from the combined fit to ν_μ disappearance and ν_e appearance data. Left panels show 68% and 90% confidence limits in $(\Delta m^2_{32},\ \sin^2\theta_{23})$ calculated for normal hierarchy (top) and inverted hierarchy (bottom). Right panels show log-likelihood profiles for each hierarchy plotted for Δm^2_{32} (top) and $\sin^2\theta_{23}$ (bottom).

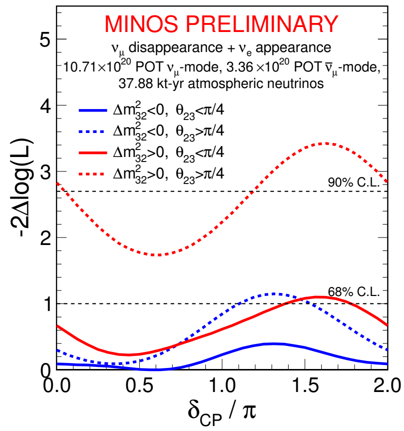

Figure 2. The log-likelihood profile for δ_{CP}, plotted separately for each combination of hierarchy and θ_{23} octant. The dashed horizontal lines indicate the 68% (90%) single-parameter confidence limits, which disfavor 36% (11%) of the parameter space defined by the mass hierarchy, octant, and δ_{CP}.

4. Sterile neutrino search

The three-flavor oscillation model describes most of the current available data very well. However, a number of experiments have observed anomalies in the neutrino rate at short distances which could imply the existence of light sterile neutrinos. Notably, the LSND [6] and MiniBooNE [7] experiments have observed $> 3\sigma$ evidence of $\nu_\mu \to \nu_e$ oscillations with a characteristic L/E of order 1 km/GeV.

Such an oscillation scenario would affect the rate of both CC and NC neutrino interactions in MINOS. Using a $3+1$ sterile neutrino model, MINOS has released preliminary results on the search for these effects using both the Near and Far Detectors. These results have been restricted to the mass-squared splitting $\Delta m^2_{43} = 0.5$ eV^2 in which spectral distortions are minimal in both detectors. With this choice, our analysis is not sensitive to the relative shape uncertainties between the ND and the FD at high energies for which refined treatments are under development.

For this particular Δm^2_{43}, MINOS has found no evidence for active and sterile neutrino mixing and we set a limit on the mixing angle $\theta_{24} < 4.8°$ at 90% C.L. Additionally, we performed a combined fit of the MINOS and Bugey data, setting stringent limits on the effective mixing angles relevant to $\nu_\mu \to \nu_e$ in the vicinity of $\Delta m^2_{43} = 0.5$ eV^2. We find $\sin^2\theta_{\mu e} < 7.7 \times 10^{-5}$ at 90% C.L., which excludes, with high significance, oscillations at this Δm^2_{43} as the source of ν_e appearance in the LSND and MiniBooNE experiments. Figure 3 shows the preliminary MINOS exclusion limits in comparison to the LSND and MiniBooNE allowed ranges in a $3+1$ oscillation model.

5. The future with MINOS+

With the onset of the medium energy neutrino running of NuMI, the MINOS experiment has come to an end. However, the MINOS detector will remain in operation in this new beam, with higher intensity and higher energy. This new configuration comprises the MINOS+ experiment

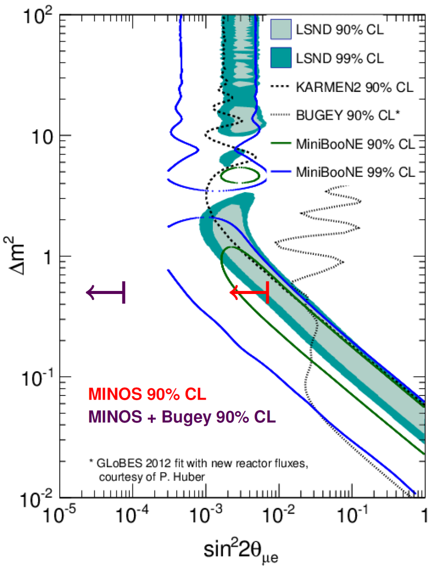

Figure 3. MINOS and Bugey combined 90% confidence level limit on the sterile mixing parameter $\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2|U_{\mu 4}|^2$ at $\Delta m^2_{43} = 0.5$ eV^2, obtained from the individual disappearance limits of each experiment on the size of $|U_{\mu 4}|^2$ and $|U_{e4}|^2$, respectively. Regions of parameter space to the right of the arrows are excluded at 90% CL. The Bugey 90% CL limit is computed from a GLoBES 2012 fit provided by P. Huber. It accounts for the new calculation of reactor fluxes, as described in [8]. The MiniBooNE contours are those published in [7].

which will rapidly accumulate high statistics, enabling more precise tests of the three-flavor paradigm. Several new phenomena can also be probed with MINOS+, including more sensitive searches to the sterile neutrino anomaly and searches for non-standard interactions, extra dimensions, neutrino decoherence and neutrino decay.

6. Conclusion

MINOS has analyzed precision measurements of oscillation parameters in a three-flavor framework. These new results combine multiple data sets to exploit the full capability of the experiment, providing the best measurement of the Δm^2_{32} parameter together with new constraints on the mass hierarchy and θ_{23} octant. They represent the first use of a combination of appearance and disappearance data in a long-baseline experiment. In the near future, MINOS+ will continue to test the three-flavor paradigm and to search for new phenomena in a broad range of energies.

Acknowledgments

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