PROCEEDINGS OF SCIENCE

The MINOS experiment: 2012 results

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Data taking has now finished for the low-energy phase of the MINOS experiment. The main osillation results from these data are presented. The disappearance of muon neutrinos and muon anti-neutrinos from the NuMI beam are combined with atmospheric data to produce a best fit for the atmospheric oscillation parameters. The $|\Delta m^2_{32}|$ measurement, which is the most constraining in the world, is $(2.39^{+0.09}_{-0.10}) \times 10^{-3}\mathrm{eV}^2$. The value of $\sin^2(2\theta_{32})$ is measured to be $0.957^{+0.035}_{-0.036}$. The latest results of the electron neutrino appearance search are presented and rule out $\theta_{13} = 0$ at 2σ. Results from the MINOS time of flight study are also presented and a preview of the physics available in the next phase of the experiment, MINOS+ is given.

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1. Introduction

The first phase of the MINOS long baseline experiment, the one where the low energy beam configuration is used, has just ended with a record 15×10^{20} protons on target (POT) delivered since the experiment started in 2005. The far detector has also been collecting atmospheric neutrino events since 2003. MINOS has an on-axis muon-neutrino beam, produced by a proton beam from the main injector at Fermilab, with a spectrum peaked around 3 GeV and a baseline of 735.3 km to the far detector which is in the Soudan Underground Laboratory in Minnesota. It is optimized to make high-precision measurements of the 'atmospheric' neutrino oscillation sector with a mass splitting of $O(2.5 \times 10^{-3})$ eV. It is also able to study the θ_{13} sector using electron neutrino appearance and can search for possible oscillation to sterile neutrinos.

The NuMI beam line supplies the MINOS experiment with a neutrino beam, generated from 120 GeV protons at the main injector in spills of about 10 μs duration every 2.1 s. The beam run ended on April 30th, 2012 and has accumulated 10.71×10^{20} (3.36×10^{20}) protons on target in low-energy neutrino (anti-neutrino) mode. A variety of other beam settings are available by modifying the configurations of the horns; by comparing these, the experiment is able to constrain the hadron production uncertainties to a large extent (which would otherwise be one of the most challenging parts of the measurement). Additionally, MINOS has identical near and far detectors which is exploited in the analysis to significantly reduce the impact of neutrino cross sections and nuclear reinteraction effects.

The far detector is a magnetized spectrometer/calorimeter which has been described elsewhere [1] consisting of alternating steel and scintillator planes perpendicular to the beam direction. The steel is 25 mm thick and the scintillator planes are 10 mm thick and segmented into 41 mm wide strips whose direction alternates from one plane to the next in order to give two orthogonal 2-dimensional side views of the events. A hole down the middle of all the planes houses a conductor which produces a field of 1.2 T on average within the steel planes to bend μ^- (μ^+) towards the centre of the detector during neutrino (anti-neutrino) running. The detector is read out with both ADC and TDCs and is 'triggerless', i.e. all hits are transferred to a processor farm where they are assembled into events. The near detector is of identical construction but smaller, and is readout with a beam gate which is capable of taking the higher rate of hits which are experienced nearer the neutrino source.

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2. Neutrino and anti-neutrino disappearance

For the first time in an oscillation experiment, MINOS has combined both beam and atmospheric data into the oscillation fits. The individual beam spectra and atmospheric L/E distributions are shown in figure 1. Sets of beam data were taken with each of the two polarities of horn-current; forward horn current (FHC) with a prominently neutrino beam, peaked around 3 GeV from the horn focusing and a broader distribution towards higher energy of both neutrinos and anti-neutrinos; and reverse horn current (RHC) with prominently anti-neutrinos in the 3 GeV peak. The events, which are required to be close in time to a pulse of neutrinos from the main injector, are characterized by a long track which is designated the muon and a shower which comprises the other energy deposited close to the neutrino interaction site. The neutrino energy is reconstructed by adding the muon

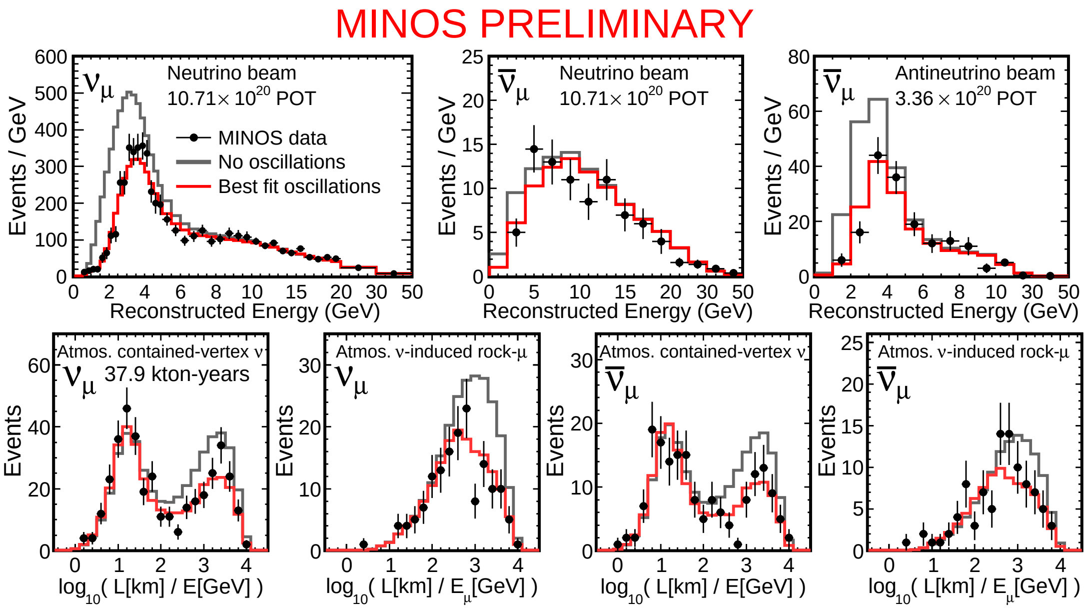

Figure 1: Event samples used for the neutrino oscillation measurements (see text). The top row shows beam neutrino and anti-neutrino energy spectra, from left to right: neutrinos in forward horn-current, anti-neutrinos in forward horn-current and anti-neutrinos in reverse horn-current data. The bottom row shows atmospheric data as a function of L/E for contained and rock-muon events separated into neutrino and anti-neutrino data. The data are shown as points, the no-oscillation expectation in black, and the best fit to oscillations in red.

energy (estimated from range for contained muons or curvature) to the calorimetric energy of the shower. The expected oscillated energy spectra are obtained by studying with high statistics the spectra in the near detector, and translating to the far detector [2, 3] using Monte-Carlo; a technique which exploits the relatively simple two-body decays in which the majority of the beam neutrinos are produced.

The atmospheric neutrino events are from our 37.9 kton-year sample of data which has been collected almost continuously between 2003 and 2011 which is a large fraction of an 11-year solar cycle. Two separate samples of muon neutrino candidates are made with (a) contained vertices and (b) from events where a muon from a neutrino interaction in the rock enters the detector. Timing of the hits is used to determine the direction of the muons to exclude downward going entering tracks which occur at a rate of about 0.5 Hz due to high energy muons produced in the atmosphere. A cut is applied to events for which the direction of curvature of the muon is not well measured (i.e. where it was traveling parallel to the magnetic field for too long, or was too short a track). The data are split into four samples depending on the expected event-by-event L/E resolution.

The samples shown in figure 1 have been combined into both beam-only, atmospheric-only and combined oscillation fits. Only the combined oscillation fits have been presented at this conference. A total of 2894 beam candidate events are used in the fits while the expected number without oscillations would be 3564. The allowed contours are shown in figure 2 (top left), and compared with both T2K [4] and SuperKamiokande [5]. The following results are from a two oscillation

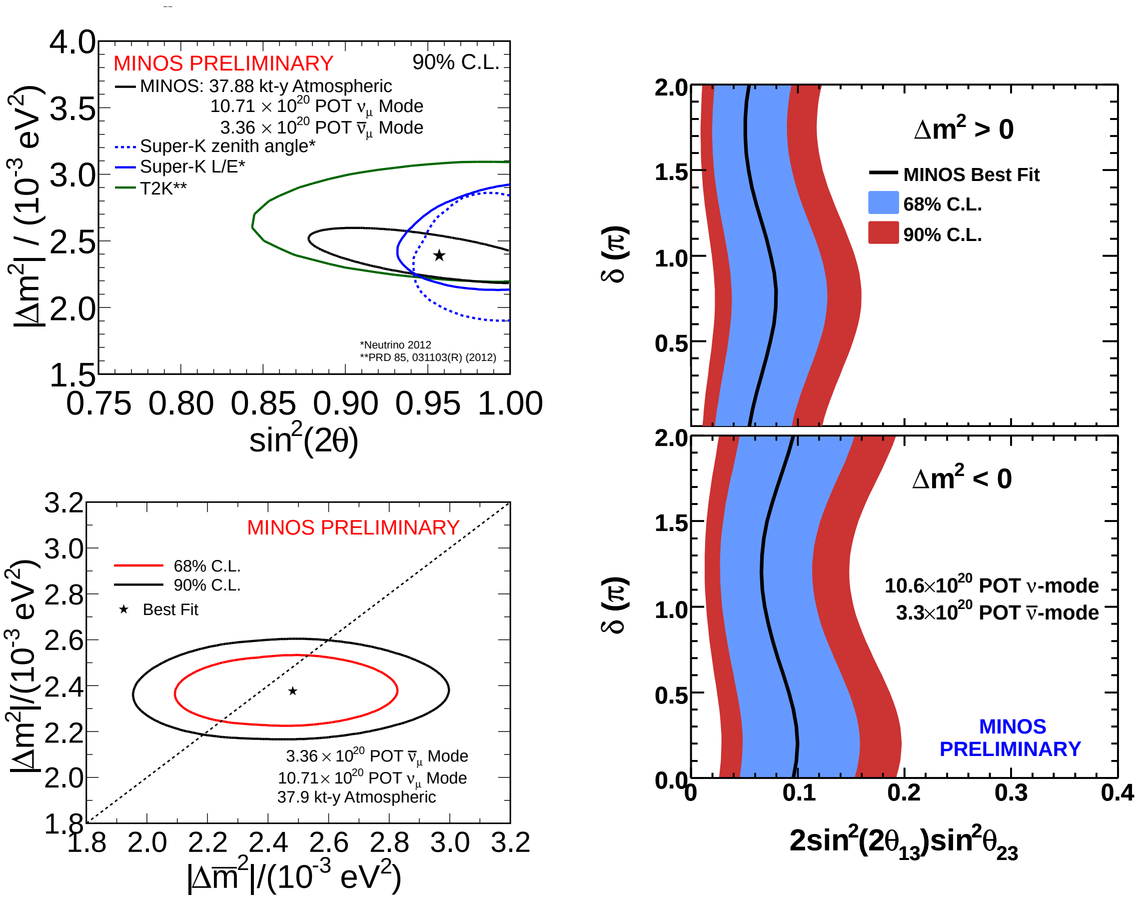

Figure 2: Left top: Disappearance measurement: 90% confidence level contours from the two parameter fit from MINOS beam and atmospheric data compared with published Super-Kamiokande and T2K neutrino contours. Right top: Disappearance measurement: 68% and 90% confidence level contours from the four parameter fit for the mass splittings for neutrinos and anti-neutrinos. Top and bottom right: Appearance measurement: Allowed ranges and best fits for $2\sin^2(\theta_{23})\sin^2(2\theta_{13})$ as a function of δ (vertical axis) and normal (inverted) hierarchy in the top (bottom) right panel.

parameter fit,

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

assuming the parameters for neutrinos and anti-neutrinos are the same. The mass splitting is measured (preliminary) to be $|\Delta m^2| = 2.39^{+0.09}_{-0.10} \times 10^{-3}$ eV^2 which is the highest precision measurement of this parameter and consistent with other measurements. The mixing parameter $\sin^2(2\theta)$ is measured to be $0.957^{+0.035}_{-0.036}$ which is consistent with maximal mixing, but, unlike previous MINOS measurements has a best fit point below maximal mixing. $\sin^2(2\theta) > 0.90$ at 90% C.L. from this fit. In a separate four oscillation parameter fit in which the neutrino and anti-neutrino parameters are allowed to be different, the neutrino and anti-neutrino mass splitting values are found to be consistent, the contours are shown in figure 2 (bottom left) and the best fit point is at $\Delta m^2 = (2.38^{+0.10}_{-0.10}) \times 10^{-3}$ eV^2 and $\Delta \overline{m}^2 = (2.48^{+0.22}_{-0.27}) \times 10^{-3}$ eV^2.

3. Electron neutrino appearance

The pattern recognition to distinguish an electromagnetic shower within a ν_e charged current event from backgrounds has improved significantly during the time the experiment has been running, even though it is challenging due to the coarse granularity of the detector. The 'Library Event Matching' (LEM) pattern recognition algorithm proceeds by comparing the hit patterns in the two 2-dimensional views to a large library of Monte-Carlo generated signal and background events and using the truth information from the closest matches to form one discriminating LEM variable which is close to 1 for signal events and 0 for background events. The selection is applied to near detector events to determine backgrounds. The backgrounds are determined in the near detector and extrapolated to the far detector separately (they are different due to neutrino oscillation); this determination is done by varying the beam configuration (including runs with the horn off) which changes the proportions of backgrounds.

The preliminary results including the 2012 data are as follows. In the neutrino (anti-neutrino) mode, we observe 88 (12) candidate events with an expected background ($\theta_{13} = 0$) of 69.1 (10.5) events; 26.0 (3.1) more events would be expected if $\sin^2(2\theta_{13}) = 0.1$. The data are analyzed in bins of neutrino energy and the LEM discriminating variable (15 bins in total). These data lead to a favoured range of the oscillation-parameter product $2\sin^2(2\theta_{13})\sin^2\theta_{23}$ which varies depending on the as yet unknown CP oscillation parameter δ and whether the large neutrino mass splitting is above or below the small mass splitting, (normal or inverted hierarchy respectively) as shown on figure 2 (right) for the combined neutrino and anti-neutrino data. The data exclude the value $\theta_{13} = 0$ at 96% C.L. for all values of δ and mass hierarchy.

4. Neutrino time of flight

After the excitement caused by the OPERA experiment in September 2011 [6], MINOS has installed a system of GPS receivers, atomic clocks and two-way time transfer links to be able to synchronize and monitor the time stability with an absolute accuracy in the region of 1 ns. The new timing system was used to carefully study the old timing hardware and enabled us to make a retrospective analysis of the data taken in the experiment before the timing system upgrade. The neutrinos are found to arrive earlier than expected by $15 \pm 11(\text{stat}) \pm 29(\text{syst})$ ns which is consistent with the speed of light. The analysis of the data collected with the new timing system is in progress.

5. MINOS+

The Fermilab NuMI beam ended its low energy phase of running in April 2012. It is being reconfigured for higher intensity and a higher energy, optimal for the NOνA off-axis experiment and will start again in April 2013. The MINOS near and far detectors will remain in operation collecting data. The on-axis MINOS+ beam peaks above the oscillation dip, so we will collect a large number of events and, combined with the MINOS lower energy data will map out the oscillation curve with high statistics. About 4000 events are expected at the far detector per year. These can be used to look for unconventional neutrino oscillation scenarios with unprecedented precision, for example, by combining with existing measurements, MINOS+ can study almost all of the low-mass LSND anomaly region.

6. Summary

The low-energy era of NuMI running of the MINOS detectors has now ended and the preliminary oscillation results using all this data are presented.

The muon neutrino samples from beam and atmospheric data have been combined for the first time by an experiment and give the mass-squared difference $|\Delta m^2| = 2.39^{+0.09}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$ which is the best measurement to date worldwide. The mixing parameter is measured to be $\sin^2(2\theta) = 0.957^{+0.035}_{-0.036}$ which is consistent with maximal mixing, but has a best fit point below maximal. The electron neutrino appearance signal in the far detector rules out $\theta_{13} = 0$ at 90% confidence level, consistent with the recent high precision reactor experiment results and with T2K. MINOS has reinvigorated it's original time of flight studies. The MINOS detectors will continue running in the NOνA era.

References

[1] D. G. Michael *et al.* [MINOS Collaboration], "The Magnetized steel and scintillator calorimeters of the MINOS experiment," Nucl. Instrum. Meth. A **596** (2008) 190

[2] P. Adamson *et al.* [MINOS collaboration], "A Study of Muon Neutrino Disappearance Using the Fermilab Main Injector Neutrino Beam,“ Phys. Rev. **D77**, 072002 (2008)

[3] J. Evans, D. Phil thesis, Oxford University (2008).

[4] K. Abe *et al.* [T2K Collaboration], "First Muon-Neutrino Disappearance Study with an Off-Axis Beam," Phys. Rev. D **85** (2012) 031103

[5] Y. Itow, "Atmospheric neutrinos: Results from running experiments," at the 15th Intl. Conf. on Neutrino Physics and Astrophysics (Neutrino 2012), Kyoto, June 2012.

[6] T. Adam *et al.* [OPREA Collaboration], "Measurement of the neutrino velocity with the OPERA detector in the CNGS beam," [arXiv:1109.4897v1 (22 Sep 2011)], [arXiv:1109.4897v4 (12 Jul 2012)]