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Recent results and future prospects for the MINOS experiment

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Summary. — The MINOS experiment uses the intense NuMI beam created at Fermilab and two magnetized tracking calorimeters, one located at Fermilab and one located 735 km away at the Soudan Mine in Minnesota, to study lepton-flavor violation in the neutrino sector. We present results of the precise measurement of the atmospheric neutrino oscillation parameters, from the search for sterile neutrinos and from the search for the θ_{13} mixing angle by searching for ν_e appearance in the ν_μ beam. Future prospects for measurements by MINOS will also be discussed.

PACS 14.60.Pq – Neutrino mass and mixing.
PACS 14.60.St – Non-standard-model neutrinos, right-handed neutrinos, etc.

1. – The MINOS experiment

The Main Injector Neutrino Oscillation Search (MINOS) experiment was designed to primarily confirm the phenomenon of neutrino oscillations via a precise measurement of the atmospheric neutrino oscillation parameters Δm^2 and $\sin^2(2\theta)$. MINOS data are also used to search for sterile neutrinos and the yet-unobserved θ_{13} mixing angle via $\nu_\mu \to \nu_e$ oscillations. Futhermore, MINOS is capable of conducting tests of CPT and atmospheric neutrino and cosmic ray studies, however these analyses will not be covered in this presentation.

Neutrino oscillation measurements in MINOS primarily utilize the Neutrinos at the Main Injector (NuMI) beam at Fermi National Laboratory. NuMI is a very pure and intense beam of muon neutrinos aimed at an underground laboratory 735 km from the NuMI production target in Soudan, MN. A 5.4 kton magnetizied iron tracking calorimeter (the Far Detector, FD) located at the Soudan laboratory is used to detect the neutrinos [1]. A functionally identical 0.98 kton Near Detector (ND) is located approximately 1 km downstream from the NuMI target. The neutrino energy spectrum is measured using both detectors. The shapes of the two energy spectra are compared and used to measure and constrain neutrino oscillation parameters.

In the analyses of MINOS data presented here, neutrino interactions in the MINOS detectors are characterized by an event energy and interaction type. There are three types of neutrino interactions of interest: ν_μ charged-current (CC), neutral-current (NC) and ν_e CC events. CC events are characterized by having the corresponding lepton in the final state; furthermore, all of the incident neutrino energy is contained in the event. Therefore, ν_μ CC events are characterized by a long muon track with a shower at the vertex, whereas ν_e CC events are shorter and have an electromagnetic shower profile. NC events, on the other hand, are "flavor-blind" and the final state consists of a hadronic shower and a neutrino which carries away at least some of the energy of the incident neutrino; these events are short, but diffuse. Each analysis discussed here uses one of these types of events as the signal and the other events are backgrounds for the same analysis. The energy of the event is the sum of the reconstructed shower energy and the reconstructed energy of the muon (if one is found). Muon energies are determined from a combination of curvature and range; shower energies are determined from Monte Carlo (MC) simulations tuned to external data.

2. – Measurement of Δm^2 and $\sin^2 2\theta$

The determination of the atmospheric neutrino oscillation parameters Δm^2 and $\sin^2(2\theta)$ is accomplished by measuring the probability that a muon neutrino of energy E and traveling a distance L is observed in the muon neutrino weak eigenstate. This neutrino oscillation "survival probability" may be written as

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right), \tag{1}$$

where $\theta \simeq \theta_{23}$, $\Delta m^2 \simeq \Delta m^2_{32}$ is in units of eV^2, L is in km and E in GeV. A comparison of the measured muon neutrino energy spectra in the ND and FD yields the parameters $\sin^2(2\theta)$ and Δm^2.

The dominant background to ν_μ CC events is NC events that are reconstructed as low-energy ν_μ CC interactions. NC events are separated from ν_μ CC events based on topological characteristics that indicate a muon in the final state: track length, mean pulse height, fluctuation in pulse height and transverse track profile. A CC/NC separation parameter cut is determined that maximizes the CC event selection efficiency and minimizes the NC background [2]. A comparison of the selection parameter distribution in the ND data and MC shows excellent agreement above the final CC/NC parameter cut.

The energy spectrum for ν_μ CC events is measured in the ND and extrapolated to the FD. The extrapolation is non-trivial because the neutrino events seen in the ND appear to be coming from a line source, whereas events in the FD appear to be coming from a point source. MC simulations are therefore used to determine energy smearing and acceptance corrections for the expected FD energy spectrum. The dominant systematic uncertainties in the predicted FD spectrum are a 4% normalization uncertainty, a 10.3% hadronic energy calibration uncertainty and a 50% uncertainty on the NC background that pass the CC cut selection criteria. The normalization and hadronic energy uncertainties primarily effect the measurement of Δm^2 at the level of $\pm 0.081 \times 10^{-3}\,\mathrm{eV}^2$ and $\pm 0.052 \times 10^{-3}\,\mathrm{eV}^2$, respectively. The NC background is the largest effect on the measurement of $\sin^2(2\theta)$ at the level of ± 0.016.

Figure 1 shows the measured FD energy spectrum, the expected spectrum with no oscillations, the best oscillation fit to the data, and the NC background (significant only in the lowest energy bin). A total of 848 events are observed in the FD, with 1065 ± 60 events expected under the no-oscillation hypothesis for a data set based on 3.36×10^{20} protons

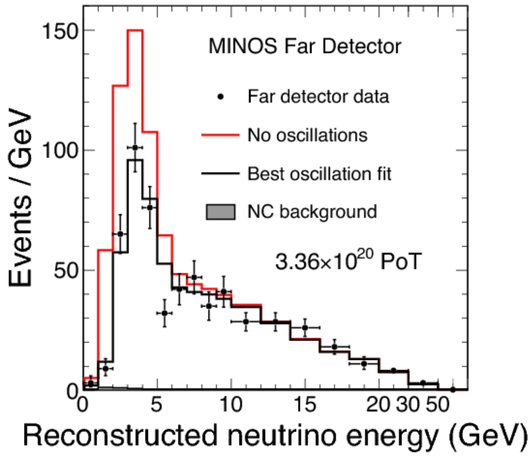

Fig. 1. – (Colour on-line) The Far Detector ν_μ energy spectrum determined from CC events. The data are shown as black points with error bars; the NC background is shown in shaded gray and is only significant in the first bin. The predicted spectrum for the no-oscillation hypothesis is shown in red. The black line represents the best-fit spectrum for the oscillation hypothesis.

on target (POT). Fitting the observed energy spectrum to the survival probability, and constraining the fit parameters to their physically meaningful values, we find $\Delta m^2 = 2.43 \pm 0.13 \times 10^{-3}$ and $\sin^2(2\theta) > 0.90$ (90% CL), with a $\chi^2/ndof = 90/97$. Figure 2 shows the oscillation parameter phase space allowed by the latest MINOS measurement, with comparisons to other experiments. MINOS has the most precise measurement of Δm^2 to-date. Alternative hypotheses of neutrino decay [3] and neutrino decoherence [4] have also been tested with the MINOS data, and these are disfavored with respect to the osciallation hypothesis by 3.7σ and 5.7σ, respectively.

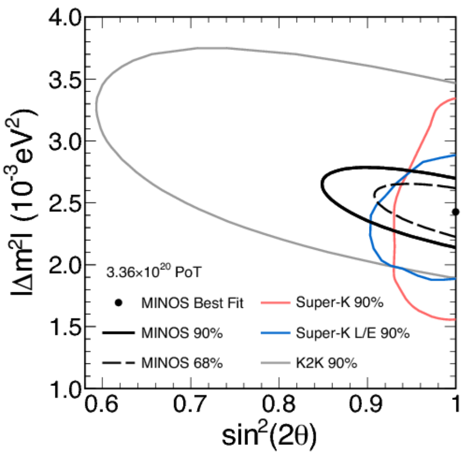

Fig. 2. – 68% and 90% contour lines for the oscillation fit parameters Δm^2 and $\sin^2(2\theta)$ compared to other experimental measurements.

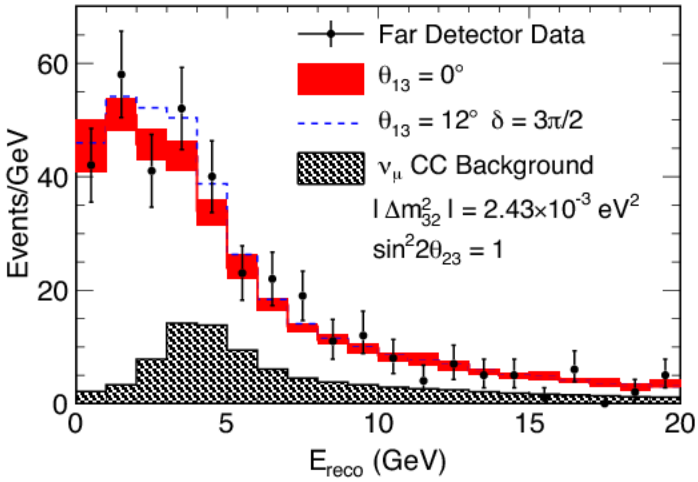

Fig. 3. – (Colour on-line) Visibile energy spectrum of NC events in the FD. Data are shown in black points. The predicted spectrum obtained from the ND NC spectrum is shown is red for $\theta_{13} = 0$ (dashed blue for θ_{13} at the CHOOZ limit).

3. – The search for sterile neutrinos

Since the NC event rate is independent of neutrino flavor, and thus unaffected by oscillations between the three active neutrino flavor states, a deficit in the NC rate in the FD would indicate the existence of at least one additional neutrino that does not interact via the weak force ("sterile neutrino", ν_s). The dominant background in this measurement are low-energy ν_μ CC events that do not have a clear muon track. NC events are selected and their visible energy determined from reconstructed "shower-like" events. The ND NC spectrum is extrapolated to the FD, and several sterile neutrino models are tested against these two spectra.

The quantity $f_s = (P_{\nu_\mu \to \nu_s})/(1 - P_{\nu_\mu \to \nu_\mu})$ describes the fraction of ν_μ that have oscillated to ν_s in a simple four-flavor model where oscillations to sterile neutrinos occur at the same mass splitting as the ν_μ disappearance measured from the CC interactions. The search for sterile neutrinos using MINOS data is sensitive to two sterile neutrino models: the case where $m_4 = m_1$ and the case where $m_4 \gg m_3$.

Figure 3 shows the measured visible energy spectrum in the FD, based on 3.18×10^{20} POT, along with the expected spectra for θ_{13}=0 (solid red) and θ_{13} at the CHOOZ limit [5] (dashed blue) and the predicted ν_μ CC event background (hashed black). In the case where $m_4 = m_1$ and θ_{13}=0, the 90% CL limit on f_s is 0.51 (0.55 for $\theta_{13} = 12°$). In the case where $m_4 \gg m_3$, the limit on f_s is 0.52 (0.55). A detailed description and results of the search for sterile neutrinos in MINOS may be found [6].

4. – The search for θ_{13} via $\nu_\mu \to \nu_e$

For the search of ν_e appearance in the MINOS detector we again make use of CC events; in this case, we are looking for an excess of events with an electron in the final state in the MINOS FD compared to the expected number from measurements in the MINOS ND. The MINOS detectors were optimized for muon identification in the final

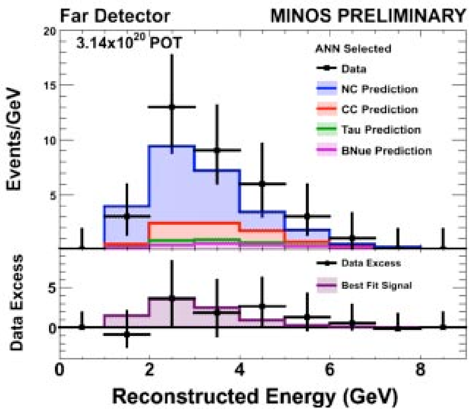

Fig. 4. – (Colour on-line) Top: the Far Detector ν_e energy spectrum determined from CC events. The data are shows as black points with error bars; backgrounds are shown as solid, colored histograms. Bottom: data—predicted background as a function of energy. The data excess is represented by the black points, the best fit to the signal is represented by the solid histogram.

state; therefore the search for electron-neutrino appearance in MINOS is very challenging because of the very large background of NC events (low-energy ν_μ CC events also contribute a non-negligible amount to the background). However as mentioned previously, ν_e CC events do differ topologically from NC events and are tagged by selecting events that have electromagnetic-like shower profiles. Using topological cuts and a neural-network to classify events, the signal-to-background ratio is reduced from 1:55 to 1:4.

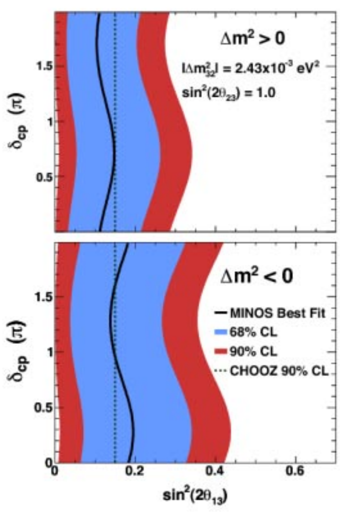

Fig. 5. – (Colour on-line) Best-fit value of $\sin^2(2\theta_{13})$ as a function of the CP-violating phase δ_{CP}. 68% and 90% contour lines for $\sin^2(2\theta_{13})$ are shown as solid red and blue lines. The CHOOZ limit is drawn as a dashed line for comparison.

The top of the left plot of fig. 4 shows the measured ν_e CC spectrum for an exposure of 3.14×10^{20} POT in the MINOS FD (solid black points) with the backgrounds overlaid. The dominant NC background is in blue, the ν_μ CC background in red, and τ and beam ν_e CC events are in green and magenta, respectively. The bottom of the left plot shows the amount of data excess (black points) as a function of energy, with the best fit for the $\nu_\mu \to \nu_e$ oscillation hypothesis plotted in solid purple. A total of 35 events are observed in the MINOS FD with a predicted background of $27 \pm 5(\text{stat}) \pm 2(\text{syst})$ events, which corresponds to a 1.5 σ excess. The observed excess is comparable to the CHOOZ [5] limit for $|\Delta m^2| = 2.43 \times 10^{-3}\,\text{eV}^2$ and $\sin^2(2\theta_{23}) = 1.0$. With these results, $\sin^2(2\theta_{13}) = 0$ is included at the 92% confidence level. The contours on the right of fig. 5 show the best-fit values of $\sin^2(2\theta_{13})$ as a function of the CP-violating phase δ_{CP}, with 68% (blue) and 90% (red) CL intervals for the normal (top) and inverted (bottom) hierarchies. Further details of this analysis may be found in [7].

5. – Future outlook

At the time of this conference, the MINOS Collaboration had completed and published analyses based on approximately 3×10^{20} POT exposure but had collected more than twice that amount of data ($\sim 7 \times 10^{20}$ POT). All analyses were being redone to incorporate not only the additional data, but also improvements in reconstruction, particle identification algorithms and background reductions. In some cases, the backgrounds have been reduced by a factor of two. MINOS expects to produce new results for all of these analyses in the summer of 2010 that will incorporate all of these improvements. Furthermore, MINOS has collected $\sim 1.5 \times 10^{20}$ POT of reverse-horn-current data; this configuration results in a $\bar{\nu}_\mu$-dominated beam. These data will be analyzed and a measurement of the atmospheric oscillation parameters $\Delta\bar{m}^2$ and $\sin^2(2\bar{\theta})$ will be forthcoming from MINOS in the summer of 2010 with obviously limited statistics. MINOS plans to continue collecting data through 2011, but it is not clear yet under which beam configuration.

REFERENCES

[1] Michael D. G. *et al.*, *Nucl. Instrum. Methods A*, **596** (2008) 190.
[2] Adamson P. *et al.*, *Phys. Rev. Lett.*, **101** (2008) 131802.
[3] Barget V. *et al.*, *Phys. Rev. Lett.*, **82** (1999) 2640.
[4] Fogli G. L. *et al.*, *Phys. Rev. D*, **67** (2003) 093006.
[5] Apollonio M. *et al.*, *Eur. Phys. J. C*, **27** (2003) 331.
[6] Adamson P. *et al.*, *Phys. Rev. D*, **81** (2010) 052004.
[7] Adamson P. *et al.*, *Phys. Rev. Lett.*, **103** (2009) 261802.