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The latest results from the MINOS oscillation experiment

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Summary. — The MINOS experiment is a long-baseline neutrino oscillation experiment, which utilizes neutrinos from the Fermilab NuMI muon neutrino beam. The neutrino flux from this beamline is studied before and after oscillation with two separate magnetized tracking calorimeter detectors. MINOS has recently carried out several studies in the field of neutrino oscillations, using 7.2×10^{20} protons on target of neutrino data, and 1.71×10^{20} protons on target of antineutrino data. These studies include a precision study of the atmospheric neutrino oscillation parameters $\sin^2(2\theta_{23})$ and $|\Delta m^2_{23}|$, a comparative study of the atmospheric antineutrino oscillation parameters $\sin^2(2\bar{\theta}_{23})$ and $|\Delta \bar{m}^2_{23}|$, an attempt to measure θ_{13} by looking for $\nu_\mu \to \nu_e$ oscillations, and a search for oscillations to an additional sterile state.

PACS `14.60.Pq` – Neutrino mass and mixing.
PACS `14.60.Lm` – Ordinary neutrinos (ν_e, ν_μ, ν_τ).
PACS `29.27.-a` – Beams in particle accelerators.

1. – The MINOS experiment

The MINOS experiment studies neutrinos provided by the Fermilab NuMI beamline using both a Near and a Far Detector, which measure the flux of these neutrinos, respectively before and after oscillations. The NuMI beamline [1] is an on-axis muon neutrino beamline. Neutrino production begins when the Main Injector collides 120 GeV protons with a graphite target, producing pions and kaons. These hadrons are then focused by two separate magnetic focusing horns. K^- and π^- are focused to create a neutrino beam, while K^+ and π^+ are focused to create an antineutrino beam. The hadrons then travel down a 675 m long decay pipe. The final product is a beamline with 91.7% ν_μ, 7.0% $\bar{\nu}_\mu$, and 1.3% ν_e and $\bar{\nu}_e$. The current in the focusing horns, along with the relative positions of the target and horns, can be adjusted to create different beam configurations. The beam is normally run in "low energy" mode to produce a beam peak at 3.1 GeV (rms 1.1 GeV), in order to best explore the region of atmospheric oscillations [2]. The analyses discussed in this paper employ 7.2×10^{20} protons on target worth of neutrino data, and 1.71×10^{20} protons on target worth of antineutrino data.

The neutrinos are then studied by two separate functionally equivalent magnetized tracking calorimeter detectors [3]. The Near Detector is smaller (with a 0.029 kT fiducial mass) and is situated 1 km down the beamline at Fermilab; this detector measures neutrinos in their unoscillated state. The beam then travels 735 km northwest through the Earth to the Far Detector in Soudan, Minnesota. This detector has a larger mass of 4.0 kT and is located (for cosmic shielding purposes) at a depth of 2100 mwe. The Far Detector is intended to measure neutrinos after they have oscillated. Both detectors consist of a series of octagonal planes with two separate layers: first, a layer of 1 inch thick steel, which forms the target mass for neutrino interaction, and second, a layer of 1 cm thick by 4 cm wide strips of plastic scintillator, which collect photons from the interactions. The detectors are also magnetized with a 1.3 T field, to allow discrimination between muon tracks from ν_μ and $\bar{\nu}_\mu$.

2. – Recent analysis results from MINOS

2˙1. ν_μ *disappearance.* – The MINOS detectors have been primarily designed to look for the disappearance of muon neutrinos. The survival probability for muon neutrino oscillation is as follows:

$$\mathrm{P}(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23}) \sin^2(1.27 \Delta m^2_{32} L/E). \tag{1a}$$

It is presumed that the remainder of the muon neutrinos oscillate to tau neutrinos; tau neutrinos are not directly observed in MINOS, however (due to the high production threshold for τ), so this oscillation is seen as disappearance. MINOS, having a fixed oscillation length L and energy range E, is capable of searching for the behavior in eq. (1) to make a precision measurement of the oscillation parameters θ_{23} and Δm^2_{32}. Muon neutrinos are detected in MINOS via ν_μ Charged Current interactions, which leave a hadronic shower and a distinctive muon track. The Near Detector spectrum is used to make a prediction of the spectrum at the Far Detector in the absence of oscillations. The (presumably oscillated) data spectrum is then compared to the unoscillated prediction. For this analysis, 2451 ± 60 events are predicted in the Far Detector without oscillations, and 1986 events are observed in the data. The predicted and data spectra, along with their ratio, can be seen in fig. 1. When a fit for the oscillation in eq. (1) is performed, best fit values of $|\Delta m^2_{32}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$ and $\sin^2(2\theta_{23}) > 0.90$ (90% CL) are obtained, along with the allowed regions in fig. 2. Comparisons to the previous Super-K [4, 5] and K2K results [6] are also shown. This MINOS result is the most precise measurement of these parameters to date. The $\nu_\mu \rightarrow \nu_\tau$ hypothesis is also well-supported by the data, with the alternative hypotheses of pure decoherence [7] and pure decay [8] ruled out respectively at greater than 9 and 7 sigma. Further details of this analysis can be found in reference [9].

2˙2. $\bar{\nu}_\mu$ *disappearance.* – In addition to this precision study of neutrino oscillation, MINOS also has the unique ability to do a direct comparative measurement of the antineutrino oscillation parameters $\bar{\theta}_{23}$ and $\Delta \bar{m}^2_{32}$:

$$\mathrm{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = 1 - \sin^2(2\bar{\theta}_{23}) \sin^2(1.27 \Delta \bar{m}^2_{32} L/E). \tag{2a}$$

As stated earlier, the current in the NuMI focusing horn can be reversed to focus the opposite charge sign of hadrons, producing a beam with an enhanced antineutrino

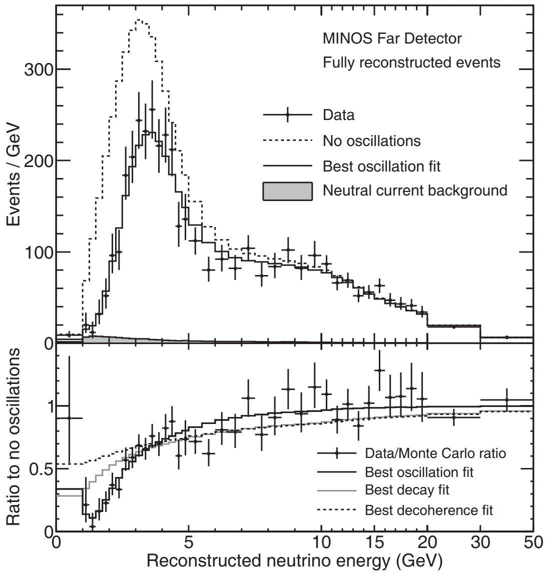

Fig. 1. – The top plot shows the predicted and observed energy spectra distributions for fully reconstructed ν_μ Charged Current events in the MINOS Far Detector. The dashed line indicates the prediction for the no-oscillation case. The solid line shows the best fit for oscillations. The black markers indicate the data distribution. The bottom plot shows the background-subtracted ratio of the data and the no-oscillation prediction, with best fits for oscillation, decoherence, and decay. This plot is for an exposure of 7.2×10^{20} protons on target.

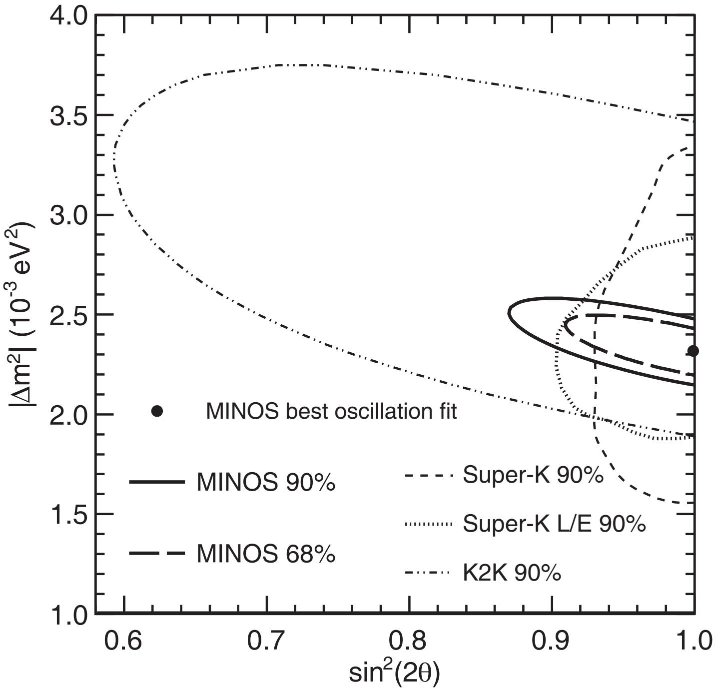

Fig. 2. – 90% and 68% CL for allowed regions of $\sin^2(2\theta_{23})$ and $|\Delta m^2_{32}|$ for the 2010 MINOS analysis. Previous results from Super-K [4, 5] and K2K [6] are shown for comparison.

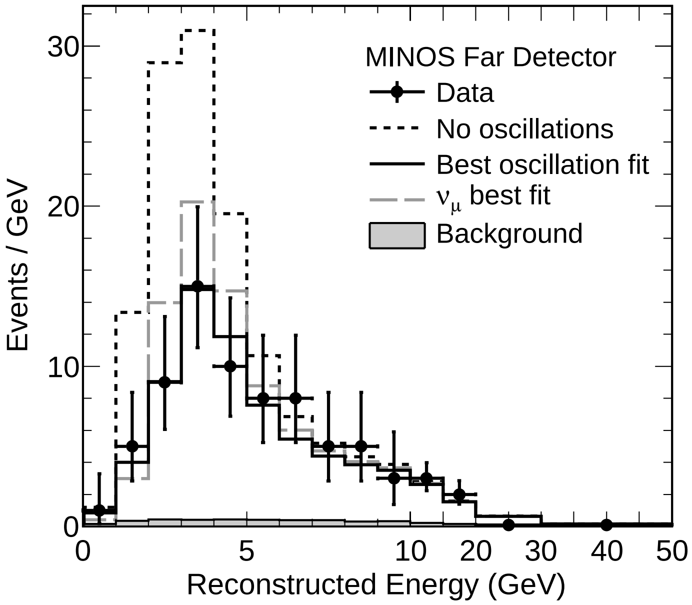

Fig. 3. – Predicted and observed energy spectra distributions for fully reconstructed $\bar{\nu}_\mu$ Charged Current events in the MINOS Far Detector. The black dashed line indicates the prediction for the no-oscillation case. The black markers indicate the observed spectrum. The solid black line shows the best fit for antineutrino oscillations. The grey dashed line shows the expected distribution if the same best fit values as the neutrino analysis were obtained.

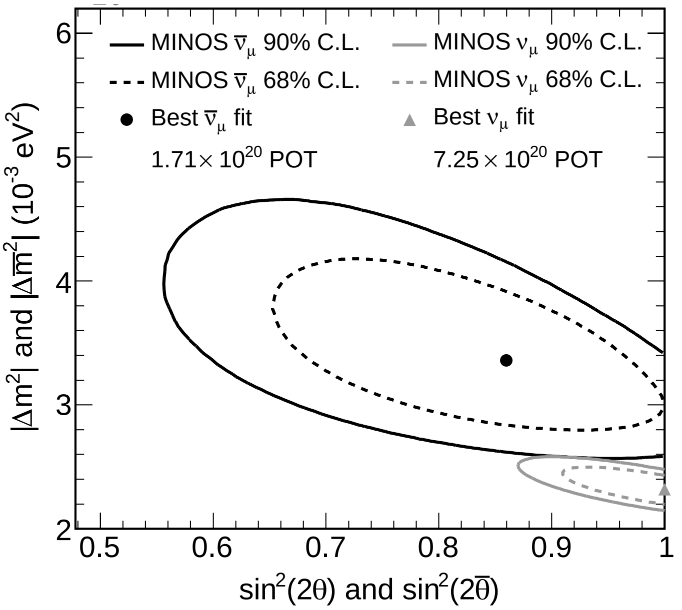

Fig. 4. – 90% (solid line) and 68% CL (dashed line) for allowed regions of $\sin^2(2\theta_{23})$ and $|\Delta m^2_{32}|$ for antineutrino (black) and neutrino (grey) oscillations, with best fits.

flux. Muon antineutrinos can then be separated from muon neutrinos by examining the curvature of the $\mu^{-(+)}$ track from a muon neutrino Charged Current interaction. The Near Detector selection is again used to make a prediction of the unoscillated muon antineutrino Far Detector spectrum. 156 events are expected, while 97 are observed, as seen in fig. 3. For this analysis, the final result is dominated by low statistics, including a 30% uncertainty on contamination by the muon neutrino background. Best fit values of $|\Delta m^2_{32}| = 3.36^{+0.46}_{-0.40}(\text{stat.}) \pm 0.06(\text{syst.}) \times 10^{-3}\,\text{eV}^2$ and $\sin^2(2\theta_{23}) = 0.86^{+0.11}_{-0.12}(\text{stat.}) \pm 0.01(\text{syst.})$ are obtained. As can be seen in contour in fig. 4, there is some tension between this result and the earlier neutrino oscillation result, with the two measurements consistent at the 2.0% confidence level (for identical true oscillation parameters). An effort will be made in 2011 to double the 1.71×10^{20} protons on target antineutrino data set which was used in this analysis. Further details of the current analysis can be found in [10].

2˙3. $\nu_\mu \to \nu_e$ *oscillations.* – The standard explanation for ν_μ disappearance is oscillation to tau neutrinos. This does not rule out other modes of oscillation, and in particular, the oscillation of muon neutrinos to electron neutrinos. Observing this mode of oscillation would allow MINOS to set a limit or possibly make a measurement of the as-yet-unmeasured mixing angle θ_{13}. A non-zero θ_{13} in turn would allow for the possibility of neutrinos exhibiting CP violation. The two-neutrino approximation of this mode is the following:

$$\text{P}(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32}L/E). \tag{3a}$$

The current best limit for θ_{13} comes from the CHOOZ reactor experiment, which finds $\sin^2(2\theta_{13}) <\sim 0.16$ (at the current MINOS best-fit limit for Δm^2_{32}) [11]. Unlike a reactor experiment like CHOOZ, however, the MINOS measurement of θ_{13} is also dependent on the CP violation phase δ_{CP}, $\sin^2(2\theta_{23})$, and the choice of mass hierarchy (normal or inverted).

A MINOS observation of $\nu_\mu \to \nu_e$ is difficult, due in large part to a small expected signal (ν_e Charged Current events) and a large expected background contamination (mostly from Neutral Current hadronic shower events). To separate signal from background, a series of preselection cuts are applied, followed by a particle ID consisting of an artificial neural network trained on eleven separate variables quantifying event shape and energy profile. These cuts have an efficiency of 40% for ν_e signal events and result in a predicted Far Detector sample with a purity of Signal:Background = 1:2 for a CHOOZ-size signal. This set of selection cuts is applied to the Near Detector to make a prediction of the amount of background expected at the Far Detector. The predicted Far Detector background is $49.1 \pm 7(\text{stat.}) \pm 2.7(\text{syst.})$ events. 54 events are observed, corresponding to a non-signficant excess of 0.7σ. The resulting contours can be seen in fig. 5. Assuming $2\sin^2(\theta_{23}) = 1$, $\delta_{\text{CP}} = 0$, and $|\Delta m^2_{32}| = 2.43 \times 10^{-3}\,\text{eV}^2$, MINOS finds $\sin^2(2\theta_{13}) < 0.12$ for the normal hierarchy, and $\sin^2(2\theta_{13}) < 0.20$ for the inverted hierarchy. Further details of this analysis can be found in ref. [12].

2˙4. *Looking for a sterile neutrino.* – Muon neutrinos in MINOS could also potentially be oscillating to other "sterile" neutrino flavors. The cross section for Neutral Current interactions is the same for all three neutrino flavors. For a three neutrino scenario, in which all three neutrinos interact, there will therefore be no change in the rate of

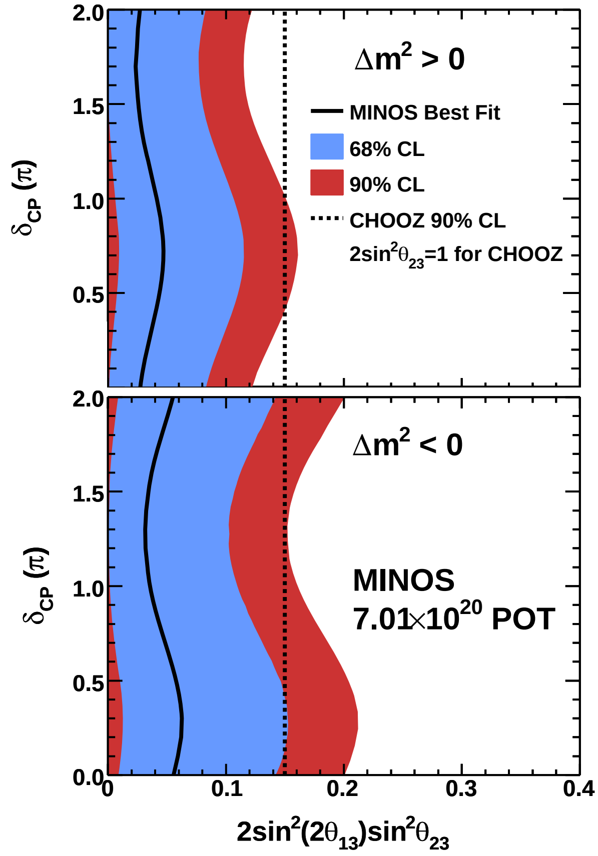

Fig. 5. – 90% and 68% exclusion limits on the value of θ_{13} (horizontal) *versus* δ_{CP} (vertical). The contours are shown for both the normal (top) and inverted (bottom) hierarchies, and assume $|\Delta m^2_{32}| = 2.43 \times 10^{-3}\,\mathrm{eV}^2$. This study was done for an exposure of 7.0×10^{20} protons on target.

NC events at the Far Detector due to oscillation. If there is oscillation to sterile states, however, there will be a deficit in the number of observed Neutral Current events.

A selection designed to select Neutral Current hadronic shower events is applied to the Near Detector to predict the rate of NC events at the Far Detector. $754 \pm 28(\text{stat.}) \pm 37(\text{syst.})$ events are expected at the Far Detector (assuming the mixing angle $\theta_{13} = 0$), and 802 events are observed. The observed distribution, as compared to the expected distribution, can be seen in fig. 6. The ratio of observed to expected NC candidate events is found to be $R = 1.09 \pm 0.06(\text{stat.}) \pm 0.05(\text{syst.}) - 0.08(\nu_e)$ (where the final term is derived from the MINOS 90% CL limit on the value of θ_{13}). A limit is therefore placed on the fraction $\mathrm{f_s}$ of disappearing ν_μs which could be oscillating to a sterile state. This limit is $\mathrm{f_s} < 0.22$, and $\mathrm{f_s} < 0.40$ in the presence of $\nu_\mu \to \nu_e$ oscillations, at 90% CL The full details of this analysis can be found in [13].

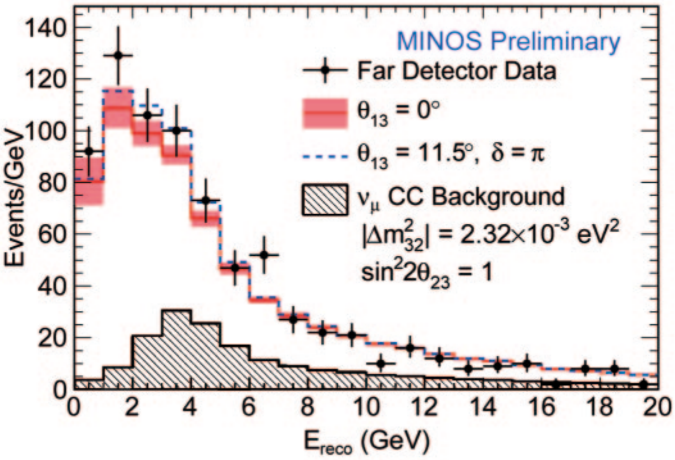

Fig. 6. – (Colour online) The Far Detector NC selected spectrum. The black markers indicate the data. The solid line (red) indicates the best fit (with error bars) for the case where $\theta_{13} = 0$, and the dotted line (blue) shows the best fit for $\theta_{13} = 11.5°$ (the MINOS best fit). The expected ν_μ CC background is also shown. This plot is for an exposure of 7.2×10^{20} protons on target.

3. – Conclusion

The MINOS experiment has carried out an extensive research program looking at neutrino oscillations in several different parts of the atmospheric sector. By looking at the disappearance of muon neutrinos ($\nu_\mu \to \nu_x$) MINOS has placed the most precise limits on the mixing parameters Δm^2_{32} and $\sin^2(2\theta_{23})$ to date, with $|\Delta m^2_{32}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\text{eV}^2$ and $\sin^2(2\theta_{23}) > 0.90$ at 90% CL Additionally, a measurement was also made of the equivalent antineutrino mixing parameters, finding best fits $|\Delta m^2_{32}| = 3.36^{+0.46}_{-0.40}(\text{stat.}) \pm 0.06(\text{syst.}) \times 10^{-3}\,\text{eV}^2$ and $\sin^2(2\theta_{23}) = 0.86^{+0.11}_{-0.12}(\text{stat.}) \pm 0.01(\text{syst.})$ The neutrino and antineutrino are consistent at the 2.0% confidence level. In order to resolve this tension, an attempt will be made in 2011 to double the amount of antineutrino data. A search for oscillation to sterile neutrinos was also conducted, looking for a deficit in the rate of Neutral Current events in the Far Detector. No signficant evidence of this oscillation mode was found, with the total fraction of muon neutrino disappearance caused by oscillation to sterile states being < 0.22 at 90% CL. Finally, an attempt was also made to search for $\nu_\mu \to \nu_e$ oscillations to measure the mixing angle θ_{13}. This study found that (for $2\sin^2(\theta_{23}) = 1$, $\delta_{\text{CP}} = 0$, and $|\Delta m^2_{32}| = 2.43 \times 10^{-3}\,\text{eV}^2$) $\sin^2(2\theta_{13}) < 0.12$ for the normal hierarchy, and $\sin^2(2\theta_{13}) < 0.20$ for the inverted hierarchy. This result will also be followed up in 2011 in a new analysis which will incorporate both new data and improved analysis techniques.

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