Latest results from the MINOS experiment

Justin EVANS[*][†]

University College London
E-mail: evansj@hep.ucl.ac.uk

The MINOS experiment utilizes the NuMI neutrino beam to study the phenomenon of neutrino oscillations. Muon neutrinos are sent over a baseline of 735 km, with a detector near the production point at Fermilab and one at the Soudan underground laboratory in northern Minnesota. By observing the ν_μ disappearance characteristic of oscillations, MINOS can measure the oscillation parameters. MINOS has previously made the best measurement of the atmospheric-regime mass splitting to date. New results are presented in which the data-set is doubled. Further analysis improvements, and the inclusion of additional event samples, further improve the sensitivity to the oscillation parameters. The mixing angle θ_{13} is currently not measured to differ from zero. By searching for ν_e appearance in the ν_μ beam, MINOS is able to set new limits on the value of θ_{13}. An observation of the neutral current interaction rate at the far detector allows limits to be placed on the existence of sterile neutrinos. From September 2009 to March 2010, MINOS has taken data with a dedicated $\overline{\nu}_\mu$ beam, allowing the first direct precision measurement of the antineutrino oscillation parameters in the atmospheric regime.

---

[*]Speaker.

[†]For the MINOS collaboration.

1. The MINOS experiment

The MINOS neutrino oscillation experiment uses the NuMI facility to produce a ν_μ or $\overline{\nu}_\mu$ beam. Two magnetized steel-scintillator calorimeters [1], the near detector (ND) at Fermilab, and the far detector (FD) 735 km from the neutrino source, measure the neutrino energy spectra before and after oscillations have occurred. This two-detector arrangement makes oscillation measurements robust against many sources of systematic uncertainty which affect both detectors similarly.

2. Muon neutrino disappearance search

The neutrino oscillations measured by MINOS are driven by the largest neutrino mass splitting Δm^2_{atm}. The primary oscillation signal observed by MINOS is the disappearance of muon neutrinos. The magnitude of the disappearance is governed by the mixing angle θ_{23}. Observation of this energy-dependent disappearance allows a measurement of Δm^2_{atm} and $\sin^2(2\theta_{23})$. The charged current (CC) interactions of muon neutrinos, $\nu_\mu + N \rightarrow \mu^- + N'$ (where N is a nucleus in the detector), are used for this analysis since the muon produced tags the flavour of the incoming neutrino.

The result reported here updates the previously published result [2]. The data-set is more than doubled. Additionally, a number of analysis improvements further increase the sensitivity to the oscillation parameters. An improved method of identifying CC-ν_μ interactions improves the selection efficiency, particularly at low energies [3]. Cuts are no longer applied on the charge of the reconstructed muon, regaining mis-identified CC-ν_μ events at low energies [4]. A new hadronic shower energy estimator improves the hadronic energy resolution by more than 30% at low energies [5]. Events are the FD are separated into bins according to their energy resolution, maximizing the use of oscillation information contained in the most well-measured events [6].

At the FD, 2451 CC-ν_μ-like events are observed under the assumption of no oscillations. 1986 events are observed. The observed and expected FD energy spectra are shown in figure 1. The observed energy spectrum is fit for oscillations, including the dominant sources of systematic uncertainty as penalty terms in the fit. This fit yields a measurement of the oscillation parameters of $\Delta m^2_{atm} = 2.35^{+0.11}_{-0.08} \times 10^{-3} \, eV^2$, $\sin^2(2\theta_{23}) > 0.91$ (90% C.L.). The allowed regions for the neutrino oscillation parameters are shown in figure 2. The energy dependence of the observed deficit at the FD allows the process behind the disappearance to be investigated. Pure neutrino decay [8] is disfavoured at better than 6σ; pure neutrino decoherence [9] is disfavoured at better than 8σ.

3. Electron neutrino disappearance search

The third neutrino mass state is predominantly an almost equal mix of ν_μ and ν_τ flavour. The possibility remains of a small ν_e component, the size of which is parameterized by the angle θ_{13}; this angle has not been measured to differ from zero. A non-zero value of θ_{13} would result in ν_e appearance in the ν_μ beam at the MINOS FD.

Electron neutrinos are tagged by their CC interactions $\nu_e + N \rightarrow e^- + N'$. The electron produces an electromagnetic shower: a much denser energy deposition than the hadronic shower of typical NC interactions. To select CC-ν_e events, eleven variables are used which characterize the shape of the energy deposition in the shower. These variables are combined in a neural network to produce a single selection variable.
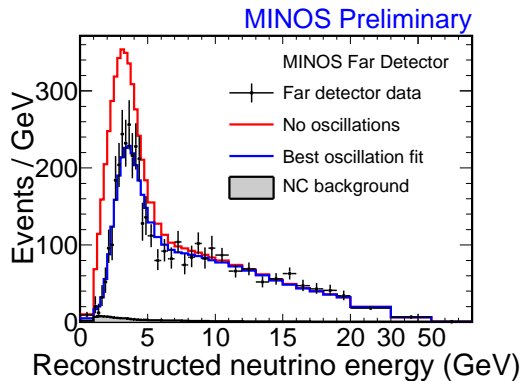
Figure 1: The reconstructed energy spectrum of selected charged current ν_μ events at the far detector, also showing the prediction in the case of no disappearance and the best fit to oscillations.
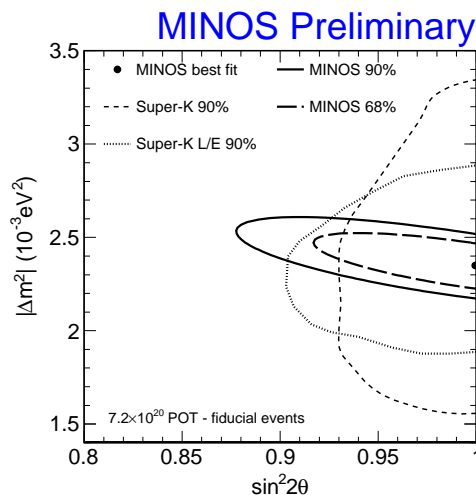

Figure 2: Regions of oscillation parameter space allowed by the MINOS data, compared to other experimental results [7].
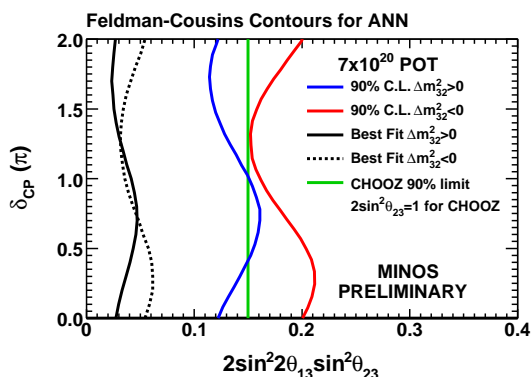

Figure 3: The MINOS 90% allowed regions for $2\sin^2(2\theta_{13})\sin^2(\theta_{23})$ for the normal (blue) and inverted (red) mass hierarchies. Also shown are the MINOS best fit value (black) and the Chooz 90% limit [11] (green).

At the FD, $49.1 \pm 7.0\,(\text{stat.}) \pm 2.7\,(\text{syst.})$ background events are expected. 54 ν_e-like events are observed. This 0.7σ excess shows no evidence for ν_e appearance. This observation can be interpreted as a limit on the size of θ_{13}. The limit depends on the size of the unknown parameter δ_{CP} (which describes the amount of CP violation in the neutrino sector), and the mass hierarchy (the sign of Δm_{atm}^2), and is shown in figure 3 [10].

4. Neutral current disappearance search

The NC interaction rates of all three active neutrino flavours are identical. Therefore oscillations between the three active flavours produce no depletion in the NC event rate. Any deficit in the NC event rate would thus be evidence for oscillation to one or more sterile neutrino flavours.

NC events consist of hadronic showers with no associated muon. The selection criteria look for these shower-like events. At the FD, 757 events are expected. 802 NC-like events are observed,
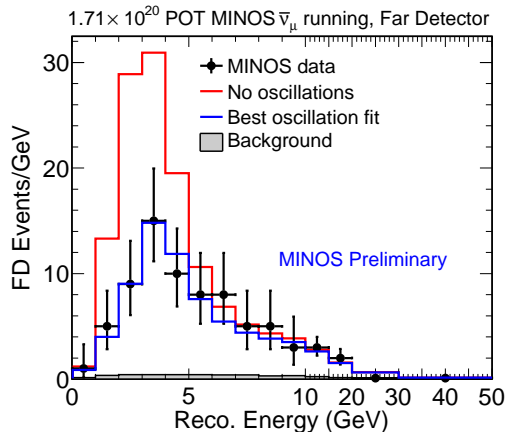
Figure 4: The reconstructed energy spectrum of selected CC-$\overline{\nu}_\mu$ events at the FD. Also shown are the prediction in the case of no disappearance and the best fit of this data to oscillations.
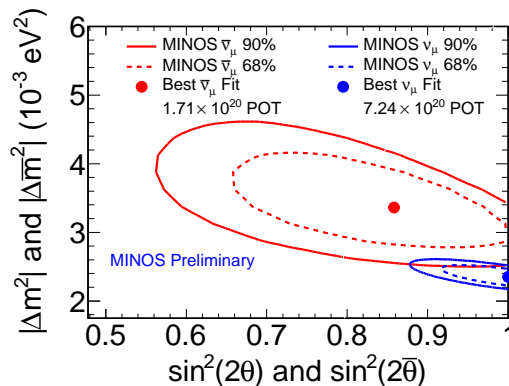
Figure 5: Regions of $\overline{\nu}_\mu$ oscillation parameter space allowed by the MINOS data, compared to the MINOS ν_μ measurement.

showing no evidence for oscillation into sterile neutrinos.

Of the muon neutrinos known to have disappeared from the CC-ν_μ measurement, the fraction which have oscillated to sterile neutrinos can be limited to less than 0.22 (90% C.L.), assuming no ν_e appearance (0.40 for $\theta_{13} = 11.5^\circ$).

5. Muon antineutrino disappearance search

The NuMI beam can be configured to produce a $\overline{\nu}_\mu$-enhanced beam. By observing the charge of the muon produced, MINOS is able to perform excellent event-by-event separation of CC ν_μ and $\overline{\nu}_\mu$ interactions, achieving a CC-$\overline{\nu}_\mu$ purity of 98% below 6 GeV.

At the FD, 155 CC-$\overline{\nu}_\mu$ events are expected without oscillations; 97 are observed. Figure 4 shows the predicted and observed energy spectra. A fit to oscillations yields a best value for the antineutrino oscillation parameters of $\Delta\overline{m}^2_{\text{atm}} = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\text{eV}^2$, $\sin^2(2\overline{\theta}_{23}) = 0.86 \pm 0.11$.

The allowed region for the antineutrino oscillation parameters is shown in figure 5, compared to the MINOS allowed region measured with ν_μ interactions. A tension exists between the MINOS ν_μ and $\overline{\nu}_\mu$ measurements which is being addressed with additional $\overline{\nu}_\mu$ data taking.

References

[1] Nucl. Instrum. and Meth. A **596**, 190 (2008).

[2] Phys. Rev. Lett. **101**, 131802 (2008).

[3] J. Ratchford, Ph.D. Thesis, U-T Austin (2011).

[4] S. Coleman, Ph.D. Thesis, C. William & Mary (2010).

[5] C. Backhouse, Ph.D. Thesis, U. Oxford (2011).

[6] J. Mitchell, Ph.D. Thesis U. Cambridge (2011).

[7] Phys. Rev. Lett. **93**, 101801 (2004); Phys. Rev. D **71**, 112005 (2005).

[8] Phys. Rev. Lett, **82**, 2640 (1999).

[9] Phys. Rev. D **67**, 093006 (2003).

[10] Phys. Rev. D **82**, 051102 (2010).

[11] Eur. Phys. J. C **22**, 221 (2003).