RECENT RESULTS FROM MINOS

Gwenaëlle LEFEUVRE for the MINOS Collaboration
Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, England

The MINOS experiment (Main Injector Neutrino Oscillation Search) uses two detectors separated from 735 km to measure the oscillation parameters of the beam of muon neutrinos produced by the NuMI facility. Neutrino oscillations are observed by comparing the observed energy spectrum at the Far Detector, in Northern Minnesota, with the expectation extrapolated from the measured spectrum at the Near Detector at Fermilab. This paper describes four results from the first three years of operation. Firstly, the observation of muon neutrino disappearance that gives the best measurement of Δm^2_{23} to date. Secondly, the result from the 7% component of muon antineutrinos in the beam that allows us to study, for the first time in a long-baseline accelerator experiment, antineutrino oscillations and set a limit on their oscillation parameters. Thirdly, the search for electron neutrino appearance that sets a limit on the mixing angle $\sin^2(2\theta_{13})$. Finally, the analysis of the neutral current energy spectrum that produces an upper limit on the fraction of sterile neutrinos mixing with muon neutrinos.

1 The MINOS Experiment

MINOS (Main Injector Neutrino Oscillation Search) is a long-baseline experiment running at Fermilab since 2005 in the intense NuMI (Neutrinos at the Main Injector) beam. The beam is produced from 120 GeV protons and is composed of 98.7% $\nu_\mu + \bar{\nu}_\mu$ and 1.3% $\nu_e + \bar{\nu}_e$. Both detectors are magnetized (1.3 T) calorimeters made of alternated layers of 2.54-cm thick steel and solid-scintillator planes. The latter are composed of scintillator strips with a rectangular cross-section of 4.1×1 cm^2 [1]. The neutrino energy spectra are measured at the Near Detector, 1 km from the source, before oscillations have had time to occur. They are then measured again at the Far Detector, 735 km from the source at the Soudan Underground Laboratory in northern Minnesota. Comparing the energy spectra at the two detectors allows the relevant oscillation parameters to be measured. Their similar design permits to reduce systematic uncertainties due to neutrino interaction physics, beam flux and detector response. The integrated exposure of the dataset analysed and presented here is over 3×10^{20} protons on target ("pot"), with a neutrino yield of about one neutrino per proton. The intrinsic divergence of the beam reduces the neutrino flux at the Far Detector by a factor 10^6 compared to the Near Detector. All results reported here were obtained using the methodology of blind analysis.

2 ν_μ Disappearance Oscillations

The design goal of the MINOS experiment is to use quasi-elastic ν_μ interactions to make a precision measurement of the atmospheric oscillations parameters $\sin^2(2\theta)$ and Δm^2. In the two-flavour approximation, the survival probability of a ν_μ of energy E_ν [GeV] observed after traveling some distance L [km] is given by

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

where Δm^2 $[eV^2]$ is the square mass difference between ν_2 and ν_3 and $\sin^2(2\theta)$ is the mixing amplitude between these two mass eigenstates.

The events are characterised by a long muon track and a hadronic shower. The analysis selected 848 events as ν_μ with good purity[2]. The observed, unoscillated near detector signal is used to calculate an expectation of 1065 ± 60 events at the far detector. The best fit oscillation parameters are $\Delta m^2 = (2.43 \pm 0.13) \times 10^{-3} eV^2$ (68% C.L.) and $\sin^2(2\theta) > 0.90$ (90% C.L.). The data set is now double and an updated and refined analysis will allow to improve this measurement.

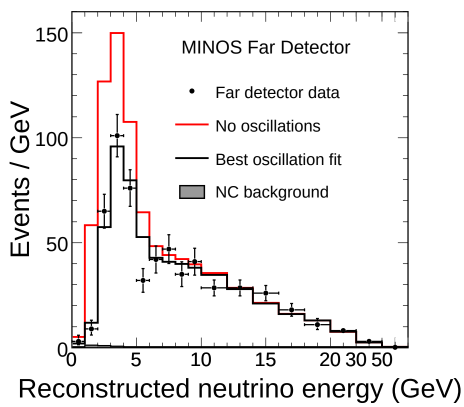

Figure 1: The reconstructed energy spectrum of charged current ν_μ events at the Far Detector, along with the best fit to oscillations and the prediction in case of no oscillations.

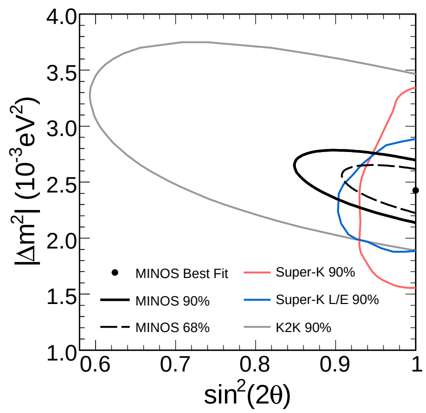

Figure 2: Region of oscillation parameter space allowed by MINOS, compared with the results from Super-Kamiokande and K2K.

3 $\bar{\nu}_\mu$ Appearance Oscillations

The magnetized nature of the MINOS detectors allows the event-by-event determination of the charge sign of muons, and thus the identication of the nature of the parent (neutrino or anti-neutrino). Selection of wrong-sign muons in the ν_μ beam tests if $\bar{\nu}_\mu$ oscillate in the same fashion as ν_μ and tests CPT conservation.

In the neutrino beam, only 6.4% of the events are due to anti-neutrinos, hence the backgrounds are relatively higher and the statistics considerably lower. In addition, the peak of the $\bar{\nu}_\mu$ energy spectrum is around 8 GeV, away from the expected signal region (around 2 GeV). The $\bar{\nu}_\mu$ result from the ν_μ beam will have a lower precision.

$64.6 \pm 8.0_{stat} \pm 3.9_{syst}$ $\bar{\nu}_\mu$ events were expected in the case of no oscillation, $58.3 \pm 7.6_{stat} \pm 3.6_{syst}$ in the case of CPT conserving oscillations, and 42 observed. This excludes the no oscillation hypothesis at 99% C.L. The MINOS data also rules out a region of previously allowed oscillation parameter space: at maximal mixing, MINOS disfavours $\Delta\bar{m}^2 < 2.0 \times 10^{-3} eV^2$ and $5.0 \times 10^{-3} < \Delta\bar{m}^2 < 80 \times 10^{-3} eV^2$ at 90% C.L..The anti-neutrino oscillation parameters are consistent with the neutrino ones given the low statistics. A dedicated run of the NuMI beam optimized to produce anti-neutrinos has been taken between September 2009 and March 2010, that will allow to improve this measurement and understand better anti-neutrino oscillations.

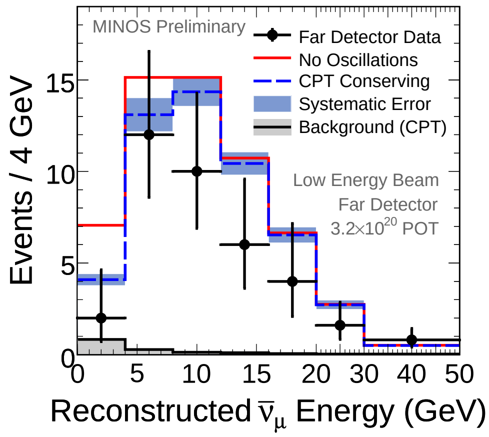

Figure 3: The reconstructed energy spectrum of charged current $\bar{\nu}_\mu$ events at the Far Detector along with the no oscillation and CPT conserving predictions. The blue band encompasses the total systematic uncertainty on the prediction. Also shown is the estimated background.

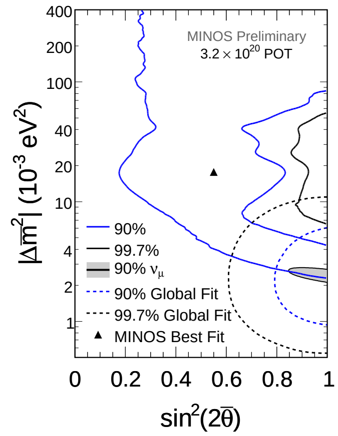

Figure 4: Region of oscillation parameter space allowed by MINOS for $\bar{\nu}_\mu$ oscillations. The MINOS ν_μ contour and global fit are also shown.

4 ν_e Appearance

If θ_{13} is non-zero[4], this will cause oscillations through the subdominant channel $\nu_\mu \rightarrow \nu_e$. MINOS was optimised to be a good muon calorimeter and does not have a good resolution of GeV electromagnetic showers, but it retains sensitivity to a ν_e appearance signal close to the CHOOZ limit ($\sin^2(2\theta_{13}) < 0.15$). These CC-$\nu_e$ events are selected by looking for events with compact electromagnetic showers with a signal efficiency of 41%. Near Detector data with the NuMI focusing horn switched off is used to correct the simulated backgrounds (CC-ν_μ and Neutral Current). The final uncertainty on the predicted Far Detector event rate is 7.3% and a statistical uncertainty of 19%. 35 events were observed at the Far Detector, for a prediction of $27 \pm 5_{stat} \pm 2_{syst}$, representing a 1.5$\sigma$ excess. The fit is consistent with no ν_e appearance and just below the CHOOZ limit [5].

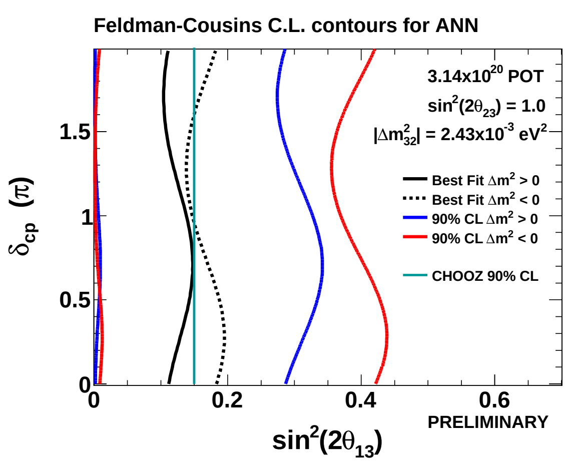

Figure 5: The MINOS allowed regions for $\sin^2(2\theta_{13})$ for the normal and inverted hierarchies. Also shown are the MINOS best fit for each hierarchy and the CHOOZ limit.

5 Neutral Current Analysis

Another possible explanation for ν_μ disappearance is the oscillation into a sterile neutrino flavour. If this channel exists, it would suppress the Neutral Current (NC) event rate. NC events are characterised by a hadronic shower without a muon track. The analysis is made under the hypothesis of a single sterile flavour mixing with ν_μ and ν_τ at the same Δm^2. No deficit is seen in the Far Detector data when compared to the prediction from the Near Detector: the fraction of active neutrino that oscillate into a sterile species is constrained to be below 0.55 [3].

6 The Future

The analyses presented above have used a dataset of over 3×10^{20} protons on target (POT). As of the June 2009 shutdown, MINOS has accumulated 7×10^{20} POT. Updated results using this doubled dataset will be presented in the summer 2010. In September 2009, the current in the NuMI focusing horns was reversed, producing a $\bar{\nu}_\mu$ beam. This allowed MINOS to obtain a greatly enhanced $\bar{\nu}_\mu$ sample concentrated around the expected oscillation maximum. With this, MINOS is making the first precision measurement of the neutrino oscillation parameters in the atmospheric regime, being able to precisely test CPT conservation in the neutrino sector.

Acknowledgments

The author would like to thank her MINOS colleagues for the work presented in these pages, and the organisers of the Moriond Electroweak conference for inviting MINOS to present its results. MINOS is supported by the U.S. Department of Energy, the U.K. Science and Technologies Facilities Council, the U.S. National Science Foundation, and the State and University of Minnesota.

References

1. Michael D. G. et al. (MINOS) *Nucl. Instrum. Methods* A **596**, 190 (2008)
2. Adamson P. et al. (MINOS) *Phys. Rev. Lett.* **101**, 131802 (2008)
3. Adamson P. et al. (MINOS) *Phys. Rev. Lett.* **101**, 221804 (2008)
4. ApollonioM. et al. (CHOOZ) Eur.Phys.J. **C27**,331(2003)
5. Adamson P. et al. (MINOS) *Phys. Rev. Lett.* **103**, 261802 (2009)