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New MINOS Oscillation Results

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Abstract. The MINOS experiment (Main Injector Neutrino Oscillation Search) is a two detector long-baseline neutrino oscillation experiment. Oscillation parameters are determined by comparing the spectrum and composition of the neutrino beam measured at the far detector with that measured at the near detector. This paper summarises the four main beam neutrino oscillation results: muon neutrino and muon anti-neutrino disappearance, electron neutrino appearance and oscillations to sterile neutrinos, derived from the data collected during MINOS' first four years of operation.

1. The MINOS experiment and the Neutrino Beam

The MINOS experiment [1] was designed to accurately measure the atmospheric neutrino oscillation parameters Δm^2_{32} and $\sin^2(2\theta_{23})$ using the Neutrinos at the Main Injection(NuMI) beam at Fermi National Accelerator Laboratory. It consists of two functionally identical, steel/scintillator sampling calorimeters. The 0.98 kton near detector is located approximately 1 km from the NuMI target, the 5.4 kton far detector is located 734 km further downstream in the Soudan Mine Underground Lab in northern Minnesota. The detectors consist of alternating steel and scintillating planes. The scintillating planes are comprised of strips measuring 4.1 cm wide and 1.0 cm thick. Each scintillating plane is attached to a 2.54 cm thick toroidally magnetised (1.3 T) steel plane. Neighbouring scintillating layers are rotated by 90° to allow for three dimensional track reconstruction, and the magnetic field allows particle charge and momentum determination.

The NuMI neutrino beam is generated by the decay of focused πs and Ks produced when 120 GeV protons strike the NuMI target. The neutrino energy can be controlled by the location of the target with respect to the focusing horns. Changing the polarity of the focusing horns allows MINOS to either produce a predominantly muon neutrino beam, or a beam with a larger anti-neutrino component. In the standard configuration, the Low Energy(LE) Forward Horn Current(FHC) mode of operation the beam is comprised of 91.7% ν_μ, 7.0% $\overline{\nu}_\mu$ and 1.3% (ν_e+$\overline{\nu}_e$) and peaks around a few GeV. With the horn polarity reversed(RHC) the beam is 39.9% ν_μ, 58.1% $\overline{\nu}_\mu$ and 2.0% (ν_e+$\overline{\nu}_e$).

2. Oscillation Analyses

Each of the MINOS oscillation analyses are performed utilizing a different neutrino interaction. The $\nu_\mu/\overline{\nu}_\mu$ disappearance analysis identifies charged current (CC) interactions. These interactions are characterized by a hadronic shower at the event vertex and a long (anti-)muon track. Similarly the ν_e appearance analysis looks for CC events which possess both a hadronic and electromagnetic shower. By summing the hadronic and leptonic energy components of the

event the original neutrino energy can be reconstructed. The Neutral Current interactions, which contain no flavour information on the incident neutrino, are characterised by short diffuse hadronic showers. The scattered neutrino carries off some of the original neutrino energy so the NC analysis is performed using the visible shower energy.

The unoscillated neutrino energy spectra are first measured at the near detector and then measured further downstream at the far detector. Comparing the shape and composition of the spectra allow the oscillation parameters to be measured and the similarity of the two detectors minimises the systematic errors relating to beam, and neutrino interaction uncertainties.

The muon neutrino disappearance, electron neutrino appearance and oscillations to sterile neutrinos results presented below are determined using 7.0×10^{20} protons-on-target in the standard low energy(LE) forward horn current(FHC) running scenario. The muon anti-neutrino disappearance result is from 1.7×10^{20} POTs delivered in the low energy configuration with both the focussing horn polarity and detector magnetic field polarities reversed.

2.1. ν_μ Disappearance

The MINOS experiment measures the atmospheric oscillation parameters Δm^2_{32} and $\sin^2(2\theta_{23})$ by measuring the probability that a given muon neutrino will oscillate while it travels between the near and far detector. In the simple two-flavour approximation, the survival probability of a ν_μ with an energy E [GeV] travelling a distance L [km] is given by:

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

where Δm^2 is the mass splitting and θ is the mixing angle. Figure 1 shows the selected charged current ν_μ spectrum at the far detector. The unoscillated far detector spectrum is predicted by first measuring the neutrino spectrum at the near detector. The beam Monte-Carlo is then tuned to match the observed near detector spectrum. This tuning determines the kinematics of the hadrons at the production point, which then can be used to extrapolate the spectrum at the far detector.

The ν_μ charged currents events are characterized by a hadronic shower, and a long muon track. The neutral current background becomes non-negligible at low neutrino energies where the muon track does not extend outside the shower. A total of 1986 events are observed, where as in the absence of neutrino oscillations are 2451 are expected. The best fit to the far detector spectrum places $|\Delta m^2_{23}|$=$2.35^{+0.11}_{-0.08}\times10^{-3}$eV^2, and constrains $\sin^2(2\theta_{23}) > 0.91$ at 90% C.L. The contours for the best fit to the data in Figure 1 can be found in Fig 2. Alternative neutrino disappearance models where also fit; including pure neutrino decay[8], disfavoured at $>6\sigma$; and neutrino decoherence [9], disfavoured at $>8\sigma$.

Further details of this analysis can be found in [2, 3].

2.2. $\overline{\nu}_\mu$ Disappearance

A similar study to that discussed in the previous section was performed on the anti-neutrino data set. A total of 1.7×10^{20} protons on target were accumulated in the reversed horn current running period between September 2009 and March 2010. Despite the large muon-neutrino contamination in the RHC running, the magnetic field facilitates the separation of μ^+ from μ^- resulting in a high anti-neutrino purity in the final data set, >98% for $E_\nu < 6$GeV.

Figure 3 plots the reconstructed energy spectrum of $\overline{\nu}_\mu$ CC events at the far detector. A total of 97 events are observed with the no-oscillation prediction of 155 events[1]. This result disfavours the null oscillation hypothesis at 6.3σ. The best fit oscillation parameters to the anti-neutrino

[1] For an equivalent number POTs we observe fewer anti-neutrino events due to their lower interaction cross-section and their lower production rate.

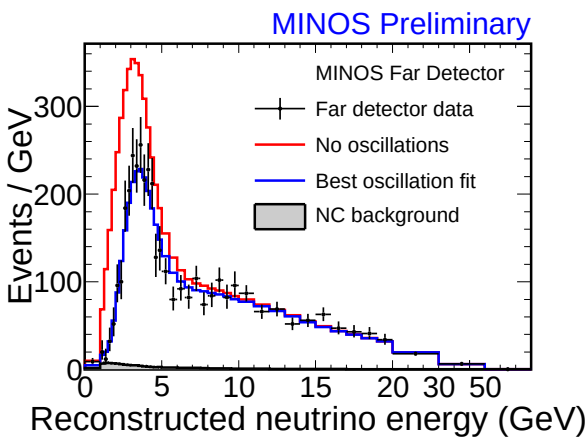

Figure 1. The reconstructed energy spectrum of selected ν_μ CC events at the far detector. The red line in this prediction in the case of no oscillations, the blue line is the best fit to oscillations.

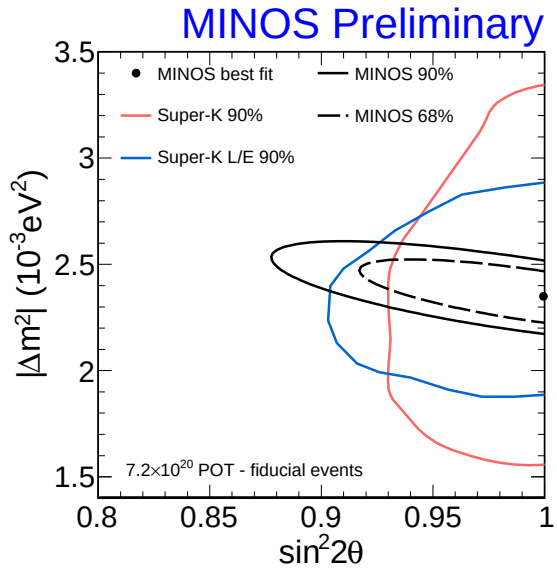

Figure 2. Contours for the oscillation fit to the data in Fig.1. Previous experimental limits are also shown.

data in Figure 3 are $|\overline{\Delta m^2_{32}}|$=$3.36^{+0.45}_{-0.40}\times10^{-3}$ eV^2 and $\sin^2(2\overline{\theta_{23}})$=0.81±0.11. The contours for the neutrino and anti-neutrino oscillation figures are shown in Figure 4. While the anti-neutrino data favours a slightly higher $|\Delta m^2|$ than the neutrino data, which would violate CPT, the results are consistent at 2σ. MINOS plans to double the anti-neutrino data set through another period of RHC running in early 2011 to investigate this further.

2.3. ν_e Appearance

In the instance where θ_{13} is non-zero electron neutrinos are expected to be produced through the sub-dominant oscillation channel $\nu_\mu \rightarrow \nu_e$. The MINOS detectors where optimised for muon identification; the width of the scintillating strips is on the order of a Moliere radius making electromagnetic shower identification difficult. However, an 11 variable artificial neural network (ANN) was developed relying mostly on characterisations of the longitudinal and transverse energy deposition profiles. The ANN selection variable measured and predicted at the far detector is plotted in Figure 5.

As the data is expected to be background dominant, at the CHOOZ limit MINOS expects a signal to background ratio of 1:2, a data driven approach was used to determine the exact composition of the background at the MINOS near detector. The NC, CC and beam ν_e are then extrapolated separately to the far detector. A total of 49.1 ± 7.0(stat)±2.7(syst) events are expected, and 54 events are observed. This corresponds to a 0.7σ excess, consistent with no ν_e appearance.

Using this data we are then able to place limits on the θ_{13} parameter. Further more, due to matter effects MINOS is sensitive to the neutrino mass hierarchy. In the scenario where Δm^2_{32}=2.43×10^{-3}eV^2, $\sin^2(2\theta_{23})$=1 and δ_{CP}=0 we constrain $\sin^2(2\theta_{13}) < 0.12$ in the normal mass hierarchy and $\sin^2(2\theta_{13}) < 0.2$ in the inverted mass hierarchy at 90% C.L. The 90% contours as a function of δ_{CP} are shown in Figure 6. Further details of this analysis can be found in [4, 5].

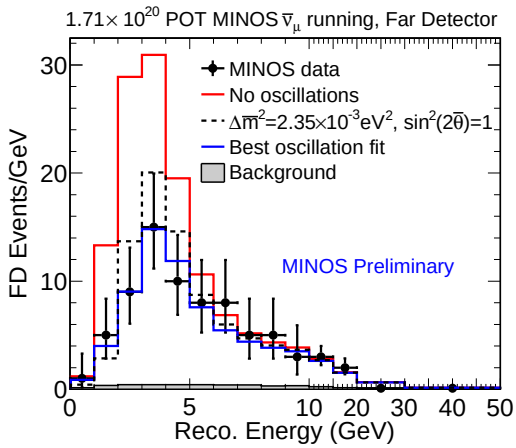

Figure 3. The reconstructed energy spectrum of selected $\overline{\nu}_\mu$ CC events at the far detector. The red line in this prediction in the case of no oscillations, the dashed line is the prediction using the fit to neutrino data, the blue line is the best fit to oscillations.

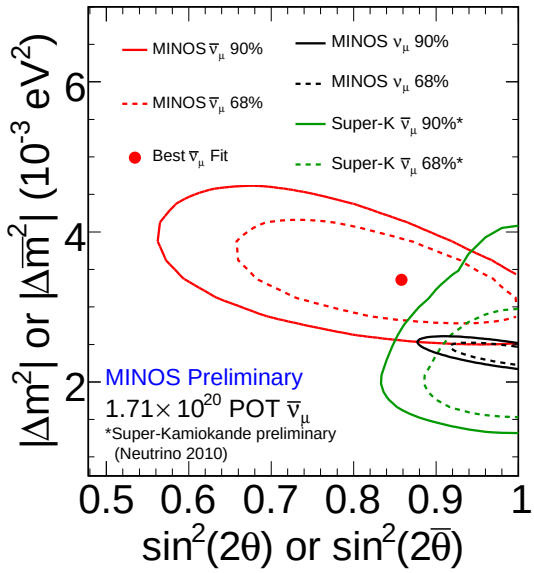

Figure 4. Contours for the oscillation fit to the anti-neutrino data in Figure 3(in red). Previous experimental limits are also shown(in green). The MINOS neutrino disappearance contours from Figure 2 are also shown.

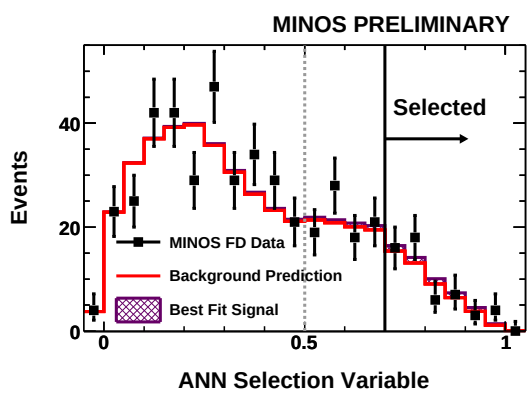

Figure 5. The reconstructed PID of all selected events at the far detector. Events with values a value of 0.7 are ν_e-like. The solid line is the background prediction in the case of no ν_e appearance.

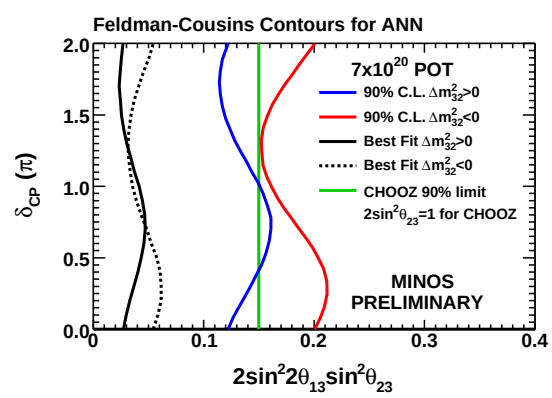

Figure 6. θ_{13} contours, the green vertical line is the CHOOZ limit for a Δm^2=2.43×10^{-3}eV^2

2.4. Neutral Current Interactions

The Neutral Current event rate should not change in the standard three active flavour oscillation model. A deficit in the Neutral Current event rate could indicate mixing to sterile neutrinos. Presented here are the results assuming a single sterile neutrino with mass splitting equivalent

to the atmospheric mass scale.

The selection of neutral current events relies mainly on the exclusion of a long muon track, low energy ν_μ CC interactions where the muon track does not extend past the hadronic shower represent an irreducible background to the NC signal. Furthermore, the prediction of the event rate at the far detector is dependent on the assumed value of θ_{13} as a non-zero value will produce an excess of ν_e CC events at the far detector which, by virtue of not having a track will be identified as NC.

Figure 7 plots the visible energy of the selected NC events at the far detector. In total we expect 757 events, where as 802 events are observed. This result is consistent with no deficit of neutral current events.

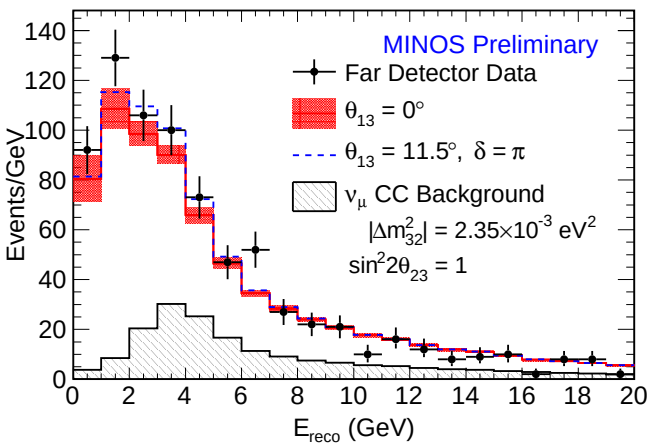

Figure 7. The visible energy spectrum of the selected far detector NC event sample, including the predictions at differing θ_{13} and the CC ν_μ background.

Defining the fraction of neutrinos which oscillate to sterile flavours as

$$f_s = \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} \tag{2}$$

we find that $f_s < 0.22(0.40)$ at 90% C.L. without(with) ν_e appearance.

3. Conclusions

MINOS has measured neutrino oscillation parameters with great precision; it currently has the best measurement of Δm^2_{32}, $\Delta \overline{m^2_{32}}$, and the worlds best constraints on the θ_{13} mixing angle and the sterile neutrino fraction f_s. The results presented here are based on 7×10^{20} POTs in the FHC running scenario and 1.7×10^{20} POTs RHC. The MINOS experiment continues to accumulate data and will further improve all the measurements presented here.

4. Acknowledgements

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