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Current MINOS neutrino oscillation results

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Abstract. The MINOS experiment is now making precise measurements of the ν_μ disappearance oscillations seen in atmospheric neutrinos, tests possible disappearance to sterile ν by measuring the neutral current flux, and has extended our reach towards the so far unseen θ_{13} by looking for ν_e appearance in the ν_μ beam. It does so by using the intense, well-understood NuMI neutrino beam created at Fermilab and observing it 735km away at the Soudan Mine in Northeast Minnesota. High-statistics studies of the neutrino interactions themselves and the cosmic rays seen by the MINOS detectors have also been made. Results from MINOS' first three years of operations will be presented.

1. Introduction

The MINOS experiment uses two magnetized steel/scintillator calorimeters [1] to investigate the neutrino oscillations previously observed using atmospheric neutrinos [2, 3]. This long-baseline experiment observes the intense and well-understood NuMI beam both near its source at Fermilab with a 0.98 kton "near detector", and again 735 km to the northwest in the Soudan Mine Underground Lab with the 5.4 kton "far detector". This before and after comparison of the neutrinos as seen in the similar detectors greatly reduces the systematic errors associated with comparing the differences in the observed neutrino spectra to various neutrino oscillation scenarios, allowing for a more accurate probe of the physics of neutrino propagation. The NuMI beam is composed of 92.9% ν_μ, 5.8% $\overline{\nu}_\mu$, 1.2% ν_e and 0.1% $\overline{\nu}_e$. The bulk of the data come from the "low energy" beam configuration, peaked at several GeV (see the red line in Fig. 1). This paper summarizes the status of several analyses of the neutrino data acquired over the two year time period starting with the beginning of NuMI operations in May of 2005 and ending during the summer shutdown in June 2007, an integrated exposure of over 3×10^{20} protons on target ("pot") with a neutrino yield on order of one neutrino per proton. The intrinsic divergence of the beam results in a neutrino flux at the far detector which is a factor of 10^6 lower than that at the near detector.

2. Oscillation Analyses

2.1. 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 mixing. A ν_μ of energy $E_\nu[GeV]$ observed after traveling some distance $L[km]$ has a probability of being detected as a ν_μ given by $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$, where $\Delta m^2[eV^2]$ is the mass difference between ν_2 and ν_3 and $\sin^2(2\theta)$ is the mixing amplitude. The oscillation minima at the 735 km baseline is less than the τ production threshold, so the oscillatory signature is that of ν_μ disappearance.

An exposure of 3.36×10^{20} pot has been analyzed [4], selecting 848 events as ν_μ with good purity. The observed, unoscillated near detector signal is used to calculate an expectation of 1065±60 far detector events, including a small background of 2.3 external μ, 5.9 neutral current ("NC") induced showers, and 1.5 τ decays, and are shown with the observed data in Fig. 1. Systematic errors (dominated by relative normalization, NC background, and overall hadronic energy scale) are still smaller than statistical errors, so the measurement will improve as data from the current run is added.

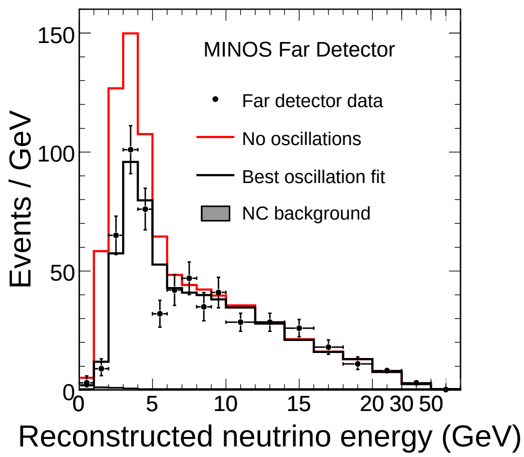

Figure 1. The MINOS far detector $\nu_m u$ spectrum [4]. The data (points with statistical errors) show a significant deficit from the null hypothesis (red line), but well-match a $\nu_\mu \leftrightarrow \nu_\tau$ oscillation scenario (black line), with best fit mass splitting $|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 (68% cl) and mixing angle $\sin^2(2\theta) > 0.90$ (90% cl).

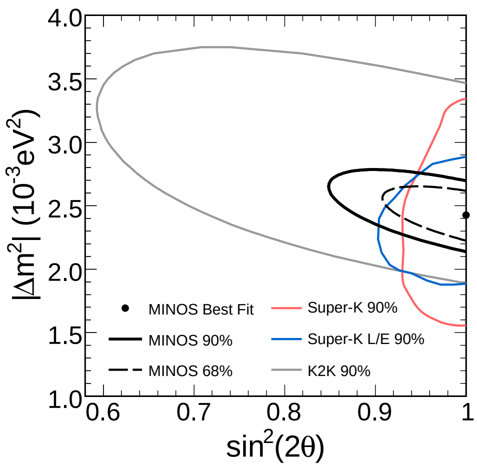

Figure 2. The allowed region in oscillation parameter space for the data in Fig. 1, at 90% (solid black) and 68% (dashed black) confidence levels. Two Super-K atmospheric analyses are shown in red [3] and blue [2], and the K2K long baseline experiment results produce the grey contour [5].

2.2. Anti-neutrinos

The magnetized nature of the MINOS detectors allows the event-by-event determination of the charge sign of muons, and thus the identification 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 in Sec. 2.1, and if some fraction α of disappearing ν_μ reappear as $\bar{\nu}_\mu$ – both tests of CPT conservation. Given that only 6.4% of the neutrino events in a 3.2×10^{20} pot far detector exposure are due to anti-neutrinos, the relative backgrounds are higher and statistics lower. 42 $\bar{\nu}_\mu$ events are seen while $64.6 \pm 8.0_{stat} \pm 3.9_{syst}$ are expected in the no-oscillation case, and $58.3 \pm 7.6_{stat} \pm 3.6_{syst}$ if CPT is conserved given the observed ν_μ oscillation parameters. This places a 90%cl upper limit on $\alpha < 0.026$, and the anti-neutrino oscillation parameters are consistent with the neutrino parameters given these low statistics. The next year of NuMI beam running will be optimized to produce anti-neutrinos to better understand anti-neutrinos.

2.3. Sterile Neutrinos

Another possible explaination of the ν_μ disappearance is oscillation into sterile neutrinos which experience no interactions. This would suppress the rate of NC events in the far detector compared to the traditional explanation of sub-threshold ν_τ, since ν_τ still undergo NC interactions. Thus, NC showers have been selected from an exposure of 3.18×10^{20} pot, following the analysis outlined in [6].

The ratio of observed to expected NC events in the far detector is $R = 1.04 \pm 0.08_{stat} \pm 0.07_{syst} - 0.10_{\nu_e}$, resulting in a limit on the fraction of ν_s participation of $f_s < 0.51$ at 90%cl.

2.4. The Search for ν_e Appearance

MINOS was designed to be a good muon calorimeter for ν_μ disappearance, but is coarse for resolution of ~GeV electromagnetic showers. It retains sensitivity to the ~2% ν_e appearance signal which a θ_{13} near the CHOOZ limit [7] would create, and the first 3.14×10^{20} pot of MINOS data have been examined [8] by a neural network to select electromagnetic shower candidates. When applied to Monte Carlo data this is 41% efficient while rejecting >92% of NC showers (the dominant background) and >99% of ν_μ charged current ("CC") interactions (high-y hadronic showers). Given the small expected signal and large uncertainties in hadronic shower modeling, data-driven methods are used to better estimate the background. At the near detector no oscillation has yet occurred, so with the exception of the well-modeled inherent beam ν_e, all events selected must be examples of such background events. This yields an expected background of 26.6 (18.2 NC, 5.1 CC, and 2.2 beam ν_e) at the far detector, while 35 ν_e like events are seen, a 1.5 σ excess (including 7.3% statistical and 19% systematic errors) (Fig. 3). If fit for oscillations, this is just below the CHOOZ limit and consistent within errors with no ν_e appearance.

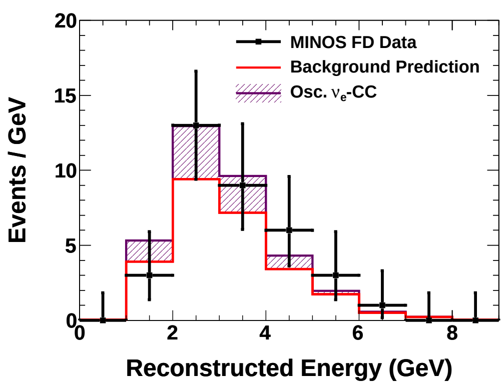

Figure 3. The spectrum of potential ν_e interactions in the MINOS far detector, with statistical plus systematic error bars [8]. The 1.5σ excess is consistent with both the expected large background (red) and a $\sin^2(2\theta_{13})$ comparable to the CHOOZ limit [7] (purple).

3. Conclusions

MINOS has measured neutrino oscillation parameters in the "atmospheric" $\nu_2 \leftrightarrow \nu_3$ sector with high precision, favoring standard $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. Further statistics will be of great interest to investigate the possibility of ν_e appearance just under the CHOOZ limit.

Acknowledgments

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