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Recent Results and Future Prospects From MINOS

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Abstract

The MINOS experiment uses the intense NuMI beam created at Fermilab and two magnetized tracking calorimeters, one located at Fermilab and one located 735 km away at the Soudan Mine in Minnesota, to make precise measurements of ν_μ disappearance oscillation parameters. We present recent results from the first two years of NuMI beam operations, including the precise measurement of the atmospheric neutrino oscillation parameters and the search for sterile neutrinos. Future prospects for MINOS will also be discussed, including an improved limit on the θ_{13} mixing angle by searching for ν_e appearance in the ν_μ beam.

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The Main Injector Neutrino Oscillation Search (MINOS) experiment was designed to primarily confirm neutrino oscillations by allowing a precise measurement of the atmospheric neutrino oscillation parameters Δm^2 and $\sin^2(2\theta)$. MINOS is also capable of searching for sterile neutrinos and the subdominant $\nu_\mu \rightarrow \nu_e$ oscillation.

MINOS utilizes the intense Neutrinos at the Main Injector (NuMI) beam at Fermi National Laboratory. A very pure beam of muon neutrinos is aimed at an underground laboratory 735 km from the NuMI production target in Soudan, MN, where a 5.4 kton magnetizied iron tracking calorimeter (the Far Detector, FD) is used to detect the neutrinos[1]. A functionally identical 0.98 kton Near Detector (ND) is located approximately 1 km downstream from the NuMI target.

The measurement of the atmospheric neutrino oscillation parameters Δm^2 and $\sin^2(2\theta)$ is accomplished by comparing the measured muon neutrino energy spectra in the ND and FD. Charged-current (CC) interaction events are separated from neutral-current (NC) events in the detectors based on topological characteristics that indicate a muon in the final state: track length, mean pulse height, fluctuation in pulse height and transverse track profile. A CC/NC separation parameter cut is determined that maximizes the CC event selection efficiency and minimizes the NC background[2].

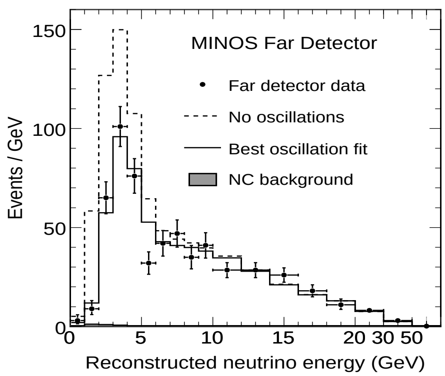

Fig. 1. Measured ν_μ energy spectrum in the MINOS FD (black points), compared to the expected spectrum for the case of no oscillations.

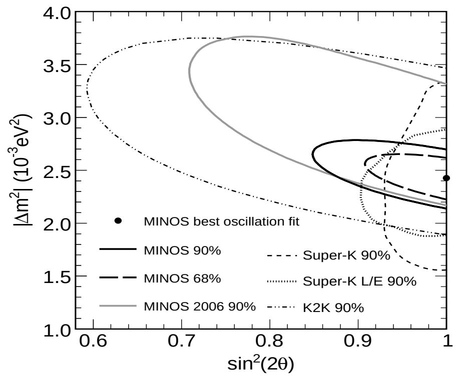

Fig. 2. 68% and 90% contour lines for the oscillation fit parameters Δm^2 and $\sin^2(2\theta)$ compared to other experimental measurements.

The energy spectrum for CC events is measured in the ND and extrapolated to the FD. The extrapolation method uses MC to determine energy smearing and acceptance corrections for the expected FD energy spectrum. The dominant systematic uncertainties in the predicted FD spectrum are a 4% normalization uncertainty, a 10.3% hadronic energy calibration uncertainty and a 50% uncertainty on the NC background that pass the CC cut selection criteria. The normalization and hadronic energy uncertainties primarily effect the measurement of Δm^2 at the level of $\pm 0.081 \times 10^{-3}$ eV^2 and $\pm 0.052 \times 10^{-3}$ eV^2 respectively. The NC background is the largest effect on the measurement of $\sin^2(2\theta)$ at the level of ± 0.016.

Fig. 1 shows the measured FD energy spectrum, the expected spectrum with no oscillations, the best oscillation fit to the data, and the NC background (significant only in the lowest energy bin). A total of 848 events are observed in the FD, with 1065 ± 60 events expected under the no-oscillation hypothesis for a data set based on 3.36×10^{20} protons on target (POT). Fitting the observed energy spectrum to the survival probability, and constraining the fit parameters to their physically meaningful values, we find $\Delta m^2 = 2.43 \pm 0.13 \times 10^{-3}$ and $\sin^2(2\theta) > 0.90$ (90% CL), with a $\chi^2/ndof = 90/97$. Fig. 2 shows the oscillation parameter phase space allowed by the latest MINOS measurement, with comparisons to other experiments and the previous MINOS measurement. Alternative hypotheses of neutrino decay[3] and neutrino decoherence[4] have also been tested with the MINOS data, and these are disfavored with respect to the osciallation hypothesis by 3.7σ and 5.7σ respectively.

Since the NC event rate is independent of neutrino flavor, and thus unaffected by oscillations between the three active neutrino flavor states, a deficit in the NC rate in the FD would indicate the existence of at least one additional sterile neutrino (ν_s). The visible energy spectrum of NC (shower-like) events in the ND is extrapolated to the FD in search for such a deficit.

Fig. 3 shows the measured visible energy spectrum in the FD, based on 2.46×10^{20} POT, along with the expected spectra for θ_{13}=0 and θ_{13} at the Chooz limit[5] and the predicted

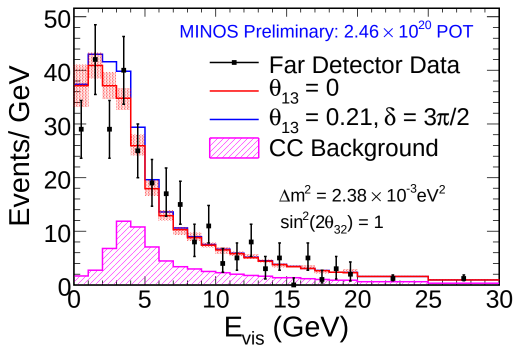

Fig. 3. Visible energy spectrum for NC events in the FD compared to the dominant CC ν_μ background and predicted spectra for θ_{13}=0 and θ_{13} at the Chooz limit.

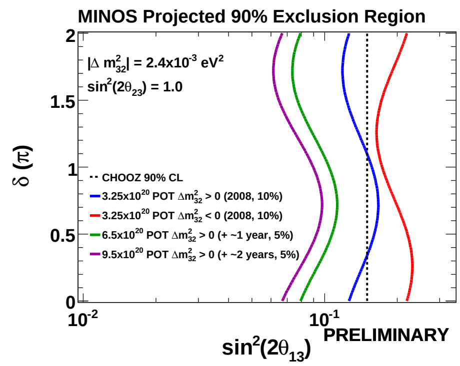

Fig. 4. MINOS sensitivity to $\sin^2(2\theta_{13})$ for various data sets. The current data set will produce a sensitivity roughly equal to the current best limit (solid black line).

ν_μ CC event background. The quantity $f_s = (P_{\nu_\mu \to \nu_s})/(1 - P_{\nu_\mu \to \nu_\mu})$ describes the fraction of ν_μ that have oscillated to ν_s in a simple four-flavor model where oscillations to sterile neutrinos ocurr at the same mass splitting as the ν_μ disappearance measured from the CC interactions. For the case of θ_{13}=0, $f_s = 0.28^{+0.25}_{-0.28}$ (stat. + syst.) or $f_s < 0.68$ (90% CL). For the case of θ_{13} at the Chooz limit, $f_s = 0.43^{+0.23}_{-0.27}$ (stat. + syst.) or $f_s < 0.80$ (90% CL) [6].

An excess of ν_e events in the MINOS FD would indicate $\nu_\mu \to \nu_e$ oscillations and a non-zero value for the θ_{13} oscillation term. CC ν_e events in the MINOS detectors are tagged by searching for events that have electromagnetic shower profiles in the final state. The CC ν_e events appear very similar to NC events which are the dominant background, although low-energy CC ν_μ events also contribute significantly to the background in this measurement. For a data set based on 3.25×10^{20} POT, approximately 12 CC ν_e events are expected in the FD with 42 background events.

Fig. 4 shows the MINOS sensitivity to $\sin^2(2\theta_{13})$ as a function of the CP violating phase δ. With the current data set being analyzed based on 3.25×10^{20} POT, the sensitivity of the MINOS measurement is roughly that of the current best limit; within about a year, we expect an improvement in the limit by about a factor of two based on a doubling of statistics and a reduction by 50% of the estimated backgrounds. We expect to present first results on the search for ν_e appearance in the MINOS detectors by spring of 2009.

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