MINOS Experiment at Fermilab

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Abstract

MINOS is a two-detector experiment to study neutrino oscillations in the NuMI high-intensity neutrino beam at the Fermi National Accelerator Laboratory. Results on ν_μ disappearance, ν_e appearance, sterile neutrino mixing (ν neutral current 'disappearance'), and $\bar{\nu}_\mu$ disappearance are summarized for an exposure of $\approx 3 \times 10^{20}$ protons on target. Data from a 7×10^{20} POT exposure already in hand are being analyzed.

1 Introduction

MINOS (**M**ain **I**njector **N**eutrino **O**oscillation **S**earch) is a long-baseline experiment running at Fermilab since 2005 in the intense NuMI (**Neu**trinos at the **M**ain **I**njector) beam. The 1-kton **N**ear **D**etector (ND) is located 1 km from the target at Fermilab, and the 5.4 kton **F**ar **D**etector is located 735 km away, 700 m underground, in the Soudan Underground Mine State Park in Soudan, Minnesota. Both detectors constist of 2.54-cm thick steel planes interleaved with solid-scintillator planes composed of scintillator strips with a rectangular cross-section of 4.1×1 cm^2. Each strip has a wavelength-shifting optical fiber embedded that is read out by a multianode photomultiplier tube. Both detectors are magnetized to 1.3 T.[1]

All results reported here were obtained using the methodology of blind analysis.

In addition to studying oscillations, the large-statistics data sample of ν interactions in the Near Detector is being analyzed for various aspects of non-oscillation neutrino physics.

2 ν_μ Disappearance

A multivariate 'k-nearest-neighbors' algorithm was used to separate ν_μ **C**harged-**C**urrent (CC, final-state muon track present) and **N**eutral-**C**urrrent (NC, final-state muon track absent) interactions for this analysis. The resulting CC sample had an NC background of only 0.6%.

As the neutrino energy, E_ν, distributions differ by 20% due to meson-decay kinematics, beamline geometry and detector acceptance, care has to be taken when extrapolating the ND spectrum to the FD to provide the expected 'no-oscillations' spectrum. For the CC analysis, the differences between ND and FD distributions were encoded into a Beam Transfer Matrix using Monte Carlo simulation.

The ν_μ CC data set included both Low-Energy (LE) and High-Energy (HE) beam data from an exposure of 3.36×10^{20} **P**rotons **O**n **T**arget (POT). MINOS observed 848 events in 3.36×10^{20} POT, while 1065 ± 60 events were expected with no oscillations. The ν_μ CC disappearance was confined to $E_\nu < 10$ GeV. When analyzed within the framework of two-neutrino mixing, $\nu_\mu \rightarrow \nu_\tau$, the MINOS data yielded the following limits on the mixing parameters: [2] $|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 at the 68% C.L., and $\sin^2(2\theta) > 0.95$ at the 68% C.L. (and > 0.90 at 90% C.L.). The fit had $\chi^2/N_{DoF} = 90/97$.

The same data disfavor a pure decay as a reason for the ν_μ disapppearance at 3.7σ. (It is 5.4σ when CC and NC data are combined.) Pure decoherence is disfavored by the CC data at 5.7σ.

3 ν_e Appearance

Search for ν_e appearance represents an attempt to find a small signal in the presence of a large background. The MINOS ν_e analysis group developed the following strategy for the task: *(i)* Select ν_e CC candidate events in both MINOS detectors; *(ii)* Selected 'ν_e' events in the Near Detector are all background - misidentified NC events, misidentified high-y ν_μ CC events, and intrinsic beam ν_e interactions; *(iii)* Extrapolate the number of background events to the Far Detector taking into account $\nu_\mu \rightarrow \nu_\tau$ oscillation for the ν_μ CC background; *(iv)* Look for an excess of ν_e CC events in the FD data.

Event selection, including preliminary cuts (track length < 25 planes, $1 < E_\nu < 8$ GeV, shower present) and an applicaton of the Artificial Neural Network algorithm, leads to reduction of the Signal-to-Background ratio from 1:55 to 1:4. To measure the composition of the background, MINOS is using a data-based method utilizing different NC and CC content in the Horn-on and Horn-off beam configuration. The resulting composition was found to be (57±5)% NC, (32±7)% CC, and (11±3)% beam ν_e at the Near Detector. This background was propagated from the ND to the FD yielding an expected background in the Far Detector of 27±5(stat)±2(sys) for an exposure of 3.14×10^{20} POT. [1]

The signal determination algorithm was established prior to "Blinded Box" opening by maximizing the Figure of Merit, $FOM = Signal/\sqrt{(Background + \sigma^2_{syst})}$. MINOS observed 35 events in the FD after selection, representing an 'excess' of 1.5σ over the expected background. When fitted to the $\nu_\mu \rightarrow \nu_e$ oscillation hypothesis, this excess yields 90% C.L. contours in δ_{CP} vs. $\sin^2(2\theta_{13})$ depicted in Fig. 1 for both normal and inverted neutrino mass hierarchy.

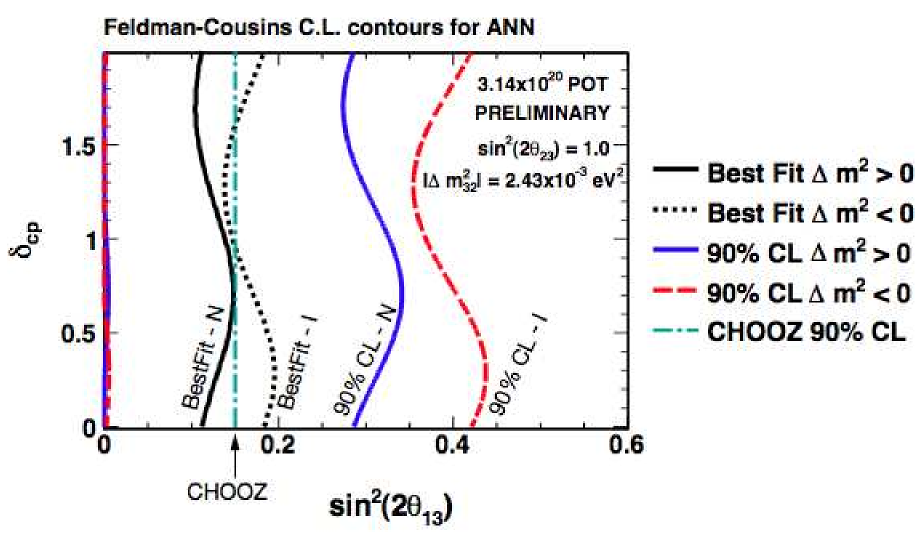

Figure 1: MINOS ν_e appearance contours: 'N' = Normal Hierarchy, 'I' = Inverted Hierarchy.

[1]Alternate algorithms for event selection and bckground decomposition yielded values compatible with the results given here.

4 Neutral-Current disappearance and ν_s mixing

The MINOS NC analysis group looked for a dearth of NC neutrino interactions at the FD as a possible indication of sterile neutrino mixing. As the NC interaction rates are the same for all active ν flavors, the oscillations among the active flavors do not affect the NC spectrum. The ν_s would not interact in the detector, hence the ν_s footprint would be an energy-dependent depletion of the NC spectrum at the FD.

The analysis is cut based, and any remaining CC background is straightforward to estimate. The final NC sample was selected with an efficiency of 90% and purity of 60%. Extrapolation from ND to FD used the "Far/Near" method, $FD_i^{predicted} = (FD_i^{MC}/ND_i^{MC})ND_i^{data}$ in bins of E_ν.

For a beam exposure of 3.18×10^{20} POT, MINOS observes 388 events in the FD, when 377±19(stat)±18(syst) events were expected. indicating that the data is consistent with no NC disappearance. (This result updates report [3] describing a 2.46×10^{20} POT data set.)

5 $\bar{\nu}_\mu$ Disappearance

In the NuMI beam running in the "Forward-Horn-Current" LE configuration, 91.7% of the beam neutrinos are ν_μ, however, the beam also contains 7.0% $\bar{\nu}_\mu$, the remainder being electron flavored ν. The ν_μ energy distribution is optmized for studying oscillations (peak at 3 GeV), while the $\bar{\nu}_\mu$ energies are higher, with a peak at 8 GeV - not optimal for measuring $\bar{\nu}_\mu$ oscillation, that is. But MINOS tried anyway.

The $\bar{\nu}_\mu$ analysis group devised an event selection suitable to minimize the background of misidentified ν_μ CC events (μ^- misidentified as $\mu+$) and NC events (π^+ misidentified as μ^+). This selection had an efficiency of 80% and purity of 95%. The selected data were then extrapolated from ND to FD via the Beam Transfer Matrix method. The MINOS $\bar{\nu}_\mu$ data sample at the FD had 42 events for a LE beam exposure of 3.2×10^{20} POT. The prediction was 64.6±8.0(stat)±3.0(syst) events in the case of null oscillations, and 58.3±7.6(stat)±3.6(syst) events for oscillation parameters measured by MINOS for ν_μ oscillations.

This represents the first direct observation of $\bar{\nu}_\mu$ disappearance of an accelerator long-baseline experiment. The difference between the fractions of ν_μ and $\bar{\nu}_\mu$ events that 'disappeared' is 1.9σ. Extensive checks did not yield any evidence for a bias in the $\bar{\nu}_\mu$ event count. When analyzed in terms of the oscillation parameters $|\Delta m^2|$ and $\sin^2(2\theta)$, the best-fit point for ν_μ (see Section 2) was found to lie within the 90% C.L. contour obtained for the $\bar{\nu}_\mu$ oscillations.

6 Conclusions

All MINOS physics groups are in the process of improving their software, both for data analysis and for simulation, to prepare for processing a new data set representing a beam exposure of 7×10^{20} POT, already on hand. The data taking will commence again in October 2009 in a Reverse-Horn-Current Low-Energy beam configuration to provide $\bar{\nu}_\mu$ data in the energy range appropriate for the study of antineutrino oscillations.

References

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[2] MINOS Collaboration, P. Adamson *et al.*, *Phys. Rev. Lett.* 101 (2008) 131802

[3] MINOS Collaboration, P. Adamson *et al.*, *Phys. Rev. Lett.* 101 (2008) 221804