Results from the First Year of MINOS Data with Accelerator Neutrinos

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Abstract. Reported here are results, which have been published in [6], from the MINOS experiment from its first year of data-taking with neutrinos from Fermilab's NuMI beam. During this period, 1.27×10^{20} protons were delivered to the neutrino target. MINOS consists of two detectors, located 1 km and 735 km from the neutrino beam origin. A deficit of ν_μ neutrinos are observed in the far detector, with only 215 events observed below 30 GeV, compared to 336±14 events expected in the absence of neutrino oscillations. The data are consistent with neutrino oscillations with $|\Delta m^2_{23}| = 2.74^{+0.44}_{-0.26} \times 10^{-3}$ eV^2 and $\sin^2(2\theta_{23}) > 0.87$, at the 68% confidence level.

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INTRODUCTION

Over the past decade, compelling evidence for neutrino flavor change has emerged. The flavor change is well described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, which describes a rotation between the neutrino mass and flavor eigenstates[1][2]. This matrix contains 3 angles and one phase. The probability of observing a neutrino in a given flavor state depends on this matrix and on the differences between the neutrino masses. In the limit of two-neutrino flavors, the survival probability of a neutrino of flavor ν_α is

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

where θ is the mixing angle, Δm^2 is the difference in the squares of the neutrino masses in eV$^2/c^4$, L is the distance the neutrino has travelled in km, and E is the neutrino energy in GeV.

MINOS (Main-Injector Neutrino Oscillation Search) was designed to study changes in the flavor composition of neutrinos over a long distance, using a beam of primarily muon neutrinos produced at Fermilab. The experiment uses two detectors, located at very different distances from the neutrino production point. Unexpected differences in the neutrino energy distributions recorded in the two detectors point to neutrino flavor changes. Muon neutrino disappearance in a L/E range comparable to that of MINOS has previously been observed in atmospheric neutrinos[3] [4], and in accelerator-produced neutrinos[5]. The results reported here from MINOS on the disappearance of muon neutrinos have been published in [6].

NEUTRINO BEAM

MINOS utilizes NuMI (Neutrinos at the Main Injector) beam at Fermilab, which is initiated by 120 GeV protons striking a graphite target. The resulting positively-charged secondary particles are focussed by two magnetic horns, and are allowed to decay inside a 675 m long evacuated pipe. The beamline points down into the earth at approximately 3.3 degrees, towards the far underground site in Soudan, Minnesota. The neutrino energy of the beam peaks between 3 and 4 GeV and is initially composed of approximately 92.9% ν_μ, 5.8% $\bar{\nu}_\mu$, 1.2% ν_e, and 0.1% $\bar{\nu}_e$. Each beam spill is 10 μs in duration, and one spill occurs approximately every 2 to 3 seconds.

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DETECTORS AND BEAM TUNING

MINOS has two detectors: a 1 kton near detector at Fermilab that sits 1 km from the target, and a far detector located 735 km from the target, in the Soudan Mine. Both detectors use the same media to detect neutrinos. Each detector is composed of alternating layers of 2.54 cm thick steel and 1 cm thick plastic scintillator. Current-carrying coils running through the detectors create a toroidal magnetic field in the steel plates, with an average magnetic field of 1.3 T. The scintillator is divided into 4.1 cm wide strips. The light produced when a charged particles passes through a scintillator strip is collected by a wavelength-shifting fiber running through a groove in the strip. The fibers are coupled to multi-anode Hamamatsu PMTs. The far detector, composed of 486 octagonal steel plates that are each 8 m wide, is 705 m underground, and has a total mass of 5.4 ktons. The near detector, with its 282 "squashed-octagonal" steel plates, has a total mass of 1 kton, and is located 103 m underground. The near detector sees tens of neutrino interactions per beam spill, and its 19 nsec timing resolution allows the individual events to be separated.

The pattern of hit scintillator strips in the detector resulting from a neutrino interaction are reconstructed into tracks and showers. The total reconstructed energy is the sum of the track energy (obtained from the track length in the detector or the track curvature) and the visible shower energy. A 60-plane calibration test detector[7] was placed in test beams at the CERN PS to determine the energy scale for electrons, muons, and hadrons. Stopping cosmic-ray muons are used provide the strip-to-strip calibrations for the scintillator, as well as to determine the relative near/far energy scale. The hadronic shower resolution is approximately 2%+56%/$\sqrt{E}$, while the electromagnetic shower resolution is approximately 4.1%/E + 21%/$\sqrt{E}$. The muon energy resolution in the detectors is approximately 6% for the energy determined from track range (for muons that stop in the detector) and is approximately 13% for the energy determined from the track curvature.

To constrain the hadron production in the target, a series of special runs were taken with the NuMI target moved from its nominal position relative to the horns or with the magnetic field in the focussing horns changed from the nominal value. By comparing the predicted and observed near detector reconstructed energy distributions, the pion and kaon yields in the target were varied as a function of their transverse and longitudinal momentum. The best fit values were obtained from a simultaneous fit to the near detector data from the nominal and special beam configurations.

DATASET AND EVENT SELECTION

The results presented here are for data collected between May 20, 2005 and March 3, 2006. During this period, the far detector was live while 98.9% of the beam was delivered, representing 1.27×10^{20} protons delivered to the target.

Charged-current ν_μ interactions, in which a muon is produced, were selected by first requiring the events to have at least one reconstructed track. Then a likelihood-based procedure was used to separate charged current (CC) and neutral-current (NC) events. The a particle identification parameter (PID) was constructed from probability density functions for 3 event quantities: the event length (in planes), the fraction of the event pulse height that was contained in the reconstructed track, and the average track pulse height per plane. Charged-current events were selected as those with a PID > -0.2 in the far detector and >-0.1 in the near detector. The efficiency of these cuts is estimated to be 87%, with a purity of 98% in the resulting selected sample.

A blind analysis was performed, with an unknown fraction of the events removed in a way that would distort the energy spectrum, until the analysis procedure was finalized. In addition to the PID cut, the events in the far detector were required to have an initial track direction within 53° of the beam direction, to begin more than 50 cm from the edges of the detector, and to fall within a -20 μs to +30 μs window around the expected beam time.

DATA ANALYSIS

A search for ν_μ oscillations can be performed by comparing the expected unoscillated event spectrum in the far detector to the observed one. The energy spectrum in the near detector is not identical to the energy in the far detector as the near detector sees the decay pipe as an extended line source, while the the far detector effectively sees a point source. A wider range of pion decay angles will produce neutrinos that reach the near detector than the far detector. To account for these spectral differences, it is necessary to extrapolate the near detector energy spectrum to the far detector. The primary method that was used in MINOS for this extrapolation was a beam matrix method. At the core of this method is a matrix that relates the probability that the underlying distribution of hadrons exiting the target yield neutrinos in an energy bin at the far detector for a given energy bin the the near detector. The events observed in the

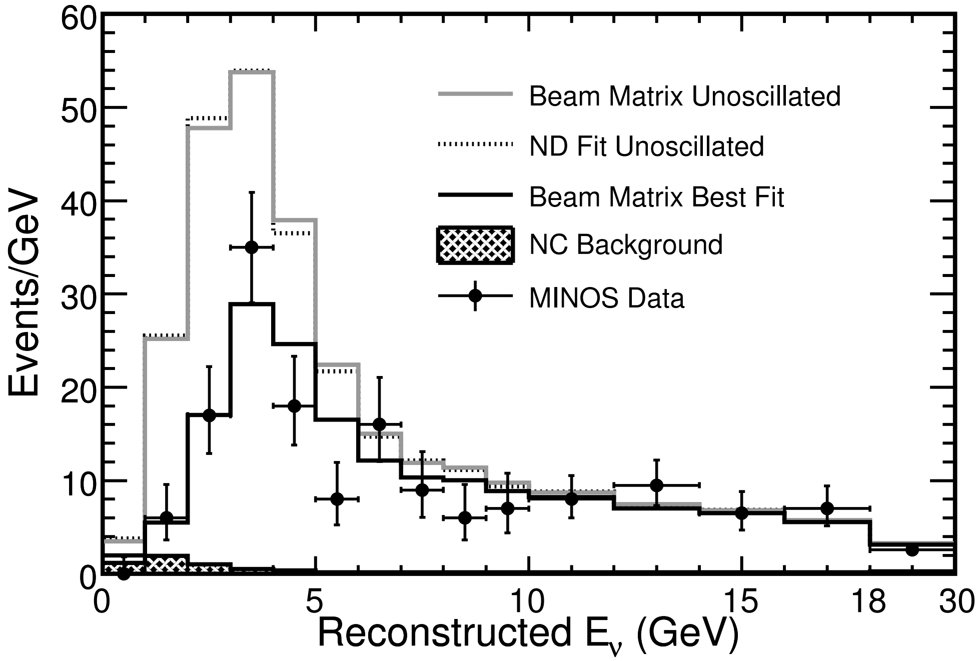

FIGURE 1. This plot shows the observed far detector event energy spectrum (the points with error bars) and two predicted far detector unoscillated energy sprectra (from the beam matrix method, described in this document, and from a near detector fit method). The last energy bin contains events from 18 to 30 GeV. Also shown, in the solid black line, is event spectrum obtained with best fit values for the oscillation parameters.

near detector are first converted into a neutrino flux, by dividing by the cross section and applying a correction for the acceptance. Then the matrix is applied to the near detector neutrino flux to yield a far detector neutrino flux. The predicted far detector event spectrum is obtained by multiplying this predicted far detector flux by the cross section and then applying the far detector predicted acceptance.

In the far detector data, 215 events were observed below 30 GeV, as compared to 336±14.4 predicted events in the absence of neutrino flavor changes. Below 10 GeV, the significance increases as 122 events were observed while 238±11 events were expected. Figure 1 shows the energy spectrum of the observed events, as well as the predicted reconstructed energy spectrum.

A fit was for Δm^2 and θ was performed within the two-flavor [2] oscillation hypothesis (following Equation 1) by minimizing the difference between the expected and predicted event spectra for a given set of Δm^2 and θ. Included in the χ^2 of the fit are 3 penalty terms corresponding to the largest sources of systematic uncertainty on the predicted far spectrum. The largest uncertainty comes from the NC background. Though the NC contamination in the CC event sample is 2% of the total selected signal, the uncertainty on this contamination has been estimated at 1%. The next largest systematic uncertainties arise from the 4% uncertainty on the near/far normalization (due to the uncertainty on the detector fiducial masses and the relative selection efficiencies), and from the uncertainty on the energy scale (dominated by the hadronic energy scale uncertainty and the uncertainty on the effects of intranuclear rescattering). The best fit values for the neutrino oscillation parameters were found to be $|\Delta m^2_{23}| = 2.74^{+0.44}_{-0.26} \times 10^{-3}$ eV^2 and $\sin^2(2\theta_{23}) > 0.87$ at the 68% confidence level. The event reconstructed energy spectrum expected for these best fit values is included in Figure 1. Figure 2 shows the resulting contours for the 68% and 90% confidence levels for the values of the oscillation parameters resulting from the fit to the MINOS data. Also included on the plot are the 90% confidence level contours from the Super-Kamiokande and K2K experiments. The MINOS best fit values are

[2] The mass difference required to explain the neutrino flavor changes seen in solar neutrino experiments [8] and long-baseline reactor neutrino experiments [9] is too small to have significant effects at the energies and distances of the MINOS experiment. So, the two-flavor assumption is adequate to describe this data.

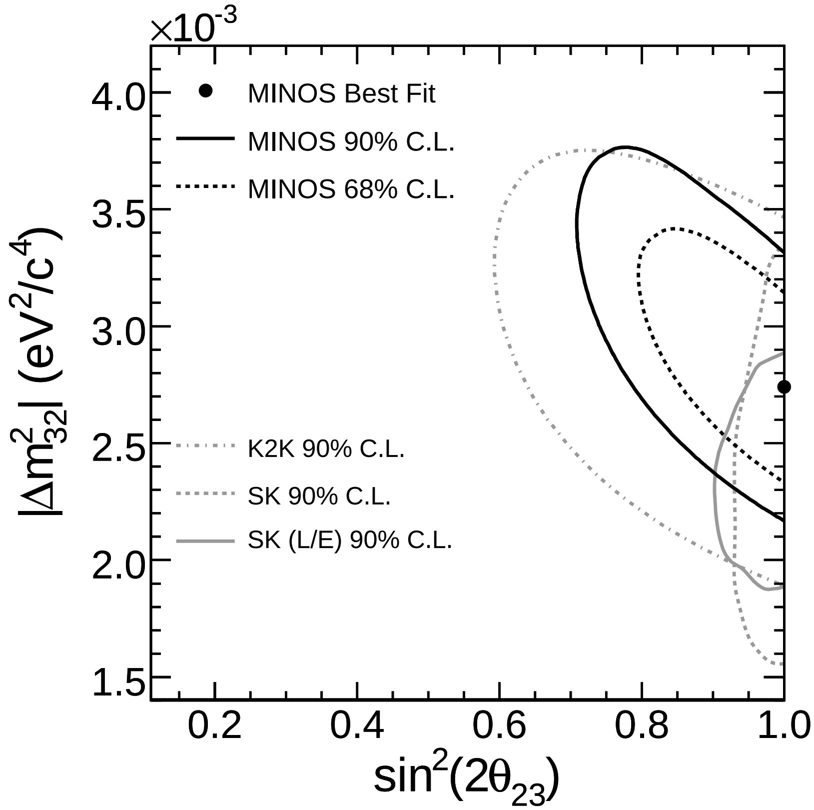

FIGURE 2. This figure shows the confidence intervals obtained for the neutrino oscillation parameters after a fit to the oscillation hypothesis. The far predicted spectrum used for this fit was obtained via the beam matrix method. Systematic errors have been included. Also shown are the contours from the Super-Kamiokande and K2K experiments.

in good agreement with the results from those experiments. MINOS will continue to collect neutrino beam data for several more years and should significantly improve on our current understanding of the value of $|\Delta m^2_{23}|$.

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