Neutrino Oscillation Results from MINOS.

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Abstract. We report an updated measurement of muon neutrino disappearance in the NuMI neutrino beam performed using the MINOS detectors. This preliminary result is based on an increased data set corresponding to $2.50 \times 10^{20}$ protons on the NuMI target, and incorporates a number of improvements to our analysis. We observe 563 candidate $\nu_{\mu}$ CC interactions in the far detector data, compared with an expectation of $738 \pm 30$ in the absence of oscillations. A maximum likelihood fit to the observed far detector energy spectrum assuming two-flavour $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations yields best fit oscillation parameters of $\Delta m_{23}^2 = 2.38_{-0.10}^{+0.20} \times 10^{-3}$ eV$^2$ and $\sin^2 2\theta_{23} = 1.00 \pm 0.08$ with errors quoted at the 68% confidence level.

1. Introduction.
MINOS is a long baseline neutrino experiment performing a precision study of neutrino oscillations using an accelerator beam of muon neutrinos. The primary aim of the experiment is to precisely determine the values of the oscillation parameters $\Delta m_{23}^2$ and $\sin^2 2\theta_{23}$ by measuring the disappearance of muon neutrinos in the beam due to the dominant $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillation mode; an additional aim is to discover or improve the limit on the mixing angle $\theta_{13}$ by searching for the appearance of electron neutrinos due to the sub-dominant $\nu_{\mu} \rightarrow \nu_{e}$ oscillation mode.

The neutrino beam is generated by the NuMI facility at Fermilab by directing 120 GeV protons extracted from the Main Injector ring onto a graphite target. The protons are delivered to the target in 10 μs spills every 2.4 seconds, with each spill containing up to $4.0 \times 10^{13}$ protons. The positively charged secondaries emitted from the target (mainly $\pi^+$ and $K^+$) are focused by two pulsed parabolic horns into a 675 m evacuated pipe where they decay to produce neutrinos. The relative position of the target and first horn, and the current through the horns, are variable and are used to configure the beam spectrum. The majority of running has been carried out in the “low energy” configuration, which optimizes neutrino production in the 1-3 GeV region, where the maximum oscillations are expected. The beam is described in detail in [1].

The NuMI beam is sampled by the two MINOS detectors. A 1 kT near detector located at Fermilab is used to measure the beam spectrum prior to oscillations; a 5.4 kT far detector constructed 735 km away at the Soudan mine is then used to measure the oscillation signal. The MINOS detectors are designed to be as functionally similar as possible in order to minimize systematic uncertainties. Both detectors are fine-grained steel-scintillator sampling calorimeters with toroidal magnetic fields. The detectors are synchronized to the beam by GPS receivers, enabling the identification of beam spills. The detectors are described in detail in [2].

The MINOS collaboration has previously reported oscillation results based on the data collected during the first period of NuMI operations between May 2005 and February 2006, which corresponded to an overall exposure of $1.27 \times 10^{20}$ protons on the NuMI target [3] [4].
Here, we report updated results on muon neutrino disappearance obtained from a re-analysis of this data set along with an additional data set collected between June 2006 and March 2007. This has increased the overall exposure to $2.50 \times 10^{20}$ protons on target.

2. Analysis Procedure.

Most aspects of the updated analysis follow on from the previous analysis. In each detector, candidate neutrino events are reconstructed from clusters of tracks and showers coincident with beam spills. A $\nu_\mu$ CC event is characterized by the presence of a muon track, with the vertex reconstructed inside the fiducial volume of the detector and the propagation direction correlated with the incoming neutrino beam. A multivariate algorithm is used to separate the $\nu_\mu$ CC events from the background of NC events using a number of event topology and kinematic variables. The neutrino energy is then reconstructed by summing the energy of the muon track with the visible energy of the hadronic system. For the preliminary results presented here, only neutrinos (tagged by a negatively charged muon) are considered.

A number of improvements have been incorporated in this updated analysis. A new track reconstruction algorithm is employed which identifies and fits an additional 4% of the muons produced by $\nu_\mu$ CC interactions. The far detector fiducial volume has also been expanded, generating a 3% increase in the event yield. The separation of the $\nu_\mu$ CC signal from the NC background is now based on an extended multivariate likelihood procedure which combines an increased number of event variables and also accounts for their correlation with event length. This new selection procedure generates a modest increase in the $\nu_\mu$ CC selection efficiency, and reduces the NC background to approximately half its previous value. The Monte Carlo simulation uses an upgraded neutrino interaction simulation featuring more accurate models of hadronization, intra-nuclear re-scattering and deep inelastic scattering. To further improve the Monte Carlo simulation, the hadron production model and other elements of the beam and detector simulation are tuned by fitting the neutrino and anti-neutrino energy spectra obtained at the near detector in different beam configurations.

An oscillation analysis is performed based on the neutrino energy spectrum in each detector. The observed far detector energy spectrum is compared with a set of oscillated predictions derived from the observed near detector energy spectrum, and a maximum likelihood procedure is used to fit the oscillation parameters. The extrapolation from the near to the far detector is performed using a beam transfer matrix derived from the tuned Monte Carlo simulation. This matrix relates neutrino interactions in the near and far detectors via their parent hadrons. The beam matrix algorithm has been cross-checked by a number of alternative extrapolation methods, and the fluctuations between different methods are found to be much smaller than the expected statistical error bands.

3. Oscillation Results.

For an exposure of $2.50 \times 10^{20}$ protons on target, a total of 563 candidate muon neutrinos are observed in the far detector data, compared with an expectation of $738 \pm 30$ for no oscillations. In the low energy region of the spectrum, the observed deficit of events is highly significant. Below 5 GeV, a total of 198 events are selected, compared with an expected 350 $\pm 14$ events. The Monte Carlo expectation for the NC contamination in this sample is $5.6 \pm 2.8$ events.

The systematic errors in the oscillation parameters resulting from uncertainties in the predicted far detector spectrum are evaluated by performing oscillation fits to Monte Carlo data sets which have the assigned uncertainties applied to them. The three largest systematic errors are found to arise from the uncertainty in the relative near to far normalization (4%), the absolute hadronic shower energy scale (10%), and the neutral current normalization (50%). These systematic uncertainties are incorporated as nuisance parameters in the oscillation fit. Our systematic studies show that this analysis is dominated by statistical errors.
Figure 1. The reconstructed charged current $\nu_\mu$ energy spectrum at the far detector, showing the prediction for the best fit oscillation parameters (red), null oscillations (black), and the observed data (points).

Figure 2. The new MINOS best fit point, along with the 68% and 90% contours. Overlaid are the 90% contours from the Super-Kamiokande zenith angle [5] and L/E [6] analyses, along with the K2K contour [7].

A maximum likelihood fit to the observed far detector energy spectrum is used to extract the oscillation parameters $\Delta m_{23}^2$ and $\sin^2 2\theta_{23}$ approximating two-flavour $\nu_\mu \rightarrow \nu_\tau$ oscillations. The best fit oscillations occur at: $\Delta m_{23}^2 = 2.38^{+0.20}_{-0.16} \times 10^{-3}\text{eV}^2$ and $\sin^2 2\theta_{23} = 1.00^{+0.08}_{-0.08}$, corresponding to $\chi^2 = 41.2$ for 34 degrees of freedom. The quoted uncertainties represent the 68% confidence intervals and are estimated from the parameter values that increase the $\chi^2$ by one unit relative to the best fit value when minimized with respect to all the other parameters.

Figure 1 shows the predicted far detector spectrum for the best fit oscillation parameters (red), and without any oscillations (black), compared to the spectrum observed for the data (points). The characteristic dip expected for neutrino oscillations is evident in the data.

Figure 2 shows the best fit point and 68% and 90% confidence intervals in oscillation parameter space, calculated in the approximation of Gaussian errors. We have confirmed the coverage of these confidence intervals using the unified approach of Feldman and Cousins [8]. A more detailed description of the preliminary results reported here can also be found in [9].

We are currently analysing the full data set collected in the first two years of beam running, corresponding to an exposure of $3.5 \times 10^{20}$ protons on the NuMI target.

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