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RECENT RESULTS FROM THE MINOS EXPERIMENT [1)]

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Abstract

MINOS is a long baseline neutrino oscillation experiment. Protons from the Fermilab main injector are used to generate an intense muon neutrino beam, which is directed at the Soudan underground laboratory in Northern Minnesota. The result from two years of running with a total exposure of 2.5×10^{20} protons on target from the NuMI beam is reported. We made a preliminary measurement by comparing the event rate and energy spectra of charge current muon neutrino interactions in the two detectors, which are 1 and 735 km from the neutrino production target. The data is consistent with ν_μ to ν_τ oscillation in the so-called atmospheric parameter range with $\Delta m^2 = (2.38^{+0.20}_{-0.16}) * 10^{-3}\mathrm{eV}^2$ and $\sin^2 2\theta = 1_{-0.08}$.

1 Introduction

There is now substantial evidence that neutrinos oscillate [2]. This oscillation requires having a distinct set of mass and flavour eigenstates, which are related by the PMNS matrix [3, 4]. The parameters of neutrino oscillation are 3 mixing angles, a CP-violating phase and the two mass differences between the 3 mass eigenstates. The Main Injector Neutrino Oscillation Search (MINOS) has been designed to study the flavour transitions of neutrinos produced by the .Neutrinos at the Main Injector. (NuMI) beam line at the Fermi Nation Accelerator Laboratory (FNAL). MINOS employs two detectors, one on the FNAL campus only 1 km from the neutrino production target, the other in the Soudan Underground Laboratory, a further 734 km away in northern Minnesota. From the comparison of the reconstructed neutrino energy spectra and event rates at both locations the oscillation parameters Δm^2 and $\sin^2 2\theta$ are extracted.

1.1 The Beam

The NuMI neutrino beam is produced by depositing around $2.5 * 10^{13}$ protons, with energy of 120 GeV each, every 2-3 s onto a 94 cm long, segmented carbon target. The protons are bent downward 58 mrad to point toward both MINOS detectors and are delivered in 10 μs spills. The positively charged particles produced in the target are focused by two magnetic horns into the 675 m long evacuated decay pipe, where they are allowed to decay to produce neutrinos. The target position relative to the first horn and the horn current are variable to allow particles of different momenta to be focused into the decay volume, thus allowing modification of the neutrino energy spectrum. The recorded neutrino interactions are predicted to be 92.9% ν_μ, 5.8% $\bar{\nu}_\mu$, 1.2% ν_e and 0.1% $\bar{\nu}_\mathrm{e}$. For the results reported here, the target was inserted around 25 cm into the horn yielding a peak in the neutrino energy spectrum in the 2-6 GeV range. A total of $2.5 * 10^{20}$ protons on target were taken in this position between May 2005 and April 2007. This roughly doubles the statistics in comparison with the result we published earlier [5].

1.2 The Detector

Both MINOS detectors [6] are iron/scintillator tracking calorimeters with an average toroidal magnetic field of 1.3 T. The iron planes are 2.54 cm think and are interleaved with scintillator planes. The scintillator are made up of 4.1 cm wide and 1 cm thick, TiO_2 coated extruded plastic scintillator strips, which are up to 8 m long. The light produced in the scintillator is captured by 1.2 mm wavelength shifting fibers, which are imbedded in a groove along the scintillator and is guided to multi-anode photomultiplier tubes (PMTs). The planes are

oriented 45° from the vertical and 90° with respect to the previous plane. The 5.4 kton far detector (FD), situated around 700 m underground in the Soudan underground laboratory, has 484 octagonal 8 m wide instrumented planes read out at both ends via Hamamatsu M16 PMTs [7] and custom electronics [8]. Eight WLS fibers from strips separated by about 1 m are coupled to a single PMT pixel. The coupling pattern is different on both sides of the detector to allow the resolution of ambiguities. The MINOS near detector (ND), 100 m underground, has a total mass of 0.98 kton and is located at the Fermi National Accelerator Laboratory close to Chicago. In order to cancel uncertainties in the neutrino interaction and detector modeling, the two detectors have been built as similar as possible. However, the event rate in the ND is $\sim 10^5$ higher than in the FD, which required some design difference between them. The geometry of the ND has been optimized to contain hadronic showers, while at the same time providing sufficient flux return to achieve a magnetic field similar to the FD. The steel planes have the same thickness as the FD, but are 282 irregular 4×6 m^2 octagons. The scintillator strips have identical cross section and are coupled via WLS fibers to one pixel of a Hamamatsu M64 PMT [9]. The ND readout system [10] is dead-timeless during the spill and integrates the PMT charges at a rate of 53.1 MHz. Minimum ionizing particles produce 6-7 photoelectrons in both detectors. The data acquisition system accepts data above a threshold of around 0.25 photo-electrons. In the FD, the events are recorded in a window of 100 μs around the beam spill, while in the ND, all data is retained during the spill. The trigger efficiency is expected to be 100% for neutrino events with a visible energy above 0.5 GeV.

The detectors are calibrated using an in-situ light injection system and cosmic ray muons. The LED light, which is monitored by PIN diodes is injected into the WLS fibers and tracks the changes in PMT and electronics response on short to medium timescales. The energy depositions of through going cosmic muons are used to calibrate the relative response of the individual strips in each detector. Stopping muons are used to fix the relative energy scale of the two detectors, which is known to about 3%. The energy scale of single hadrons and electrons was determined from the results of an experiment using a smaller un-magnetized copy of the MINOS detector in a test-beam at CERN. The uncertainty of the absolute hadronic energy scale is estimated to be 6%.

Neutrino production is calculated using a FLUKA [11] simulation of the hadron production in our carbon target. These simulations have an uncertainty of $20-30\%$ stemming from the lack of relevant hadron production data in thick targets. Particles are tracked through the horn and decay pipe using a GEANT3 [12] based simulation. Neutrino interactions in the MINOS detector is simulated using a tuned version of NEUGEN3 [13]. CC production cross sections below 10% have an uncertainty at the 20% level. The products of

the neutrino interaction are propagated out of the iron nucleus using the INTRANUKE [14] code. The response of the detector is modeled using GEANT3 with the GCALOR model to simulate hadronic interactions. The effect of photon propagation, transmission through the WLS fiber, the PMT, and the electronics is also taken into account.

2 Data Reconstruction

The initial step in the reconstruction of the FD data is the removal of the eight-fold hit-to-strip ambiguity using information from both strip ends. In the ND, timing and spatial information are first used to separate individual neutrino interactions from the same spill. Subsequently, tracks are found and fitted and showers are reconstructed in the same way in both detectors. For muon neutrino CC events, the total reconstructed event energy is obtained by summing the muon energy and the visible energy of the hadronic system. The FD data set was left blind until the selections and analysis procedure was understood and fixed. The blinding procedure hid a substantial fraction of the FD events, with the precise fraction depending on the event length and energy being unknown. CC muon neutrino interactions were selected by requiring negatively charged tracks with a vertex in the fiducial volume. The event time must be within 50 μsec of the spill time corrected for the time of flight. Cosmic ray events were further suppressed in the FD by requiring the track to point within 53° of the neutrino beam direction. A new particle identification parameter (PID) incorporating one and two dimensional probability density functions for the event length, the number of planes with just a reconstructed track, the average energy depositions along the track and the hadronic energy fraction were used to separated muon neutrino interactions from the NC background.

3 Data Analysis

To constrain hadron production in the NuMI target, a series of six runs with similar exposure was taken where the target position and the magnitude of the horn current, i.e. its magnetic field, was varied. Comparing the reconstructed energy spectrum of CC event in the ND with the prediction of the FLUKA based hadron production model showed an energy dependent discrepancy that changed with the beam settings and thus implying that the primary effect is cased by beam modelling, rather than detector or cross section effects. To bring data and MC into better agreement, we re-tuned the hadron production cross section as a function of longitudinal and transverse momentum, thus changing the pion and kaon production yields. In addition, potential systematic effects as beam focussing, NC background and reconstruction energy scales and offsets were allowed to vary within their uncertainties. All fitted parameters were

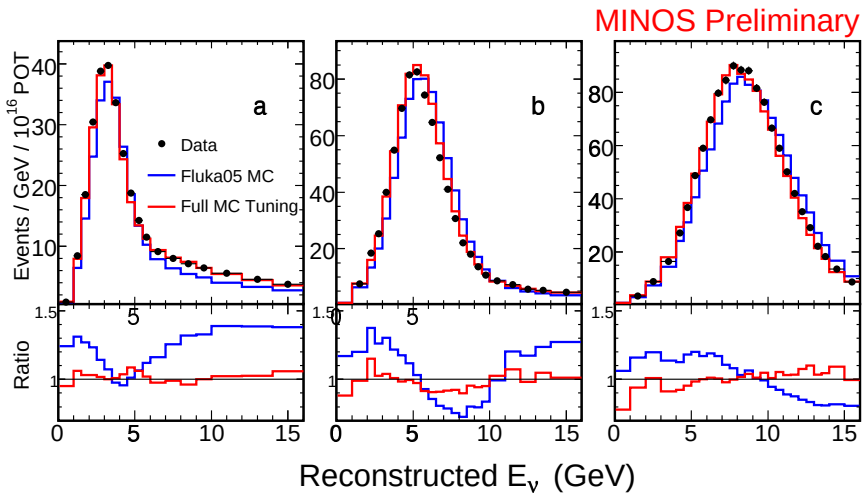

Figure 1: *Comparison of the ND energy spectrum for different beam sittings with the MC expectations before and after tuning of the hadron production parameters.*

found to agree well with our expectations and the resulting energy spectrum agrees well with the ND data. (See Fig. 1)

The measured ND neutrino energy spectrum is used to predict the un-oscillated spectrum at the FD. The oscillation hypothesis is tested relative to this prediction. The prediction takes into account the ND and FD spectral differences that are present, even in the absence of oscillations, due to pion decay kinematics and beamline geometry. The shape differences are up to 20% on either side of the peak. We have used the so called Beam Matrix method [5], in which the agreement between data and MC is not very important as the ND data itself is used to predict the FD energy spectrum. It corrects for all effects which are common to both detectors such as beam modeling, neutrino cross sections and detector response. It utilizes the beam simulation to derive a transfer matrix that relates the neutrinos in the two detectors via their parent hadrons. The matrix elements M_{ij} give the relative probability that the distribution of secondary hadrons which produce neutrinos of a certain E_i in the ND will produce a neutrino of energy E_j in the FD. The reconstructed ND energy spectrum is first translated into a flux using efficiencies, resolution and background estimations for the ND MC. This flux is multiplied by the matrix to yield the predicted un-oscillated FD flux, which is translated into the reconstructed FD energy spectrum using the FD MC simulation. A clear

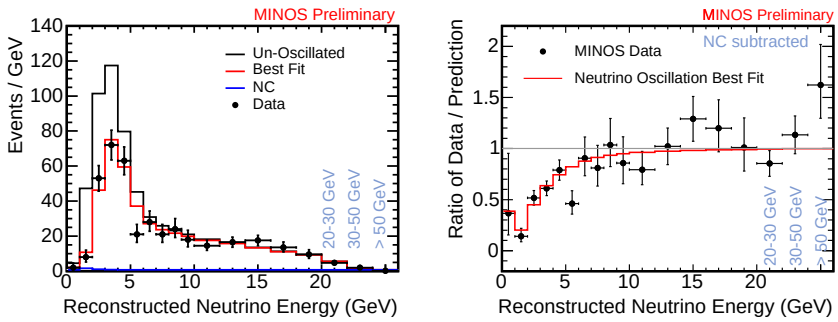

Figure 2: *The left plot shows the reconstructed energy spectrum of the selected muon neutrino charge current events together with the expected un-oscillated prediction from the near detector and the best fit oscillation result. The right hand plot shows the ratio of the date and oscillated MC to the un-oscillated prediction. One can clearly see that the data nicely follows the expectation from neutrino oscillations.*

deficit of neutrinos was observed, which was concentrated at low reconstructed energies. Under the assumption that the observed deficit is due to ν_μ to ν_τ oscillations, a fit is performed to the parameters Δm^2 and $\sin^2 2\theta$ using the following expression for the muon neutrino survival probability:

$$P(\nu_\mu \to \nu_\mu) = 1. - \sin^2(2\theta) * \sin\left(\frac{\Delta m^2 L}{4E}\right),$$

where L is the distance travel and E the energy of the neutrino. The FD data is binned in reconstructed energy and the observed number of events in each bin is compared to the expected number of events for this hypothesis. The best fit parameters are those which minimize $\chi^2 = -2\ln\mathcal{L}$, where $\mathcal{L}$ is the likelihood ratio as defined in [5]. The main systematic effects (relative normalization of the ND and FD data set, absolute hadronic energy scale including effects of intra-nuclear re-scattering and the amount of NC background in the NC sample) were included as nuisance parameters in the fit. The total systematic errors are 1.1×10^{-4} eV^2 and 0.008 for Δm^2 and $\sin^2 2\theta$ respectively. The data, together with un-oscillated prediction and the best fit result are shown in Fig.2. The best fit point and 68% and 90% CL contours for the oscillation parameter are shown in Fig.3.

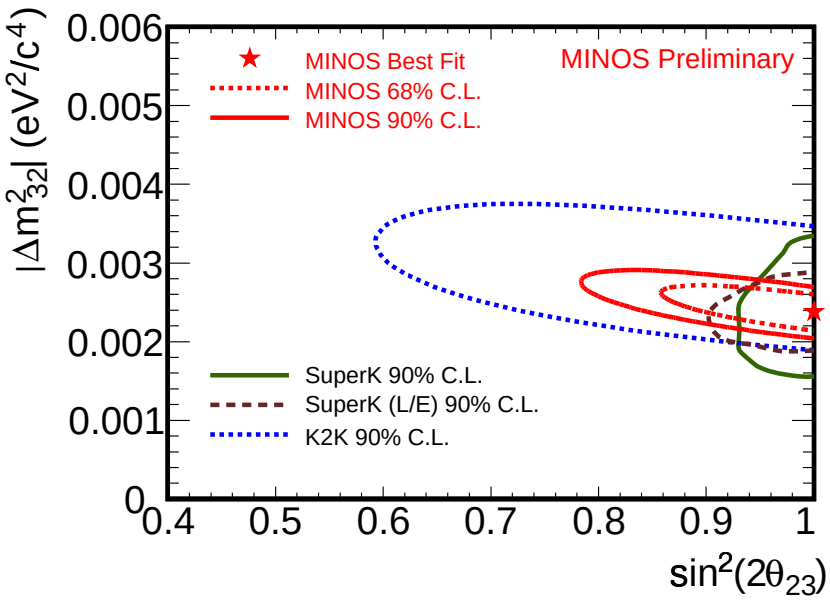

Figure 3: *68% and 90% confidence limit contours for with* Δm^2 *and* $\sin^2 2\theta$ *together with results from the SuperK and K2K experiments (from* [2]*) and references therein).*

4 Summary, Conclusion and Outlook

Using 2.5×10^{20} protons on target from the NuMI beam at Fermilab, MINOS has made a preliminary measurement of the "atmospheric" neutrino oscillations parameters to be $\Delta m^2 = (2.38^{+0.20}_{-0.16}) * 10^{-3}\mathrm{eV}^2$ and $\sin^2 2\theta = 1_{-0.08}$. The measurement is the world's most precise measurement of Δm^2 and is in good agreement with the previous measurements performed by MINOS and other experiments. The MINOS experiment expects to more than triple the data set presented in this note over the coming years and thus will drastically improve the current measurement. It will be able to limit alternative non-oscillation models and also look for alternative oscillation channels involving sterile and electron neutrinos.

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