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Neutrino Oscillation Results from MINOS

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Abstract: The **M**ain **I**njector **N**eutrino **O**scillation **S**earch (MINOS) long-baseline experiment has been actively collecting beam data since 2005, having already accumulated 3×10^{20} protons-on-target (POT). MINOS uses the **Neu**trinos at the **M**ain **I**njector (NuMI) neutrino beam measured in two locations: at Fermilab, close to beam production, and 735 km downstream, in Northern Minnesota. By observing the oscillatory structure in the neutrino energy spectrum, MINOS can precisely measure the neutrino oscillation parameters in the atmospheric sector. These parameters were determined to be $|\Delta m^2_{32}|$ = $2.74^{+0.44}_{-0.26} \times 10^{-3}\,\mathrm{eV}^2/c^4$ and $\sin^2(2\theta_{23}) > 0.87$ (68% C.L.) from analysis of the first year of data, corresponding to 1.27×10^{20} POT.

The NuMI Beam and the MINOS Detectors

The MINOS experiment is a complete long-baseline neutrino oscillation study. A neutrino beam created at Fermi National Accelerator Laboratory (Fermilab) is sampled first by the Near Detector (ND), on-site at Fermilab, at 1 km from the target, and then by the Far Detector (FD), 735 km away in the Soudan Underground Laboratory in Minnesota. The oscillation parameters $|\Delta m^2_{32}|$ and $\sin^2(2\theta_{23})$ are extracted by comparing the reconstructed neutrino energy spectra at the Near and Far locations.

The NuMI neutrino beam is produced using 120 GeV protons from the Main Injector. The protons are delivered in $10\,\mu$s spills with up to 4.0×10^{13} protons per spill. Positively charged particles produced by the proton beam in a graphite target (mainly π^+ and K^+) are focused by two pulsed parabolic horns and are then allowed to decay in a 675 m long, 2 m diameter, evacuated decay pipe. The target position relative to the first horn and the horn current are variable. For most of the collection of data used in the oscillations analysis presented here, the target was inserted 50.4 cm into the first horn to maximize neutrino production in the 1-3 GeV energy range. The data described here were recorded in this position, between May 2005 and February 2006, and correspond to a total of 1.27×10^{20} POT. The charged current (CC) neutrino event yields at the ND are predicted to be 92.9% ν_μ, 5.8% $\overline{\nu}_\mu$, 1.2% ν_e and 0.1% $\overline{\nu}_e$.

The MINOS detectors are designed to be as similar as possible in order to minimize systematic uncertainties. The detectors are fine-grained tracking calorimeters with an inch thick absorber layer of steel and a 1 cm active layer of plastic scintillator constituting one "plane". Each scintillator layer is constructed from 4.1 cm wide strips. Signals from the scintillator are collected via wavelength-shifting (WLS) fibers and carried by clear optical fibers to photomultiplier tubes (PMTs). The Near and Far detectors are both magnetized with a current carrying coil producing an average field of 1.3 T in the fiducial volume, allowing a measure of muon momentum from curvature in addition to that from range. Below 10 GeV, the hadronic energy resolution was measured to be 56%/$\sqrt{E[\mathrm{GeV}]} \oplus 2\%$ and the EM resolution was measured to be 21.4%/$\sqrt{E[\mathrm{GeV}]} \oplus 4.1\%/E[\mathrm{GeV}]$. The muon energy resolution $\Delta E_\mu/E_\mu$ varies smoothly from 6% for E_μ above 1 GeV where most tracks are contained and measured by range, to 13% at high energies, where the curvature measurement is primarily used.

The 0.98 kton ND, 103 m underground, has 282 irregular $4\times6\,\mathrm{m}^2$ octagonal planes. Each scintillator strip is coupled via WLS fibres to one pixel of a Hamamatsu M64 PMT. The 5.4 kton FD, 705 m underground, has 484 octagonal, 8 m wide instrumented planes read out at both ends via Hamamatsu M16 PMTs. Eight WLS fibers from strips in the same plane are coupled to each pixel. Due to the ND proximity to the target, the signal rate in the ND is $\sim 10^5$ times larger than in the FD.

Event Selection and FD Extrapolation

The initial step in the reconstruction of the FD data is the removal of the eightfold hit-to-strip ambiguity using information from both strip ends. In the ND, timing and spatial information is 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 ν_μ CC events, the total reconstructed event energy is obtained by summing the muon energy and the visible energy of the hadronic system. To prevent human biases when assessing the oscillation analysis results, a blinding mechanism was applied to the FD data set. This procedure hid a substantial fraction of the FD events with the precise fraction and energy spectrum of the hidden sample unknown. The data was unblinded only after the event selection methodology was defined and the prediction of the unoscillated spectrum understood. Events are preselected in both detectors, by requiring total reconstructed energy below 30 GeV and a negatively charged track. The track vertex must be within a fiducial volume such that cosmic rays are rejected and the hadronic energy of the event is contained within the volume of the detector. The pre-selected ν_μ event sample is predominantly CC with a 8.6% neutral current (NC) event background estimated from Monte Carlo (MC) simulations. The fiducial mass of the FD (ND) is 72.9% (4.5%) of the total detector mass.

A particle identification parameter (PID) incorporating probability density functions for the event length, the fraction of energy contained in the track and the average track pulse height per plane provides separation of ν_μ CC and NC events. The PID is shown in Fig. 1 for ND and FD data overlaid with simulations of NC and CC events. Events with PID above -0.2 (FD) and -0.1 (ND) are selected as being predominantly CC in origin. These

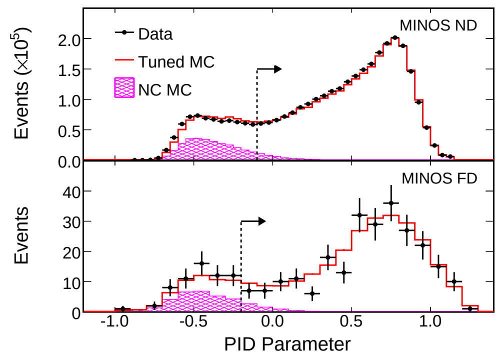

Figure 1: Data and tuned MC predictions for the PID variable in the ND (top) and FD (bottom). The arrows depict the positions of the ND and FD selection cuts. The FD MC distribution for CC events uses the best fit parameters discussed in the text.

values were optimized for both detectors such that the resulting purity of each sample is about 98%. The efficiencies for selecting ν_μ CC events in the fiducial volume with energy below 30 GeV are 74% (FD) and 67% (ND).

The measurement of the energy spectrum at the ND is used to predict the unoscillated spectrum at the FD. Fits to the ND data yield tuning parameters for the predicted neutrino flux. These fits are based on parameterisations of the secondary pion production at the NuMI target as a function of x_F and p_T. The FD prediction must also take 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. This extrapolation is achieved using the *Beam Matrix* method. It utilizes the beam simulation to derive a transfer matrix that relates ν_μs in the two detectors via their parent hadrons. The ND reconstructed event energy spectrum is translated into a flux by first correcting for the simulated ND acceptance and then dividing by the calculated cross-sections for each energy bin. This flux is multiplied by the matrix to yield the predicted, unoscillated FD flux. After the inverse correction for cross-

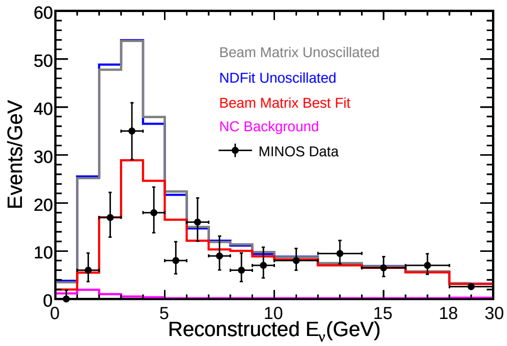

Figure 2: Comparison of the Far Detector spectrum with predictions for no oscillations for both analysis methods and for oscillations with the best-fit parameters from the Beam Matrix extrapolation method. The estimated NC background is also shown. The last energy bin contains events between 18-30 GeV.

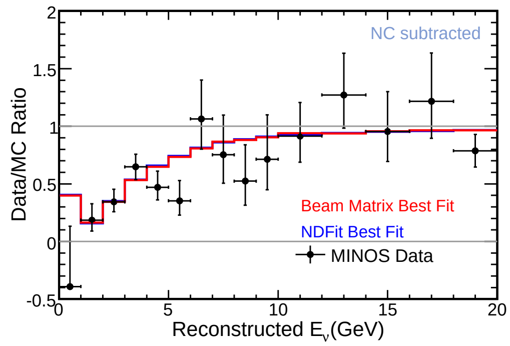

Figure 3: Ratio of MINOS data over MC prediction for no oscillations. Also shown is the comparison of the equivalent ratios using predictions for both the Beam Matrix and NDFit analysis methods for oscillations with their respective best-fit parameters. The estimated NC background is subtracted for each case.

section and FD acceptance, the predicted FD visible energy spectrum is obtained. The oscillation hypotheses are then tested relative to this prediction. A distinct extrapolation method, referred to as *ND Fit* was also applied to the data, yielding similar results.

In total, 215 events are observed below 30 GeV compared to 336.0±18.3(stat.)±14.4(syst.) events expected in the absence of oscillations. The systematic error is mostly due to NC contamination, ND to FD normalization and the hadronic shower energy scale. In the region below 10 GeV, 122 events are observed compared to the expectation of 238.7±15.4±10.7. The observed energy spectrum is shown along with the predicted spectra for both extrapolation methods in Fig. 2. In Fig. 3, the ratio of data and MC prediction is shown for both methods, after NC background subtraction. The characteristic dip expected for neutrino oscillations is evident.

Oscillation Analysis Results

Under the assumption that the observed deficit is due to $\nu_\mu \to \nu_\tau$ oscillations, a χ^2 fit is performed to the parameters $|\Delta m^2_{32}|$ and $\sin^2(2\theta_{23})$ using the expression for the ν_μ survival probability:

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32}\frac{L}{E}) \quad (1)$$

where L[km] is the distance from the target, E[GeV] is the neutrino energy, and $|\Delta m^2_{32}|$ is measured in eV^2/c^4. The FD data are binned in reconstructed event energy and the observed number of events in each bin is compared to the expected number of events for this oscillation hypothesis. The best fit parameters are those which minimize χ^2=$-2\ln\lambda$ where λ is the likelihood ratio:

$$\chi^2 = \sum_{nbins}(2(e_i - o_i) + 2o_i\ln(o_i/e_i)) + \sum_{nsys}\frac{\Delta s_j^2}{\sigma^2_{s_j}} \quad (2)$$

where o_i and e_i are the observed and expected numbers of events in bin i, and the $\Delta s_j^2/\sigma^2_{s_j}$ are the penalty terms for nuisance parameters associated with the systematic uncertainties. The e_i include the small contribution from selected ν_τ events produced in the oscillation process. The resulting 68% and 90% confidence intervals are shown in Fig. 4 as determined from $\Delta\chi^2$=2.3 and 4.6, respectively. The best fit value for $|\Delta m^2_{32}|$ is $|\Delta m^2_{32}|$=(2.74$^{+0.44}_{-0.26}$) $\times$ $10^{-3}\,\mathrm{eV}^2/c^4$ and $\sin^2(2\theta_{23}) > 0.87$ at 68% C.L. with a fit probability of 8.9%. At 90% C.L. (2.31<$|\Delta m^2_{32}|$<

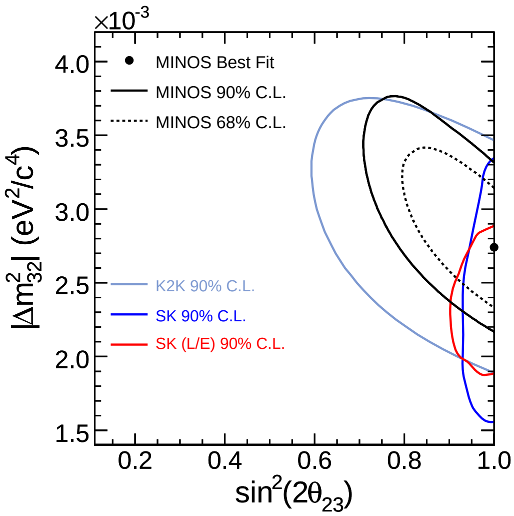

Figure 4: Confidence intervals for the fit using the Beam Matrix method including systematic errors. Also shown are the contours from the previous highest precision experiments [1, 2, 3].

$3.43) \times 10^{-3}\,\mathrm{eV}^2/c^4$, and $\sin^2(2\theta_{23}) > 0.78$. The data and best fit MC are shown in Fig. 2. If the fit is not constrained to be within the physical region, $|\Delta m^2_{32}|$=$2.72 \times 10^{-3}\,\mathrm{eV}^2/c^4$ and $\sin^2(2\theta_{23})$= 1.01, with a 0.2 decrease in χ^2. With additional data, it is expected that the systematic uncertainties will be reduced. More details of this analysis are available in [4]. An update on this result using 2.58×10^{20} POT is expected during the Summer 2007. In Fig. 5, the sensitivity of MINOS to neutrino oscillations is illustrated. The final attained sensitivity strongly depends on the total number of POT collected. Work on other oscillation analyses is underway, namely on a search for $\nu_\mu \rightarrow \nu_e$ appearance, which could potentially improve on the CHOOZ limit [5] and on a search for exotic phenomena such as oscillations into sterile neutrinos, by looking for disappearance in the observed NC energy spectrum, as described elsewhere in these proceedings [6].

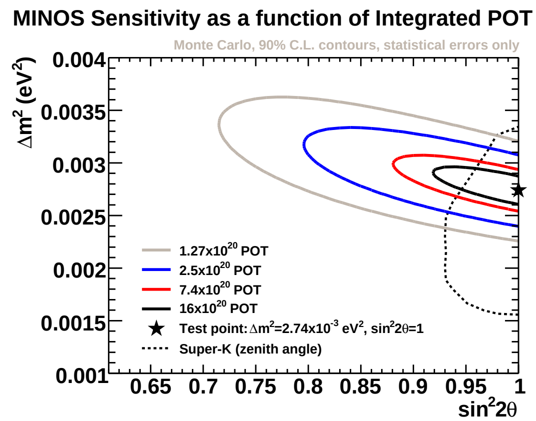

Figure 5: MINOS sensitivity to the oscillation parameter measurement as a function of the number of Protons on Target.

Acknowledgments

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