

# Neutrino oscillation parameters in MINOS

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**Abstract.** We present results of measurements of atmospheric neutrino oscillation parameters performed by the MINOS experiment. The experiment uses an intense Main Injector neutrino beam at Fermilab and two detectors: one located at Fermilab, and one situated 735 km away from Fermilab in the Soudan Underground Laboratory in northern Minnesota. The oscillation parameters were determined to be  $|\Delta m_{32}^2| = (2.43 \pm 0.13) \times 10^{-3} \text{eV}^2$  (68% confidence level) and  $\sin^2(2\theta_{23}) > 0.90$  (90% confidence level) from analysis of the two years of data.

We also report the first result of the search for the  $\nu_e$  appearance, that gives the upper limit of  $\sin^2(2\theta_{13}) < 0.29$  at 90% confidence level for the normal neutrino hierarchy and  $\sin^2(2\theta_{13}) < 0.42$  for the inverted hierarchy at  $\delta_{CP} = 0$ .

**Keywords:** neutrino oscillations MINOS

## I. INTRODUCTION

The MINOS experiment uses an intense accelerator beam of neutrinos to make the precise measurement of neutrino oscillation parameters that were first determined in interactions of atmospheric neutrinos [1]. In this region, the neutrino oscillations are dominated by the channel  $\nu_\mu \rightarrow \nu_\tau$ , but it is possible that a small fraction of muon-neutrinos oscillates into electron-neutrinos. The experiment studies the phenomenon of disappearance of muon-neutrinos from the beam, described by the oscillation parameters  $|\Delta m_{32}^2|$  and  $\sin^2(2\theta_{23})$ . It also searches for the appearance of electron neutrinos due to the sub-dominant  $\nu_\mu \rightarrow \nu_e$  oscillation mode. This transition is described by the unknown mixing angle  $\theta_{13}$  in the neutrino oscillation matrix.

The neutrino beam is produced at Fermilab and directed into two MINOS detectors: Near (ND) and Far (FD). The first neutrinos were produced at the beginning of 2005 and since then, the experiment has accumulated statistics corresponding to  $7 \times 10^{20}$  protons-on-target (pot). The reported results are based on the data from the first two years of running ( $3.36 \times 10^{20}$  pot for the disappearance analysis and  $3.14 \times 10^{20}$  pot for the appearance analysis). Both measurements were performed according to the rules of blind analysis.

## II. THE NuMI BEAM AND THE MINOS DETECTORS

The neutrinos from the NuMI beam [2] are produced by directing protons of energy 120 GeV from the Main Injector at Fermilab onto a graphite target. Currently, the accelerator delivers up to  $3.7 \times 10^{13}$  protons in 10  $\mu\text{s}$  spills every 2.2 s. The positively

charged pions and kaons, produced in the interactions with the target are then focused by two magnetic horns, and subsequently allowed to decay in the 675m long steel pipe. The resulting neutrino beam consist mainly of muon-neutrinos. The unique feature of the NuMI beamline is the possibility to change the energy distribution of the neutrino flux by changing the relative position of the target and the horns. Most of the data used for the analyses described here, were taken with the target inserted into the first magnetic horn (low energy configuration). In this configuration the number of produced neutrinos in the 1-3 GeV region, where the oscillation maximum is expected, is maximized. The beam contains of 91.7%  $\nu_\mu$ , 7%  $\bar{\nu}_\mu$  with an admixture of 1.3 %  $\nu_e + \bar{\nu}_e$  from decays of muons produced in pion decays and from kaon decays. Below 8 GeV, beam  $\nu_e$  contamination comes mainly from muon decays and is constrained by using  $\bar{\nu}_\mu$  events from different beam configurations.

The detectors of the MINOS experiment are located on the NuMI beam axis. The smaller of the two, the 1kt Near Detector, measures the unoscillated neutrino spectrum and is located at Fermilab, about 1km downstream of the target. The Far Detector, of mass 5.4 kt, is situated 735km away from Fermilab in the Soudan Underground Laboratory in Minnesota to study the phenomenon of neutrino oscillations. The Near and Far detectors share the same basic design: they are sampling, tracking calorimeters composed of 2.45cm thick planes of steel and 1cm thick planes of polystyrene scintillator. Each scintillator plane is segmented into 4.1 cm wide and up to 8m long strips, which have orthogonal orientation in the alternate planes. The scintillator light is collected by the wavelength shifting fibers and read out by multi-anode photomultiplier tubes (PMTs). One detector layer is equivalent to  $\sim 1.4$  radiation length. Below 10 GeV, the hadronic energy resolution was measured in the calibration detector [3] to be  $56\%/\sqrt{E[\text{GeV}]} \oplus 2\%$  and the electro-magnetic resolution was measured to be  $21.4\%/\sqrt{E[\text{GeV}]} \oplus 4.1/E[\text{GeV}]\%$ . The steel in both detectors is magnetized to an average field of 1.3 Tesla, allowing of the measurement of muon momentum from curvature in addition to that from range. The muon energy resolution  $\Delta E_\mu/E_\mu$  changes from 6% for  $E_\mu$  above 1 GeV, where most tracks are contained, to 13% at high energies where muon momentum is primarily measured from curvature.

Due to the high beam intensity, in the Near Detector, in one spill more than one neutrino interaction is recorded (for spill intensity  $3 \times 10^{13}$  protons, ND records on

average 10 events). The MINOS detectors are described in detail in [4].

### III. DISAPPEARANCE OF MUON-NEUTRINOS

The probability of disappearance of muon neutrinos from the beam, in the model of neutrino oscillations can be described by the approximate formula:

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \frac{1.27 \Delta m_{32}^2 L}{E_\nu} \quad (1)$$

where  $E_\nu$  [GeV] is the neutrino energy and  $L$  [km] is the distance from the target. Thus, from the disappearance analysis the two parameters of the neutrino oscillation model:  $\Delta m_{32}^2$  [eV<sup>2</sup>] and  $\sin^2 2\theta_{23}$  can be derived. Here we present the recent results on the disappearance of muon-neutrinos, based on the data collected by MINOS during the first two years of running.

Muon neutrinos can be detected by looking for the products of the interactions  $\nu_\mu + Fe \rightarrow \mu^- + X$ .

A characteristic feature of such interactions is the presence of a long muon track emerging from the hadronic shower  $X$ . To select this type of events, the new algorithm based on a multivariate likelihood has been implemented [5]. It includes four input variables that characterize the muon track: the average signal from scintillator per plane along the track; the transverse energy deposition profile of the track; the event length and the fluctuation of the energy deposited in scintillator strips. The resulting, average efficiency to select the  $\nu_\mu$  charged-current (CC) interactions in the Far Detector is 81.5 %, with the very small 0.6% contamination from the neutral-current (NC) interactions ( $\nu + Fe \rightarrow \nu + X$ ). After applying the above selection, 848  $\nu_\mu$ -CC candidates were observed in the Far Detector, compared to the unoscillated expectation of  $1065 \pm 60$  (syst.). The reconstructed energy distribution in the Far Detector is shown in Figure 1. The spectrum is compared to the Monte Carlo predictions with and without oscillations. The MC predicts the following numbers of background events in the final sample: 5.9 NC, 1.5  $\nu_\tau$ -CC, 0.7 events from cosmic ray muons and 2.3 events from neutrino interactions in the upstream rock. The ratio of the FD data and the expected spectrum is shown in Figure 2. Black, solid lines in Figures 1 and 2 represent the results of the best fit of the oscillation model, performed using the expression 1. In fitting the data,  $\sin^2 2\theta_{23}$  was constrained to lie in the physical region. The three, dominant systematic uncertainties: for  $\Delta m_{32}^2$  [eV<sup>2</sup>] uncertainty in the absolute, hadronic energy scale and on the predicted FD event rate, and for  $\sin^2 2\theta_{23}$  uncertainty on the NC contamination, were included as nuisance parameters in the fit. The resulting best fit gives  $|\Delta m_{32}^2| = (2.43 \pm 0.13) \times 10^{-3} \text{eV}^2$  (68% confidence level) and mixing angle  $\sin^2(2\theta_{23}) > 0.90$  (90% confidence level). The fit  $\chi^2$  is 90 for 97 degrees of freedom. Alternative models: decay of neutrinos to lighter particles [6], and the decoherence of the neutrino quantum-mechanical wave packet [7] are disfavoured

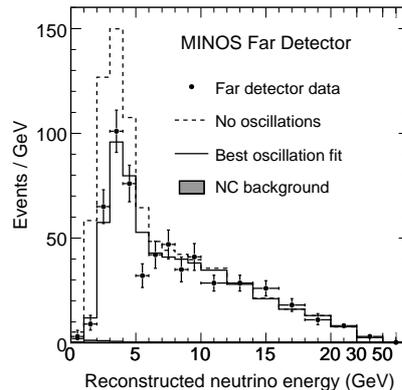


Fig. 1. Comparison of the reconstructed neutrino energy spectrum in the Far Detector with the predictions for the  $\nu_\mu$ -CC energy distributions with and without oscillations. Only statistical errors are shown.

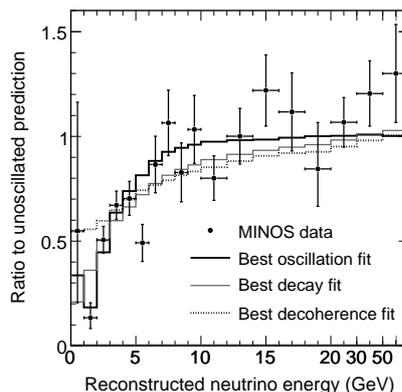


Fig. 2. Ratio of the FD data and the expected  $\nu_\mu$  energy spectrum in the absence of oscillations. Black, thick line represents the best oscillation fit curve. Also shown are the best fit curves for the alternative models of neutrino disappearance.

with respect to the oscillation hypothesis at the 3.7 and 5.7 standard-deviation levels. Intervals for the oscillation parameters  $\Delta m_{32}^2$  [eV<sup>2</sup>] and  $\sin^2 2\theta_{23}$  are shown in Figure 3.

More details concerning the disappearance analysis can be found in [11].

### IV. APPEARANCE OF ELECTRON-NEUTRINOS

Observation of electron-neutrino appearance in the beam of muon-neutrinos, in the atmospheric oscillation domain, would imply a non-zero value of the mixing angle  $\theta_{13}$ . The probability of  $\nu_e$  appearance,  $P(\nu_\mu \rightarrow \nu_e)$ , is expressed [12] by the formula more complicated than for  $\nu_\mu$  disappearance, and depends not only on  $\theta_{13}$ , but also on the unknown CP-violation phase  $\delta_{CP}$ , on the neutrino mass hierarchy and other parameters of the neutrino oscillation model. From the previous

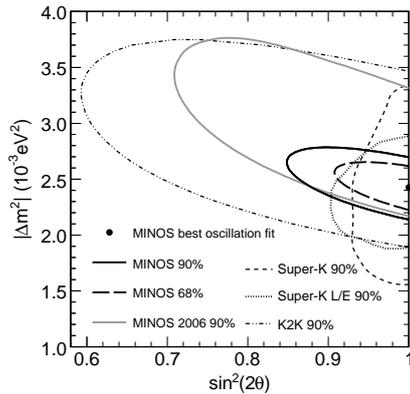


Fig. 3. Comparison of the MINOS 68% and 90% C.L. regions from oscillation fits with contours from previous experiments [8][9] and with the previous MINOS result [10]

experiments it is known that the contribution from the  $\nu_\mu \rightarrow \nu_e$  oscillations, if exists, is small [13]. The best experimental limit was set by the CHOOZ experiment [14] to  $\sin^2(2\theta_{13}) < 0.15$  at the MINOS best fit value for  $|\Delta m_{32}^2|$ . Here we present the first results on the search of the appearance of electron-neutrinos, based on the data collected by MINOS in the same period of time as for the disappearance analysis.

Electron neutrinos can be detected by looking for the products of the interactions  $\nu_e + Fe \rightarrow e^- + X$ . In MINOS, electrons are expected to produce compact showers, spanning only a few planes and strips. The largest backgrounds to the search originate from the NC interactions and  $\nu_\mu$ -CC interactions where most of the energy is transferred into hadronic state. Smaller background is related to the intrinsic electron-neutrino component of the beam. Additional background component in the Far Detector is due to the CC interactions of tau-neutrinos from the  $\nu_\mu \rightarrow \nu_\tau$  oscillations.

The  $\nu_e$ -CC event selection is performed in the three main stages. First, the data are filtered to ensure data and beam quality. Then, preselection cuts are imposed to reduce the backgrounds. Final selection is done with the help of a multivariate method. At the preselection stage, an event is required to have a reconstructed shower and at least 5 contiguous planes with energy deposition greater than 0.5 MIP to remove NC events that does not have a dense core. An event can not have a long track, as the presence of a long track is characteristic for the  $\nu_\mu$ -CC events. Moreover, events are required to have the reconstructed energy between 1 and 8 GeV. The lower energy cut removes NC events, while the higher energy cut removes part of the intrinsic beam  $\nu_e$ -CC events. The preselection cuts improves the signal to background ratio from 1:55 to 1:12, assuming the  $\theta_{13}$  is close to the CHOOZ limit. The final selection, based on Artificial Neural Network (ANN), improves further this ratio to 1:4. The ANN technique uses 11 input variables characterizing

transverse and longitudinal energy deposition profiles. The signal efficiency for the ANN method is 40%. The selection removes 99% of  $\nu_\mu$ -CC and 93% of NC background. The reconstructed energy distribution of the  $\nu_e$ -CC selected events in the Near Detector is shown in Figure 4. The histogram shows MC simulation, with shaded regions indicating systematic uncertainties due to the hadronic shower modeling. All the events selected in the Near Detector are background events, as the detector is situated too close to the neutrino source to observe the neutrino oscillations. The ND events are used to estimate the number of background events expected in the Far Detector. To extrapolate the background to the FD, the selected events have to be divided into NC,  $\nu_\mu$ -CC and beam  $\nu_e$ -CC components, as each component is extrapolated to the FD in the different way. The components of the background are determined using additional data, taken with the magnetic horns turned off. In this configuration, charged pions and kaons are not focused, thus the data sample is enriched in NC events. The number of events in each bin of energy from the standard, horn-on configuration can be expressed as a sum of the three components:

$$N^{on} = N_{NC} + N_{CC} + N_{beam\nu_e} \quad (2)$$

The data from the horn-off configuration can be written as the sum of the same components, multiplied by the ratios  $r_i = N_i^{off}/N_i^{on}$ :

$$N^{off} = r_{NC}N_{NC} + r_{CC}N_{CC} + r_{\nu_e}N_{beam\nu_e} \quad (3)$$

The above two equations are solved to obtain  $N_{NC}$  and  $N_{CC}$ . Ratios  $r_i$  and the intrinsic beam  $\nu_e$  component are taken from the Monte Carlo simulation.

Each background component is then multiplied by the Far to Near ratio, taken from the MC simulation. Oscillations are included when predicting  $\nu_\mu$ -CC and  $\nu_\tau$ -CC background in the Far Detector. Finally, all background components in the Far Detector are summed together. The total background for the ANN selection is expected to be 26.6 events, of which 18.2 are NC, 5.1 are  $\nu_\mu$ -CC, 2.2 are beam  $\nu_e$  and 1.1 are  $\nu_\tau$ -CC. The total systematic error on the number of background events selected by the ANN technique is 7.3%, while the current statistical uncertainty is equal 19%. After applying the ANN  $\nu_e$  selection, 35  $\nu_e$ -CC candidates were observed in the Far Detector. The background expectation is  $27 \pm 5(stat) \pm 2(syst.)$ . The reconstructed energy distribution of the  $\nu_e$ -CC selected events in the Far Detector, is shown in Figure 5. Shaded histograms show the predictions for background components: NC,  $\nu_\mu$ -CC,  $\nu_\tau$ -CC and beam  $\nu_e$  (from largest to smallest). The observed number of  $\nu_e$ -CC candidates in the Far Detector is consistent with the background expectation within  $1.5\sigma$ . Figure 6 shows the values of  $\sin^2(2\theta_{13})$  and  $\delta_{CP}$  that can produce excess of events consistent with the observation. Two middle, curved lines show results of the best fit for the normal neutrino hierarchy (solid line) and inverted hierarchy (dotted line). Also shown are the 90% C.L.

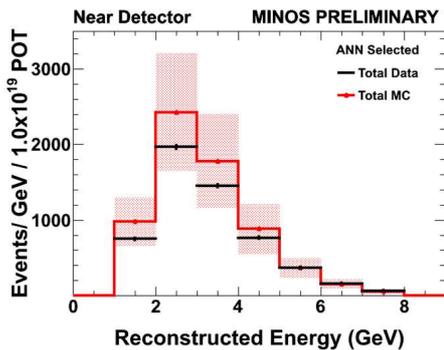


Fig. 4. Reconstructed energy distribution for the  $\nu_e$ -CC candidates in the Near Detector. Histogram shows predictions from Monte Carlo simulation. Shaded regions represent systematic uncertainties due to hadronic shower modeling. For data, only statistical errors are shown.

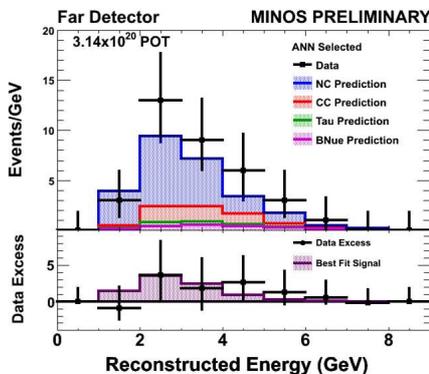


Fig. 5. Reconstructed energy distribution for the  $\nu_e$ -CC candidates in the Far Detector. Histogram shows predictions from Monte Carlo simulation for background components (from highest to smallest): NC,  $\nu_\mu$ -CC,  $\nu_\tau$ -CC, and from the internal beam  $\nu_e$  component. Only statistical errors are shown.

boundaries for the normal and inverted hierarchy and for the reference, the limit on  $\theta_{13}$  from the CHOOZ experiment (straight line). For the analysed data set, corresponding to the  $3.14 \times 10^{20}$  pot, the best fit is just below or just above the CHOOZ limit. The following upper limits were set:  $\sin^2(2\theta_{13}) < 0.29$  at 90% confidence level for the normal hierarchy and  $\sin^2(2\theta_{13}) < 0.42$  for the inverted hierarchy, for  $\delta_{CP} = 0$ .

## V. SUMMARY

The MINOS experiment performed the measurement of atmospheric parameters of the neutrino oscillation model and found them to be  $|\Delta m_{32}^2| = (2.43 \pm 0.13) \times 10^{-3} \text{eV}^2$  (68% confidence level) and mixing angle  $\sin^2(2\theta_{23}) > 0.90$  (90% confidence level) from analysis of the two years of data. This measurement is the world-best determination of the mass splitting  $|\Delta m_{32}^2|$ . The first result of the search for the  $\nu_e$  appearance gives the upper limit of  $\sin^2(2\theta_{13}) < 0.29$  at 90% confidence level for the normal hierarchy and  $\sin^2(2\theta_{13}) < 0.42$  for the inverted hierarchy at  $\delta_{CP} = 0$ .

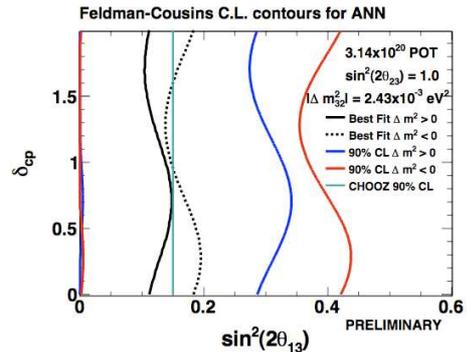


Fig. 6. Range of values of  $\sin^2(2\theta_{13})$  and CP-violation phase  $\delta_{CP}$  that can produce a number of events consistent with the observation. Two middle, curved lines show results of the best fit for the normal neutrino hierarchy (solid line) and inverted hierarchy (dotted line). Also shown are the 90 % C.L. boundaries for the normal and inverted hierarchy and for the reference, the limit on  $\theta_{13}$  from the CHOOZ experiment (straight line).

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