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MINOS: Selected topics

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MINOS was a two-detector long-baseline experiment at Fermilab to study neutrino oscillations. The experiment started its operations in February 2005 and finished in April 2012. The total beam exposure delivered to the two magnetized spectrometers was 14.07×10^{20} protons-on-target. Starting somewhat earlier, the deep-underground Far Detector collected atmospheric neutrinos for an exposure of 37.88 kton-years. Over the years, data from MINOS have allowed the derivation of some of the most stringent constraints for neutrino and antineutrino oscillations to date. In the conference talk, we presented preliminary results of the three-flavor muon neutrinos disappearance analysis. However, these results have been recently superseded by a more global analysis incorporating the MINOS disappearance and appearance beam measurements with the atmospheric data, so these are the preliminary results that we are reporting in these proceedings.

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1. Introduction

The long-baseline MINOS experiment at Fermilab was proposed about 20 years ago when the world of particle physics was puzzled by the solar neutrino "deficit" and the atmospheric neutrino "anomaly". Much has changed since then. MINOS has now completed its data taking in the dedicated low-energy NuMI neutrino beam. We present preliminary results of the final three-flavor analysis that combines beam neutrinos and antineutrinos disappearance and appearance measurements with the observations of atmospheric neutrinos in the 5.4 kton Far Detector located in the 700 m deep Soudan Underground Laboratory. The two detectors continue their on-axis operations, as MINOS+, in the reconfigured NuMI beam optimized for the off-axis NOνA experiment.

MINOS was designed to be sensitive to the "atmospheric", or larger of the two, mass-squared differences and has set some of the most stringent oscillation constraints for neutrinos and antineutrinos. The planning, the design, and the construction of the MINOS experiment turned out to be challenging largely due to the complexity of the civil construction of the neutrino beam line and related funding. The experiment, comprising two detectors and a beam line, was fully commissioned in early 2005, although the Far Detector started collecting atmospheric neutrino data almost two years earlier. The lesson learned is that it is the beam that is the most difficult to build, and even when it is built, it takes time to fully commission it and improve its intensity.

2. MINOS exposures

The two-horn NuMI neutrino beam is produced by injecting Booster batches of 8 GeV protons into the Main Injector, accelerating them to 120 GeV, and extracting them onto a graphite target. About 3.5×10^{13} protons-on-target (POT) were extracted every 2.2 s, corresponding to the beam power of about 320 kW. This was achieved only towards the end of the MINOS beam exposure, as depicted in Figure 1. The seven years of ever-higher intensity running challenged many aspects of beam operations. It took seven graphite targets and four horns to complete these runs and to collect 14.07×10^{20} POT (10.71×10^{20} POT taken in the neutrino mode, and 3.36×10^{20} POT taken in the antineutrino mode), producing the event statistics given in Table 1. The Far Detector, that functioned also as an atmospheric neutrino observatory since 2003, accumulated a fiducial exposure of 37.88 kton-years during about eight years of operations.

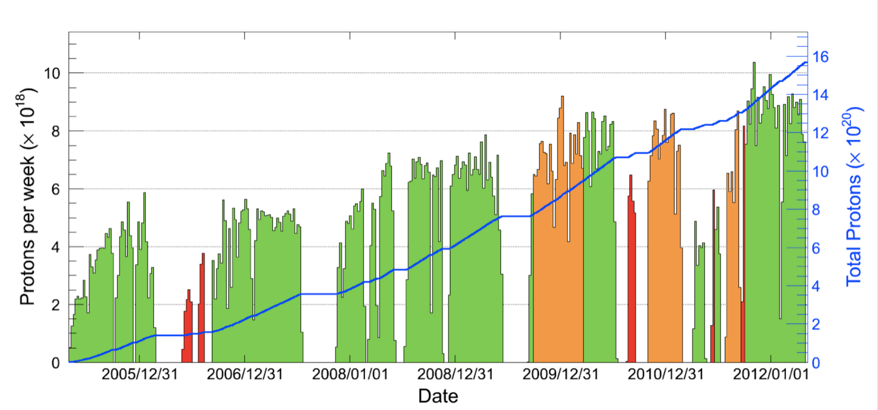

Figure 1: History of the MINOS beam exposure spanning years 2005 through 2012.

Event category	Observed data	Predicted no oscillations	Best fit 2ν	Best fit 3ν disappear.	Best fit 3ν disappear. + appear.
Beam in neutrino mode					
contained vertex ν_μ	2579	3201	2543	2549	2549
contained vertex $\overline{\nu}_\mu$	312	363	324	325	325
non-fiducial muons	2911	3197	2862	2844	2844
Beam in antineutrino mode					
contained vertex $\overline{\nu}_\mu$	226	313	227	227	228
Atmospheric neutrinos					
contained vertex $\nu_\mu+\overline{\nu}_\mu$	905	1100	881	877	878
neutrino induced $\mu^+ + \mu^-$	466	570	467	466	466
contained vertex showers	701	727	724	717	716
Total	8100	9471	8028	8005	8006

Table 1: MINOS events statistics.

3. The oscillation analysis

The most significant statistical observables for the most important event categories measured in MINOS, the energy spectra, are presented in Figures 2 and 3. Previous disappearance results used a two-flavor framework [1, 2]. The analysis of the complete data set was performed in distinct steps: first with the two-flavor approximation, then with the three-flavor framework using disappearance data, and finally with the three-flavor framework using disappearance and appearance [3] data. The analysis employs constraints on the value of θ_{13} from reactor experiments. For the MINOS baseline ($L_\nu = 734$ km) and the NuMI beam neutrino energy range [$E_\nu \approx (1-6)$ GeV], the survival and ν_e appearance probabilities in the three-flavor framework can be approximated by:

$$P(\nu_\mu \to \nu_\mu) = 1 - 4\sin^2\theta_{23}\cos^2\theta_{13}(1-\sin^2\theta_{23}\cos^2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32}L_\nu}{4E_\nu}\right),$$
$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L_\nu}{4E_\nu}\right).$$

The full formalism for oscillations includes terms with matter effects that depend on δ_{CP} and the mass hierarchy. For the beam neutrinos, the $\nu_\mu \to \nu_e$ appearance probability can be approximated by an expansion in $\alpha = \Delta m^2_{21}/\Delta m^2_{32} \approx 1/32$ [4]:

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta(1-A)}{(1-A)^2} + \alpha J\cos(\Delta \pm \delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin^2\Delta(1-A)}{(1-A)}$$
$$+ \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\Delta A}{A^2},$$

where $J = \cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}$, $A = \pm 2\sqrt{2}G_F n_e E_\nu/\Delta m^2_{31}$, n_e is the density of electrons in the earth's crust, and $\Delta = \Delta m^2_{13}L_\nu/4E_\nu$. The plus (minus) signs correspond to neutrinos (antineutrinos). The parameter A is sensitive to the neutrino mass hierarchy. For atmospheric neutrinos, $\nu_\mu \to \nu_e$ oscillations are primarily expected for upward-going multi-GeV neutrinos due to the MSW resonance.

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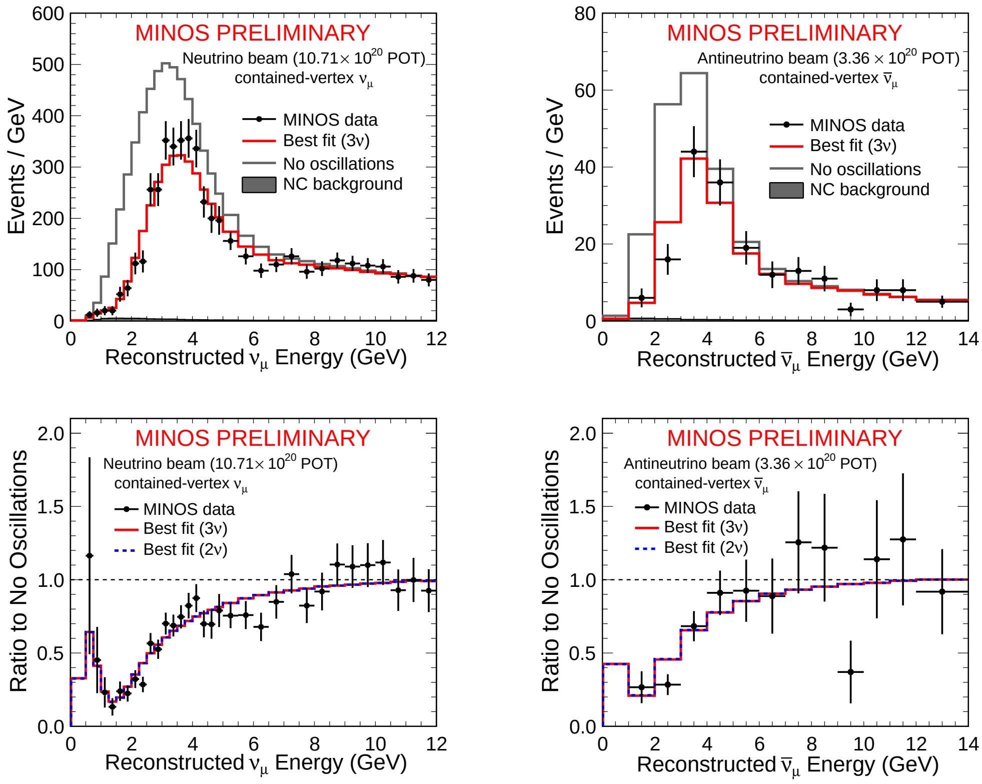

Figure 2: The reconstructed energy spectra for contained vertex beam neutrinos and antineutrinos (top two plots) and the ratio of data to predicted spectra with no oscillations (bottom two plots).

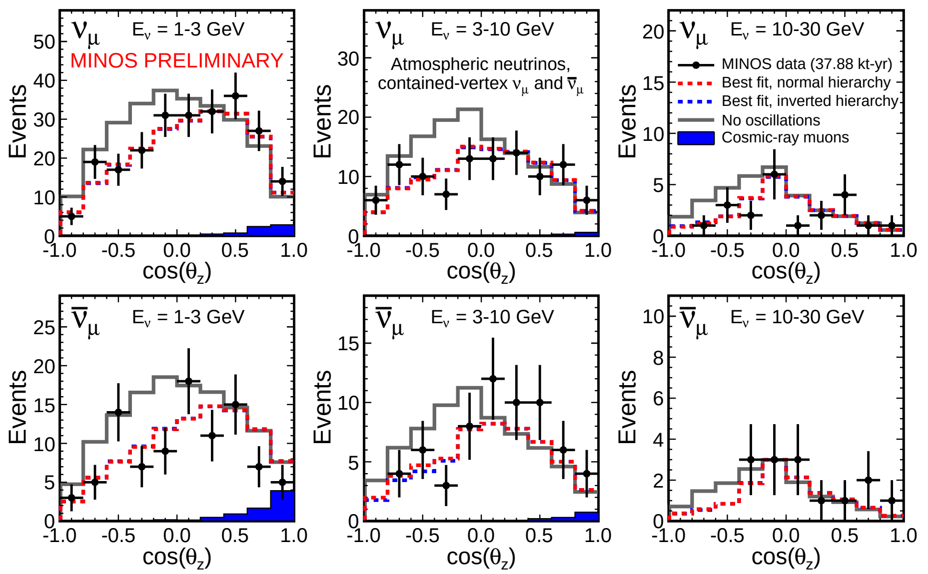

Figure 3: Distributions of atmospheric neutrino data, plotted as a function of zenith angle and separated into bins of reconstructed neutrino energy.

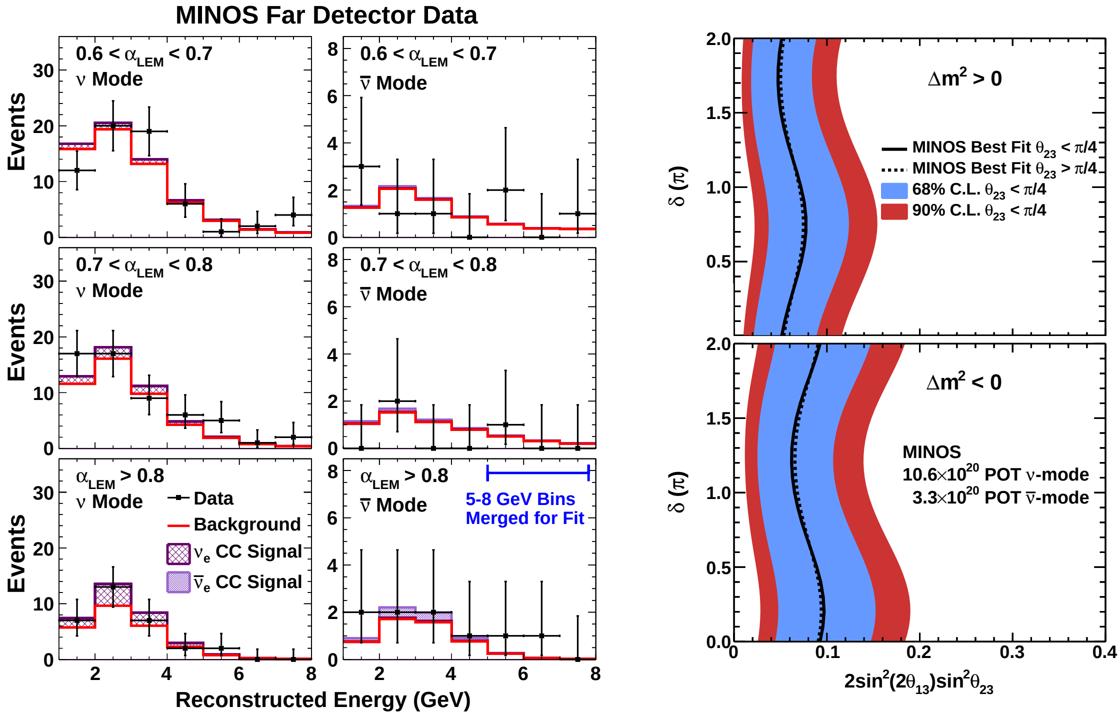

Figure 4: Left: The reconstructed energy distributions for three ranges of the LEM ν_e event classifier α_{LEM}. The signal predictions assume $\sin^2(2\theta_{13}) = 0.051$, $\Delta m^2_{32} > 0$, $\delta = 0$, and $\theta_{23} = \pi/4$. The plots in the left (right) column correspond to data collected in the neutrino (antineutrino) beam mode. Right: Allowed ranges and best fits for $2\sin^2(\theta_{23})\sin^2(2\theta_{13})$ as a function of $\delta \equiv \delta_{CP}$. The upper (lower) panel assumes the normal (inverted) neutrino mass hierarchy. For $\delta = 0$ and normal (inverted) hierarchy, the best fit is 0.051 (0.093), and the 90% allowed range is 0.01-0.12 (0.03-0.18), and is excluding zero at 96% C.L..

4. Final results

MINOS detectors are magnetized tracking and sampling calorimeters and provide very cleanly separated samples of neutrinos and antineutrinos [2]. The identification of ν_e events required a special Library Event Matching (LEM) algorithm that enhances the sensitivity of selection of electromagnetic showers [3]. Figure 4 shows ν_e appearance results. All beam and atmospheric data sets were used to produce previous MINOS results [1, 2, 3], but were not employed in a combined fit.

The oscillation parameters are derived from adding log-likelihoods from appearance and disappearance measurements as a function of Δm^2_{23}, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, and δ_{CP}. The fit includes penalty

Mass hierarchy	θ_{23} octant	$\Delta m^2_{23}/10^{-3}\,\mathrm{eV}^2$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}/π	$-2\Delta\log(L)$
$\Delta m^2_{23} > 0$	$\theta_{23} < \pi/4$	+2.37	0.41	0.0242	0.44	0.23
$\Delta m^2_{23} > 0$	$\theta_{23} > \pi/4$	+2.35	0.61	0.0238	0.62	1.74
$\Delta m^2_{23} < 0$	$\theta_{23} < \pi/4$	-2.41	0.41	0.0243	0.62	-
$\Delta m^2_{23} < 0$	$\theta_{23} > \pi/4$	-2.41	0.61	0.0241	0.37	0.09

Table 2: Preliminary MINOS results from a three-flavor fit to the complete beam and atmospheric data sets.

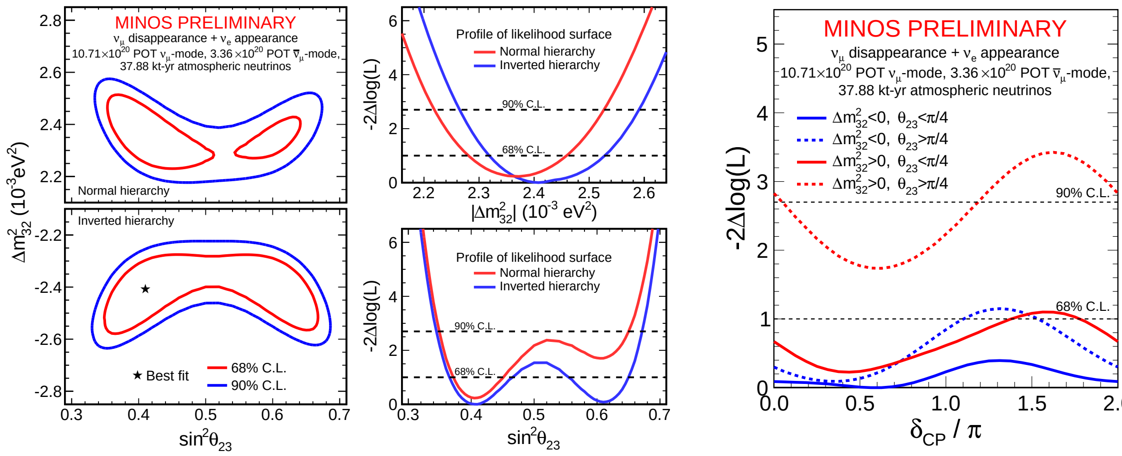

Figure 5: Left: Preliminary contour and profile plots from the combined fit to ν_μ disappearance and ν_e appearance data. Right: The preliminary likelihood profile for the δ_{CP} parameter, plotted separately for each combination of hierarchy and θ_{23} octant.

terms that reflect main systematic uncertainties in each event sample, as discussed in earlier publications [1, 2, 3]. The value for angle θ_{13} has a penalty term constrained by the reactor experiments [5]. The preliminary results, shown in Table 2 and Figure 5, provide stringent constraints of the "atmospheric" oscillation parameters, and give new constraints for the θ_{23} octant and δ_{CP}. Clearly, much more data are needed to establish these parameters firmly.

5. Conclusions

The MINOS experiment has concluded the long-baseline beam and atmospheric ν_μ disappearance and the $\nu_\mu \to \nu_e$ appearance measurements, and conducted analysis that incorporates transition probabilities in a three-flavor framework. With an additional input on θ_{13} from reactor experiments, the main preliminary results constrain $|\Delta m^2_{32}| = [2.28 - 2.46] \times 10^{-3}\,\mathrm{eV}^2$ at 68% C.L., and $\sin^2\theta_{23} = [0.35 - 0.65]$ at 90% C.L. for the normal neutrino mass hierarchy, and $|\Delta m^2_{32}| = [2.32 - 2.53] \times 10^{-3}\,\mathrm{eV}^2$ at 68% C.L., and $\sin^2\theta_{23} = [0.34 - 0.67]$ at 90% C.L. for the inverted hierarchy. The data also provide constraints, albeit still feeble, on δ_{CP}, the θ_{23} octant, and the mass hierarchy.

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References

[1] P. Adamson *et al.* [MINOS Collaboration], Phys. Rev. D **86**, 052007 (2012).

[2] P. Adamson *et al.* [MINOS Collaboration], Phys. Rev. Lett. **110**, 251801 (2013).

[3] P. Adamson *et al.* [MINOS Collaboration], Phys. Rev. Lett. **110**, 171801 (2013).

[4] A. Cervera *et al.* Nucl. Phys. B **579**, 17 (2000) [Erratum-ibid. B **593**, 731 (2001)].

[5] F. An *et al.* (Daya Bay), Chin. Phys. **C37**, 011001 (2013); J. Ahn *et al.* (RENO), Phys. Rev. Lett. **108**, 191802 (2012); Y. Abe *et al.* (Double Chooz), Phys. Rev. **D86**, 052008 (2012).