New Results from MINOS

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Introduction

- Theory Introduction
- The MINOS Experiment
- Recent MINOS Results
- Electron Neutrino Appearance – NEW Result
- Summary
Neutrinos and Physics Motivation

- There are 3 generations of neutrino: $\nu_e$, $\nu_\mu$, $\nu_\tau$
- neutrinos have mass and they oscillate
- neutrino oscillations are governed by the PMNS matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Atmospheric and accelerator experiments (Super-Kamiokande, MINOS):
$\Delta m^2_{atm} = 2.32 \times 10^{-3} \text{eV}^2$
$\sin^2 2\theta_{23} > 0.9 \Rightarrow \Theta_{23} \approx 45^\circ$

$\Theta_{13}$ is small and CP-violating phase $\delta$ is unknown

Solar experiments (SNO, Kamland):
$\Delta m^2_{\text{sol}} = 8 \times 10^{-5} \text{eV}^2$
$\Theta_{12} \approx 34^\circ$
MINOS Experiment

Iron scintillator calorimeters, functionally identical

Far Detector:
- Spectrum after oscillations
- 5.4 kT, 8m x 8m x 30m,
- 484 steel/scintillator planes, veto shield

Near Detector:
- Spectrum before oscillations
- 1 kT, 3.8m x 4.8 m x 15m,
- 282 steel planes, 153 steel/scintillator planes

Steel/scintillator planes:
- 1-inch thick steel planes alternating with planes of scintillator strips
- Alternative scint. planes are orthogonal to each other for 3D reconstruction of events
The NuMI Beam

- 120 GeV protons from Main Injector
- impact on graphite target
- ~10µs spill every ~2s, currently ~3.5x10^{13} protons on target/spill
- produced hadrons focused by 2 magnetic horns
- decay into neutrinos and other particles
- absorber/rock remove heavier particles, leave neutrinos
- neutrino energy spectrum can be changed with target position, horn current can be reversed to produce an anti-neutrino beam
Protons on Target to Date

The electron neutrino appearance result presented here uses data from the normal low energy beam configuration – $8.12 \times 10^{20}$ POT (green only)
MINOS Event Topology

Charged Current – muon $\nu$

Neutral Current

Charged Current – electron $\nu$

MINOS New Results from the MINOS Experiment – Anna Holin
Muon Neutrino Disappearance

Muon neutrinos are observed to disappear as they travel. The most precise result in $\Delta m^2$ was obtained by MINOS:

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

$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{eV}^2$

$\sin^2 (2\theta) > 0.90 (90\%C.L.)$

Expected 2451 events
Observed 1986 events

Exclude decay at 7 $\sigma$
Exclude decoherence at 9 $\sigma$
Muon Anti-Neutrino Disappearance

By reversing the horn current, NuMI can create an anti-neutrino beam, can analyze the resulting data in a similar way to the neutrino data

- No oscillation Prediction: 156 events
- Observe: 97 events
- No oscillations disfavored at 6.3σ

\[
|\Delta m^2| = (3.36^{+0.46}_{-0.40} \text{(stat.)} \pm 0.06 \text{(syst.)}) \times 10^{-3} \text{ eV}^2
\]

\[
\sin^2(2\bar{\theta}) = 0.86^{+0.11}_{-0.12} \text{(stat.)} \pm 0.01 \text{(syst.)}
\]
Electron Neutrino Analysis Procedure

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right) \]

- Determine the criteria for selecting electron neutrino CC events from a background of predominantly NC events
- Translate the observed ND data spectrum into a background prediction for the FD
- Compare the data to the prediction and fit observed spectrum to obtain final exclusion limits
- New for this analysis: shape fitting in 15 bins – 3 bins in PID and 5 in energy
Selection of electron neutrino events

Cuts are applied to remove obvious non-signal events. Those cuts include:

- long track events
- events without a shower and well-defined shower core
- events with energies below 1GeV and above 8GeV

After this pre-selection, a selection PID (also new since last analysis) is used to hone in on the signal events:

- LEM – Library Event Matching Algorithm – it uses a library of 20 million signal and 30 million NC events
- The 50 best matches are found for each event – 3 discriminant variables are constructed and combined in a neural network to obtain the PID
Near Detector Background Decomposition

There are three ND components:
• Neutral current background
• High-\(Y\) charged current muon neutrino background (muon track is short and is lost in the shower)
• Intrinsic beam electron neutrino CC events

Those individual components need to be extrapolated to the FD separately so as to account for oscillations.

The MC and data do not agree perfectly, but we want to use the ND data to make a FD prediction =>

=> Need to decompose the ND data.

To calculate each component, can use ND data taken in different beam configurations.
Near Detector Background Decomposition

To calculate each background component, ND data taken in different beam configurations can be used:

- Can use the total measured data in each beam configuration
- Can use the MC simulations for the relative interaction rates for each background
- Can thus fit for the background components in the standard LE sample
Extrapolation to the Far Detector

Use Far/Near ratios to extrapolate the individual backgrounds to the FD:

Accounts for:
- Flux (e.g. $1/R^2$ fall off)
- Cross-section
- Fiducial volume
- Energy smearing
- Detector effects
- Muon neutrino disappearance

A tau neutrino appearance component is added from oscillated muon neutrinos to the FD prediction.
Far Detector Prediction

<table>
<thead>
<tr>
<th>NC</th>
<th>$\nu$ $\mu$ -CC</th>
<th>Beam $\nu_e$ -CC</th>
<th>$\nu_\tau$ -CC</th>
<th>Total</th>
<th>$\nu_e$ -CC Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>7</td>
<td>6</td>
<td>2</td>
<td>49</td>
<td>30</td>
</tr>
</tbody>
</table>

For $8.2 \times 10^{20}$ POT in the signal enhanced region $\text{LEM}>0.7$, signal at Chooz limit, and $\Delta m^2_{32}=2.32 \times 10^{-3} \text{eV}^2$, $\sin^2 2 \theta_{23}=1$

Systematic uncertainty is 5.7% on the background prediction in region $\text{LEM}>0.7$

Uncertainties include:
- Composition of the ND spectrum
- Far/Near ratio:
  - Calibration – e.g. relative energy calibration, gains, absolute energy calibration
  - Relative Near/Far normalization
- Hadronisation model
- Other smaller uncertainties
Appearance Result for 15-Bin Fitting

The fit uses 15 bins – three in PID and 5 in reconstructed energy.

Best Fit:

\[ \sin^2 2\theta_{13} = 0.040 \]

for \( \delta = 0 \) and \( \sin^2 2\theta_{23} = 1 \), normal mass hierarchy

Signal enhanced region LEM>0.7:
expect \( 49.5 \pm 7.0 \text{(stat.)} \pm 2.8 \text{(syst.)} \), observed 62 events in the FD
MINOS has updated its electron neutrino appearance analysis for an exposure of $8.2 \times 10^{20}$ POT, with shape fitting and a new selection variable

$\sin^2(2\theta_{13}) < 0.12$ for normal mass hierarchy, $< 0.19$ for inverted hierarchy, at 90% C.L., for $\delta = 0$

$\sin^2(2\theta_{13}) = 0.04$ (0.08) are the best fit values

$\sin^2(2\theta_{13}) = 0$ excluded at 89% C.L.

For the first time, an experiment has been able to exclude beyond the Chooz limit in all of the parameter space for the normal mass hierarchy
Region Allowed by Fit – Comparison to T2K Result

\[ \Delta m^2 > 0 \]

- MINOS Best Fit
- 68% CL
- 90% CL
- CHOOZ 90% CL
  \[ 2\sin^2 \theta_{23} = 1 \text{ for CHOOZ} \]

\[ \Delta m^2 < 0 \]

- 8.2 \times 10^{20} \text{ POT}
- MINOS PRELIMINARY

\[ \Delta m_{23}^2 > 0 \]

- Best fit to T2K data
- 68% CL
- 90% CL

\[ \Delta m_{23}^2 < 0 \]

- T2K
  \[ 1.43 \times 10^{20} \text{ p.o.t.} \]
MINOS has updated its electron neutrino appearance analysis for an exposure of $8.2 \times 10^{20}$ POT, with shape fitting and a new selection variable $\sin^2(2\theta_{13}) < 0.12$ for normal mass hierarchy, $<0.19$ for inverted hierarchy, at 90% C.L., for $\delta = 0$

For the first time, an experiment has been able to exclude beyond the Chooz limit in all of the parameter space for the normal mass hierarchy

MINOS is planning to present further new results very soon.
Back-Up
Electron Neutrino Analysis Sensitivity

MINOS sensitivity increased since last analysis in 2010 significantly:

- 17% more data ($1.2 \times 10^{20}$ POT)
- 15% better from improved selection variable
- 12% better from shape fit

90% upper limit we would set if we observe the background prediction exactly
Electron Neutrino Appearance Candidate Event

- **Entries**: 19
- **Mean**: 3.305
- **RMS**: 2.377
- **χ²/ndf**: 10.95/27
- **a**: $2.028 \pm 0.359$
- **b**: $0.4127 \pm 0.0838$
- **e0**: $57.51 \pm 7.54$

**Energy (MEU)**

**Transverse Energy Profile by Strip (U/V Views)**

- **FD RUN**: 37761
- **EVENT ID**: 13502
- **Reco. Energy**: 2.58 GeV
- **LEM PID**: 0.91
- **ANN PID**: 0.98
Electron Neutrino Appearance

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13}) \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{\text{atm}} L}{4 E}\right) \]  

(minor term)

MINOS 2010:
- Predicted: 49 background events
- Observed: 54 events

MINOS sensitivity beyond the Chooz limit for normal mass hierarchy

T2K:
- Predicted: 1.5 events
- Observed: 6 events

Cite paper

Chooz limit

Cite paper
Overlay of MINOS and T2K Results

MINOS PRELIMINARY

\[ \Delta m^2 > 0 \]

\[ \Delta m^2 < 0 \]

2sin^22\theta_{13}sin^2\theta_{23}

MINOS allowed

T2K allowed

MINOS best fit

T2K best fit
MINOS signal expected at T2K best fit

Far Detector Prediction (LEM > 0.7)

- NC
- $\nu_\mu$ CC
- $\nu_\tau$ CC
- Beam $\nu_e$ CC
- FD Data
- Signal (T2K)

$\sin^2(2\theta_{13}) = 0.11$, $\Delta m^2_{32} > 0$, $\delta_{CP} = 0$

Merged for Fit
Muon Anti-Neutrino Disappearance

Future sensitivity for anti-neutrino mode:

[Graph showing the future sensitivity for anti-neutrino mode with MINOS Preliminary data and 90% MC Sensitivity for different POT values.]
Neutral Current Events in the Far Detector

Expected 757 events
Observed 802 events
No deficit of NC events
Can set limit on oscillations to sterile neutrinos

\[ f_s \equiv \frac{P_{\nu_\mu \rightarrow \nu_s}}{1 - P_{\nu_\mu \rightarrow \nu_\mu}} < 0.22 \ (0.40) \text{ at } 90\% \text{ C.L.} \]