Latest Results from MINOS

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Outline

• Overview

• $\nu_\mu$ Disappearance ($\Delta m_{23}^2$ & $\sin^2(2\theta_{23})$)

• $\bar{\nu}_\mu$ Disappearance ($\Delta \bar{m}_{23}^2$ & $\sin^2(2\bar{\theta}_{23})$)
  – sensitive to $\nu_\mu \rightarrow \bar{\nu}_\mu$

• Look for deficit in neutral-current interactions
  – Sterile neutrino limits

• $\nu_e$ Appearance ($\theta_{13}$)

• Summary
NuMI beam production

• Neutrino beam produced from 120 GeV protons striking a graphite target
  - $\pi$ and $K$ decays produce (LE beam):
    - 91.8% $\nu_\mu$, 6.9% $\bar{\nu}_\mu$, 1.3% ($\nu_e + \bar{\nu}_e$)
• Beam performance:
  - $2.4 \times 10^{13}$ POT/spill (Runs 1 & 2) $\rightarrow 3.0 \times 10^{13}$ (Run 3)
  - 275 kW beam power
  - $\sim 10^{18}$ POTs/day

- Energy tuned by distance between target and 1st horn.
Soudan Underground Laboratory

- Oldest Iron Mine in Minnesota
- Current occupants: MINOS far detector and CDMS II
NuMI Performance

Current results on data through Run II

Results based on Runs I and II:

\( \nu_\mu : 3.3 \times 10^{20} \) POT  \( \overline{\nu}_\mu : 3.2 \times 10^{20} \) POT  NC: \( 3.18 \times 10^{20} \) POT  \( \nu_e : 3.14 \times 10^{20} \) POT
MINOS Detectors

Near Detector
- 0.98 kton
- 1.04 km from target (FNAL)
- 100 m underground
- $3.8 \times 4.8 \times 15$ m$^3$
- 282 steel planes
- 153 scintillator planes

Iron and Scintillator tracking calorimeters
(functionally identical detectors)
- magnetized steel planes $B \approx 1.3T$
- Multi-anode PMT readout
- GPS time-stamping to synchronize FD data to ND Beam
- Main Injector spill times sent to the FD for a beam trigger

Far Detector
- 5.4 kton
- 735.3 km from target (Soudan)
- 705 m underground
- $8 \times 8 \times 30$ m$^3$
- 486 steel planes
- 484 scintillator planes
Near Detector Events

- On average there are 16 interactions per spill in the near detector.
- Events are separated by space and time ("slices").
Far Detector Events

- In the far detector there is 1 event in $10^4$ spills.
- Cosmic ray backgrounds are suppressed by direction, rock, and timing.
- Trigger from NuMI (10 $\mu$s window every 2.2 sec)
Two-detector $\nu$ disappearance

- Produce a high intensity beam of neutrinos at Fermilab
- Measure the energy spectrum at both the near detector & the far detector
- Near spectrum tells you what the far spectrum looks like without oscillation

\[
P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 (1.267 \Delta m^2 \frac{L}{E})
\]

Given $L = 735\text{km}$, oscillation parameters $\Delta m^2_{23}$ & $\sin^2 2\theta_{23}$ may be extracted from differences in measured vs. unoscillated energy spectra
Near Detector data used to extrapolate to far detector. -MC provides energy smearing and acceptance corrections -pion decay kinematics and beamline geometry encoded in transfer matrix.

$\nu_\mu$ CC Event selection algorithm uses four inputs:

a) Track Length in planes
b) Mean PH/plane
c) Fluctuations in PH
d) Transverse track profile

$\nu_\mu$ CC Analysis
Far Detector $\nu_\mu$ CC Spectra

- Significant energy-dependent suppression of $\nu_\mu$ CC events observed
- Neutrino oscillation favored by $3.7\sigma$ over pure decay\(^1\) & $5.7\sigma$ over pure decoherence\(^2\)

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\(^1\) V. Barger et al., PRL82:2640 (1999)
Result of $\nu_\mu$ CC Oscillation Fit

\[ P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin 2(1.27 \Delta m^2_{23} L/E) \]

\[ |\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2 \text{ (68\% c.l.)} \]

\[ \sin^2 2\theta > 0.90 \text{ (90\% c.l.)} \]

\[ \chi^2/ndf = 90/97 \text{ (constrained. to physical region)} \]

Without constraint $\sin^2 2\theta$ value is 1.07 and $\chi^2$ changes by 0.6.

Test whether $\bar{\nu}_\mu$ oscillates with same parameters as $\nu_\mu$ (CPT).

6.9% of ND events are $\bar{\nu}_\mu$.

Selection:
- Relative angle (Is track focused or defocused by magnetic field?).
- Significance of charge determination
- Likelihood based on track length and pulse height. NC suppression.

Efficiency 87% & Purity 95%

42 events observed:
Predictions:
64.6±8.0±3.9 No oscillation
58.3±7.6±3.6 CPT-conserving osc.
\[ \overline{\nu}_\mu \] Oscillation Analysis

Preliminary

- No oscillation excluded @ 99% CL.
- \( \nu_\mu \) CC analysis best fit is within 90% CL
- Assuming maximal mixing we exclude: 
  \[ (5 < \Delta m^2 < 81) \times 10^{-3} \text{ eV}^2 \] @ 90% CL

Note: Fraction of \( \nu_\mu \) that disappear and reappear as \( \overline{\nu}_\mu \) < 2.8%

Dashed lines display global fit to previous data, from Gonzalez-Garcia and Maltoni - *Phys. Rept. 460 (2008)*
NC Disappearance/\nu_{\text{sterile}}\text{ Search}

All three flavors contribute to NC interactions. Appearance of sterile neutrino would result in energy dependent depletion. Topological cuts for NC selection:
- Expect short tracks (or no tracks) in NC events
- NC are typically much shorter than CC events
Primary background is inelastic muon-neutrino CC interactions. Selection is 90% efficient with 60% purity.
• Shown is a comparison of the NC energy spectrum to the 3-flavor expectation.

• Observed 388 events.

• Expectation from MC:
  377$^{+19.4}_{-18.5}$ events

• $R=1.04^{+0.08}_{-0.07}$\(-0.10$(\nu_e)$

\[
\sin^22\theta_{23} = 1 \text{ (SuperKamiokande)} \\
\Delta m_{32}^2 = 2.43 \times 10^{-3} \text{ eV}^2 \text{ (MINOS CC)} \\
\Delta m_{21}^2 = 7.59 \times 10^{-5} \text{ eV}^2, \theta_{12} = 35^\circ \text{ (KamLAND + SNO)} \\
\theta_{13} = 0 \text{ or } 12^\circ \text{ (Chooz limit)} \\
\delta_{CP} = 3\pi/2 \text{ (maximal } \nu_e \text{ appearance)} \\
\text{Normal mass hierarchy}
\]
NC Disappearance/$\nu_{\text{sterile}}$ Search

4-Flavor Analysis:
Additional Sterile Neutrino

Assume:
$|\Delta m_{43}^2| >> |\Delta m_{32}^2|$
$\theta_{14}=0$ & $|\Delta m_{21}^2| \sim 0$

Result
$\theta_{34} < 38^\circ$ (56$^\circ$ $\nu_e$)
$\theta_{24} < 10^\circ$ (10.6$^\circ$ $\nu_e$)

Sterile fraction:
$f_s < 51\%$ (55$\%$ $\nu_e$) @90%CL

Note: NC spectrum can improve rejection of neutrino decay models. NC+CC fit disfavors pure decay by 5.4$\sigma$. CC only: 3.7$\sigma$. 

$$f_s = \frac{P_{\nu_\mu \rightarrow \nu_s}}{1 - P_{\nu_\mu \rightarrow \nu_\mu}}$$
For an appearance measurement there is no signal to extrapolate to the Far Detector.

However MINOS, dominated by non-active material, is not ideal for electron identification. Backgrounds are substantial. Our background is measured in the near detector and extrapolated to the far detector.

NC and μ-CC are significant backgrounds. There is also an intrinsic $\nu_e$ component to the beam. The energy distribution for the intrinsic $\nu_e$ is quite different.

This is a challenging measurement but simulation suggested that we could expect a limit a little below the existing Chooz limit (on average).

So we looked.
Neutrino Event Topologies

- **CC Event**
  - $\nu_\mu$ CC Event
  - $\nu_e$ CC Event

- **NC Event**
  - $\pi^0$
  - $\nu_e$ NC Event
\( \nu_e \) Appearance in MINOS

- When selecting \( \nu_e \) event candidates in the Near Detector we will have a mix of components that do not extrapolate in the same way to the Far Detector.
- Simply extrapolate NC and beam \( \nu_e \)
- \( \nu_\mu \) CC must be oscillated out of the far detector spectrum
- \( \nu_\tau \) CC must be oscillated into the far detector spectrum.
- Then look for the \( \nu_e \) excess arising from \( \nu_\mu \) to \( \nu_e \) oscillations in the Far Detector.
Candidates must contain a compact shower and exhibit characteristic EM profile.

**longitudinal:**

\[
\frac{dE}{dt} = E_0 b \left( \frac{(bt)^{a-1}}{\Gamma(a)} \right) e^{-bt}
\]

- fraction of energy deposited within 2,4,6 planes
- longitudinal energy projection

**transverse:**

- 90% containment radius
- lateral shower spread (RMS)
- fraction of energy deposited within 3 strips along shower axis
Horn-Off Data

• The beam $v_e$ flux is obtained from the $v_\mu$ CC flux which is constrained by data in the different beam configurations.

• The two main background components can be estimated using the number of data events in the horn on and horn off configurations: $N^{on}$ and $N^{off}$.

\[
N^{on} = N_{NC} + N_{CC} + N_e \quad (1)
\]

\[
N^{off} = r_{NC} * N_{NC} + r_{CC} * N_{CC} + r_e * N_e \quad (2)
\]

from MC: $r_{NC(CC,e)} = N_{NC(CC,e)}^{off} / N_{NC(CC,e)}$

• Producing data-driven predictions for NC and $v_\mu$ CC background for the horn on configuration.
The two data-driven methods, Horn on/off and MRCC, are in excellent agreement in the Far Detector.

~1 event difference is well within errors.

The horn on/off is the primary separation method.

The background prediction at $3.14 \times 10^{20}$ POT is: $27 \pm 5 \text{(stat)} \pm 2 \text{(sys)}$
• We observe a total of 35 events in this sample
MINOS 90% CL in $\sin^2 2\theta_{13}$

- Plot shows 90% limits in $\delta_{CP}$ vs. $\sin^2 2\theta_{13}$
  - shown at the MINOS best fit value for $\Delta m_{32}^2$ and $\sin^2 2\theta_{23}$.
  - for both mass hierarchies
- A Feldman-Cousins method was used.
- Results are for primary selection and primary separation method.
• MINOS Results Summary:
  • World’s most precise measurement of $\Delta m^2_{23}$
  • Presented constraints on sterile neutrinos and test of CPT.
  • Data significantly disfavor neutrino decay and decoherence.
  • Our 1st results on $\sin^2 \theta_{13}$ from $\nu_e$ appearance presented.
  • Factor of 2 increase in statistics coming.
  • Reversed horn current data accumulating until March 2010.

• Many analyses not covered: (Near Detector Physics, Rock Interactions, Atmospheric, neutrino Velocity, Global Analysis)
| Uncertainty                                      | $|\Delta m^2|_{(10^{-3}\text{ eV}^2)}$ | $\sin^2(2\theta)$ |
|------------------------------------------------|-------------------------------|-------------------|
| (a) Abs hadronic $E$ scale ($\pm$ 10.3%)       | 0.052                         | 0.004             |
| (b) Rel hadronic $E$ scale ($\pm$ 3.3%)        | 0.027                         | 0.006             |
| (c) Normalization ($\pm$ 4%)                   | 0.081                         | 0.001             |
| (d) NC contamination ($\pm$ 50%)               | 0.021                         | 0.016             |
| (e) $\mu$ momentum (range 2%, curv 3%)         | 0.032                         | 0.003             |
| (f) $\sigma_{\nu}(E_{\nu} < 10 \text{ GeV})$ ($\pm$12%) | 0.006                         | 0.004             |
| (g) Beam flux                                  | 0.010                         | 0.000             |
| Total Systematic Uncertainty                   | 0.108                         | 0.018             |
| Expected Statistical Uncertainty               | 0.19                          | 0.09              |
Basic Data Quality Cuts

– Beam quality and detector quality cuts.

– Fiducial volume cuts:
  • Near Detector:
    \[1m < z < 5m, r < 0.8m\]
  • Far Detector:
    \[0.5m < z < 14.3 \text{ or } 16.3m < z < 28m,\]
    \[0.5m < r < 3.7m\]

– Cosmic rejection cuts based on steepness.
**ν_e Preselection Cuts**

- **Preselection requirements:**
  - Track length < 25 planes.
  - Track like length < 16 planes.
  - Reconstructed energy 1-8 GeV.
  - At least one shower and 4 contiguous planes with > 0.5 MIP energy units.

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**Signal at CHOOZ limit**

### Far Detector
- **MINOS PRELIMINARY**
  - **Monte Carlo**
    - ν\_osc\_signal
    - NC
    - ν\_μ\_CC
    - ν\_e\_beam CC
    - ν\_e\_CC

### Number of track planes

- **Events/3.14×10^{20}POT**
  - 10⁴
  - 10³
  - 10²
  - 10
  - 1

### Reconstructed Energy (GeV)

- **Events/3.14×10^{20}POT**
  - 10²
  - 10
  - 1

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**Before Monte Carlo**

**After Monte Carlo**

- **Signal/Background 1:55**
- **Signal/Background 1:12**

- ν\_μ\_CC
- ν\_e
- NC

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[Diagram showing signal distribution before and after preselection cuts.]
Selecting $\nu_e$ events with ANN

- 11 variables chosen describing length, width and shower shape.
- ANN algorithm achieves:
  - signal efficiency 41%
  - NC rejection >92.3%
  - CC rejection >99.4%
  - signal/background 1:4

\[ \Delta m^2_{32} = 0.0024 \text{ eV}^2, \sin^2\theta_{23} = 1.0 \]
**$ν_e$ selected Near Detector data**

- MC tuned to external bubble chamber data for hadronization models.
  - External data sparse in our kinematic range.
  - Strong background rejection leaves just tails of distributions.
- It is not surprising that the data/MC shows disagreement with the model.
- Discrepancy is within the large uncertainties of the model.
- We have developed two data-driven methods to correct the model to match the data.

![Graph showing events versus reconstructed energy](image)

- The **MRCC method** uses muon removed $ν_μ$ CC to study the hadronic showers and correct MC.
- The **Horn on/off method** uses the difference in background composition of the two horn configurations.
Muon Removal Technique

- Remove the muon track in a selected $\nu_\mu$ CC event and use the rest as a hadronic shower only event.

- We use events that pass our $\nu_\mu$ Charged Current event selection, i.e. that have a well defined track.

- Well understood $\nu_\mu$ CC spectra, with well known efficiency and purity from the $\nu_\mu$ disappearance analysis.
• When beam horns are turned off, the parent pions do not get focused, resulting in the disappearance of the low energy peak in the neutrino energy spectrum.

• The consequence is a spectrum dominated by NC arising from the long tail in true neutrino energy that gets measured in our region of interest in visible energy.
Horn-Off Data

- Horn off/on ratios for $\nu_\mu$ CC and NC selected events match well between data and MC after fiducial volume cuts.
- Similar ratios are used to solve the horn on/off equations.

MC error statistical plus systematic.
Horn-Off Results (ND)

- The NC and $\nu_\mu$ CC components for the standard beam configuration are simultaneously solved in the horn on/off method and are by definition equal to the data after beam $\nu_e$ subtraction.
Far Data $\nu_e$ selected distributions
Future 90% CL contours
7.0 x10^{20} POT

If data excess persists.

If excess cancels with more data.
\( \nu_e \) appearance result:

Observation 35 events

Expected Background \( 27 \pm 5 \text{(stat)} \pm 2 \text{(sys)} \) for \( 3.14 \times 10^{20} \) POT

MINOS PRELIMINARY
We observe a total of 35 events.

We expect $27\pm5\text{(stat)}\pm2\text{(sys)}$ background events.

Results are $1.5\,\sigma$ above expected background.
$\nu_e$ Appearance

- Measurement of $\sin^2 2\theta_{13}$
  
  \[ P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{23} L/E) \]

- Expect signal/background = 0.3 at the CHOOZ limit for current MINOS exposure

- Data-driven systematic uncertainty: $\sim 10\%$

- Hope to improve to 5% systematic uncertainty in the future

- 1st results expected later this year with sensitivity below the CHOOZ limit
Signal Collection Based on MINOS Active Detector

- Plastic Scintillator ➔ Liquid Scintillator
- 8 m length ➔ 15.7 m length
- 1 cm thick ➔ 6 cm thick
- 1.2 mm wavelength shifting fiber ➔ 0.7 mm wls fiber
- Straight fiber read out each side ➔ Loop fiber read out one side
- Hamamatsu multi-anode PMTs ➔ Hamamatsu multi-pixel Avalanche Photodiodes
- 8 cells/pixel multiplexing ➔ 1 cell/pixel
Candidate $\nu_e$ in the FD data

- Typical EM shower characteristics:
  - steel thickness: 2.54cm $\sim 1.44X_0$
  - strip width: 4.12cm (Moliere rad $\sim 3.7$cm)

Run: 32687  Snarl: 90343
Reco Energy: 4.6 GeV
## FD background systematic errors
### Total errors

<table>
<thead>
<tr>
<th>Preliminary Uncertainties</th>
<th>Horn On/Off</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Extrapolation</td>
<td>6.4%</td>
</tr>
<tr>
<td>(2) Systematic (separation method)</td>
<td>2.7%</td>
</tr>
<tr>
<td>(3) Statistical (separation method)</td>
<td>2.3%</td>
</tr>
<tr>
<td>Total (sum in quadrature)</td>
<td>7.3%</td>
</tr>
<tr>
<td><strong>Statistical error (data)</strong></td>
<td><strong>19%</strong></td>
</tr>
</tbody>
</table>

Systematic uncertainties are dominated by error in the extrapolation. Statistical uncertainties dominate.
\( \nu_{\text{sterile}} \) NC Analysis Results

- Fit FD spectrum to a 4-neutrino model (3 + 1 sterile) with mixing occurring at one \( \Delta m^2 \)

- Oscillation and survival probabilities become:
  \[
  P(\nu_\mu \rightarrow \nu_\mu) = 1 - \alpha_\mu \sin^2(1.27 \Delta m^2 L/E)
  \]
  \[
  P(\nu_\mu \rightarrow \nu_s) = \alpha_s \sin^2(1.27 \Delta m^2 L/E)
  \]

- Simultaneous fit to CC & NC energy spectra performed:
  \[
  f_s = P(\nu_\mu \rightarrow \nu_s)/[1-P(\nu_\mu \rightarrow \nu_\mu)] = 0.28^{+0.25}_{-0.28} \text{ (stat+sys)}
  \]
  \[
  f_s < 0.68 \text{ (90\% c.l.)}
  \]

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