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On behalf of the MINOS Collaboration

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MINOS

Main Injector Neutrino Oscillation Search

Strategy

- Two functionally similar magnetized detectors
- High intensity, flexible beam
  - $3.5 \times 10^{13}$ protons/pulse (320 kW beam)
  - two magnetic horns
  - movable target
    (→ adjustable energy spectrum)
Making a neutrino beam

Neutrino mode
Horns focus $\pi^+$, $K^+$

Events

- $\nu_\mu$: 91.7%
- $\bar{\nu}_\mu$: 7.0%
- $\nu_e + \bar{\nu}_e$: 1.3%

120 GeV/c $p$'s from MI

Target

Focusing Horns

2 m

15 m

30 m

675 m

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Making an anti-neutrino beam

Neutrino mode
Horns focus $\pi^+, K^+$

- $\nu_\mu$: 91.7%
- $\overline{\nu}_\mu$: 7.0%
- $\nu_e + \overline{\nu}_e$: 1.3%

Anti-neutrino mode
Horns focus $\pi, K^-$

- $\overline{\nu}_\mu$: 39.9%
- $\nu_\mu$: 58.1%
- $\nu_e + \overline{\nu}_e$: 2.0%

K. Lang, U. of Texas at Austin, MINOS, Neutrino Telescopes, Venice, March 12, 2013
Protons-on-target (POT) history of MINOS

May 1, 2005  April 30, 2012

7 years, 7 targets, 2 horns, $15.6 \times 10^{20}$ POT

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Near and Far Detectors and event classification

U V planes
+/- 45°
2.54 cm Fe

Beam + atmospheric

Beam + atmospheric

Beam
ν_e

ν_e CC Event

Charged Current neutrino event
ν_μ → μ^−
W
N
Hadrons

Neutral Current neutrino event
ν → ν
Z
N
Hadrons

Charged Current electron-neutrino event
ν_e → e
W
N
Hadrons
MINOS disappearance data sets: beam and atmospheric events

Main stats: 2579 beam nus     312 beam anti-nus     2072 atmospheric

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Assume CPT oscillations
neutrino and antineutrino parameters the same

\[ \Delta m^2 \equiv \Delta m^2 \]
\[ \bar{\theta} \equiv \theta \]

\[ |\Delta m^2| = 2.41^{+0.09}_{-0.010} \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2(2\theta) = 0.950^{+0.035}_{-0.036} \]
\[ \sin^2(2\theta) > 0.890 \quad (90\% \ C.L.) \]

\[ P(\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu) \equiv P(\nu_\mu \rightarrow \nu_\mu) \]
\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta) \sin^2 \left( \frac{1.267 \Delta m^2 (\text{eV}^2) L(\text{km})}{E(\text{GeV})} \right) \]

PRELIMINARY
Systematics: 2-parameter fit

PRELIMINARY

\[
\begin{align*}
\Delta m^2 / (10^{-3} \text{ eV}^2) & \quad \sin^2(2\theta) \\
3.36 \times 10^{20} \text{ POT } \nu_\mu \text{ Mode} & \quad 10.71 \times 10^{20} \text{ POT } \nu_\mu \text{ Mode} \\
37.88 \text{ kt-y Atmospheric} & \\
\end{align*}
\]

Beam:
- Normalization
- NC Background
- Shower Energy
- Track Energy

Atmospheric:
- Normalization (CV)
- Normalization (Rock \mu)
- $\bar{\nu}_\mu/\nu_\mu$ Ratio (CV)
- $\bar{\nu}_\mu/\nu_\mu$ Ratio (Rock \mu)
- Spectrum ($\nu_\mu$)
- Spectrum ($\bar{\nu}_\mu$)
- Others

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\[ \Delta m^2 \quad \Delta \bar{m}^2 \quad \theta \quad \bar{\theta} \]

\[ |\Delta \bar{m}^2| = 2.50^{+0.23}_{-0.25} \times 10^{-3} \text{eV}^2 \]

\[ \sin^2(2\bar{\theta}) = 0.97^{+0.03}_{-0.08} \]

\[ \sin^2(2\bar{\theta}) > 0.83 \quad (90\% \text{ C.L.}) \]

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

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = 1 - \sin^2(2\bar{\theta}) \sin^2 \left( \frac{1.267 |\Delta \bar{m}^2| (\text{eV}^2) L(\text{km})}{E(\text{GeV})} \right) \]
\[ |\Delta m^2| - |\Delta \bar{m}^2| = 0.12^{+0.24}_{-0.28} \times 10^{-3} \text{ eV}^2 \]
Electron-$\nu$ and anti-$\nu$ appearance

- $10.6 \times 10^{20}$ POT positive-focus + $3.3 \times 10^{20}$ POT negative-focus
- Cannot distinguish $\Rightarrow$ combine $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Full 3-flavor electron neutrino appearance analysis

Automation of Library Event Matching (LEM) + ANN

PRELIMINARY
Electron-$\nu$ appearance event selection

Increasing Signal strength $\alpha_{LEM} \to 1$

![Graph showing event selection criteria with $0.6 < \alpha_{LEM} < 0.7$ and $0.7 < \alpha_{LEM} < 0.8$ for both $\nu$ and $\bar{\nu}$ modes.]

<table>
<thead>
<tr>
<th>Event Type</th>
<th>$\nu$ beam mode</th>
<th>$\bar{\nu}$ beam mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC</td>
<td>89.4</td>
<td>13.9</td>
</tr>
<tr>
<td>$\nu_\mu$-CC and $\bar{\nu}_\mu$-CC</td>
<td>21.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Intrinsic $\nu_e$-CC and $\bar{\nu}_e$-CC</td>
<td>11.9</td>
<td>1.8</td>
</tr>
<tr>
<td>$\nu_\tau$-CC and $\bar{\nu}_\tau$-CC</td>
<td>4.8</td>
<td>0.8</td>
</tr>
<tr>
<td>$\nu_\mu \rightarrow \nu_e$-CC</td>
<td>33.0</td>
<td>0.7</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$-CC</td>
<td>0.7</td>
<td>3.2</td>
</tr>
<tr>
<td>Total</td>
<td>161.4</td>
<td>21.4</td>
</tr>
<tr>
<td>Data</td>
<td>152</td>
<td>20</td>
</tr>
</tbody>
</table>

TABLE II: Expected FD event yields for events with a value of $\alpha_{LEM} > 0.6$, assuming $\sin^2(2\theta_{13}) = 0.1$, $\delta = 0$, $\theta_{23} = \pi/4$, and a normal mass hierarchy.
Cannot distinguish between $\nu_e$ and anti-$\nu_e$ events, so we perform a combined analysis:

At $\delta_{CP} = 0$ and $\theta_{23} < \pi / 4$

- Assuming normal hierarchy:
  
  \[
  2 \sin^2 (2\theta_{13}) \sin^2 (\theta_{23}) = 0.051^{+0.038}_{-0.030} \\
  0.01 < 2 \sin^2 (2\theta_{13}) \sin^2 (\theta_{23}) < 0.12 \quad (90\% \ C.L.)
  \]

- Assuming inverted hierarchy:
  
  \[
  2 \sin^2 (2\theta_{13}) \sin^2 (\theta_{23}) = 0.093^{+0.054}_{-0.049} \\
  0.03 < 2 \sin^2 (2\theta_{13}) \sin^2 (\theta_{23}) < 0.18 \quad (90\% \ C.L.)
  \]
Reactor $\theta_{13} + \text{Electron-}\nu$

$\rightarrow$ constraints on octant $\theta_{23}$ vs $\delta$

Use reactor results:

$$\sin^2(2\theta_{13}) = 0.098 \pm 0.013$$

Vary $\delta$, octant of $\theta_{23}$, mass hierarchy

$\rightarrow$ Compare against data (all uncertainties included)
3-flavor mixing framework
sensitivities studies

Sensitivities
(Lower Octant)

2-flavor framework

Sensitivities
(Higher Octant)
3-flavor mixing framework
sensitivities studies
Beam + atmospheric

Sensitivities
(Lower Octant)

Sensitivities
(Higher Octant)
Neutrino Time of Flight (ND → FD 735 km)

- Baseline ND – FD = 2,449,316.3 ns
- Neutrino events:
  \[ \delta = (-2.4 \pm 0.1)_{\text{stat}}^{\pm 2.6}_{\text{syst}} \text{ ns} \]
  \[ \left( \frac{v}{c} - 1 \right) = (1.0 \pm 1.1) \times 10^{-6} \]

Systematic uncertainty

| Common view GPS | 2.3 ns |
| TWTT GPS | 1.0 ns |
| NIST-NGS-Fermilab | 0.6 ns |
| Auxiliary Detectors | 0.5 ns |
| **TOTAL** | **2.6 ns** |
Near future

MINOS+
MINOS+

- **ME beam (new)**
  - New target
  - New horn 1
  - Horn 2 \( \rightarrow \) 10m downstream
  - 1.33 sec cycle
  - 700 kW beam power
  - \( 6 \times 10^{20} \) POT/year

- **Physics goals**
  - Precision measurements of atmospheric oscillations
  - Probes higher energy region
  - Search for sterile neutrinos
  - Search for NSI

- **Corollary:**
  - 3 years of running in 4-10 GeV
  - Significant reduction in stat. uncertainty
  - Collect \( \sim 3000 \) numu’s CC events/year
Calibration and monitoring

Tools: light injection and stopping muons

Light yield

PMT gains

Raw response

Fully calibrated

Light yield: -3%/year

PMT gains: +2%/year
- Significant statistical improvement on the “rising” edge of oscillations
- Using reactor experiments (e.g., Bugey) and high stat. MINOS+ can almost rule out the allowed low mass LSND region
Sensitivities (Higher Octant)

\[
\frac{1}{2} (\Delta m^2_{32} + \Delta m^2_{21}) / 10^{-3} \text{eV}^2
\]

\(\sin^2 \theta_{23}\)

Sensitivities (Lower Octant)

\[
\frac{1}{2} (\Delta m^2_{32} + \Delta m^2_{21}) / 10^{-3} \text{eV}^2
\]

\(\sin^2 \theta_{23}\)
Summary

- **End of MINOS**
  

- Set stringent constraints on disappearance
  
  \[ |\Delta m^2| = 2.41^{+0.09}_{-0.10} \times 10^{-3} \text{eV}^2 \]
  
  \[ \sin^2(2\theta) = 0.950^{+0.035}_{-0.036} \quad \text{sin}^2(2\theta) > 0.890 \quad (90\% \text{ C.L.}) \]

- Constraints on long-baseline electron-neutrino appearance
  
  \[
  \begin{align*}
  \text{NH:} & \quad 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.051^{+0.038}_{-0.030} \\
  \text{IH:} & \quad 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.093^{+0.054}_{-0.049}
  \end{align*}
  \]
  + illustration of combined LB & reactors analysis

- 3-flavor analysis coming soon…

- **MINOS+** → new high statistics data (with medium energy beam)

- **NuMI** – the most powerful beam with 4 experiments w/ 5 detectors
  
  ⇒ MINOS+ ND, NOvA ND, NOvA NDOS, Minerva, microBooNE
The PMNS Fitter

- Framework for global fit with deeply involved from all current experiments (not just likelihood surface, but systematic contributions).

- “Bayesian Analysis Toolkit” (BAT based on Bayes’ theorem and MCMC) is used as backbone.

- Using MINOS data to test framework (by comparing with MINOS published results)

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
\sin^2(2\theta_{13}) = 0.098 \pm 0.009
\]

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Viet Nus, December 21, 2012