Latest Results from MINOS and MINOS+

Will Flanagan, UT Austin
Neutrinos... are a pathway to discovery

- Nobel 1988: Lederman, Schwartz and Steinberger ($\nu_\mu$)
- Nobel 1995: Reines ($\nu_e$)
- Nobel 1988: Davis and Koshiba (astrophysical neutrinos)
- Nobel 2015: Kajita and McDonald (neutrino oscillations)
Neutrinos... are a pathway to discovery

...for the discovery of neutrino oscillations, which shows that neutrinos have mass...
What is our current picture of neutrino oscillations?

\[
\begin{bmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{bmatrix} =
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{bmatrix}
\begin{bmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{bmatrix}.
\]

\[
\Delta m^2_{atm} \approx 2.4 \times 10^{-3} \text{eV}^2
\]

\[
\Delta m^2_{sol} \approx 7.5 \times 10^{-5} \text{eV}^2
\]
\[ \nu_\mu \text{ disappearance } \approx P(\nu_\mu \rightarrow \nu_\tau) \]

\[ P_{\nu_\mu \rightarrow \nu_\tau} = [\sin(2\theta)\sin\left(\frac{(\Delta m)^2 c^3}{4\hbar E}\right)L]^2 \]

- Three flavor formalism and higher order terms bring in sensitivity to \( \theta_{13} \) and \( \delta_{CP} \).

\[ L=735\text{km} \quad \sin^2(2\theta_{23})=0.9 \]

\[ L=735\text{km} \quad \Delta m_{32}^2=2.3\times10^{-3} \]

\[ \Delta m_{32}^2=2.0 \times 10^{-3}\text{eV}^2 \]
\[ \Delta m_{32}^2=2.3 \times 10^{-3}\text{eV}^2 \]
\[ \Delta m_{32}^2=2.6 \times 10^{-3}\text{eV}^2 \]

\[ \sin^2(2\theta_{23})=0.8 \]
\[ \sin^2(2\theta_{23})=0.9 \]
\[ \sin^2(2\theta_{23})=1.0 \]
NuMI Beamline for MINOS

- Accelerator neutrino source at Fermilab
  - 120 GeV ‘Main Injector’
  - Neutrinos at the Main Injector: NuMI
  - Adjustable beam optics using magnetic horns
- Main Injector Neutrino Oscillation Search
  - NuMI now also feeds MINERνA and NOνA

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The MINOS Detectors

- $L_{\text{Near}} = 1$ km, $m_{\text{Near}} = 0.98$ kton
- $L_{\text{Far}} = 735$ km, $m_{\text{Far}} = 5.4$ kton
- Two functionally similar steel-scintillator sampling calorimeters
  - 2.5cm thick steel planes, plastic scintillator with WLS fibers to M16/M64 Hamamatsu PMTs
MINOS/MINOS+ Data

- MINOS collected from low energy beam February 2006 to April 2012
- MINOS+ with NOνA-era beam since September 2013
  - 500+ kW, 120 GeV beam, with $2-5 \times 10^{13}$ protons per pulse
  - MINOS+ recorded $9.7 \times 10^{20}$ protons on target through June 2016.
- Beneficiaries of the Fermilab proton improvement plan (PIP)

![Graph showing neutrino events and protons on target]

Total NuMI protons-on-target (POT)

- Low Energy neutrinos
- Low Energy antineutrinos
- Higher Energies
- Medium Energy neutrinos

<table>
<thead>
<tr>
<th>Date</th>
<th>Total protons ($\times 10^{20}$)</th>
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<tr>
<td>2005/04/27</td>
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<tr>
<td>2006/09/20</td>
<td>5</td>
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<tr>
<td>2008/02/12</td>
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<td>2015/02/05</td>
<td>10</td>
</tr>
<tr>
<td>2016/06/29</td>
<td>15</td>
</tr>
</tbody>
</table>

**This talk**:
- 10.56$x10^{20}$ POT
- 3.36$x10^{20}$ POT
- 5.80$x10^{20}$ POT
Latest result from first two years of MINOS+ data
Consistent with MINOS result

MINOS+ Preliminary

Far Detector

Reconstructed $\nu_\mu$ Energy (GeV)

Events /GeV

0
100
200
300
400
500
600
700

MINOS+ data
Prediction, no oscillations
MINOS+ fit
POT 5.80 $\times 10^{20}$ POT $\nu_\mu$-mode MINOS+

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MINOS/MINOS+ Combination

Energy (GeV)

MINOS, MINOS+ data
Prediction, no oscillations
MINOS, MINOS+ combined fit

5.80 x 10^{20} POT ν_µ-mode MINOS+
10.71 x 10^{20} POT ν_µ-mode MINOS
3.36 x 10^{20} POT ν_µ-mode MINOS

MINOS+ Preliminary

Reconstructed Events / GeV

POT

0 5 10 15 20 30 50

Energy (GeV)

Reconstructed ν_µ Energy (GeV)

MINOS, MINOS+ data
Prediction, no oscillations
MINOS, MINOS+ combined fit
PRL 112, 191801 (2014)

10.71 x 10^{20} POT ν_µ-mode MINOS
3.36 x 10^{20} POT ν_µ-mode MINOS
5.80 x 10^{20} POT ν_µ-mode MINOS+

MINOS+ Preliminary

Ratio to No oscillations

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

MINOS+ Preliminary
MINOS/MINOS+ Combination

48.67 kt-yr atmospheric \( \nu \)
MINOS: \( \nu_\mu \) disappearance + \( \nu_e \) appearance
POT: \( 10.71 \times 10^{20} \) \( \nu_\mu \)-mode, \( 3.36 \times 10^{20} \) \( \nu_\mu \)-mode
MINOS+: \( \nu_\mu \) disappearance
POT: \( 5.80 \times 10^{20} \) \( \nu_\mu \)-mode

-2\Delta \log(L)
\( |\Delta m^2_{32}| \) (10\(^{-3}\) eV\(^2\))

Profile of likelihood surface
Normal ordering
Inverted ordering

MINOS+ Preliminary

☆ Best fit
☆ PRL 112, 191801 (2014)

68% C.L.
90% C.L.

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How about the field as a whole?

MINOS, MINOS+ combined analysis

MINOS+ Preliminary

Normal hierarchy

IceCube 90% C.L.
Neutrino 2016

NOvA 90% C.L.

T2K 90% C.L.

Neutrino 2016

$\Delta m_{32}^2 \left(10^{-3} \text{eV}^2\right)$

$\sin^2 \theta_{23}$
Hints for a fourth type of neutrino have been seen at:

- solar neutrino experiments (the gallium anomaly)
- accelerator experiments (LSND, MiniBooNE)
- reactor experiments (the reactor antineutrino anomaly)
Many orders of magnitude in $\Delta m^2$ parameter space available.

Oscillations possible at both near and far MINOS detectors.
Unlike the $|\Delta m^2_{32}|/\sin^2 \theta_{23}$ measurement, the near detector can’t be used to predict the far detector.

- Data previously fit as Far/Near ratio.
- Simultaneous two detector fit in current result.
• Particular improvement for high $\Delta m^2$ region where oscillations occur in both near and far detectors.
  • The point below is $\Delta m_{14}^2 = 80\text{eV}^2$ and $\theta_{24} = 0.2$
44 sources of systematics uncertainty considered. 
- NC energy scale and CC cross sections dominate.
Above are the CC spectra and below are the NC spectra
Exclusions contours in Feldman-Cousins unified framework.
Combination with Daya Bay Collaboration published earlier this year.

- Includes Bugey-3 data
- Combination through CLs technique
Preliminary result part of an ongoing joint effort between MINOS+ and Daya Bay.

Combination with larger Daya Bay data set planned.
We are searching for sterile neutrinos arising from other scenarios (Large Extra Dimensions) and other channels ($\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_s$)
Conclusions

- Neutrino oscillations entering precision era.
  - MINOS+ continues to improve precision on $|\Delta m_{32}^2|/\sin^2\theta_{23}$.
- Increased tension in 3+1 parameter space.
  - New results with simultaneous two detector fit.
- Stay tuned!
MINOS $\nu_\mu$ (Beam and Atmospheric)

Latest Results from MINOS and MINOS+

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MINOS $\nu_e$ Appearance

- MC-based Library Event Matching (LEM) technique used to distinguish $\nu_e$ events from NC events.
- Non-zero value of $\theta_{13}$
- Sensitivity to $\delta_{CP}$ when incorporating reactor limits (Daya Bay, RENO) and $\theta_{23}/\Delta m^2_{32}$ measurements.