Results from MINOS and MINOS+

Selected Topics:
+ Beams and detectors
+ Standard oscillations
+ Sterile neutrinos
+ Large extra dimensions

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On behalf of the MINOS+ Collaboration
MINOS & MINOS+

BEAMS AND DETECTORS
MINOS, MINOS+, and NuMI

- **Far Detector (FD) on axis**
  - 735 km from target
  - 5.4 kt, 8m octagon
  - ~1.2 T B field
  - Segmented, sampling, iron/scint. tracking calorimeter

- **Near Detector (ND) on axis**
  - 1,040 m from target
  - 1kt, 4m `squeezed’ octagon
  - ~1.2 T B field
  - Same technology as FD

- **2-horn focusing 185 kA**
- **2λ graphite target (movable)**
- **Up to ~600 kW beam**
- **3.5x10^{13} ppp**
- **1.33 s cycle time**

- **MINOS Proposed 1995**
- **Main Injector 2000**
- **Beam data 2005-2012**
- **NuMI reconfigured for NOvA 2013**
- **MINOS+ 2013-2016**

K. Lang, U. of Texas at Austin, Results from MINOS and MINOS+, Int. Symposium on Neutrino Frontiers, ICISE, Quy Nhon, July 16, 2018
MINOS: Near and Far Detectors

K. Lang, U. of Texas at Austin, Results from MINOS and MINOS+, Int. Symposium on Neutrino Frontiers, ICISE, Quy Nhơn, July 16, 2018
MINOS and MINOS+ exposures
2005 → 2016

NuMI neutrino exposure history - Protons-on-target (POT)

Date

Total Protons (x10^{20})

Protons per week (x10^{18})

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

MINOS (2005-2012)
10.56 \times 10^{20} \text{ POT}

MINOS+ (2013-2016)
3.36 \times 10^{20} \text{ POT}

9.69 \times 10^{20} \text{ POT}

Not fully analyzed
MINOS & MINOS+ atmospheric neutrinos

MINOS+ Preliminary
Atmospheric Neutrinos (60.75 kt-yr)

- - - - Mean event rate

Full dataset (2003 – 2016)
60.8 kt-yr

New: 12.1 kt-yr
(~20% of total sample)

K. Lang, U. of Texas at Austin, Results from MINOS and MINOS+, Int. Symposium on Neutrino Frontiers, ICISE, Quy Nhon, July 16, 2018
MINOS & MINOS+

STANDARD OSCILLATIONS
Event types in MINOS

- $\nu_\mu$ Charged Current ($\nu_\mu$ CC)
- $\nu_x$ Neutral Current (NC)
- $\nu_e$ Charged Current ($\nu_e$ CC)

K. Lang, U. of Texas at Austin, Results from MINOS and MINOS+, Int. Symposium on Neutrino Frontiers, ICISE, Quy Nhon, July 16, 2018
Atmospheric neutrinos and antineutrinos

- Fit in bins of $\cos(\theta_{\text{zen}})$ and energy
- Separate neutrino and antineutrino (mass hierarchy discrimination)
- Complements beam neutrino samples

K. Lang, U. of Texas at Austin, Results from MINOS and MINOS+, Int. Symposium on Neutrino Frontiers, ICISE, Quy Nhon, July 16, 2018
MINOS+
Charged current ($\nu_\mu$-CC) vs Neutral current (NC) classification

Event classification:
k Nearest-Neighbors (kNN)

MINOS+ Far Detector $\nu_\mu$-CC

- Efficiency: 85.9%
- Purity: 99.3%

K. Lang, U. of Texas at Austin, Results from MINOS and MINOS+, Int. Symposium on Neutrino Frontiers, ICISE, Quy Nhon, July 16, 2018
Improved beam flux calculations

- Fit hadron production from HORNS OFF (i.e., no focusing B-field)
- Fit for focusing effects in HORNS ON (i.e., with focusing B field)

K. Lang, U. of Texas at Austin, Results from MINOS and MINOS+, Int. Symposium on Neutrino Frontiers, ICISE, Quy Nhon, July 16, 2018
Combined fit MINOS & MINOS+ (beam + atmospheric)

MINOS+ Preliminary

MINOS+ only

MINOS+ Preliminary

MINOS+ Preliminary

MINOS+ Preliminary

K. Lang, U. of Texas at Austin, Results from MINOS and MINOS+, Int. Symposium on Neutrino Frontiers, ICISE, Quy Nhon, July 16, 2018
$\chi^2$ contours and projections

Best fit: $\Delta m^2_{32} = + 2.42 \ (\times 10^{-3} \text{eV}^2)$
$\sin^2 \theta^2_{23} = 0.42$

Normal $\Delta m^2_{32} = (2.28 \leftrightarrow 2.55) \ (\times 10^{-3} \text{eV}^2)$
$\sin^2 \theta^2_{23} = (0.37 \leftrightarrow 0.65)$

Inverted $\Delta m^2_{32} = - (2.33 \leftrightarrow 2.60) \ (\times 10^{-3} \text{eV}^2)$
$\sin^2 \theta^2_{23} = (0.36 \leftrightarrow 0.65)$
Comparison of latest results

MINOS, MINOS+ combined analysis

MINOS+ Preliminary

NOvA 90% C.L. Neutrino 2018

T2K 90% C.L.

PRD 96, 092006 (2017)

IceCube 90% C.L.
PRL 120, 071801 (2018)
MINOS & MINOS+

SEARCH FOR STERILE NEUTRINOS
The “3+1” mixing

\[
U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{pmatrix}
\]

◆ (New) Oscillation parameters:

- 3 mass scales:  \( \Delta m^2_{21}, \Delta m^2_{32}, \Delta m^2_{41} \)
- 6 mixing angles:  \( \theta_{12}, \theta_{23}, \theta_{13}, \theta_{14}, \theta_{24}, \theta_{34} \)
- 3 CP-violating phases:  \( \delta_{13}, \delta_{14}, \delta_{24} \)

◆ Search for

- neutral current disappearance  \( \Rightarrow \) sensitive to  \( \Delta m^2_{41} \) and  \( \theta_{24}, \theta_{34} \)
- \( \nu_\mu \)-charged current disappearance  \( \Rightarrow \) sensitive to  \( \Delta m^2_{41} \) and  \( \theta_{24} \)
“3+1” oscillations

Small $\Delta m^2_{41} \sim 0.5$ eV$^2$
- Almost no oscillations at the ND
- Oscillations at high E at the FD

Large $\Delta m^2_{41} \sim 5$ eV$^2$
- Oscillations at the ND
- Finite energy resolution averages out rapid oscillations at the FD
The 2016 sterile neutrino analysis used the ratio of FD & ND energy spectra*:

- Many systematics cancel in the ratio
- Ratio uncertainty dominated by FD statistics
- Effect of high-mass sterile neutrino cancels

Two-detector fit strategy

- ND and FD fits simultaneously

- Flux derived using MINERvA PPFX method (uses hadron production data)

- Systematic uncertainties encoded in the covariance matrices
  - 26 sources of systematic uncertainties
  - Accounts for correlations

- Use $\nu_\mu$-CC and NC spectra in a joint $\chi^2$ fit

$$\chi^2 = \sum_{i,j=1}^{N} (\text{obs}_i - \text{pred}_i)[V^{-1}]_{ij}(\text{obs}_j - \text{pred}_j)$$
\(\nu_\mu\) Charged Current energy spectra

- Covariance matrix fits do not include systematics as nuisance parameters
- The error bands and prediction account for off-diagonal

Far Detector

Near Detector
Neutral Current energy spectra

- Covariance matrix fits do not include systematics as nuisance parameters
- The error bands and prediction account for off-diagonal

Far Detector

Near Detector
Fit and contour results

- Use full NC and CC samples in two detectors
- Fit for $\theta_{23}$, $\theta_{24}$, $\theta_{34}$, $\Delta m^2_{32}$, and $\Delta m^2_{41}$
- Fix $\delta_{13}$, $\delta_{14}$, $\delta_{24}$, and $\theta_{14}$ to zero
- Median sensitivity from Feldman-Cousins corrected 90% CL contours from pseudo-experiments

Best fit:
- $\Delta m^2_{41} = 2.33 \times 10^{-3} \text{ eV}^2$
- $\sin^2 \theta_{24} = 1.1 \times 10^{-4}$
- $\theta_{34} < 8.4 \times 10^{-3}$
- $\sin^2 2\theta_{23} = 0.92$
- $\chi^2_{\text{min}} / \text{dof} = 99.3 / 140$
- $\chi^2(4\nu) - \chi^2(3\nu) = 0.01$
Sterile neutrino bounds

- MINOS and MINOS+ 90% C.L. exclusion limit over 7 orders of magnitude in $\Delta m_{41}^2$

- Improvement at large $\Delta m_{41}^2$ over previous MINOS result due to:
  - Near Detector statistical power
  - Sensitivity to normalization shifts
  - Improved binning around atmospheric dip in Far Detector

- Increased tension with global best fit
  - Displayed here with $|U_{e4}|^2 = 0.023$

- Posted to arXiv:1710.06488 and submitted to PRL
  - See arXiv paper and ancillary materials for more details

- Final year of data is still to be analyzed

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MINOS & MINOS+

LARGE EXTRA DIMENSIONS (LED)
Introduce extra spatial dimension compactified on a circle with radius $R$

3 sterile fields that live in the bulk

Sterile fields act as Kaluza-Klein towers of infinite sterile neutrinos

$P(\nu_\mu \rightarrow \nu_\mu) = \sum_{j=1}^{3} \sum_{n=0}^{+\infty} U_{\mu j} U_{\mu j}^* (W_{j}^{(0n)})^2 \exp \left[ i \left( \frac{\lambda_j^{(n)}}{R} \right)^2 \left( \frac{L}{2E} \right) \right]^{2}$

$\Delta m_{21}^2 = 7.54 \times 10^{-5} \text{ eV}^2$

$\Delta m_{32}^2 = 2.37 \times 10^{-3} \text{ eV}^2$

$\sin^2 \theta_{12} = 0.308$

$\sin^2 \theta_{13} = 0.022$

$\sin^2 \theta_{23} = 0.410$

$\delta_{\text{CP}} = 0$

Three-flavor

- 735 km baseline
- MINOS FD

$R = 0.60 \mu m, m_0 = 0.010 \text{ eV}$

- 735 km baseline
- MINOS FD

$P(\nu_\mu \rightarrow \nu_\mu) = \sum_{j=1}^{3} \sum_{n=0}^{+\infty} U_{\mu j} U_{\mu j}^* (W_{j}^{(0n)})^2 \exp \left[ i \left( \frac{\lambda_j^{(n)}}{R} \right)^2 \left( \frac{L}{2E} \right) \right]^{2}$

Mixing in towers

Neutrino masses
Previous results:
Far-over-Near method

MINOS+ and MINOS data
Two-detector method

$R < 0.30 \mu m$ at 90% C.L.
for vanishing $m_0$
MINOS & MINOS+

THE END GAME

MINOS excavation ca. 2000
MINOS & MINOS+

- 11 years of operations, 25 POT exposure, up to 600 kW beam
- Best to date $\Delta m^2_{32}$ (68% CL), no octant preference at 90%CL for $\theta_{23}$

Normal \[ \Delta m^2_{32} = +2.42^{+0.08}_{-0.09} \times 10^{-3} \text{eV}^2 \]
\[ \sin^2 \theta_{23} = 0.42 \ (0.37 \leftrightarrow 0.65 \ [90\%C.L.]) \]

Inverted \[ \Delta m^2_{32} = -2.48^{+0.10}_{-0.07} \times 10^{-3} \text{eV}^2 \]
\[ \sin^2 \theta_{23} = 0.42 \ (0.36 \leftrightarrow 0.65 \ [90\%C.L.]) \]

- Some of the most stringent bounds on “3+1” sterile neutrinos
  - Muon neutrino disappearance
  - Joint analysis with Daya Bay for $\nu_\mu \rightarrow \nu_e$ appearance bounds
  - Increased tension with global fits

- Bounds on LED and NSI (soon)
Then and now

Last MINOS+ FD event: 29 Jun 2016

Ely, MN, June 2012 (the proposal era)
MINOS

EXTRA IMAGES
We consider 44 total sources of systematic uncertainty in five categories. Largest contributions arise from energy calibration uncertainty for NC events and cross-section uncertainties for CC events. Statistical and systematic uncertainties are incorporated via covariance matrix. Covariance matrix cross-terms allow for cancellation of uncertainties.

\[ \chi^2 = \sum_{i,j=1}^{N} (\text{obs}_i - \text{pred}_i)[V^{-1}]_{ij}(\text{obs}_j - \text{pred}_j) \]
CC and NC probabilities/ uncertainties

\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) \]
\[ - \sin^2 2\theta_{24} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right). \] (1)

\[ P_{NC} = 1 - P(\nu_\mu \rightarrow \nu_s) \]
\[ \approx 1 - \cos^4 \theta_{14} \cos^2 \theta_{34} \sin^2 2\theta_{24} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]
\[ - \sin^2 \theta_{34} \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) \]
\[ + \frac{1}{2} \sin \delta_{24} \sin \theta_{24} \sin 2\theta_{34} \sin 2\theta_{23} \sin \left( \frac{\Delta m_{31}^2 L}{2E} \right) \] (2)

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Sensitivity to $\sin^2 \theta_{24}$ at:</th>
<th>$\Delta m_{41}^2 = 1 \text{ eV}^2$</th>
<th>$\Delta m_{31}^2 = 1000 \text{ eV}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics only</td>
<td>0.0008</td>
<td>0.0002</td>
<td></td>
</tr>
<tr>
<td>+Energy scale</td>
<td>0.0054</td>
<td>0.0003</td>
<td></td>
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<tr>
<td>+Hadron production</td>
<td>0.0131</td>
<td>0.0063</td>
<td></td>
</tr>
<tr>
<td>+Cross section</td>
<td>0.0138</td>
<td>0.0103</td>
<td></td>
</tr>
<tr>
<td>+Background</td>
<td>0.0141</td>
<td>0.0112</td>
<td></td>
</tr>
<tr>
<td>+Beam</td>
<td>0.0143</td>
<td>0.0128</td>
<td></td>
</tr>
<tr>
<td>+Other</td>
<td>0.0153</td>
<td>0.0165</td>
<td></td>
</tr>
</tbody>
</table>

Table I. The reduction in $\sin^2 \theta_{24}$ exclusion sensitivity caused by accumulation of systematic sources at two values of $\Delta m_{41}^2$. The systematic uncertainty sources are given in Eq. (4).
The “3+1” oscillations in two detectors

\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{13} \sin^2 \Delta_{31} \]

\[ - \sin^2 2\theta_{13} \sin^2 \Delta_{41} \]
4-flavor oscillations in MINOS

- MINOS is sensitive to three sterile neutrino parameters
  - $\theta_{24}, \theta_{34}$ and $\Delta m_{41}^2$
  - Small $\Delta m_{41}^2 < 0.05$ eV$^2$
  - Low $\Delta m_{41}^2$ only affects FD

- Oscillations can cause effects in both detectors
  - Rapid oscillations cause a constant deficit in FD
  - Medium $\Delta m_{41}^2 \sim 0.5$ eV$^2$

- Can’t use ND as a flux measurement in this analysis
  - High $\Delta m_{41}^2 \rightarrow$ oscillations in ND
  - Large $\Delta m_{41}^2 > 5$ eV$^2$
  - Oscillations at the ND
Large Extra Dimension: effect of $R$ and $m_0$

Ratios of energy spectra
(as in the sterile analysis)

$R = 1.00 \, \mu m$
$\mu m_0 = 0.5 \, eV$

$R = 1.00 \, \mu m$
$\mu m_0 = 0.0 \, eV$

Charged Current

Neutral Current

K. Lang, U. of Texas at Austin, Results from MINOS and MINOS+, Int. Symposium on Neutrino Frontiers, ICISE, Quy Nhon, July 16, 2018
Comparison of latest results

\[ \Delta m^2_{32} \ (10^{-3} \text{eV}^2) \]

\[ \sin^2 \theta_{23} \]

MINOS, MINOS+
combined analysis

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

MINOS+ Preliminary

NOvA 90% C.L.
Private Communication (2018)

T2K 90% C.L.
PRD 96, 092006 (2017)

IceCube 90% C.L.
PRL 120, 071801 (2018)

Normal hierarchy

K. Lang, U. of Texas at Austin, Results from MINOS and MINOS+, Int. Symposium on Neutrino Frontiers, ICISE, Quy Nhon, July 16, 2018
LED analysis details

- LED
- MINOS
- MINOS+
- Neutrino 2018

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LED analysis details

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MINOS bounds

\[ \chi^2 = \sum_{i,j=1}^{N} (o_i - e_i)[V^{-1}]_{ij}(o_j - e_j) + \left( \frac{N_{\text{data}} - N_{\text{MC}}}{\sigma_N} \right)^2 \]

Future:
- MINOS+ and MINOS data
- Two-detector method

P. Adamson et al. [MINOS Collaboration], Phys.Rev. D94 (2016) no.11, 111101
- The 2017 MINOS sterile analysis uses Far and Near Detectors energy spectra directly rather than their ratios
- Systematics through the covariance matrix
Comparison with Other Experiments

The 2017 results

◆ New limit improves constraint of the previous MINOS analysis

◆ Constraint improved by Near Detector contribution for $\Delta m^2_{41} \sim 5 \text{ eV}^2$

◆ Increased tension with global best fit

**Preliminary**: ongoing effort between MINOS+/MINOS and Daya Bay and Bugey-3 data.

- Significant increase in the constraint at $\Delta m^2_{41} > 10 \text{ eV}^2$ due to two-detector fit method.

- A new combination with a larger Daya Bay data later.

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Combined fit MINOS & MINOS+ (beam + atmospheric)

Best fits, 90% C.L.

Best fit: \[ \Delta m_{32}^2 = + 2.42 \times 10^{-3} eV^2 \]
\[ \sin^2 \theta_{23}^2 = 0.42 \]

Normal \[ \Delta m_{32}^2 = + (2.28 \leftrightarrow 2.55) \times 10^{-3} eV^2 \]
\[ \sin^2 \theta_{23}^2 = (0.37 \leftrightarrow 0.65) \]

Inverted \[ \Delta m_{32}^2 = - (2.33 \leftrightarrow 2.60) \times 10^{-3} eV^2 \]
\[ \sin^2 \theta_{23}^2 = (0.36 \leftrightarrow 0.65) \]
Systematics

\[ |\Delta m^2| / (10^{-3} \text{ eV}^2) \]

\[ \sin^2(2\theta) \]

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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MINOS disappearance and appearance


Disappearance & Appearance only