MINOS and MINOS+
Selected topics

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Outline:
- Latest oscillations results
- Search for sterile neutrinos
- Search for more exotic transitions
MINOS and NuMI

Main Injector Neutrino Oscillation Search

NuMI beam

- High intensity, flexible beam
  - $3.5 \times 10^{13}$ protons/pulse (~320 kW, 120 GeV beam)
  - two magnetic horns
  - movable target (adjustable energy spectrum)
  - Proton Improvement Plan (PIP) underway (700 kW)
  - 2.2sec. $\rightarrow$ 1.7sec. $\rightarrow$ 1.33sec. cycle time

- Two functionally similar magnetized detectors
  - Far Detector in operation since 2003
  - NuMI and Near Detector since 2005

- Medium energy beam since 2013 for off-axis NOvA
NuMI Medium Energy beam setting

- Medium Energy (ME) beam setting (new) for NOvA
  - New target, new horn 1
  - Horn 2 → 10m downstream
  - With PIP: $6 \times 10^{20}$ POT/year

Old target

New target

**Simulated Enhanced $\bar{\nu}$ Beam**
5.4 kton, $6 \times 10^{20}$ POT

- ME on-axis
- LE on-axis

14 mrad off-axis

CC Events / GeV

$E_\nu$ (GeV)
MINOS Detectors

Near Detector
(1 kton, 1km from source)

Far Detector
(5.4 kton, 735 km from source)

- Scintillator Strips w/ WLS fibers
- Multi-anode PMT’s
- Charged current $\nu_\mu$ events
- Neutral current events
- Charged current $\nu_\tau$ events

$\nu_e$ CC Event
MINOS Detectors: long-term view

- Detectors mature as expected
- Operate with sustained stability
- > 95% live-time

**Light yield (relative)**

-3% / year

**MINOS+ Era**

**MINOS Preliminary**

**Near Detector Data**

MINOS+ Preliminary

- 4th Sep - 30th Sep (2013)
- 1st Nov - 30th Nov (2013)
- 1st Dec - 31st Dec (2013)
- 1st Jan - 31st Jan (2014)
- 1st Feb - 28th Feb (2014)
- 1st Mar - 31st Mar (2014)
- 1st Apr - 24th Apr (2014)

Reconstructed neutrino energy (GeV)
Published results on $\Delta m^2_{32}$, $\theta_{23}$, $\theta_{13}$:

- $\nu_\mu$ disappearance (PRL 110, 251801, 2013)
- $\nu_\mu \rightarrow \nu_e$ appearance (PRL 110, 171801, 2013)
- Combined analysis (PRL 112, 191801, 2014)
MINOS & MINOS+ (atm.) combined analysis results
Disappearance and appearance, beam and atmospheric data

**Preliminary**

MINOS+ addition for these results:
10.79 kt*yrs of atmospheric data

**Inverted Hierarchy**

\[
|\Delta m_{32}^2| = 2.37^{+0.11}_{-0.07} \times 10^{-3} \text{eV}^2
\]

\[
\sin^2 \theta_{23} = 0.43^{+0.19}_{-0.05}
\]

0.36 < \sin^2 \theta_{23} < 0.65 (90% C.L.)

**Normal Hierarchy**

\[
|\Delta m_{32}^2| = 2.34^{+0.09}_{-0.09} \times 10^{-3} \text{eV}^2
\]

\[
\sin^2 \theta_{23} = 0.43^{+0.16}_{-0.04}
\]

0.37 < \sin^2 \theta_{23} < 0.64 (90% C.L.)
MINOS & NOvA

Projections for combining results

Published MINOS data

NOvA $2.5 \times 10^{20}$ POT

MINOS & NOvA

MINOS DATA

MINOS: All atmospheric and beam data

Normal hierarchy

Inverted hierarchy

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

NOvA SIMULATION

NOvA: $2.5 \times 10^{20}$ POT $\nu_e$-mode

Normal hierarchy

Inverted hierarchy

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

MINOS DATA & NOvA SIMULATION

MINOS: All atmospheric and beam data

NOvA: $2.5 \times 10^{20}$ POT $\nu_e$-mode

Normal hierarchy

Inverted hierarchy

68% C.L. 90% C.L.
MINOS & MINOS+ & NOvA (end 2016)

Have: 3.0 x 10^{20} POT in 2013-2014
Assume: + 2.3 x 10^{20} POT in 2014-2015
Assume: + 4.7 x 10^{20} POT in 2015-2016
Total: 10.0 x 10^{20} POT by end of 2016

Published MINOS data & MINOS+ 10 x 10^{20} POT

NOvA 7.2 x 10^{20} POT

MINOS & MINOS+ & NOvA
MINOS+ data

- MINOS: $10.56 \times 10^{20}$ in the Low $E_\nu$ mode
- MINOS+: $3.0 \times 10^{20}$ in the Medium $E_\nu$ mode (here $1.68 \times 10^{20}$)
- No beam oscillations results from MINOS+ yet

|                | $\mu^- | \mu^+$ |
|----------------|----------|
| Unoscillated Prediction | 1254.8   | 52.03    |
| Oscillated Prediction   | 1085.2   | 47.09    |
| Data                     | 1037     | 48       |

K. Lang, U. of Texas at Austin, MINOS & MINOS+, NNN 2014, APC Paris, Nov 4-6, 2014
MINOS & MINOS+ data

- MINOS: $10.56 \times 10^{20}$ in the Low $E_\nu$ mode
- MINOS+: $3.0 \times 10^{20}$ in the Medium $E_\nu$ mode (here $1.68 \times 10^{20}$)
- No beam oscillations results from MINOS+ yet
Sterile analysis: NC + CC event spectra

- Energy spectra at the Far Detector for $\nu_\mu$ events
- Observed (black crosses) vs predicted assuming no sterile neutrinos (red)

**Far Detector stats (0-40 GeV):**
- 2563 $\nu_\mu$ CC events
- 1211 NC events

**Equation:**

$$R = \frac{N_{data} - \sum Backgrounds}{Signal_{Pred NC}}$$

- $R = 1.08 \pm 0.11$ (0 - 40 GeV)
- $R = 1.11 \pm 0.10$ (0 - 3 GeV)
MINOS ratios of FD/ND energy spectra

- Ratios of energy spectra at the Far Detector to Near Detector using $\nu_\mu$ events.
- Observed (black crosses) vs predicted assuming no sterile neutrinos (red)

- Fit the observed FD/ND ratios for CC and NC
- Use $|\Delta m^2_{43}|$, $|\Delta m^2_{32}|$, $\theta_{23}$, $\theta_{24}$, $\theta_{34}$ and fix other parameters
- Systematics with the covariance matrix
- CLs use Feldman-Cousins recipe

[Images of graphs showing CC and NC ratios with relevant parameters]
Sterile neutrino analysis assumptions

- The MINOS disappearance data in the 3 + 1 model:
  - 3 active flavours ($\nu_e, \nu_\mu, \nu_\tau$)
  - Add 1 sterile flavour ($\nu_S$)
  - Add 1 extra mass state ($\nu_4$)

  $\Rightarrow 4 \times 4$ neutrino mixing matrix

- Neutrino mixing parameters:
  - Standard 3-flavour parameters:
    - $\Delta m^2_{32}, \Delta m^2_{21}$
    - $\theta_{12}, \theta_{23}, \theta_{13}, \delta_{13}$
  - Additional 4-flavour parameters
    - $\Delta m^2_{43}$
    - $\theta_{14}, \theta_{24}, \theta_{34}, \delta_{14}, \delta_{24}$
MINOS constraints on sterile neutrinos from the disappearance data

- Fit to the disappearance of NC and $\nu_\mu$ CC energy spectra

- Strongest constraints on $\nu_\mu \rightarrow \nu_s$ disappearance for $\Delta m^2_{43} < 1 \text{ eV}^2$
MINOS & Bugey

- Use best fit to NC and $\nu_\mu$ CC MINOS disappearance
- Combine MINOS with the $\nu_e$ disappearance by the Bugey reactor disappearance data
  - MINOS: 90% C.L. on $\theta_{24}$
  - Bugey: 90% C.L. on $\theta_{14}$
  - Construct combined limit on

\[ \sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14} \sin^2 2\theta_{24} \]

* Bugey limits computed by P. Huber using GLoBES 2012 and new reactor fluxes.

- These results rule out much of $\Delta m^2_{43} < 1$ eV$^2$ for sterile neutrinos

- Combined limits can be compared to MiniBooNE, LSND, ICARUS, and OPERA results

- Collaborating with Daya Bay to use their results
Future prospects: MINOS+ & MINOS sensitivity to sterile neutrinos

- Sensitivity after two years of MINOS+ data (red)
- Compared with the sensitivity of MINOS running (pink).
- The red line includes the MINOS running.
- This is entirely MC simulation (including the MINOS part)

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MINOS+ Preliminary

$\nu_\mu$ mode

MINOS simulation: $10.56 \times 10^{20}$ POT
MINOS+ simulation: $5.32 \times 10^{20}$ POT
Full MINOS systematics

- CDHS 90% CL
- CCFR 90% CL
- MiniBooNE 90% CL
- MiniBooNE+SciBooNE 90% CL
- MINOS 90% CL
- MINOS+ 90% CL
Non-Standard Interactions (NSI)

- Non-Standard Interactions (NSI) – generic extension beyond the MSW effect

\[ H = U_{PMNS} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{31}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{bmatrix} U_{PMNS}^\dagger + \sqrt{2}G_F n_e \begin{bmatrix} 1 + \epsilon_e \epsilon_{e\mu} \epsilon_{e\tau} \\ \epsilon_{e\mu} \epsilon_{\mu\mu} \epsilon_{\mu\tau} \\ \epsilon_{e\tau} \epsilon_{\mu\tau} \epsilon_{\tau\tau} \end{bmatrix} \]

- MINOS data can be used to constrain some of the parameters

  \( \epsilon_{\mu\tau} \) sensitivity is from the \( \nu_\mu \text{CC} \) disappearance

  \( \epsilon_{e\tau} \) sensitivity is from the \( \nu_e \text{CC} \) appearance
MINOS NSI results

Neutrino 2014

- $\epsilon_{\mu\tau}$ results in:
  - Presented at Neutrino 2014 in Boston
  - Follows:
    - Friedland, Lunardini, Maltoni
      PRD 70, 111301 (2004)
    - Coelho, Kafka, Mann, Schneps, Altinok
      PRD 86, 113015 (2012)

- $\epsilon_{e\tau}$ study is the first MINOS only analysis for this parameter

K. Lang, U. of Texas at Austin, MINOS & MINOS+, NNN 2014, APC Paris, Nov 4-6, 2014
Large Extra Dimensions (LED)

- Proposed by Arkani-Hamed et al. for gauge hierarchy problem
- Used on neutrinos to explain their small masses
  - left-handed neutrinos are confined to a 4 dimensional subspace
  - right-handed neutrino can propagate in more than 4 dimensions
- Assumptions:
  - one extra dimension is much larger than others
  - perturbations to standard oscillation
- Oscillation amplitude among active neutrino states $\nu_e$, $\nu_\mu$, $\nu_\tau$

$$A(\nu_\alpha \rightarrow \nu_\beta) = \sum_{i,j,k=1}^{3} \sum_{n=0}^{+\infty} U_{\alpha i} U^*_{\beta k} W_{ij}^{(0n)*} W_{ki}^{(0n)} e^{i\frac{(\lambda^{(n)}_j/a)^2}{2E}}$$

- $U$, $W$ are mixing matrices for active and Kaluza-Klein states
- $\frac{\lambda^{(n)}_j}{a}$ is the neutrino mass

- Model parameters (Machado et al.):
  - smallest mass $m_0$
  - extra dimension size $a$
We only focus on beam disappearance

Based on a specific model, for smallest neutrino mass $m_0 \rightarrow 0$
  - MINOS is sensitive to extra dimensions down to about 0.55 $\mu$m
  - MINOS+ will bring down the limit further to about 0.4 $\mu$m

Challenge:
  - Deal with possible ND oscillations
  - Proceed to “box opening”
Examples of other MINOS physics:
QE in ND and CR in FD

$$M_A = 1.23^{+0.13}_{-0.09} (\text{fit})^{+0.12}_{-0.15} (\text{syst.}) \text{ GeV}$$

- "Comparisons of annual modulations in MINOS with the event rate modulation in CoGeNT"

Summary

- New analyses of MINOS data continue improving constraints on oscillations
  - Results of a 3-flavor combined disappearance and appearance analysis
- MINOS+ will significantly impact future results
- New bounds on sterile neutrinos
  - Combine with reactors experiments
- More exotic searches under way
  - Non-standard interactions
  - Large extra dimensions
- NuMI – the most powerful ν beam will help to make more strides
Protons-on-target (POT) history of NuMI

7 years, 7 targets, 2 horns

15.6\times10^{20} \text{ POT}

Atmospheric 48.67 kt year (since 2003)

May 1 2005 to April 30 2012

\nu \quad 10.71\times10^{20}

\text{anti-}\nu \quad 3.36\times10^{20}

Special runs

Total Protons on Target (x \times 10^{20})

NOvA era

MINOS+

New target

Horn 1
MINOS & MINOS+ & NOvA (end 2015)

Have: $3.0 \times 10^{20}$ POT in 2013-2014
Assume $+ 2.3 \times 10^{20}$ POT in 2014-2015 End of PIP
Assume $+ 4.7 \times 10^{20}$ POT in 2015-2016 $\Rightarrow 700$ kW
Total $10.0 \times 10^{20}$ POT by end of 2016

Published MINOS data & MINOS+ $5.3 \times 10^{20}$ POT

NOvA $2.5 \times 10^{20}$ POT

MINOS & MINOS+ & NOvA

-2Δ\log(L) vs |Δm_{32}^2| (10^{-3} \text{ eV}^2)
-2Δ\log(L) vs \sin^2θ_{23}

MINOS ν_μ disappearance + ν_ν appearance
10.71 \times 10^{20} \text{ POT } ν_μ-dominated beam
3.36 \times 10^{20} \text{ POT } ν_μ-enhanced beam
37.88 \text{ kt-yr atmospheric neutrinos}

Profile of likelihood surface
- Normal hierarchy
- Inverted hierarchy

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

Best fit
- 68\% C.L.
- 90\% C.L.
MINOS disappearance data set
(atmospheric data include MINOS+ data taken 2011-2014)

**MINOS PRELIMINARY**

- Neutrino beam (10.71×10^{20} POT)
  - Contained-vertex $\nu_\mu$
  - MINOS data
  - Best fit
  - No oscillations
  - NC background
  - Cosmic-ray

- Contained-vertex $\nu_\mu$
- Non-fiducial muons
- Antineutrino beam (3.36×10^{20} POT)
- Contained-vertex $\bar{\nu}_\mu$

Atmospheric neutrinos (48.67 kton-years)

- $\nu_\mu$ $E_\nu = 1-3$ GeV
- $\nu_\mu$ $E_\nu = 3-10$ GeV
- $\nu_\mu$ $E_\nu = 10-30$ GeV
- $\nu_\mu$ $P_\mu < 10$ GeV
- $\nu_\mu$ $P_\mu > 10$ GeV

- $\bar{\nu}_\mu$ $E_\nu = 1-3$ GeV
- $\bar{\nu}_\mu$ $E_\nu = 3-10$ GeV
- $\bar{\nu}_\mu$ $E_\nu = 10-30$ GeV
- $\bar{\nu}_\mu$ $P_\mu < 10$ GeV
- $\bar{\nu}_\mu$ $P_\mu > 10$ GeV

K. Lang, U. of Texas at Austin, Old Generation MINOS, NNN, APC Paris, Nov 4-6, 2014
MINOS combined analysis results

Disappearance and appearance, beam and atmospheric data

Normal H.:
\[ |\Delta m_{32}^2| = [2.28 - 2.46] \times 10^{-3} \text{eV}^2 \quad (68\% \text{C.L.}) \]
\[ \sin^2 \theta_{23} = 0.35 - 0.65 \quad (90\% \text{C.L.}) \]

Inverted H.:
\[ |\Delta m_{32}^2| = [2.32 - 2.53] \times 10^{-3} \text{eV}^2 \quad (68\% \text{C.L.}) \]
\[ \sin^2 \theta_{23} = 0.34 - 0.67 \quad (90\% \text{C.L.}) \]

Sterile neutrinos signatures in MINOS

Effect in **both** MINOS detectors

◊ **Small** $\Delta m_{43}^2 (>\Delta m_{32}^2) \ (10^{-3} - 10^{-1} \text{ eV}^2)$
   - **Far Detector**: additional oscillations above 3-flavour oscillation maximum
   - **Near Detector**: no effect

◊ **Medium** $\Delta m_{43}^2 \ (10^{-1} - 1 \text{ eV}^2)$
   - **Far Detector**: oscillations become rapid and average out, causing a constant depletion (‘counting experiment’) 
   - **Near Detector**: no effect

◊ **Large** $\Delta m_{43}^2 \ (1 - 10^2 \text{ eV}^2)$
   - **Far Detector**: constant depletion
   - **Near Detector**: oscillations
Cannot distinguish between $\nu_e$ and $\bar{\nu}_e$ events, so we perform a combined analysis using library-event-matching technique:

\[
\delta_{CP} = 0 \quad \text{and} \quad \theta_{23} < \pi / 4
\]

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

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

Drift: the overall response of the detector versus time, includes:
- changes in the PMT
- electronics
- scintillator
- Decreased by ~10% since 2005