Search for Flavor Changing Non-standard Interactions with the MINOS+ Experiment

Nick Graf (University of Pittsburgh)
For the MINOS+ Collaboration

Meeting of APS Division of Particles and Fields
University of Michigan, Ann Arbor
August 4, 2015
The MINOS Experiment

Main Injector Neutrino Oscillation Search

- Located along the NuMI beamline
- Two functionally equivalent detectors 735 km apart
  - Near Detector (ND) at Fermilab
  - Far Detector (FD) at Soudan, MN
- Look for $\nu_\mu$ disappearance as a function of neutrino energy
- Use ND to predict unoscillated FD spectrum
- Compare predicted and measured FD to extract oscillation parameters

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2 (1.267 \Delta m^2 L / E)$$

MC Input: $\sin^2(2\theta) = 1.0; \Delta m^2 = 3.5 \times 10^{-3} \text{ eV}^2$
The MINOS Detectors

Both Detectors
- Alternating planes of steel and scintillator
- As similar as possible to reduce systematics associated with neutrino flux, cross sections, and detector efficiency
- Toroidal magnetic field of 1.3 T
  - Distinguish $\mu^+/\mu^-$
  - Momentum form range/curvature

Near Detector at Fermilab
- 1 km from source
- 0.98 kt, 282 planes
- Measure beam composition and energy spectrum

Far Detector at Soudan Mine
- 735 km from source
- 5.4 kt, 486 planes
- Measure energy dependent disappearance/appearance
- Indication of neutrino oscillations
• 120 GeV protons from Main Injector strike graphite target producing hadrons
• Two magnetic horns focus $\pi^+$ and $K^+$, enhancing $\nu_\mu$ flux
• Energy spectrum changed by varying target position
• Nominal configuration ~3 GeV
Antineutrino Beam

- Reverse horn current to focus $\pi^-$ and $K^-$, creating $\bar{\nu}_\mu$ enriched beam
- Due to smaller $\bar{\nu}_\mu$ cross section and less $\pi^-$ produced, $\bar{\nu}_\mu$ rate is lower and there are many high energy $\nu_\mu$

Monte Carlo
Antineutrino mode
Horns focus $\pi^-, K^-$

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

Flux $\times \sigma_{CC}$ (Arbitrary Units)
MINOS+ takes advantage of new Medium Energy (ME) beam setting (for NOvA)

- New target and new Horn 1
- Horn 2 moved 10 m downstream
- Higher intensity, higher energy beam
MINOS+ Physics

Higher Energy: Cross-check existing neutrino oscillation results in higher energy region with using new beam and cross-section systematics

Higher Statistics: Expect ~4000 events/year at FD for improved measurements of standard three-flavor oscillations (in particular, $\Delta m^2_{32}$)

Enhanced Sensitivity to New Physics:
- Search for light sterile neutrinos
- Search for flavor changing Non-standard Interactions (NSI) in mu-tau and e-tau sectors

Have analyzed first year of MINOS+ beam data ($3\times10^{20}$ POT)
- Independent test of MINOS oscillation result
- Combined MINOS and MINOS+ beam data provide significant statistical improvement of standard neutrino oscillation measurement
Non-Standard Interactions

- Coherent forward scattering of neutrinos via interactions with matter as they propagate
- Interactions beyond the standard model
- Flavor conserving or flavor changing

\[ H = U_{PMNS} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U_{PMNS}^T + \sqrt{2} G_F N_e \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \]

- MINOS is sensitive to flavor changing Non-standard Interactions (NSI) in multiple oscillation modes
  - \( \epsilon_{\mu\tau} \) through \( \nu_\mu \) disappearance
  - \( \epsilon_{e\tau} \) through \( \nu_e \) appearance
Selecting $\nu_\mu$-CC Events

- MINOS event topologies

**CC Signal Event**
- Long track with hadronic activity at vertex
- Total energy = Track + Shower
  - Use k-Nearest Neighbor (kNN) algorithm to further enrich CC sample

**NC Background Event**
- No track
- Main contamination at low energy
Selecting $\nu_e$ -CC Events

Library Event Matching (LEM)

![Diagram of event matching process](image)
Beam matrix encapsulates knowledge of pion two-body decay kinematics and geometry, relating ND and FD spectra.
\[ \varepsilon_{\nu\tau} \] Results

- Presented at Neutrino 2014 in Boston

- \( \varepsilon_{\nu\tau} \) analysis follows NSI formulation from:
  \textit{Friedland, Lunardini, Maltoni, PRD 70, 111301 (2004)}
  \textit{Coelho, Kafka, Mann, Schneps, Altinok, PRD 86, 113015 (2012)}

- Uses full MINOS beam data set

- Results consistent with no Non-standard Interactions
$\epsilon_{\mu\tau}$ Results

- Simultaneous fit to neutrino and antineutrino samples of conventional $\nu_\mu \rightarrow \nu_\tau$ oscillations with an additional NSI matter effect:

$$\Delta m^2 = 2.39^{+0.14}_{-0.11} \times 10^{-3} \text{ eV}^2$$

$$\sin^2(2\theta) = 1.00^{+0.00}_{-0.06}$$

$$\epsilon_{\mu\tau} = -0.07^{+0.08}_{-0.08}$$

with an allowed range of:

$$-0.20 < \epsilon_{\mu\tau} < 0.07 \ (90\% \ C.L.)$$

- Within errors result is consistent with no contribution to flavor change from NSI

MINOS+ $\varepsilon_{\mu\tau}$ Sensitivity

- Improvement in sensitivity from including complete MINOS beam data set

- Expect further improvement (~17%) from including first year of MINOS+ data

- Project an improvement of nearly 50% in sensitivity to $\varepsilon_{\mu\tau}$ compared to current limit by including full MINOS+ data set

- Antineutrino running contributes close to half of this improvement

- Updated result with result with full systematics and 3 flavor NSI will be released soon
Summary

• MINOS+ uses the medium energy NuMI beam and will continue to improve neutrino oscillation measurements

• MINOS+ is sensitive to NSI parameters $\varepsilon_{\mu\tau}$ through $\nu_{\mu}$ disappearance and $\varepsilon_{e\tau}$ through $\nu_{e}$ appearance

• Studies using MINOS beam data in both sectors are consistent with no NSI

• Sensitivity to NSI parameters will be significantly improved with MINOS+ data
Backup Slides
**Detector Technology**

**Tracking Calorimeters**
- 2.54 cm thick steel planes
- 1.4 radiation lengths
- 1 cm thick scintillator planes
- 1.11 x Moliere radius
- Segmented into 4.1 cm wide strips
- Scintillator strips optically coupled to multi-anode PMTs
Neutrino Oscillations

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[\theta_{13} \approx 9^\circ\]

Atmospheric, accelerator

\[\theta_{23} \approx 45^\circ\]

\[\delta \rightarrow \text{CP violating phase}\]

Solar, reactor

\[\theta_{12} \approx 34^\circ\]

From solar/reactor:

\[|\Delta m_{sol}^2| \approx 8 \times 10^{-5} \text{eV}^2\]

From atmospheric/accelerator:

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

Sign of \(\Delta m_{atm}^2\) unknown

Are neutrinos Majorana?

Is there a fourth sterile neutrino?
MINOS+ Physics

MINOS+ is the next phase of MINOS, using the medium-energy NuMI beam.

Higher Energy: Cross-check existing neutrino oscillation results in higher energy region with using new beam and cross-section systematics

Higher Statistics: Expect ~4000 events/year at FD for improved measurements of standard three-flavor oscillations (in particular, $\Delta m^2_{32}$)

Enhanced Sensitivity to New Physics:
- Search for light sterile neutrinos
- Search for flavor changing Non-standard Interactions (NSI) in mu-tau and e-tau sectors
MINOS & MINOS+ Data

**Have analyzed first year of MINOS+ beam data (3x10^{20} POT)**

- Independent test of MINOS oscillation result
- Combined MINOS and MINOS+ beam data provide significant statistical improvement of standard neutrino oscillation measurement
**NSI in the $\mu$-$\tau$ Sector**

\[ P = \cos^2(F_1) + \frac{\cos^2(2\theta)\sin^2(F_1)}{F_2} \]

- In units of GeV, km, eV$^2$

\[ F_1 = \sqrt{(1.27 \frac{\Delta m^2 L}{E})^2 \pm 2 \sin(2\theta)(1.27 \frac{\Delta m^2 L}{E})\epsilon VL + (\epsilon VL)^2} \]

\[ F_2 = 1 \pm 2 \frac{\sin(2\theta)\epsilon VL}{1.27 \frac{\Delta m^2 L}{E}} + \left( \frac{\epsilon VL}{1.27 \frac{\Delta m^2 L}{E}} \right)^2 \]

with $\epsilon = 0$; $F_1 = \left(1.27 \frac{\Delta m^2 L}{E}\right)$, $F_2 = 1$

\[ P \to 1 - \sin^2(2\theta_{23})\sin^2\left(1.27 \Delta m^2_{32} \frac{L}{E}\right) \]

![Graph showing survival probability vs. neutrino energy with labels and markers. The graph includes curves for different values of $\epsilon_{\mu\tau}$, with $\sin^22\theta = \sin^22\theta = 1.0$, $\Delta m^2 = \Delta m^2 = 2.32 \times 10^{-3}$ eV$^2$. The curves are labeled for $\epsilon_{\mu\tau} = 0.25$, $\nu$, $\epsilon_{\mu\tau} = 0.25$, $\bar{\nu}$, and $\epsilon_{\mu\tau} = 0$.](image)
Selecting $\nu_\mu$ -CC Events

kNN Algorithm
- R input variables
  - # of active planes
  - Mean PH per plane
  - PH fluctuation
  - Transverse profile
- J input variables
  - # of active planes
  - Track end PH
  - Scattering
- Select if J > 0.5 || R > 0.25
- Charge determination by curvature
Selection Efficiency

- Second kNN variable improves efficiency at low energy
- Remove tracks near coil hole in ND
  - Improves systematic uncertainty
  - Efficiency less important in ND
Selecting $\nu_\text{e}$ -CC Events

Library Event Matching (LEM)
Far Detector Spectra ($\mu\tau$ Sector)

**Neutrinos**

![Graph showing Neutrino Spectra](image)

**Antineutrinos**

![Graph showing Antineutrino Spectra](image)

**Ratio to No Oscillations**

![Graph showing Ratio to No Oscillations](image)
Far Detector Spectra After Fit

Neutrinos

Antineutrinos
$\varepsilon_{\mu\tau}$ Contours

MINOS
7.09 x $10^{20}$ POT neutrino mode
2.95 x $10^{20}$ POT antineutrino mode

$|\Delta m^2| (10^{-3} \text{eV}^2)$

MINOS
7.09 x $10^{20}$ POT neutrino mode
2.95 x $10^{20}$ POT antineutrino mode

$\sin^2(2\theta)$

MINOS
7.09 x $10^{20}$ POT neutrino mode
2.95 x $10^{20}$ POT antineutrino mode

68% C.L.
90% C.L.
Best osc. + NSI fit
Future Sensitivity Contours

MINOS+ Preliminary Sensitivity

$|\Delta m^2_{32}| \times 10^{-3} \text{ eV}^2$

$\varepsilon_{\mu\tau}$

Best Fit
MINOS 90% CL

Including MINOS+
$3 \times 10^{20}$ POT
$10 \times 10^{20}$ POT
$10 \times 10^{20}$ POT + $4.5 \times 10^{20}$ POT $\bar{\nu}_\mu$-mode

$\sin^2(2\theta_{23})$
\( \varepsilon_{\mu\tau} \) Systematic Uncertainties

- Star plot shows effect of each systematic uncertainty on the measurement.
- Right: Size of systematics compared to statistical uncertainty.
- Overall statistics limited but the neutrino sample is much larger than the antineutrino: Account for systematics in the fit.
Systematic Uncertainties

- Bands show the effect of four most significant systematics: Muon energy scale, hadronic energy scale, normalization, and neutral current background.

- Include these four systematics in fit as nuisance parameters.