Interpretation of MINOS data in terms of non-standard neutrino interactions

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work done in collaboration with Joachim Kopp and Stephen Parke

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1 Introduction

2 Framework
- General considerations
- 2 generations models

3 Simulation
- Neutral current NSI
- Charged current NSI
- Future experiments

4 Discussion
Outline

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4 Discussion
Recently, MINOS has reported a tension between $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance.

Taken from Vahle@Neutrino 2010
What could that be?
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- CPT violation?
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- Sterile $\nu +$ new gauge boson? Engelhardt Nelson Walsh 1002.4452
- Non-standard interaction?
What could that be?
Statistical fluctuation? Not very interesting... (≈ 6%)
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Non-standard interaction?←This presentation
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We are interested in $\nu_\mu$ and $\overline{\nu}_\mu$ disappearance channels at atmospheric baseline ($\nu_\mu - \nu_\tau$ subsystem).

Since $(\nu_\mu \rightarrow \nu_\mu) \overset{CPT}{\longleftrightarrow} (\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu)$, a CP phase alone can’t explain the signal, because it enters the probability formula as an even factor.

Using effective four-fermion operators to describe NSI, we can have a scalar, pseudo-scalar, vector, axial or tensor interaction.

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Neutral current NSI: let’s consider a $V - A$ effective interaction in propagation only. This will contribute to the MSW potential.
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Neutral current NSI: let's consider a $V - A$ effective interaction in propagation only. This will contribute to the MSW potential.

Charged current NSI: an axial operator would lead to the $\pi \rightarrow \mu \nu_\tau$ decay $\Rightarrow$ constrained by NOMAD, so we will consider only a vector effective operator (detection only).
Our neutral current NSI arises from an effective operator like

$$\frac{G_F}{\sqrt{2}} \varepsilon_{\alpha\beta} \left[ \bar{\nu}_\alpha \gamma^\rho \left( 1 - \gamma^5 \right) \nu_\beta \right] \left[ \bar{f} \gamma_\rho \left( 1 - \gamma^5 \right) f \right], \quad \alpha, \beta = \mu, \tau.$$

From that the Hamiltonian can be derived as

$$H = \frac{1}{2E} \left[ U \begin{pmatrix} 0 & \Delta m^2 \end{pmatrix} U^\dagger + A \begin{pmatrix} \varepsilon_{\mu\mu}^m & \varepsilon_{\mu\tau}^m \\ \varepsilon_{\mu\tau}^{m*} & \varepsilon_{\tau\tau}^m \end{pmatrix} \right],$$

$$A = 2\sqrt{2} G_F N_e E$$
Leading to the following survival probability

\[
P(\nu_\mu \rightarrow \nu_\mu) = 1 - \frac{\left| \Delta m^2 \sin 2\theta + 2\epsilon^{m}_{\mu\tau} A \right|^2}{\Delta m_N^4} \sin^2 \left( \frac{\Delta m_N^2 L}{4E} \right),
\]

\[
\Delta m_N^2 = \sqrt{(\Delta m^2 \cos 2\theta + \epsilon^{m}_{\tau\tau} A)^2 + \left| \Delta m^2 \sin 2\theta + 2\epsilon^{m}_{\mu\tau} A \right|^2}.
\]

For anti-neutrinos \( \epsilon^{m}_{\mu\tau} \rightarrow \epsilon^{m*}_{\mu\tau} \) and \( A \rightarrow -A \), so that \( P(\nu_\mu \rightarrow \nu_\mu) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \) without CPT violation.


- Leading to the following survival probability

\[
P(\nu_\mu \rightarrow \nu_\mu) = 1 - \frac{|\Delta m^2 \sin 2\theta + 2\varepsilon^m_{\mu\tau} A|^2}{\Delta m^4_N} \sin^2 \left(\frac{\Delta m^2_N L}{4E}\right),
\]

\[
\Delta m^2_N = \sqrt{(\Delta m^2 \cos 2\theta + \varepsilon^m_{\tau\tau} A)^2 + |\Delta m^2 \sin 2\theta + 2\varepsilon^m_{\mu\tau} A|^2}.
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- Symmetries lead to eightfold degeneracy:

\[
\arg (\varepsilon^m_{\mu\tau}) \rightarrow 2\pi - \arg (\varepsilon^m_{\mu\tau}) \quad \varepsilon^m_{\tau\tau} \rightarrow -\varepsilon^m_{\tau\tau}, \quad \theta \rightarrow \frac{\pi}{2} - \theta
\]

\[
\varepsilon^m_{\mu\tau} \rightarrow -\varepsilon^m_{\mu\tau}, \quad \varepsilon^m_{\tau\tau} \rightarrow -\varepsilon^m_{\tau\tau}, \quad \Delta m^2 \rightarrow -\Delta m^2
\]
Our charged current NSI arises from an effective operator like

\[ \frac{G_F}{\sqrt{2}} \varepsilon_d^{\alpha \beta} \left[ \bar{\nu}_\alpha \gamma^\rho l_\beta \right] \left[ \bar{f}' \gamma^\rho f \right] . \]

If \( \varepsilon^{d}_{\tau \mu} \) is non-zero, the following amplitudes will interfere and contribute to MINOS counting rate

\[ \nu_\mu + N \rightarrow X + \mu, \]

\[ \nu_\mu \rightarrow \nu_\tau \Rightarrow \nu_\tau + N \rightarrow X + \mu. \]
The apparent $\nu_\mu$ survival probability $\tilde{P}$ can be calculated to
\[
(\phi^d_{\tau\mu} \equiv \text{arg} \varepsilon^d_{\tau\mu})
\]
\[
\tilde{P} = 1 - \left[ 1 + 2 |\varepsilon^d_{\tau\mu}| \cot 2\theta \cos \phi^d_{\tau\mu} - |\varepsilon^d_{\tau\mu}|^2 \right] s^2 \theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) 
+ 2 |\varepsilon^d_{\tau\mu}| s^2 \theta \sin \phi^d_{\tau\mu} \sin \left( \frac{\Delta m^2 L}{4E} \right) \cos \left( \frac{\Delta m^2 L}{4E} \right).
\]

For anti-neutrino $\phi^d_{\tau\mu} \rightarrow -\phi^d_{\tau\mu}$, hence
\[
\tilde{P} (\nu_\mu \rightarrow \nu_\mu) \neq \tilde{P} (\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu).
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\[
+ 2 |\epsilon_{\tau \mu}^d| s_{2\theta} \sin \phi_{\tau \mu}^d \sin \left( \frac{\Delta m^2 L}{4E} \right) \cos \left( \frac{\Delta m^2 L}{4E} \right).
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For anti-neutrino \( \phi_{\tau \mu}^d \rightarrow -\phi_{\tau \mu}^d \), hence

\[
\tilde{P} (\nu_\mu \rightarrow \nu_\mu) \neq \tilde{P} (\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu).
\]

Symmetries leads to a fourfold and a continuous degeneracy:

\[
\phi_{\tau \mu}^d \rightarrow 2\pi - \phi_{\tau \mu}^d, \Delta m^2 \rightarrow -\Delta m^2 \quad \phi_{\tau \mu}^d \rightarrow \pi - \phi_{\tau \mu}^d, \theta \rightarrow \frac{\pi}{2} - \theta
\]

2 equations, 3 unknowns \( \Rightarrow \) 1D degeneracy set.
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Simulation details:

- 3 generations,
- Marginalization over all not shown parameters,
- Proper treatment of degeneracies,
- Energy window: 1 - 5 GeV for $\nu_\mu$ and 1 - 8 GeV for $\bar{\nu}_\mu$,
- Energy resolution tuning in order to reproduce MINOS standard contours,
- GLoBES.

![Plot of $\Delta m^2_{32}$ vs $\sin^2 2\theta_{23}$](image)

- $\nu_\mu$ 90% C.L., 68% C.L.
- $\bar{\nu}_\mu$ 90% C.L., 68% C.L.
- $\nu_\mu,\bar{\nu}_\mu$ Best fit
- $\nu_\mu,\bar{\nu}_\mu$ MINOS Best fit
- MINOS 90%, 68% C.L.
Neutral current NSI

90% excl. limits from Biggio
Blennow Fernandez–Martinez, 0907.0097.

Atmospheric 2 flavour 90% excl. limit from
Gonzalez–Garcia Maltoni, 0704.1800.
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What about the future?
The best strategy would be to run in anti-neutrino mode slightly more than in neutrino mode!
The discovery reach depends strongly on nature’s choice. Let’s hope that nature is kind to us!
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Ultimately, the effective operators generating NSI should arise from an underlying renormalizable model. Model-dependent constraints are typically much stronger than the model-independent bounds considered.

If this tension persists, it could be explained by NSI, but that would require a rather non-trivial model...
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But our inability to construct a simple model featuring large NSI should *not* be regarded as a proof that they cannot exist!
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Surprises, surprises, surprises! [S. Parke]
Backup
More simulation details:

- $\nu_\mu \rightarrow \nu_\mu$: $\sigma = 0.16E + 0.07\sqrt{E}$, 4% flux uncertainty

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$: $\sigma = 0.155E + 0.11\sqrt{E}$, 5% flux uncertainty

- Gaussian priors: $\sin^2 2\theta_{13} < 0.1$, $\theta_{12} = (34.4 \pm 1.4)\degree$, $\Delta m_{21}^2 = (7.59 \pm 0.30) \times 10^{-5}$ eV$^2$.

- Std fit: $\chi^2_{MIN}/dof = 20.1/17 = 1.18$

- NC fit: $\chi^2_{MIN}/dof = 12.6/14 = 0.9$

- CC fit: $\chi^2_{MIN}/dof = 15.9/15 = 1.06$
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Best fit points:

- **Standard:**
  - \( \sin^2 2\theta_{23} = 1 \)
  - \( \Delta m_{32}^2 = 2.42 \times 10^{-3} \text{ eV}^2 \)

- **NC NSI:**
  - \( \sin^2 2\theta_{23} = 0.94 \)
  - \( \Delta m_{32}^2 = 2.93 \times 10^{-3} \text{ eV}^2 \)
  - \( \varepsilon^m_{\mu\tau} = 0.4 \ e^{1.00\pi} \)
  - \( \varepsilon^m_{\tau\tau} = 2.16 \)

- **CC NSI:**
  - \( \sin^2 2\theta_{23} = 0.88 \)
  - \( \Delta m_{32}^2 = 2.81 \times 10^{-3} \text{ eV}^2 \)
  - \( \varepsilon^d_{\tau\mu} = 0.22 \ e^{0.19\pi} \)