Nonstandard neutrino interactions

Danny Marfatia
Nonstandard neutrino interactions ... at long-baseline experiments

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with Liao and Whisnant
(1601.00927, 1609.01786, 1612.01443)
Possible tension in standard oscillation picture

Maximal mixing \((\theta_{23} = \pi/4)\) excluded by NOvA at 2.6 sigma
Nonstandard interactions in matter

\[ \mathcal{L}_{\text{NSI}} = 2\sqrt{2}G_F \epsilon_{\alpha\beta}^{fC} \left[ \bar{\nu}_\alpha \gamma^\rho P_L \nu_\beta \right] \left[ \bar{f} \gamma_\rho P_C f \right] + \text{h.c.} \]

where \( \alpha, \beta = e, \mu, \tau \), \( C = L, R \), \( f = u, d, e \)

\[ V = A \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} e^{i\phi_{e\mu}} & \epsilon_{e\tau} e^{i\phi_{e\tau}} \\ \epsilon_{e\mu} e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau} e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau} e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix} . \]

Here, \( A \equiv 2\sqrt{2}G_F N_e E \) and \( \epsilon_{\alpha\beta} e^{i\phi_{\alpha\beta}} \equiv \sum_{f,C} \frac{fC}{N_e} \frac{N_i}{N_e} \)

On earth \( N_u = N_d = 3N_e \)
Resolving tension between NOvA and T2K

 Longer baseline at NOvA means larger matter effects and so larger NSI effects

 Muon neutrino survival probability dictated by

$$\frac{\Delta m^2}{\Delta m^2_{32}} = \sqrt{(\cos 2\theta_{23} + (\epsilon_{\tau\tau} - \epsilon_{\mu\mu})\hat{A})^2 + |\sin 2\theta_{23} + 2\epsilon_{\mu\tau}\hat{A}|^2}$$

$$\sin^2 2\theta = \left(1 + \frac{\cos 2\theta_{23} + (\epsilon_{\tau\tau} - \epsilon_{\mu\mu})\hat{A})^2}{|\sin 2\theta_{23} + 2\epsilon_{\mu\tau}\hat{A}|^2}\right)^{-1}. \quad \hat{A} = A/\Delta m^2_{32}$$

 For maximal mixing, NSI can generate nonmaximal mixing with a much larger effect in NOvA than T2K

$$\hat{A}_{NOvA} \approx 0.17 \quad \hat{A}_{T2K} \approx 0.05$$
CL at which $\theta_{23} = \pi/4$ is excluded:

$$\epsilon_{\mu\mu} = \epsilon_{\mu\tau} = 0, \quad |\epsilon_{e\tau}| < 1.2$$
To fit their data, NOvA required nonmaximal mixing and a larger mass-squared difference than T2K.

Could also fit with maximal mixing and NSI.
Future experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\frac{L}{E_{\text{peak}}}$</th>
<th>$\nu + \bar{\nu}$ Exposure</th>
<th>Signal norm. uncertainty</th>
<th>Background norm. uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUNE (LAr)</td>
<td>$\frac{1300}{3.0}$</td>
<td>$264 + 264$ (80 GeV protons, 1.07 MW power, $1.47 \times 10^{21}$ POT/yr, 40 kt fiducial mass, 3.5+3.5 yr)</td>
<td>app: 2.0%</td>
<td>app: 5-20%</td>
</tr>
<tr>
<td>T2HK (WC)</td>
<td>$\frac{295}{0.6}$</td>
<td>$864.5 + 2593.5$ (30 GeV protons, 1.3 MW power, $2.7 \times 10^{21}$ POT/yr, 0.19 Mt each tank, 1.5+4.5 yr with 1 tank, 1+3 yr with 2 tanks)</td>
<td>app: 2.5%</td>
<td>app: 5%</td>
</tr>
<tr>
<td>T2HKK-1.5 (WC)</td>
<td>$\frac{295 + 1100}{0.6 + 0.8}$</td>
<td>$1235 + 3705$ (30 GeV protons, 1.3 MW power, $2.7 \times 10^{21}$ POT/yr, 0.19 Mt each tank, 2.5+7.5 yr with 1 tank at KD and HK)</td>
<td>app: 2.5%</td>
<td>app: 5%</td>
</tr>
<tr>
<td>T2HKK-2.5 (WC)</td>
<td>$\frac{295 + 1100}{0.6 + 0.6}$</td>
<td>$1235 + 3705$ (30 GeV protons, 1.3 MW power, $2.7 \times 10^{21}$ POT/yr, 0.19 Mt each tank, 2.5+7.5 yr with 1 tank at KD and HK)</td>
<td>app: 2.5%</td>
<td>app: 5%</td>
</tr>
</tbody>
</table>

For DUNE, 1 yr = $1.76 \times 10^7$s; for HyperK, 1 yr = $1.0 \times 10^7$s.
Appearance channels

\[ P(\nu_\mu \to \nu_e) = x^2 f^2 + 2 x y f g \cos(\Delta + \delta) + y^2 g^2 \]
\[ + \quad 4 \hat{A} \epsilon_{\mu e} \left\{ x f [s_{23}^2 f \cos(\phi_{e\mu} + \delta) + c_{23}^2 g \cos(\Delta + \delta + \phi_{e\mu})] \right\} \]
\[ + \quad 4 \hat{A} \epsilon_{e\tau} s_{23} c_{23} \left\{ x f [f \cos(\phi_{e\tau} + \delta) - g \cos(\Delta + \delta + \phi_{e\tau})] \right\} \]
\[ \text{r suppressed} \quad \rightarrow \quad + y g [c_{23}^2 g \cos \phi_{e\mu} + s_{23}^2 f \cos(\Delta - \phi_{e\mu})] \}
\[ + \quad 4 \hat{A} \epsilon_{e\tau} s_{23} c_{23} \left\{ x f [f \cos(\phi_{e\tau} + \delta) - g \cos(\Delta + \delta + \phi_{e\tau})] \right\} \]
\[ \text{r suppressed} \quad \rightarrow \quad - y g [g \cos \phi_{e\tau} - f \cos(\Delta - \phi_{e\tau})] \}
\[ + \quad 4 \hat{A}^2 \left( g^2 c_{23}^2 |c_{23} \epsilon_{e\mu} - s_{23} \epsilon_{e\tau}|^2 + f^2 s_{23}^2 |s_{23} \epsilon_{e\mu} + c_{23} \epsilon_{e\tau}|^2 \right) \]
\[ + \quad 8 \hat{A}^2 f g s_{23} c_{23} \left\{ c_{23} \cos \Delta \left[ s_{23} (\epsilon_{e\mu}^2 - \epsilon_{e\tau}^2) + 2 c_{23} \epsilon_{e\mu} \epsilon_{e\tau} \cos(\phi_{e\mu} - \phi_{e\tau}) \right] \right\} \]
\[- \epsilon_{e\mu} \epsilon_{e\tau} \cos(\Delta - \phi_{e\mu} + \phi_{e\tau}) \} + \mathcal{O}(s_{13}^2, s_{13}^2, \epsilon^3), \]

\[ x \equiv 2 s_{13} s_{23}, \quad y \equiv 2 r s_{12} c_{12} c_{23}, \quad r = |\delta m_{21}^2 / \delta m_{31}^2|, \]
\[ f, \bar{f} \equiv \frac{\sin[\Delta (1 + \hat{A} (1 + \epsilon_{ee}))]}{(1 + \hat{A} (1 + \epsilon_{ee}))}, \quad g \equiv \frac{\sin(\hat{A} (1 + \epsilon_{ee}) \Delta)}{\hat{A} (1 + \epsilon_{ee})}, \]
\[ \Delta \equiv \left| \frac{\delta m_{31}^2 L}{4 E} \right|, \quad \hat{A} \equiv \left| \frac{A}{\delta m_{31}^2} \right| \]

Reduce to the SM when \( \epsilon_{ee} = 0 \)
1st order due to \( \epsilon_{e\mu} \)

1st order due to \( \epsilon_{e\tau} \)
2nd order corrections

- \( P_{\mu e} \to \bar{P}_{\mu e} \)
  \( \hat{A} \to \hat{A} (f \to \bar{f}) \),
  \( \delta \to -\delta, \quad \phi_{\alpha\beta} \to -\phi_{\alpha\beta} \)

- NH \to IH
  \( \Delta \to -\Delta, \quad y \to -y \)
  \( \hat{A} \to \hat{A} (f \leftrightarrow \bar{f}, \text{and } g \to -g) \)

Liao
$L = 1300 \text{ km, } E = 3 \text{ GeV}$

\[ P_{\nu_{\mu} \rightarrow \nu_e}(\delta) = P_{NSI}(\delta', \epsilon, \phi) \]

\[ \overline{P}_{SM}(\delta) = \overline{P}_{NSI}(\delta', \epsilon, \phi) \]
\[
\sin^2 \theta_{13} = 0.023 \pm 0.002 \\
\sin^2 \theta_{12} = (0.305 \pm 0.015) \oplus (0.70 \pm 0.017) \\
\sin^2 \theta_{23} = 0.43^{+0.08}_{-0.03}, \quad \delta = 0 \\
\delta m^2_{21} = (7.48 \pm 0.21) \times 10^{-5} \text{ eV}^2 \\
|\delta m^2_{31}| = (2.43 \pm 0.08) \times 10^{-3} \text{ eV}^2 \\
\]

\[-5.0 < \epsilon_{ee} < 5.0 \]

\[0 < \epsilon_{e\mu} < 0.5 \]

\[0 < \epsilon_{e\tau} < 1.2 \]

\[0 < \epsilon_{\mu\tau} < 0.1 \]

\[-0.6 < \epsilon_{\tau\tau} < 0.6 \]

Marginalize over NSI phases and mass hierarchy
One NSI parameter

\[
\delta m^2_{31} \rightarrow -\delta m^2_{32}, \quad \theta_{12} \rightarrow 90^\circ - \theta_{12}, \quad \delta \rightarrow 180^\circ - \delta
\]

\[
\epsilon_{ee} \rightarrow -\epsilon_{ee} - 2, \quad \epsilon_{\alpha\beta}e^{i\phi_{\alpha\beta}} \rightarrow -\epsilon_{\alpha\beta}e^{-i\phi_{\alpha\beta}} (\alpha\beta \neq ee)
\]
Mass hierarchy resolved at DUNE and T2HKK

Hierarchy not resolved
Wrong determination of the CP phase possible
$L=1300 \text{ km}$
3 NSI parameters

![Diagram showing contour plots for NSI parameters in DUNE and T2HK settings, with labels for IH, T2HKK-1.5, and T2HKK-2.5.](image)
Constraint on $e\mu$ NSI much weaker at T2K and T2HKK
Because of the lower energy J-PARC beam, the difference between SM and NSI appearance probabilities are suppressed at T2K and T2HKK for

\[ \epsilon_{e\mu} = \tan \theta_{23} \epsilon_{e\tau} \]
Symmetry around $-1$ is because the vertex of the V-shaped NH region is at 0 and the vertex of the V-shaped IH region is at $-2$. 

Correlations between $ee$ and $e\tau$
CP sensitivity

MH known

T2HKK better than DUNE for CP; is the only expt. that can measure the CP phase if MH is unknown

MH unknown

$$\delta' = \delta \text{ holds when } \epsilon = 0$$

$$\delta' = 180 - \delta$$
Sensitivity to NSI as a function of CP

One nonzero NSI parameter

\[ |\epsilon_{ee}| > 2 \text{ because of the generalized hierarchy degeneracy} \]

IH not allowed at 95.4% CL

\[ |\epsilon_{ee}| > 2 \]
3 NSI parameters

All T2HK, and T2HKK e\mu sensitivities outside the range of scan.
Sensitivity to NSI similar for both mass hierarchies

Regions are similar under

\[ \delta' \rightarrow \delta' + 180^\circ \]
Disappearance channels

\[
\text{\(\mu\tau\) sensitivity for all experiments outside the range of scan}
\]
Summary

- NOvA's exclusion of maximal mixing may be a hint of NSI

- Degeneracies between SM and NSI parameters, and between NSI parameters strongly affect sensitivities

- If ee NSI parameter is $O(1)$, impossible to determine hierarchy at LBL experiments

- DUNE has best sensitivity to NSI

- T2HKK has best sensitivity to CP phase in the presence of NSI

- Sensitivity to NSI same for both mass hierarchies at LBL expts