Probing the effects of scalar Non Standard Interactions at Long Baseline Experiments

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Outline

1. Introduction
2. Scalar Non Standard Interactions
3. Formalism and Methodology
4. Results
5. Conclusions
Neutrino oscillations essentially confirms neutrinos have masses.

It provides the first experimental evidence of physics beyond Standard Model (BSM).

The models describing BSM physics often comes with some additional unknown coupling of neutrinos.

These interactions are called Non Standard Interactions (NSIs), as it can’t be explained within the framework of SM.
Non standard interactions in neutrinos


- The impact of NSI on oscillation probability: an interesting sector to probe new physics.

- Neutrinos coupling with a scalar is an excellent probe to study new physics in Long Baseline experiments (S.-F. Ge and S. J. Parke, Phys. Rev. Lett. 122 (2019)).
Neutrino Oscillation in matter

- The weakly interacting neutrinos might interact with matter via charged-current (CC) or neutral-current (NC) when they pass through matter.
- The Hamiltonian for neutrino oscillation in matter is given by:

\[ H = E_\nu + \frac{MM^\dagger}{2E_\nu} + V_{SI} \]

Where

\[ V_{SI} = \begin{pmatrix} V_C + V_N & 0 & 0 \\ 0 & V_N & 0 \\ 0 & 0 & V_N \end{pmatrix}, \]

\[ V_C = \pm \sqrt{2} G_F n_e \text{ and } V_N = - \frac{G_F n_n}{\sqrt{2}} \]
Scalar Non Standard Interactions

- The Lagrangian of such interactions can be formulated as:

\[
\mathcal{L}_{\text{eff}}^S = \frac{y_f y_{\alpha\beta}}{m_\phi^2} (\bar{\nu}_\alpha(p_3) \nu_\beta(p_2)) (\bar{f}(p_1)f(p_4))
\]

- The corresponding neutrino Hamiltonian modifies as:

\[
\mathcal{H} \approx E_\nu + \frac{(M + \delta M)(M + \delta M)\dagger}{2E_\nu} \pm V_{SI}
\]

\[
\delta M = \sum_f \frac{n_f y_f y_{\alpha\beta}}{m_\phi^2}
\]

- The effect appears as correction/addition/perturbation to the neutrino mass term.
The effect of scalar NSI can be parametrize as a $3 \times 3$ matrix:

$$\delta M = \sqrt{\Delta m_{31}^2} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{pmatrix}$$

$\eta_{\alpha\beta}$ elements are dimensionless and quantifies the size of scalar NSI.

A framework is made with the modified Hamiltonian in GLoBES with baseline = 1300 km (DUNE).

The values of mixing parameters used in the analysis:

<table>
<thead>
<tr>
<th>$\sin^2\theta_{12}$</th>
<th>$\sin^2\theta_{13}$</th>
<th>$\sin^2\theta_{23}$</th>
<th>$\delta_{CP}$</th>
<th>$\Delta m_{21}^2$ (eV$^2$)</th>
<th>$\Delta m_{31}^2$ (eV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.308</td>
<td>0.0234</td>
<td>0.5348</td>
<td>$-\pi/2$</td>
<td>$7.54 \times 10^{-5}$</td>
<td>$2.43 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Results: effects on oscillation probabilities

L = 1300 km
$\delta_{\text{CP}} = -\pi/2$, $\theta_{23} = 47^\circ$ [NH]
- $\eta_{ee} = 0$ (SI case)
- $\eta_{ee} = 0.1$
- $\eta_{ee} = 0.2$
- $\eta_{ee} = -0.1$
- $\eta_{ee} = -0.2$

(a) $P_{\mu e}$ vs $E$ for different $\eta_{ee}$

L = 1300 km
$\delta_{\text{CP}} = -\pi/2$, $\theta_{23} = 47^\circ$ [NH]
- $\eta_{mm} = 0$ (SI case)
- $\eta_{mm} = 0.1$
- $\eta_{mm} = 0.2$
- $\eta_{mm} = -0.1$
- $\eta_{mm} = -0.2$

(b) $P_{\mu e}$ vs $E$ for different $\eta_{\mu \mu}$
Results: effects on oscillation probabilities

(a) $P_{\mu e}$ vs $\delta_{CP}$ for different $\eta_{ee}$

(b) $P_{\mu e}$ vs $\delta_{CP}$ for different $\eta_{\mu\mu}$

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Results: $P_{\mu e}$ with varied $\delta_{CP}$, $\theta_{23}$

(a) $P_{\mu e}$ vs $E$ for different $\theta_{23}$

(b) $P_{\mu e}$ vs $E$ for different $\delta_{CP}$
Results: $P_{\mu e}$ with varied $\nu$ masses

**Scalar NSI gives a possibility of probing it to various neutrino mass models.**
Results: $\chi^2$ - analysis, preliminary

- DUNE: 5 years ($\nu$) + 5 years ($\bar{\nu}$)

$\chi^2$ analysis at fixed $\delta_{\text{CP}} = -\pi/2$, $\theta_{23} = 47^\circ$

true $\eta = 0.01$ [NH]

- $\eta_{ee}$
- $\eta_{\mu\mu}$
- $\eta_{\tau\tau}$
Results: Effects on CP sensitivity

- DUNE: 5 years ($\nu$) + 5 years ($\bar{\nu}$)

The diagram shows the CP sensitivity of DUNE in the presence of NSI for different values of $\eta_{ee}$: $0$, $0.05$, $0.10$, and $0.15$. The true CP ($\delta_{CP}$) is plotted against $\sigma = \sqrt{\Delta \chi^2}$ for each case.
Scalar NSI has a notable impact in neutrino oscillations at DUNE.

The CP sensitivity of DUNE gets spoiled in presence of scalar NSI.

It is crucial to identify such subdominant effects of neutrino oscillations for accurate interpretation of data.

A good window to study new physics beyond Standard Model (BSM).

As it directly effects the neutrino mass term, it can be used to probe various neutrino mass models.

Thank You for your kind attention!

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Schematic pictures of standard matter effects (left picture) and matter non-standard neutrino interactions (right picture).

Reference: DOI:10.1088/0034-4885/76/4/044201
Back up: effects on oscillation probabilities

\[ L = 1300 \text{ km} \]
\[ \delta_{\text{CP}} = -\pi/2, \ \theta_{23} = 47^\circ \ [\text{NH}] \]

- \( \eta_{tt} = 0 \) (SI case)
- \( \eta_{tt} = 0.1 \)
- \( \eta_{tt} = 0.2 \)
- \( \eta_{tt} = -0.1 \)
- \( \eta_{tt} = -0.2 \)

(a) \( P_{\mu e} \) vs \( E \) for different \( \eta_{tt} \)

Reference: DOI:10.1088/0034-4885/76/4/044201

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