Exploring the effects of scalar Non Standard Interactions at DUNE and T2HK

Based on arXiv 2111.12943

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1. Abstract

The discovery of the phenomena of neutrino oscillations is the first firm experimental evidence of physics beyond Standard Model (BSM). The Non Standard Interactions (NSI) is an interesting window to probe new physics in different neutrino experiments. The non standard coupling of neutrinos with a scalar [1] also shows a promising possibility to probe physics BSM. In this work, we explore the effects of scalar NSI on the oscillation probabilities at different baseline (LBL) experiments (DUNE [2] and T2HK [3]) and its impact on the CP violation (CPV) sensitivities of these experiments.

2. Scalar NSI

According to SM neutrinos may interact with matter via charged-current (CC) or neutral-current (NC) interactions. The Hamiltonian is given by,

\[ H = E_N + \frac{m^2}{2E_N} \pm \nu_{0j} \]

Where \( E_N \) is Neutrino energy and \( m \) is the neutrino mass. The positive and negative sign before \( \nu_{0j} \) is for neutrino and antineutrino mode respectively.

\[ V_{0j} = \left( \begin{array}{ccc} V_{e} + V_{\mu} & 0 & 0 \\ 0 & V_{\nu} & 0 \\ 0 & 0 & V_{\bar{\nu}} \end{array} \right) \]

The effective Hamiltonian for neutrinos coupling with a scalar may be formalized as,

\[ H = E_N + \frac{(M + \Delta M)(M + \Delta M)^\dagger}{2E_N} \pm \nu_{0j} \]

Where, \( \Delta M = \sum_i \Delta m_i^2 \), \( \nu_f \rightarrow \nu_I \) Yukawa coupling of the scalar mediator \( f \) with the environmental fermion \( I \), \( Y \) is the one with neutrinos.

Hence scalar NSI appears as a medium dependent correction/perturbation to the neutrino mass matrix.

For element-wise study of scalar NSI, \( \Delta M \) can be parametrized as,

\[ \Delta M = \sqrt{\Delta m_1^2 \bar{\eta}_{\nu e} \eta_{\nu \mu} \eta_{\nu \tau}} \]

Where, \( \eta_{\nu \alpha} \) are dimensionless parameters and it quantifies the size of scalar NSI.

The hermicity of the neutrino Hamiltonian demands that the diagonal elements are real and the off-diagonal elements are complex.

To probe the effect of scalar NSI in neutrino oscillations, we have taken one element at a time viz. \( \eta_{\nu e} \) and \( \eta_{\nu \mu} \).

3. Methodology

- The benchmark values of oscillation parameters used in the analysis:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta_{12} )</td>
<td>34.51</td>
</tr>
<tr>
<td>( \theta_{13} )</td>
<td>8.44</td>
</tr>
<tr>
<td>( \delta_{CP} )</td>
<td>-47°</td>
</tr>
<tr>
<td>( \Delta m_{21}^2 )</td>
<td>( 7.56 \times 10^{-5} )</td>
</tr>
<tr>
<td>( \Delta m_{23}^2 )</td>
<td>( 2.43 \times 10^{-3} )</td>
</tr>
</tbody>
</table>

- We have used Globes [4] for our simulation studies studies and for choice of systematics and background we have used the relevant TDRs [2, 3].

- To study the effects of scalar NSI we have taken DUNE (5 years in \( \nu + 5 \text{ years in } \overline{\nu} \)) and T2HK (2.5 years in \( \nu + 7.5 \text{ years in } \overline{\nu} \)) with a baseline of 1300 km and 295 km respectively.

- The CPV sensitivity \( \chi^2 \) is defined as,

\[ \chi^2 = \min \sum_{i,j} \left( \frac{N_{\text{true}}^{ij} - N_{\text{test}}^{ij}}{N_{\text{true}}^{ij}} \right)^2, \]

where, \( N_{\text{true}}^{ij} \) and \( N_{\text{test}}^{ij} \) are the number of true and test events in the \((i,j)\)-th bin respectively.

4. Results: Effects on oscillation probabilities

- The scalar NSI element \( \eta_{\nu \mu} \) suppresses the probabilities around the oscillation maxima whereas \( \eta_{\nu e} \) enhances the probabilities around the oscillation maxima as shown in Figure 1 and Figure 2.

- The probabilities are symmetric around zero for positive and negative values of NSI elements.

- For \( \eta_{\nu e} \), the CPV improves whereas for \( \eta_{\nu \mu} \) deteriorates the CPV sensitivities whereas \( \eta_{\nu e} \) improves the experiment’s sensitivity towards CPV.

- For example, for \( \eta_{\nu e} = 0.10 \) all sensitivities lies below 5\% and \( \delta_{CP} \sim (-45°,135°) \) it lies above 3\% CL.

- In combined analysis overall sensitivities improves for each case.

- For all the chosen values of \( \eta_{\nu \mu} \) the sensitivities lies above standard sensitivities for both DUNE and DUNE + T2HK combined.

5. Results: Effect on CP violation sensitivity

- Figure 3 shows effect of NSI on the CPV sensitivities of DUNE and DUNE + T2HK for some chosen values of scalar NSI elements.

- Presence of \( \eta_{\nu e} \) deteriorates the CPV sensitivities whereas \( \eta_{\nu \mu} \) improves the experiment’s sensitivity towards CPV.

- Figure 4 shows the CPV sensitivities of DUNE and combined DUNE + T2HK.

6. Concluding Remarks

- The effects of scalar NSI on oscillation probabilities is significant.

- The presence of scalar NSI may impact the CPV sensitivities of these experiments and requires combined analysis of various LBL experiments to constrain these effects.

Acknowledgements and References

MMD would like to acknowledge the support of DST SERB grant EMR/2017/001436 for this work and AM acknowledge the support of Research and Innovation grant 2021 (DURG: NO. 31-32-160406-1604-36) to Tezpur University.