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

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Abstract: The discovery of the phenomena of neutrino oscillation was the first clear evidence of physics beyond the Standard Model (SM). It requires as extension of the SM to explain the masses and mixing of neutrinos. The models explaining beyond SM (BSM) physics naturally comes with some additional unknown interactions of neutrinos which are beyond the scope of SM, often called as Non Standard Interactions (NSIs). Wolfenstein was the first to propose the idea of NSI where he explored how neutrino coupling with a vector field can give rise to matter effect in neutrino oscillations. Apart from that, there is also a possibility of neutrinos coupling with a scalar field called scalar NSI. Instead of appearing as a matter potential, scalar NSI appears as a medium dependent correction to the mass matrix, which may offer unique phenomenology in neutrino oscillations.

In this work, we have studied the effects of scalar NSI at two proposed flagship Long Baseline Experiments - DUNE and T2HK. As the effect of scalar NSI scales linearly with the matter density, it can feel the matter density variations which makes LBL experiments one of the best candidate to probe it. We have seen that the effect of scalar NSI on the oscillation probabilities of DUNE and T2HK is significant. Moreover, scalar NSI can significantly effect the CP violation sensitivity as well as 23 octant sensitivity of these LBL experiments. Finally, we have also done a combined sensitivity of these experiments towards finding the effects of scalar NSI. In addition, as the scalar NSI affects the neutrino mass term probing it to various neutrino mass models is quite interesting and promising.

Keywords: Neutrino Oscillations, Non Standard Interactions, Beyond Standard Model.

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1. Introduction

The experimental observation of the phenomena of neutrino oscillations jointly by Super Kamiokande and Sudbury Neutrino Observatory collaboration, was the first firm experimental evidence of physics beyond Standard Model (SM). The SM needs as extension to accommodate mass and mixing of neutrinos. These extensions of SM usually comes with some additional unknown couplings of neutrinos called Non Standard Interactions, as these interactions are not incorporated within SM. The idea of NSI mediated by a vector particle was initially introduced in [1]. Later various studies [2] have been performed to study the effects of NSI on neutrinos and put some constrain on the NSI parameters. Also, the probing the effect of NSI on neutrino oscillations is a well motivated phenomenological approach to explore 'new physics' beyond SM (BSM). In addition there is also an intriguing possibility of coupling of neutrinos with a scalar [3, 7], which may offer rich phenomenology in neutrino sector. These type of couplings perturb the neutrino mass term, hence exploring this NSI opens a new window to probe physics BSM. Also scalar NSI varies linearly with matter density. As in Long Baseline (LBL) experiments neutrinos travel a large distance, it makes LBL experiments one of the suitable candidate to probe scalar NSI. In this work, we have explored the effect of scalar NSI on various LBL experiments and also performed a synergy analysis taking the combination of various neutrino experiments.

2. Scalar NSI

The effective Lagrangian for the coupling of neutrinos with a scalar may be framed as,

$$\mathcal{L}^{\rm S}_{\rm eff} = \frac{y_f y_{\alpha\beta}}{m_\phi^2}(\bar{\nu}_\alpha(p_3)\nu_\beta(p_2))(\bar{f}(p_1)f(p_4))\,. \tag{1}$$

Where, the subscript α, β refer to the neutrino flavours, f indicate the environmental matter fermions, and $\bar{f}$ is for corresponding anti fermions, $y_{\alpha\beta}$ is the Yukawa couplings of the neutrinos with the scalar mediator, ϕ, y_f is the Yukawa coupling of the mediator with the environmental fermions, and m_ϕ is the mass of the scalar mediator.

The effective Hamiltonian in presence of scalar NSI can be framed as,

$$\mathcal{H}_{NSI} \approx E_\nu + \frac{(M+\delta M)\,(M+\delta M)^\dagger}{2E_\nu} \pm V_{\rm SI}\,. \tag{2}$$

Here, $\delta M \equiv \sum_f n_f y_f y_{\alpha\beta}/m_\phi^2$, where, n_f is the number density of the environmental fermions, $V_{SI} = \sqrt{2}G_F n_e$ is the matter potential due to charge current (CC) interactions of neutrinos. The scalar NSI matrix (δM) may be parameterized as,

$$\delta M \equiv \sqrt{\Delta m^2_{31}} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{pmatrix}, \tag{3}$$

where, $\eta_{\alpha\beta}$ are dimensionless parameters and it quantifies the size of the scalar NSI. Also, the Hermicity of the neutrino Hamiltonian requires the diagonal elements to be real and the off-diagonal elements to be complex, which is represents as $\eta_{\alpha\beta} = |\eta_{\alpha\beta}|e^{i\phi_{\alpha\beta}}; \quad \alpha \neq \beta$.

3. Methodology

In this study, we have explored the effects of scalar NSI at DUNE [4] (baseline = 1300km) and T2HK [5] (Baseline = 295 km). The mixing parameter values used throughout the analysis are listed in Table 1. The effect of diagonal scalar NSI elements, η_{ee}, $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$ on the oscillation probabilities are shown in Fig. 1, Fig. 2 and Fig. 3 respectively. For all the figures left panel is for T2HK and right panel is for DUNE. It can be seen that the effect of scalar NSI is significant on the oscillation probabilities. The positive (negative) η_{ee} the probabilities get enhanced (suppressed) around the oscillation maxima. Whereas for positive (negative) non zero $\eta_{\tau\tau}$ the probabilities get suppressed (enhanced) around the oscillation maxima i.e the effect is complimentary in comparison with η_{ee}. However, for the case of $\eta_{\mu\mu}$ the peaks of oscillation probabilities gets shifted towards higher (lower) energies for positive (negative) values.

$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	δ_{CP}	$\Delta m^2_{21}(eV^2)$	$\Delta m^2_{31}(eV^2)$
0.308	0.0234	0.5348	-$\pi/2$	7.54×10^{-5}	2.43×10^{-3}

Table 1: Benchmark values of oscillation parameters.

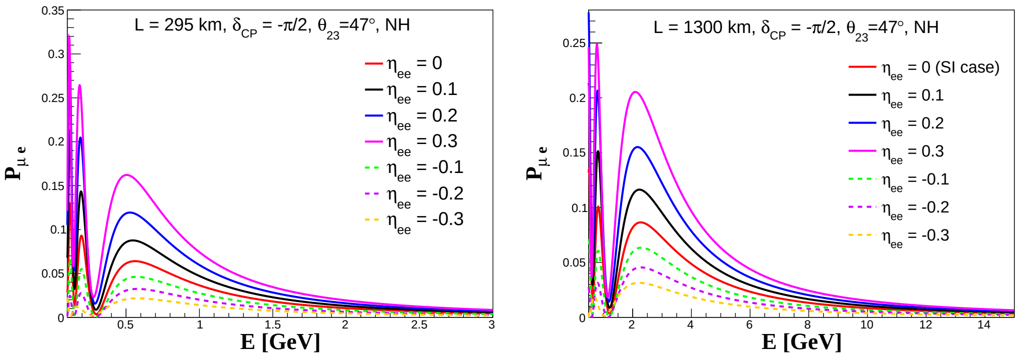

Figure 1: The effect of the scalar NSI element, η_{ee} on neutrino appearance probabilities ($P_{\mu e}$). The left (right) plot is for T2HK (DUNE) for fixed δ_{CP} = -π/2 and θ_{23} = 47°.

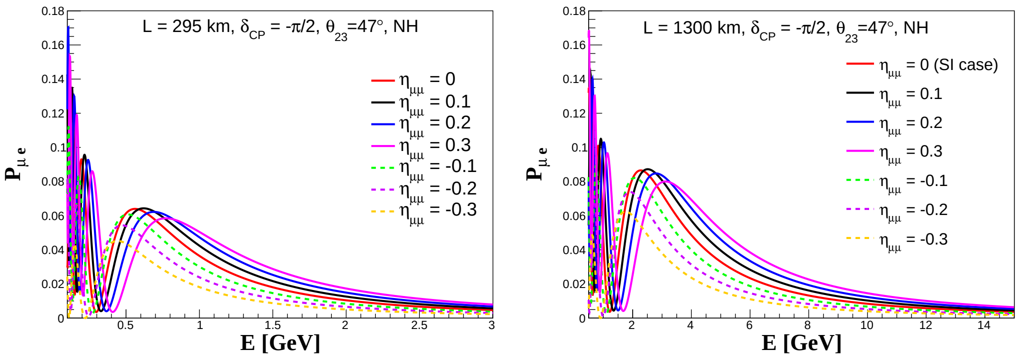

Figure 2: The effect of the scalar NSI element, $\eta_{\mu\mu}$ on neutrino appearance probabilities ($P_{\mu e}$). The left (right) plot is for T2HK (DUNE) for fixed δ_{CP} = -π/2 and θ_{23} = 47°.

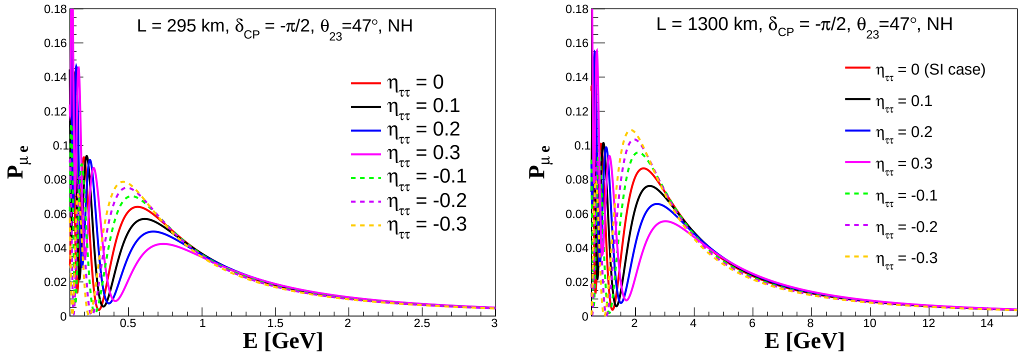

Figure 3: The effect of the scalar NSI element, $\eta_{\tau\tau}$ on neutrino appearance probabilities ($P_{\mu e}$). The left (right) plot is for T2HK (DUNE) for fixed δ_{CP} = -π/2 and θ_{23} = 47°.

We have also performed a statistical χ^2 test to obtain the sensitivity of the LBL experiments towards the CP violation (CPV). We have constructed the χ^2 function as follows to check the CPV sensitivity of the experiments,

$$\chi^2 \equiv \min_{\eta} \sum_i \sum_j \frac{\left[N^{i,j}_{true} - N^{i,j}_{test}\right]^2}{N^{i,j}_{true}}, \tag{4}$$

where, $N^{i,j}_{true}$ and $N^{i,j}_{test}$ are the number of true and test events in the $\{i, j\}$-th bin respectively. For the simulation studies we have used GLOBES [6] package. The modified scalar NSI Hamiltonian is used to probe the effects of scalar NSI.

4. Result and Discussion

The CPV sensitivities of DUNE and DUNE+T2HK in presence of scalar NSI elements, η_{ee}, $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$ is shown in Fig. 4, Fig.5 and Fig. 6 respectively. For all the plots, the left and right plot shows the CPV sensitivities of DUNE and T2HK+DUNE combined. The solid red line is for SI case whereas other colours solid (dashed) lines are for cases with non zero positive (negative) NSI elements. It can be seen that positive (negative) eta_{ee} the sensitivity gets enhanced (suppressed). Whereas for the negative non zero $\eta_{\mu\mu}$ and $\eta\tau\tau$ the sensitivity gets suppressed. However, for positive $\eta_{\mu\mu}$ and $\eta\tau\tau$ the effect on CPV sensitivities is not significant. There is an additional improvement in the sensitivities when we take combination of both T2HK and DUNE. In Figure **??** the CP precision measurement capability of DUNE in presence of scalar NSI is shown. The left (right) plot represents the cases with non zero η_{ee} ($\eta_{\mu\mu}$) element. The true value of the δ_{CP} is kept fixed at -90°. It is observed that in presence of η_{ee} the experiment's capability to constrain the δ_{CP} phase degrades as compared to the $\eta_{\mu\mu}$. With increasing values of $\eta_{\mu\mu}$ the precision measurement capability improves for DUNE.

5. Concluding Remarks

The study of subdominant effects and its impact on the sensitivity of the various neutrino experiments is highly crucial for accurate interpretation of data from the experiments. The current

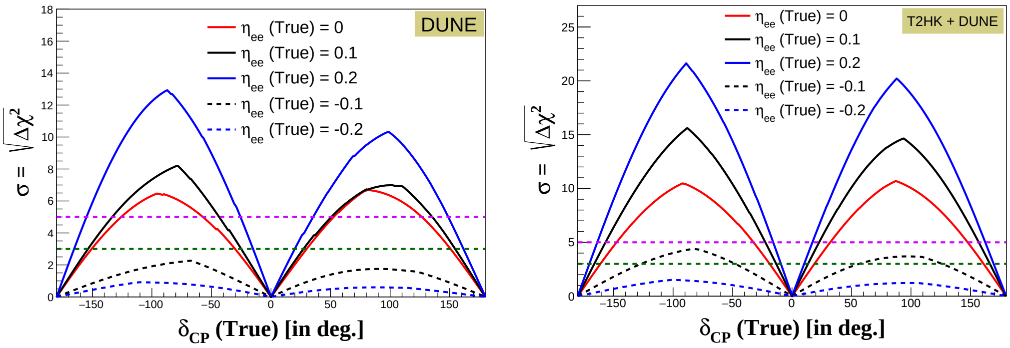

Figure 4: The plot represents CP violation sensitivity in presence of scalar NSI element η_{ee}. The left (right) plot is for DUNE (T2HK+DUNE).

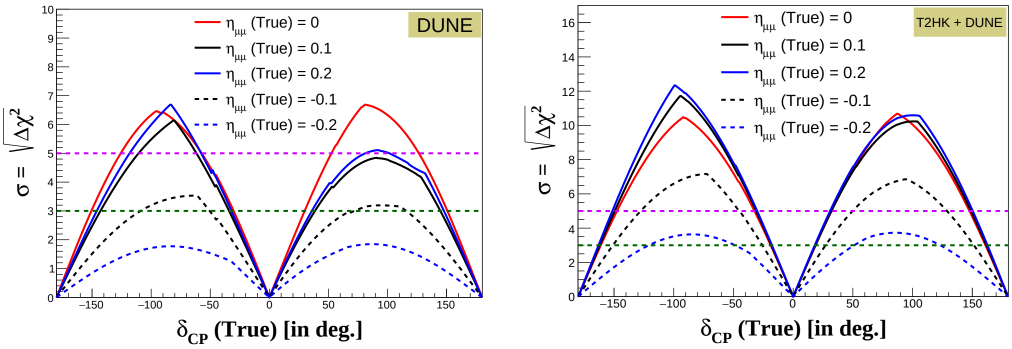

Figure 5: The plot represents CP violation sensitivity in presence of scalar NSI element $\eta_{\mu\mu}$. The left (right) plot is for DUNE (T2HK+DUNE).

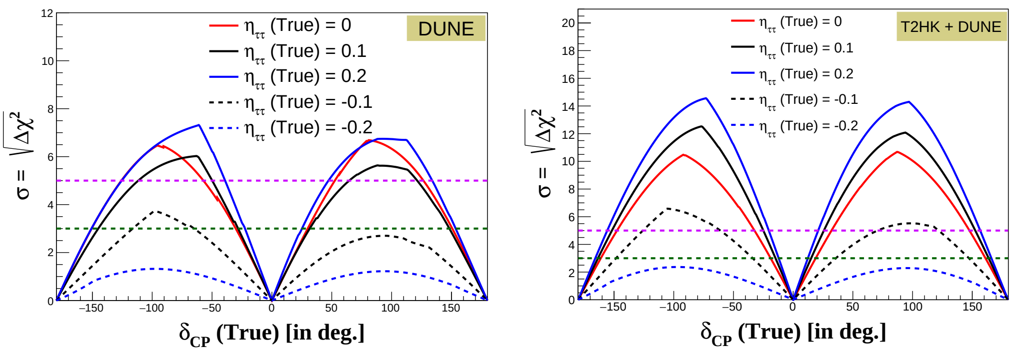

Figure 6: The plot represents CP violation sensitivity in presence of scalar NSI element $\eta_{\tau\tau}$. The left (right) plot is for DUNE (T2HK+DUNE).

precision of ongoing and proposed future neutrino experiments requires to constrain these NSI parameters. In this study we have seen that the scalar NSI can significantly effect the sensitivities of various LBL experiments. It is necessary to explore this kind of NSI effects in various experiments as well to contrain the parameters. A global effort of all the experiments is necessary to put some constrain on these parameters.

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