PROCEEDINGS OF SCIENCE

Probing scalar Non Standard Interactions at DUNE, T2HK and T2HKK

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The experimental observation of the phenomena of neutrino oscillations was the first clear hint of physics beyond the Standard Model. The Standard Model needs an extension to incorporate the neutrino masses and mixing often called as beyond Standard Model. The models describing beyond Standard Model physics usually comes with some additional unknown couplings of neutrinos termed as non–standard interactions. The idea of non–standard interaction was initially proposed by Wolfenstein, where he explored how non–standard coupling of neutrinos with a vector field can give rise to matter effect in neutrino oscillations. Furthermore, there is also an intriguing prospect of neutrinos coupling with a scalar field, called scalar non–standard interaction. The effect of this type of scalar non–standard interaction appears as a medium dependent correction to the neutrino masses, instead of appearing as a matter potential. Hence scalar non–standard interaction may offer unique phenomenology in neutrino oscillations.

In this work, we have performed a synergy study of the effects of scalar non–standard interaction at various proposed long baseline experiments, viz. DUNE, T2HK and T2HKK. As the effect of scalar non–standard interaction scales linearly with environmental matter density, it can experience the matter density variations which makes long baseline experiments one of the suitable candidate to probe its effects. We found that the effect of scalar non–standard interaction on the oscillation probabilities of long baseline experiments is notable. In addition, scalar non–standard interaction can significantly effect the CP violation sensitivities as well as θ_{23} octant sensitivities of these long baseline experiments. Finally, we have also performed a combined sensitivity of these experiments towards constraining these scalar non–standard interaction parameters.

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1. Introduction

The discovery of neutrino oscillations jointly by Super-Kamiokande (SK) [1], MACRO [2] and Sudbury Neutrino Observatory (SNO) [3], provided the first experimental proof of physics beyond Standard Model (BSM) and transformed our understanding of the phenomenology of leptonic sector in Standard Model (SM). Consequently, a series of exceptional oscillations experiments have given us precise measurement of oscillations parameters. Future experiments are aimed to address the three main unknowns of neutrino sector, namely the mass hierarchy, octant of θ_{23} and CP violating phase δ_{CP} in leptonic sector. All these analysis are carried out in 3×3 neutrino mixing scheme assuming neutrinos interact with matter only via weak interaction by exchange of W and Z Boson. However, neutrinos being massive requires new–physics beyond standard model and often these mass and mixing models of neutrinos includes some additional interactions which are termed as non–standard interactions (NSIs). Though the idea of NSIs was first proposed by Wolfenstein [4] as a possible mechanism for neutrino flavor transition, the oscillations experiments have established beyond doubt that the leading order mechanism for flavor transition is neutrino oscillations, and NSIs manifest as subdominant matter effects. It is crucial to take into account these sub leading effects in neutrino production, propagation and detection for proper interpretation of oscillations data. One such interesting possibility is the non–standard coupling of neutrinos with scalar [5–7] particles which is termed as scalar NSI and it appears as a matter dependent perturbative correction to neutrino mass term contrary to the vector mediated NSI which appears as additional matter potential [8]. The matter density dependence of scalar NSI makes Long Baseline Experiments (LBL) an interesting tool to probe these effects. In this work, we have presented the effect of scalar NSI on CP–violation (CPV) sensitivity through a combined analysis of the LBL experiments DUNE [9], T2HK [10] and T2HKK [11] and explored possible synergies among them.

2. Scalar NSI

The scalar mediated NSI for neutrinos is an interesting possibility to explore BSM–physics. The Lagrangian for this type of interaction for Dirac neutrinos can be formulated as,

$$\mathcal{L}_{SNSI} = \frac{y_f Y_{\alpha\beta}}{m_\phi^2}[\bar{\nu}_\alpha(p_3)\nu_\beta(p_2)][\bar{f}(p_1)f(p_4)], \tag{1}$$

where $\alpha, \beta = e, \mu, \tau$ refers to neutrino flavors, f and $\bar{f}$ indicates respectively the mater fermions and anti fermions, $y_{\alpha\beta}$ is the Yukawa couplings of the scalar mediator ϕ with the neutrinos and y_f is that with the matter fermions and m_ϕ represents the mass of the scalar mediator ϕ.

Scalar NSI does not appear as a matter potential because of the Yukawa coupling that is present in the Lagrangian, instead it emerges as a medium-dependent perturbative correction to the neutrino mass. This results in the following form for the scalar NSI effective Hamiltonian,

$$\mathcal{H}_{SNSI} = E_\nu + \frac{(M + \delta M)(M + \delta M)^\dagger}{2E_\nu} \pm V_{SI}, \tag{2}$$

with $\delta M = \sum_i \frac{n_f y_f Y_{\alpha\beta}}{m_\phi^2}$, where n_f is the number density of environmental fermions. We can parameterize the matrix for the scalar NSI contribution to the genuine mass term as,

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

with $\sqrt{\Delta m^2_{31}}$ as a characteristic scale. The $\eta_{\alpha\beta}$ elements are dimensionless parameters indicating the strength of scalar NSI. To preserve the hermiticity of the Hamiltonian the diagonal elements must be real and off diagonal elements must be complex and can be represented as, $\eta_{\alpha\beta} = |\eta_{\alpha\beta}|e^{i\phi_{\alpha\beta}}, \alpha \neq \beta$.

3. Methodology

In this work we have explored the effect of diagonal scalar NSI parameters considering NH as the true hierarchy and higher octant as the true octant. We have developed a framework with modified hamiltonian in GLoBES [12] with systematics and background information incorporated from corresponding technical design reports (TDR) of the three proposed LBL experiments DUNE, T2HK and T2HKK. The mixing parameter values used in our analysis are listed in table 1.

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

Table 1: Benchmark values of oscillations parameters.

To check the sensitivity of the experiments towards distinguishing between CP conserving ($\delta_{CP} = 0,\pi$) and CP violating values ($\delta_{CP} \neq 0, \pi$), we have defined the statistical χ^2 as,

$$\Delta\chi^2 = min \sum_i \sum_j \frac{[N^{i,j}_{true}(\eta) - N^{i,j}_{test}(\eta)]^2}{N^{i,j}_{true}(\eta)}. \tag{4}$$

Where $N^{i,j}_{true}$ represents simulated event number in i,jth bin with true values (CP–violating) of the oscillations parameters and $N^{i,j}_{test}$ is that for the test values (CP–conserving).

4. Results

We have explored the impact of scalar NSI parameters on the oscillation probabilities of LBL experiments. We then checked the impact of scalar NSI on the CPV sensitivities and inverstigated possible synergies among the experiments towards the measurement of δ_{CP} phase. The results of our analysis are discussed in following subsections.

4.1 Effects on oscillation probabilities

In figure 1, we show the effects of scalar NSI as a function of true neutrino energy (top–panel) and δ_{CP} (bottom–panel). We see that, a positive (negative) η_{ee} enhances (suppresses) the oscillation probabilities around the oscillation maxima. The presence of a positive (negative) $\eta_{\mu\mu}$ shifts the oscillation maxima towards higher (lower) energies with marginal suppression in the amplitude of oscillation probabilities. A positive (negative) $\eta_{\tau\tau}$ suppresses (enhances) the probabilities around the oscillation maxima. We also observe the presence of various degeneracies in the oscillation probabilities for different sets of δ_{CP}, which may effects the δ_{CP} measurement sensitivities.

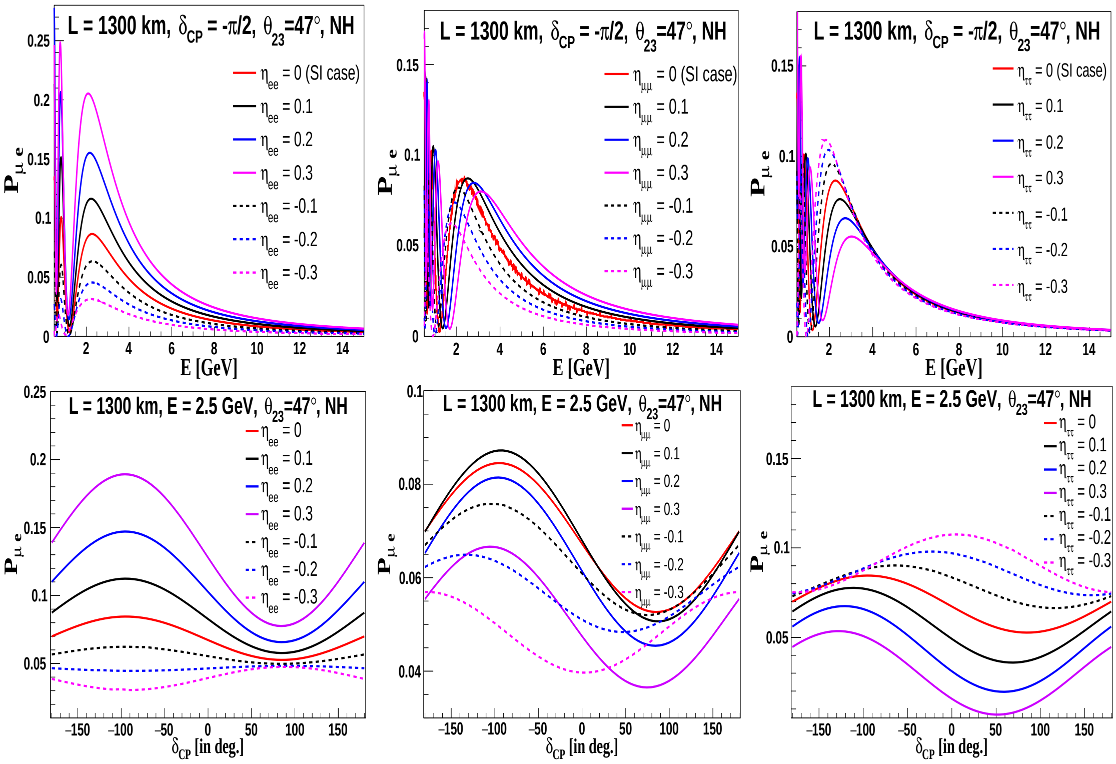

Figure 1: The effects of η_{ee} (left–column), $\eta_{\mu\mu}$ (middle–column) and $\eta_{\tau\tau}$ (right–column) on $P_{\mu e}$ at DUNE as a function of neutrino energy (top–panel) and as a function of δ_{CP} (bottom–panel) for δ_{CP} = -π/2, θ_{23} = 47° and true mass Hierarchy = NH. In all the plots, the red solid–curve is for no–NSI case while other solid (dashed) curves are for positive (negative) NSI parameters.

4.2 Effects on CP–violation sensitivity

In figure 2, we show the CPV sensitivities of DUNE for non–zero η_{ee}, $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$. To obtain the CPV sensitivity, we have excluded CP non-conserving values in the test δ_{CP} and varied the true δ_{CP} in [-π, π]. We see that, a negative $\eta_{\alpha\beta}$ deteriorates the CPV sensitivities, however a positive η_{ee} improves CPV sensitivities. In figure 3 and figure 3, we show combined CPV sensitivity for DUNE + T2HK and DUNE + T2HKK respectively. The synergy of two LBL experiments can help in lifting the degeneracies in the δ_{CP} measurement. E.g. in the region $\delta_{CP} \in$ [0, 90°], the sensitivities overlap for standard and η_{ee} = 0.1. Hence, DUNE alone can not distinguish between the standard and NSI effects in the region $\delta_{CP} \in$ [0, 90°]. However this degenaries can be lifted by combiing DUNE with T2HK or DUNE with T2HKK as shown in figure 3.

5. Summary and Concluding remarks

The supreme accuracy of the current experiments is sensitive to subdominant effects of neutrino oscillations. It is crucial to pinpoint the effect of these subdominant effects on the physics reach

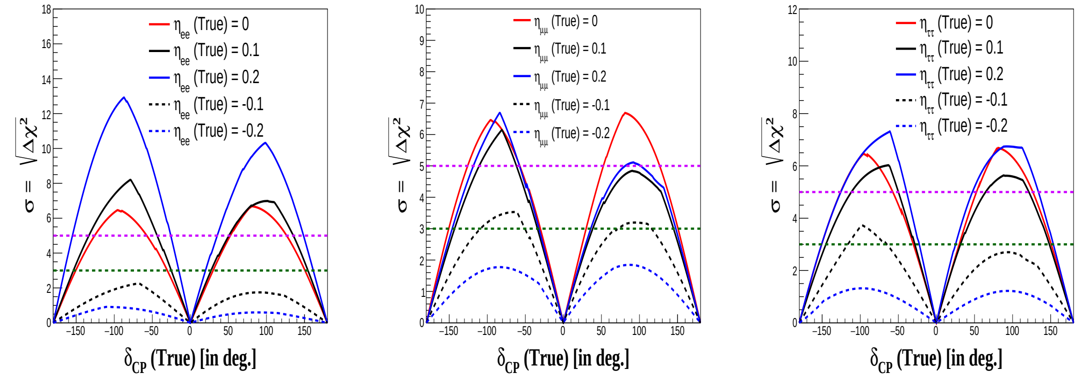

Figure 2: The CP violation sensitivity of DUNE in presence of scalar NSI. The red curve is for the no scalar NSI case whereas solid (dashed) black and blue curves are for positive (negative) non zero $\eta_{\alpha\beta}$.

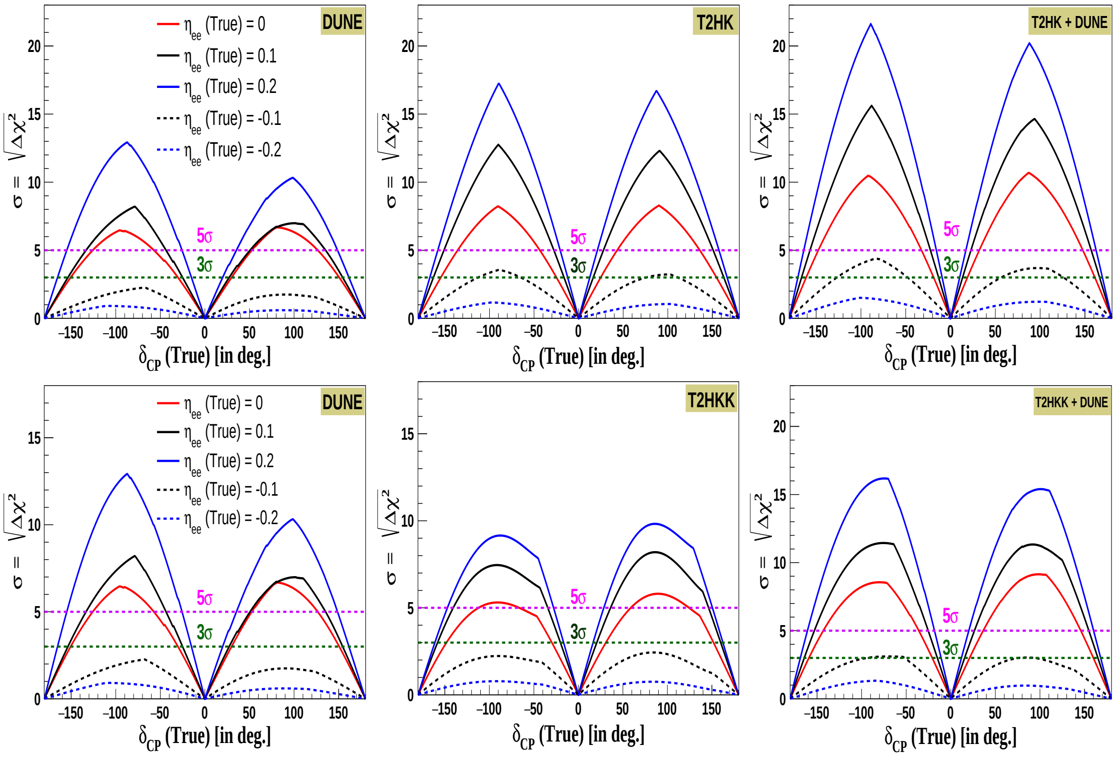

Figure 3: Top–panel: The CPV sensitivity of DUNE (left–column), T2HK (middle-column) and DUNE + T2HK (right-column) in presence of η_{ee}. Bottom–panel: The CPV sensitivity of DUNE (left-column), T2HKK (middle–column) and DUNE + T2HKK (right–column) in presence of η_{ee}. The solid-red curve is for the no scalar NSI case whereas solid (dashed) black and blue curves are for positive (negative) η_{ee}.

of various neutrino experiments. We observe that the presence of one such interactions viz. scalar NSI can have a notable impact on the oscillation probabilities as well as the CPV sensitivities of various LBL experiments. The synergies of two experiments can lift the various degenerate regions in δ_{CP} measurement.

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