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Imprints of scalar mediated NSI on long baseline experiments

Abinash Medhi,[a,*] **Moon Moon Devi**[a] **and Debajyoti Dutta**[b]

[a] *Tezpur University,*
Napaam, Sonitpur, Assam-784028, India
[b] *Assam Don Bosco University,*
Kamarkuchi, Sonapur, Assam–782402
E-mail: amedhi@tezu.ernet.in, devimm@tezu.ernet.in,
debajyoti.dutta@dbuniversity.ac.in

The experimental observation of the phenomena of neutrino oscillations, which essentially confirms non-zero masses of neutrinos, has opened a new sector to explore physics beyond the Standard Model. The models describing new-physics phenomena often come with some unknown interactions of neutrinos termed Non-Standard Interactions. It is crucial and interesting to explore the impact of Non-Standard Interactions in the ongoing and upcoming neutrino oscillations experiments to precisely measure the oscillation parameters. In this work, we have probed the impact of a scalar-mediated Non-Standard Interaction in the long baseline sector, focussing on the three upcoming long-baseline experiments: DUNE, T2HK and T2HKK. The effects of scalar Non-Standard Interaction appear as medium-dependent corrections to the neutrino mass term. Its contribution scales linearly with matter density, making long-baseline experiments among the most suitable candidates for probing such effects. We show that the presence of scalar Non-Standard Interaction may significantly impact the oscillation probabilities and the event rates at the detectors and the χ^2-sensitivities of δ_{CP}-measurements of the experiment. We also show that synergy among the long-baseline experiments (DUNE+T2HK, DUNE+T2HKK) may offer a better capability of constraining the scalar NSI parameters as well as an improved sensitivity towards CP-violation.

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*Speaker

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1. Introduction

The discovery of neutrino oscillations by Super-Kamiokande (SK) [1] and Sudbury Neutrino Observatory (SNO) [2] provides new insights into physics beyond the Standard Model (BSM), confirming neutrino mass and offering experimental hints of BSM-physics. Neutrino oscillation parameters are extensively studied in various experiments. Neutrinos present a promising avenue to explore BSM physics, including non-standard interactions (NSIs) that involve unknown neutrino couplings. Given the high precision of current and upcoming neutrino experiments, these subdominant NSI effects on neutrino oscillations can significantly impact the physics potential of these experiments. We focus on the impact of scalar mediated NSIs [4, 6, 7] on the measurement of the leptonic phase δ_{CP} in the long baseline experiments DUNE, [9], T2HK [10] and T2HKK [11]. Through a synergy analysis of these experiments, we investigate the effects of scalar NSIs in a model-independent manner.

2. Scalar NSI formalism

The neutrinos interact with matter via weak interaction and gravity. These interactions involve the mediation of a $W^{\pm}$ boson (Charge Current – CC) or a Z boson (Neutral Current – NC) [3]. While both interactions contribute to the matter potentials in the neutrino Hamiltonian, only CC-interactions affect the oscillation probabilities. NC-interactions, on the other hand, do not contribute to the oscillations as they appear as a common term in the Hamiltonian. The Lagrangian for neutrino–matter coupling via CC interactions may be written as [3],

$$\mathcal{L}_{\mathrm{cc}}^{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} \left[\overline{\nu_e}(p_3)\gamma_\mu P_L \nu_e(p_2)\right] \left[\overline{e}(p_1)\gamma^\mu P_L e(p_4)\right], \tag{1}$$

where, G_F represents the Fermi coupling constant, while p_i denotes the momenta of the incoming and outgoing states. Additionally, $P_L = (1-\gamma_5)/2$ and $P_R = (1+\gamma_5)/2$ represent the left and right chiral projection operators, respectively. The effective Hamiltonian, $\mathcal{H}_{\mathrm{eff}}$, can be framed as,

$$\mathcal{H}_{\mathrm{eff}} = E_\nu + \frac{1}{2E_\nu}\mathcal{U}\mathrm{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2)\mathcal{U}^\dagger + \mathrm{diag}(V_{\mathrm{CC}}, 0, 0), \tag{2}$$

where, $\mathcal{U}$ is the Pontecorvo-Maki-Nakagawa-Sakata matrix, E_ν is neutrino energy, $\Delta m_{ij}^2 = m_i^2 - m_j^2$, are the neutrino mass-squared differences, and $V_{\mathrm{SI}} = \pm\sqrt{2}G_F n_e$, comes due to matter interactions.

The presence of NSI between neutrinos and a scalar mediator has implications for probing physics beyond the Standard Model [4, 5]. The effective Lagrangian describing the coupling of neutrinos with the scalar, denoted as ϕ, can be expressed as,

$$\mathcal{L}_{\mathrm{eff}}^{\mathrm{S}} = \frac{y_f y_{\alpha\beta}}{m_\phi^2}(\bar{\nu}_\alpha(p_3)\nu_\beta(p_2))(\bar{f}(p_1)f(p_4)), \tag{3}$$

where, α and β correspond to the neutrino flavors e, μ, τ, f represents matter fermions (e.g., electron, up-quark, down-quark), $\bar{f}$ represents the corresponding antifermions, $y_{\alpha\beta}$ denotes the Yukawa couplings of neutrinos with the scalar mediator ϕ, y_f represents the Yukawa coupling of ϕ with f and m_ϕ represents the mass of the scalar mediator. Due to the presence of Yukawa terms,

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this Lagrangian cannot be converted into vector currents. Incorporating the effect of scalar NSI into the corresponding Dirac equation, we obtain,

$$\bar{\nu}_\beta \left[i\partial_\mu \gamma^\mu + \left(M_{\beta\alpha} + \frac{\sum_f n_f y_f y_{\alpha\beta}}{m_\phi^2} \right) \right] \nu_\alpha = 0\,, \tag{4}$$

where n_f represents the number density of environmental fermions. The effect of scalar NSI serves as a perturbation to the neutrino mass term. Thus, the effective Hamiltonian can be written as,

$$\mathcal{H}_{\rm SNSI} \approx E_\nu + \frac{M_{\rm eff} M_{\rm eff}^\dagger}{2E_\nu} \pm V_{\rm SI}\,, \tag{5}$$

where $M_{\rm eff} = M + \delta M$ represents the effective mass matrix, accounting for both the regular mass matrix M and the contribution from scalar NSI ($\delta M \equiv \sum_f n_f y_f y_{\alpha\beta}/m_\phi^2$). In this work, we explore the effects of scalar NSI in neutrino oscillations by parameterizing δM as follows:

$$\delta M \equiv \sqrt{|\Delta m_{31}^2|} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{pmatrix}\,. \tag{6}$$

The dimensionless elements $\eta_{\alpha\beta}$ quantify the size of scalar NSI. The Hermicity of the Hamiltonian requires the diagonal elements to be real and the off-diagonal elements to be complex. In our analysis, we explore the impact of a diagonal element of the scalar NSI matrix one at a time.

3. Methodology

We employed the GLoBES simulation package [12] to compute numerical probabilities and construct the statistical framework for investigating the physics sensitivities. The benchmark values of neutrino oscillation parameters used throughout the analysis are [13]- $\theta_{12} = 34.51°$, $\theta_{13} = 8.44°$, $\theta_{23} = 47°$, $\delta_{CP} = -\pi/2$, $\Delta m_{21}^2 = 7.56 \times 10^{-5} eV^2$, $\Delta m_{32}^2 = -2.497 \times 10^{-3} eV^2$ and $\Delta m_{31}^2 = 2.55 \times 10^{-3} eV^2$. By default, we assume NH as the true mass hierarchy and HO as the true octant, unless explicitly stated otherwise. We define a statistical χ^2 which is a measure of sensitivity as,

$$\chi_{pull}^2 = \underset{\zeta_j}{min} \left(\underset{\eta}{\min} \sum_i \sum_j \frac{\left[N_{true}^{i,j} - N_{test}^{i,j} \right]^2}{N_{true}^{i,j}} + \sum_{i=1}^{k} \frac{\zeta_i^2}{\sigma_{\zeta_i}^2} \right), \tag{7}$$

where, $N_{true}^{i,j}$ and $N_{test}^{i,j}$ represents the number of true and test events in the $\{i, j\}$-th bin respectively. We incorporate the systematic errors as additional parameters known as nuisance parameters (ζ_k) with the systematical errors ($\sigma_{\zeta_k}^2$).

4. Results and Discussion

We first explore the impact of scalar NSI parameters on the oscillation probabilities. We then further probe its impact on CP-violation and constraining capability towards scalar NSI elements.

4.1 Effects on oscillation probabilities

Figure 1 shows the impact of diagonal scalar NSI elements (η_{ee}, $\eta_{\mu\mu}$, and $\eta_{\tau\tau}$) on the oscillation probability as a function of neutrino energy for DUNE (top row), T2HK (middle row), and T2HKK (bottom row). The solid red line in each plot represents the case without scalar NSI, where $\eta_{\alpha\beta}$ = 0. The solid (dashed) black, blue, and magenta lines indicate positive (negative) values of η_{ee}, $\eta_{\mu\mu}$, and $\eta_{\tau\tau}$ respectively. The inclusion of scalar NSI parameters has a notable impact on the oscillation probabilities at all three baselines, particularly near the oscillation maxima. For η_{ee}, a positive (negative) value enhances (suppresses) the probabilities around the oscillation maxima, while for $\eta_{\tau\tau}$, the effects are complementary. In the case of $\eta_{\mu\mu}$, a positive (negative) value shifts the oscillation maxima to higher (lower) energies while slightly suppressing the amplitude.

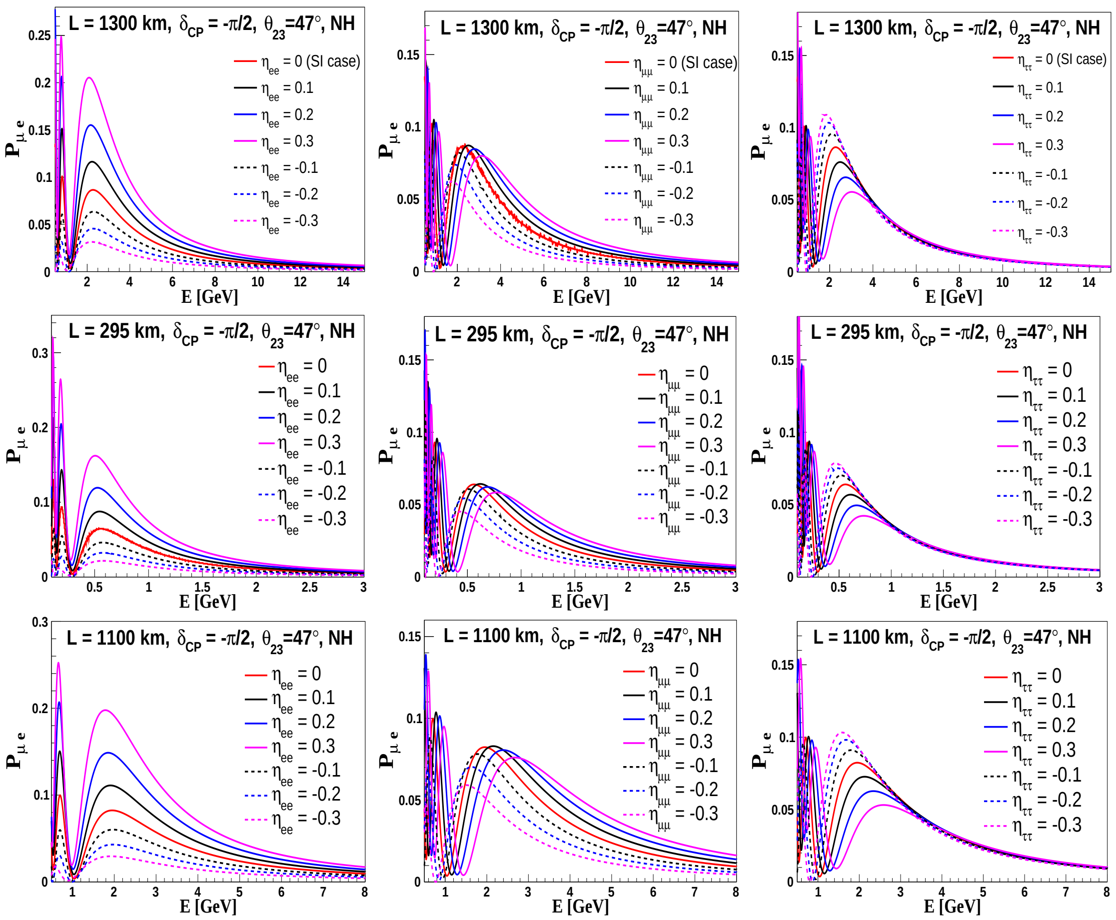

Figure 1: The effects of η_{ee} (left–column), $\eta_{\mu\mu}$ (middle–column) and $\eta_{\tau\tau}$ (right–column) on $P_{\mu e}$ at the baselines corresponding to DUNE (top–row), T2HK (middle–row) and T2HKK (bottom–row). Here, δ_{CP} = -π/2, θ_{23} = 47° and true mass Hierarchy = NH.

4.2 Constraining scalar NSI parameters

In Figure 2, we present the sensitivity of the experiments towards constraining the scalar NSI parameters, $\eta_{\alpha\beta}$, for DUNE, T2HK, and DUNE+T2HK. The plots for η_{ee}, $\eta_{\mu\mu}$, and $\eta_{\tau\tau}$ are displayed in the left-panel, middle-panel, and right-panel, respectively. We kept the true values of

$\eta_{\alpha\beta}$ fixed at 0.1 and marginalized the test $\eta_{\alpha\beta} \in$ [-0.5, 0.5]. We plotted $\Delta\chi^2$ as a function of the test $\eta_{\alpha\beta}$ parameters, where the dashed green and dashed magenta lines indicate the 3σ and 5σ confidence levels, respectively. We see that, DUNE exhibits better sensitivity (at 3σ) in constraining η_{ee} (for a true $\eta_{ee} = 0.1$) compared to T2HK. Conversely, T2HK demonstrates superior constraining capability for $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$ (for true $\eta_{\alpha\beta} = 0.1$) due to its larger detector size (approximately 374kt) leading to improved statistics. The combined study with DUNE+T2HK enhances the sensitivity for constraining the $\eta_{\alpha\beta}$ parameters and tightens the bounds on $\eta_{\alpha\beta}$. The combination of DUNE and T2HK always yields improved sensitivity due to the substantial combined data from both detectors.

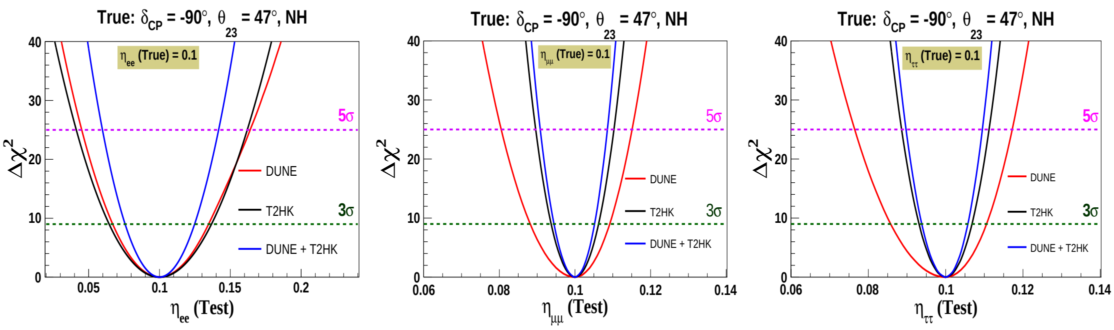

Figure 2: The sensitivity of DUNE, T2HK and DUNE + T2HK towards constraining non–zero η_{ee} (left–panel), $\eta_{\mu\mu}$ (middle–panel), and $\eta_{\tau\tau}$ (right–panel) at true δ_{CP} = -π/2 and true θ_{23} = 47°.

4.3 Effects on CP-violation sensitivity

In Figure 3, we show the impact of scalar Non-Standard Interaction on CP violation (CPV) sensitivity for DUNE (left column), T2HK (middle column), and DUNE + T2HK analysis (right column). The inclusion of scalar NSI significantly affects both DUNE and T2HK's CPV sensitivity. The plots depict the statistical significance σ (calculated as $\sqrt{\Delta\chi^2_{CPV}}$) as a function of the true δ_{CP}. The top row corresponds to η_{ee}, the middle row to $\eta_{\mu\mu}$, and the bottom row to $\eta_{\tau\tau}$. For the χ^2 study, we marginalized over the NSI parameters. The CPV sensitivity is calculated as,

$$\Delta\chi^2_{\rm CPV}\ (\delta^{\rm true}_{\rm CP}) = \min\ \left[\chi^2\ (\delta^{\rm true}_{CP}, \delta^{\rm test}_{CP} = 0),\ \chi^2(\delta^{\rm true}_{CP}, \delta^{\rm test}_{CP} = \pm\pi)\right]. \tag{8}$$

The solid red curve in each plot represents the case with no scalar NSI, i.e., $\eta_{\alpha\beta} = 0$. The solid (dashed) black and blue curves indicate chosen positive (negative) values of $\eta_{\alpha\beta}$. We observe that, for η_{ee}, a positive (negative) value mostly enhances (suppresses) CP violation sensitivities. For $\eta_{ee} = 0.1$ and $\delta_{CP}^{true} \in$ [0, 90°], the sensitivities without and with scalar NSI nearly overlap. The combined study of DUNE + T2HK improves sensitivities for all cases, including the overlapped region, primarily due to data collection in a broader range of degenerate spaces. For $\eta_{\mu\mu}$, a positive value deteriorates CPV sensitivities in the upper half plane of δ_{CP}, i.e., [0, π], for DUNE, but shows mild fluctuations for the rest of δ_{CP}. A negative $\eta_{\mu\mu}$ significantly suppresses the sensitivities for both DUNE and T2HK. At T2HK, positive $\eta_{\tau\tau}$ enhances sensitivity.

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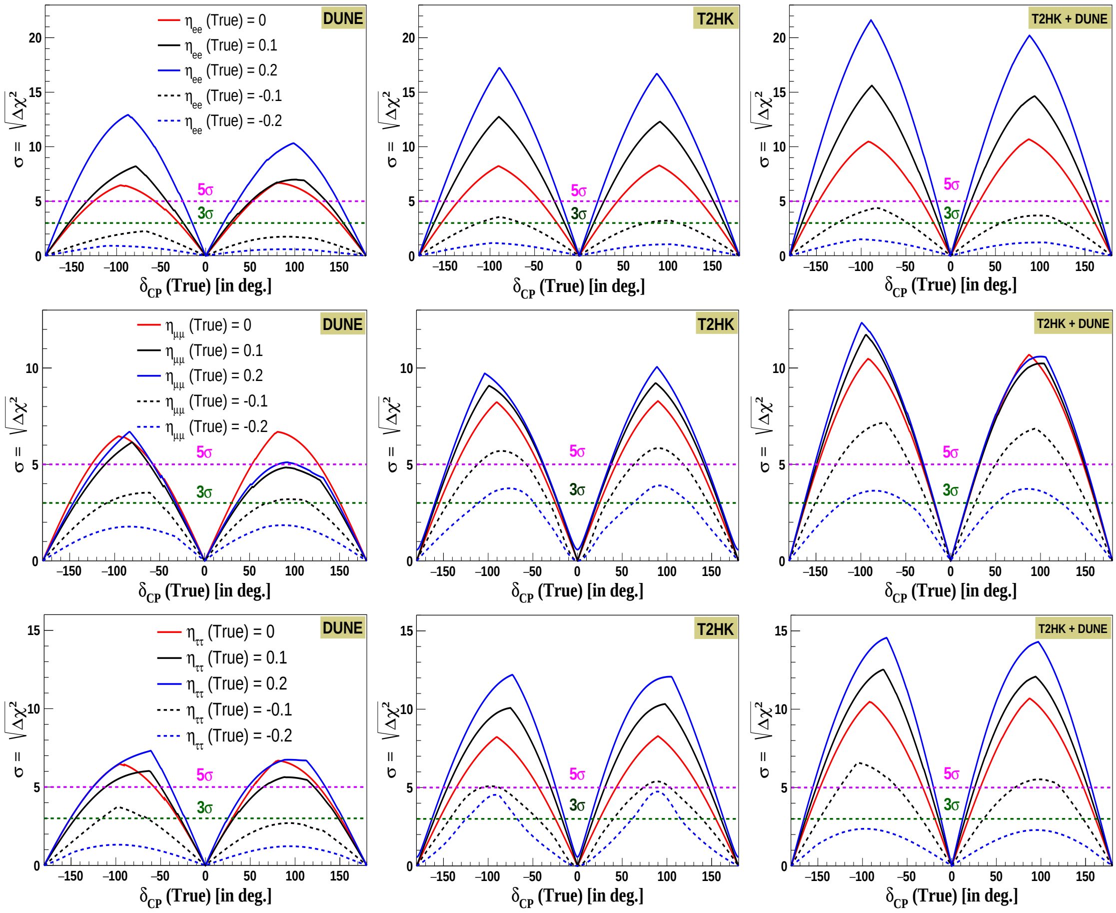

Figure 3: The CPV sensitivity of DUNE (left–column), T2HK (middle-column) and DUNE + T2HK (right-column) in presence of η_{ee} (top-row), $\eta_{\mu\mu}$ (middle-row) and $\eta_{\tau\tau}$ (bottom–row).

5. Summary and Conclusion

With the remarkable advancements in neutrino physics and cutting-edge experimental setups, the neutrino oscillation parameters are being measured with utmost precision. Currently, the least constrained parameters in neutrino physics are the CP-violating phase (δ_{CP}) and the octant of the mixing angle (θ_{23}). Identifying these subdominant effects of neutrinos and understanding their impact on the physics reach of different neutrino experiments is crucial. This study focused on investigating the effect of scalar NSI on three upcoming long-baseline experiments. The ongoing research is exploring the effects of NSI on other physics sensitivities in various neutrino experiments. A collaborative effort involving solar, atmospheric, reactor, and other experiments is essential for comprehending the impact of NSI. Equally important is placing stringent constraints on the effects of scalar NSI to interpret data from various neutrino experiments accurately.

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