Scalar NSI: A unique probe to explore neutrino mass via neutrino oscillation experiments

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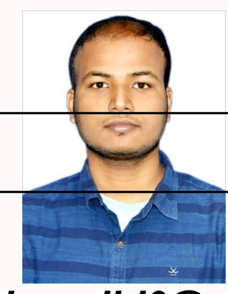

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1) Introduction

In the standard interaction framework, directly measuring absolute neutrino masses through neutrino oscillations isn't feasible since oscillations rely solely on mass-squared differences. However, the introduction of scalar non-standard interactions can incorporate additional terms in the oscillation Hamiltonian, directly impacting the neutrino mass matrix [1, 2, 3, 4]. This characteristic renders scalar NSI a unique tool for neutrino mass determinations. In this study, for the first time, we set constraints on the absolute masses of neutrinos by probing scalar NSI. We demonstrate that the presence of scalar NSI at DUNE [5] can impose a restriction on the lightest neutrino mass. We observe that the tightest constraint on the lightest neutrino mass occurs with $\eta_{\tau\tau}$ and $\eta_{\mu\mu}$ at 2σ confidence levels for normal and inverted hierarchy, respectively. This analysis suggests that scalar NSI presents an intriguing avenue for constraining absolute neutrino masses in long-baseline neutrino experiments through neutrino oscillations [6].

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,

$$H = E_\nu + \frac{MM^\dagger}{2E_\nu} \pm V_{SI} \quad (1)$$

Where E_ν is Neutrino energy and M is the neutrino mass matrix. The positive and negative sign before V_{SI} is for neutrino and antineutrino mode respectively.

$$V_{SI} = \begin{pmatrix} V_C + V_N & 0 & 0 \\ 0 & V_N & 0 \\ 0 & 0 & V_N \end{pmatrix}, \quad (2)$$

$V_C = \sqrt{2} G_F n_e$ and $V_N = \frac{G_F n_n}{\sqrt{2}}$

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

$$H = E_\nu + \frac{(UMU^\dagger + \Delta M)(UMU^\dagger + \Delta M)^\dagger}{2E_\nu} \pm V_{SI} \quad (3)$$

Where, $\Delta M = \sum_f \frac{n_f y_f Y}{m_\phi^2}$, $y_f \rightarrow$ Yukawa coupling of the scalar mediator ϕ with the environmental fermion f, 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, ΔM can be parametrized as,

$$\Delta M = \sqrt{|\Delta m^2_{31}|} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{e\tau} & \eta_{\mu\tau} & \eta_{\tau\tau} \end{pmatrix} \quad (4)$$

Where, $\eta_{\alpha\beta}$ are dimensionless parameters and it quantifies the size of scalar NSI. The hermicity of the neutrino Hamiltonian demands diagonal elements to be real and off-diagonal elements complex.

3) Methodology

- The benchmark values of oscillation parameters used:

θ_{12}	θ_{13}	θ_{23}	δ_{CP}	Δm^2_{21}	Δm^2_{31}
34.51°	8.44°	47°	$-\pi/2$	7.56×10^{-5}	2.43×10^{-3}

- We have used GLoBES[7] for our simulation studies and for choice of systematics and background we have used the relevant TDR [5].
- To study the effects of scalar NSI we have taken DUNE (3.5 years in ν + 3.5 years in $\bar{\nu}$) with a baseline of 1300 km.
- We define the parameter, $\Delta P_{\mu e} = P^{NSI}_{\mu e} - P^{SI}_{\mu e}$ to study the impact of scalar NSI on the appearance probabilities.
- The CPV sensitivity χ^2 is defines as,

$$\chi^2 = \min_{\zeta_i} \left(\min_{\eta} \sum_i \sum_j \frac{\left[N^{i,j}_{true} - N^{i,j}_{test}\right]^2}{N^{i,j}_{true}} + \sum_{i=1}^{k} \frac{\zeta_i^2}{\sigma^2_{\zeta_i}} \right), \quad (5)$$

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.

4.1) Results: Effects on oscillation probabilities

- For NH case, the element η_{ee} enhances the probabilities for all values of δ_{CP}. The enhancement is significant in the negative δ_{CP} plane. The elements $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$ suppresses the probabilities for the complete δ_{CP} space with more $\eta_{\tau\tau}$ suppression to that of $\eta_{\mu\mu}$.
- For IH case, the elements η_{ee} and $\eta_{\mu\mu}$ suppress the probabilities for complete δ_{CP} space. However, the suppression is higher for η_{ee}. The element $\eta_{\tau\tau}$ enhances the probabilities and the enhancement is higher for $\delta_{CP} \in [-60°, 40°]$.

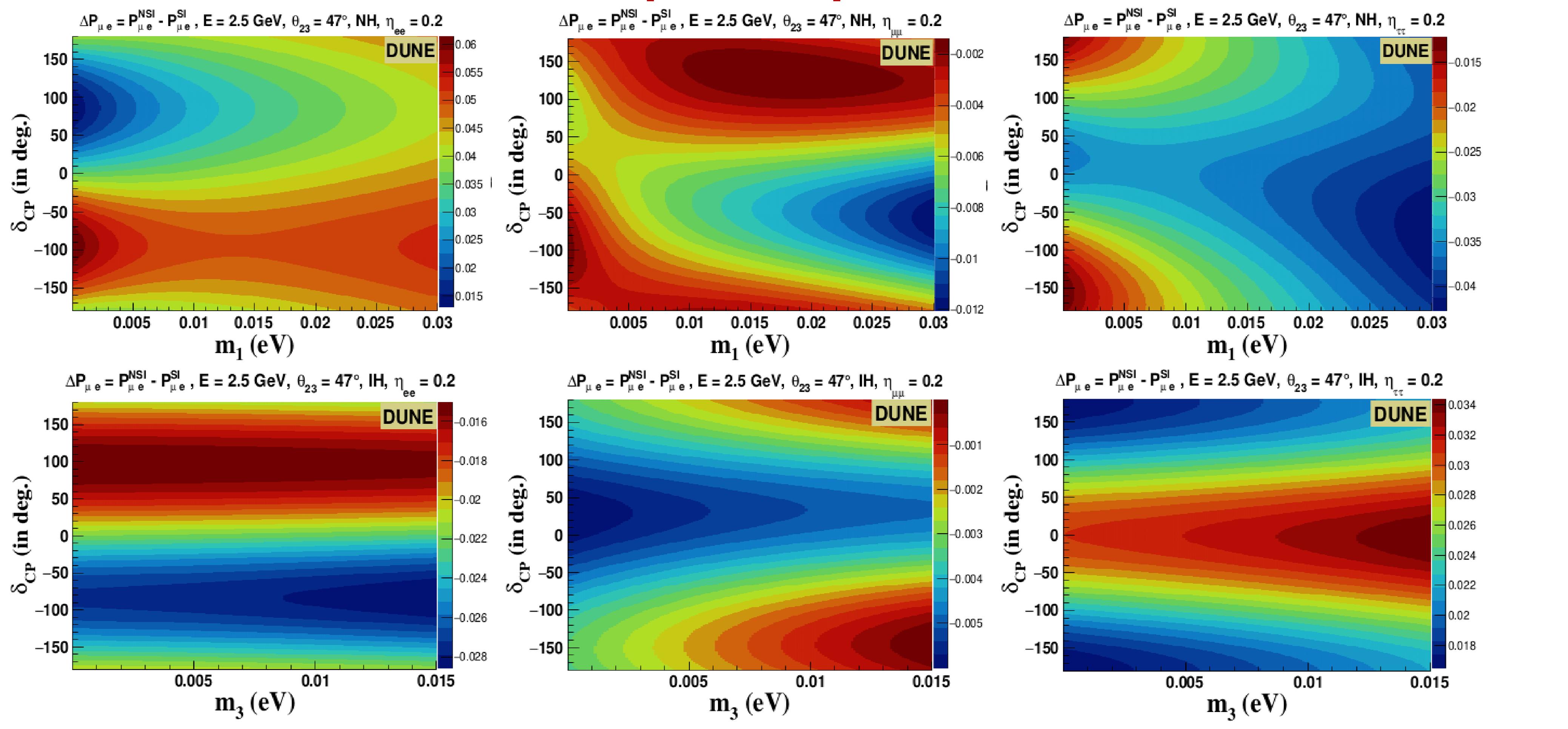

Figure 1: The effects of η_{ee} (left-panel), $\eta_{\mu\mu}$ (middle-panel) and $\eta_{\tau\tau}$ (right-panel) on $P_{\mu e}$ at DUNE.

4.2) Results: Constraining the neutrino mass

- Figure 2 shows the allowed region for 1σ, 2σ and 3σ CL in $\eta_{\alpha\beta} - m$ planes for DUNE.
- For NH (top-panel), the lightest ν-mass can be constrained as $m_1 \in [0.009, 0.03]$ eV at 1σ CL for η_{ee}. The element $\eta_{\mu\mu}$ can constrain the ν-mass as $m_1 \in [0.016, 0.024]$ eV at 1σ CL. For $\eta_{\tau\tau}$, we see a similar constrain on $m_1 \in [0.017, 0.023]$ eV at 1σ CL.
- The allowed region for all the diagonal elements in the IH (bottom-panel) is larger as compared to NH. The constraint on the lightest mass in presence of η_{ee} worsens for IH. For $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$, the allowed region at 1σ CL for the lightest mass m_3 is $\sim [0.007, 0.013]$ eV.

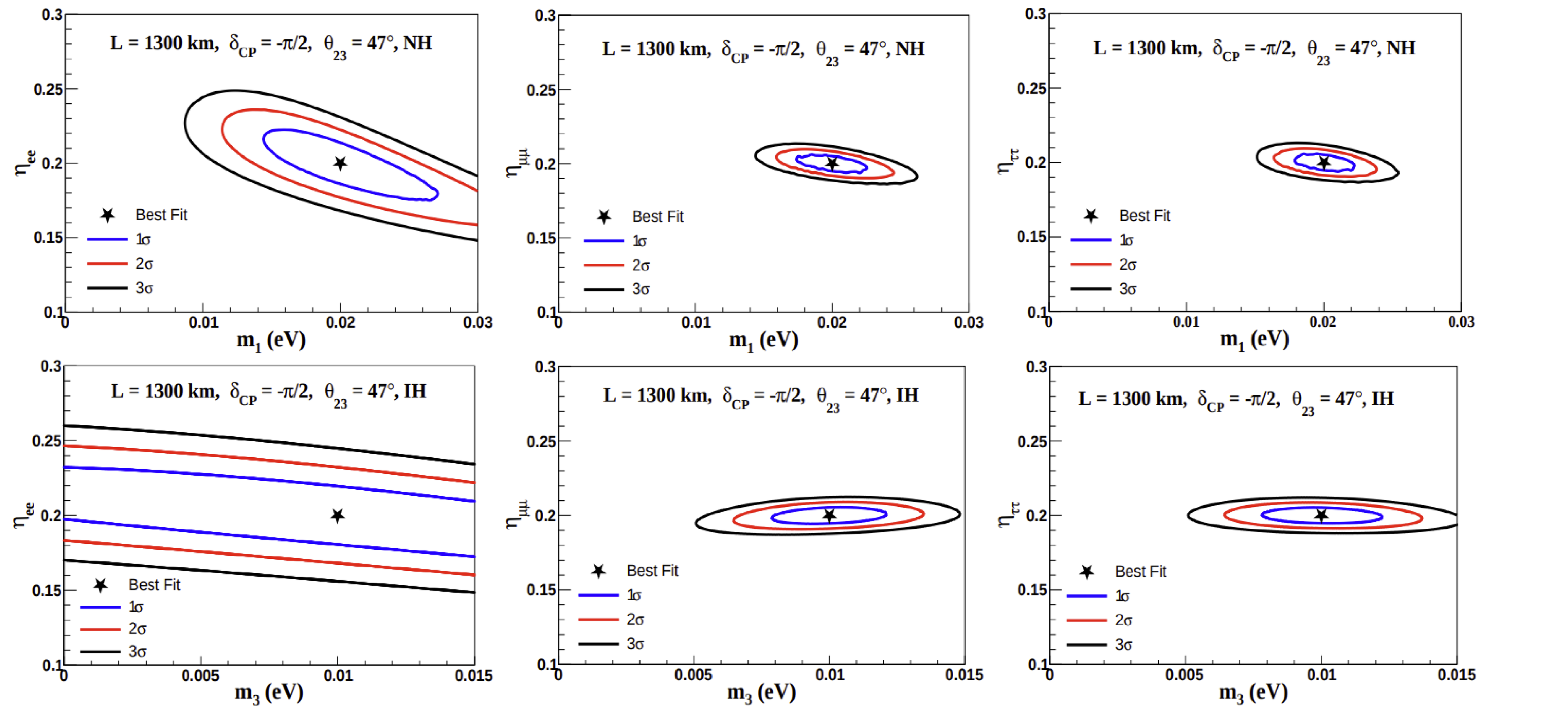

Figure 2: The effects of scalar NSI parameter η_{ee} on the CP-Violation sensitivity at LBL experiments.

5) Summary and Concluding remarks

- Scalar NSI offers an intriguing way to probe the absolute ν-masses via neutrino oscillations.
- the presence of $\eta_{\tau\tau}$ or $\eta_{\mu\mu}$ makes the constraining capability marginally better than that of η_{ee} on the lightest mass of neutrinos for both the hierarchies.
- The exploration of neutrino mass constraints holds significant importance, as it can provide crucial insights into the mechanisms underlying neutrino mass generation.

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