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

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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 Long 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,

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

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.

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

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

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

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

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,

$$\Delta M = \sqrt{\Delta m_{31}^2} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{e\tau} & \eta_{\mu\tau} & \eta_{\tau\tau} \end{pmatrix} \qquad (4)$$

Where, $\eta_{\alpha\beta}$ 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. η_{ee} and $\eta_{\mu\mu}$.

3. Methodology

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

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[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 ν + 5 years in $\bar{\nu}$) and T2HK (2.5 years in ν + 7.5 years in $\bar{\nu}$) with a baseline of 1300 km and 295 km respectively.
- The CPV sensitivity χ^2 is defines as,

$$\chi^2 \equiv \min_\eta \sum_i \sum_j \frac{\left[N^{i,j}_{true} - N^{i,j}_{test}\right]^2}{N^{i,j}_{true}}, \qquad (5)$$

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. Results : Effects on oscillation probabilities

- The scalar NSI element η_{ee} suppresses the probabilities around the oscillation maxima whereas $\eta_{\mu\mu}$ 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.

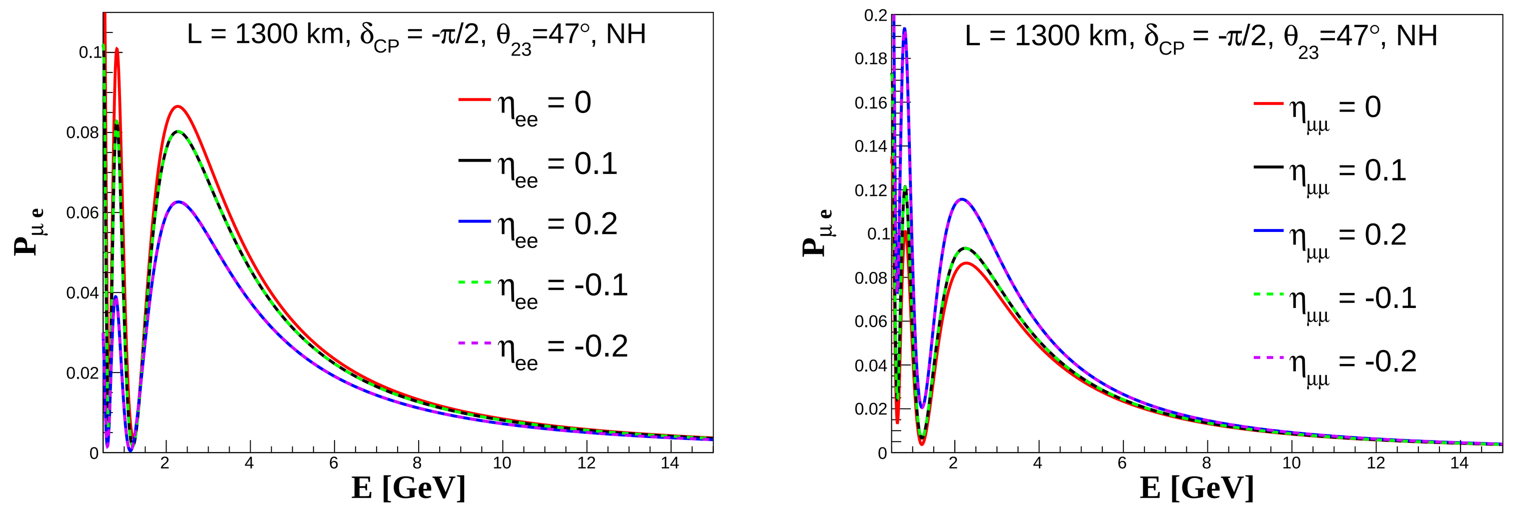

Figure 1: Oscillation Probability, $P_{\mu e}$ of DUNE for different η_{ee} (left) and $\eta_{\mu\mu}$ (right).

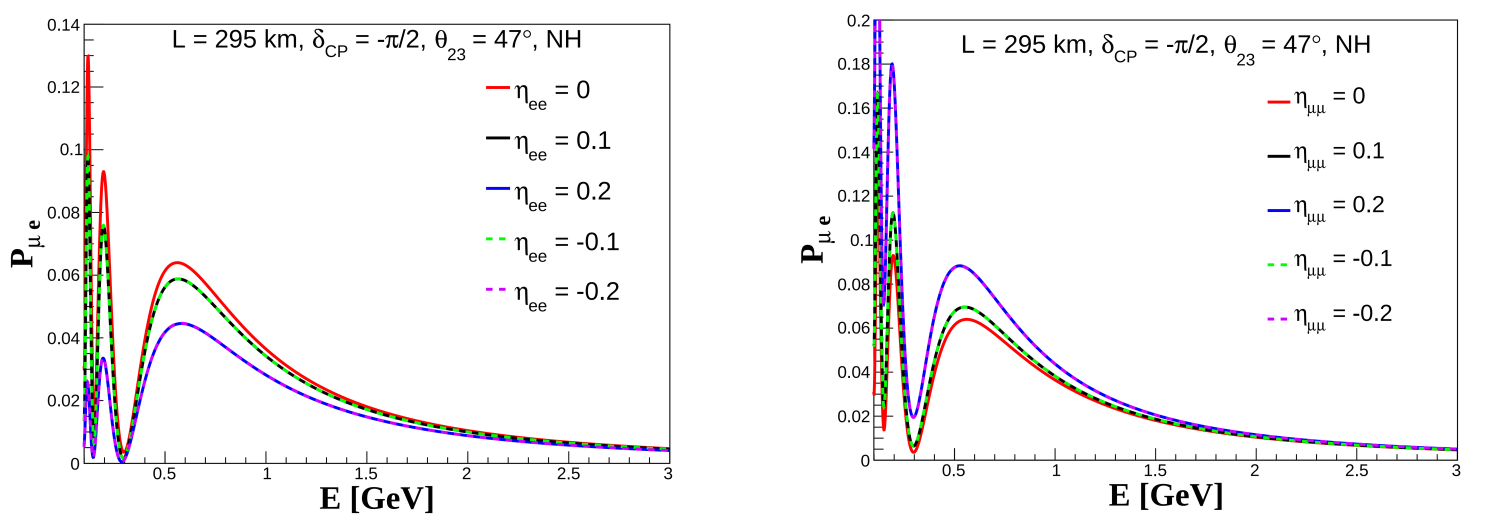

Figure 2: Oscillation Probability, $P_{\mu e}$ of T2HK for different η_{ee} (left) and $\eta_{\mu\mu}$ (right).

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 η_{ee} deteriorates the CPV sensitivities whereas $\eta_{\mu\mu}$ improves the experiment's sensitivity towards CPV.
- For example, for η_{ee} = 0.10 all sensitivities lies below 5σ and $\delta_{CP} \sim$ [-45°, -135°] and $\delta_{CP} \sim$ [50°, 140°] it lies above 3σ CL.
- In combined analysis overall sensitivities improves for each cases.
- For all the chosen values of $\eta_{\mu\mu}$ the sensitivities lies above standard sensitivities for both DUNE and DUNE + T2HK combined.

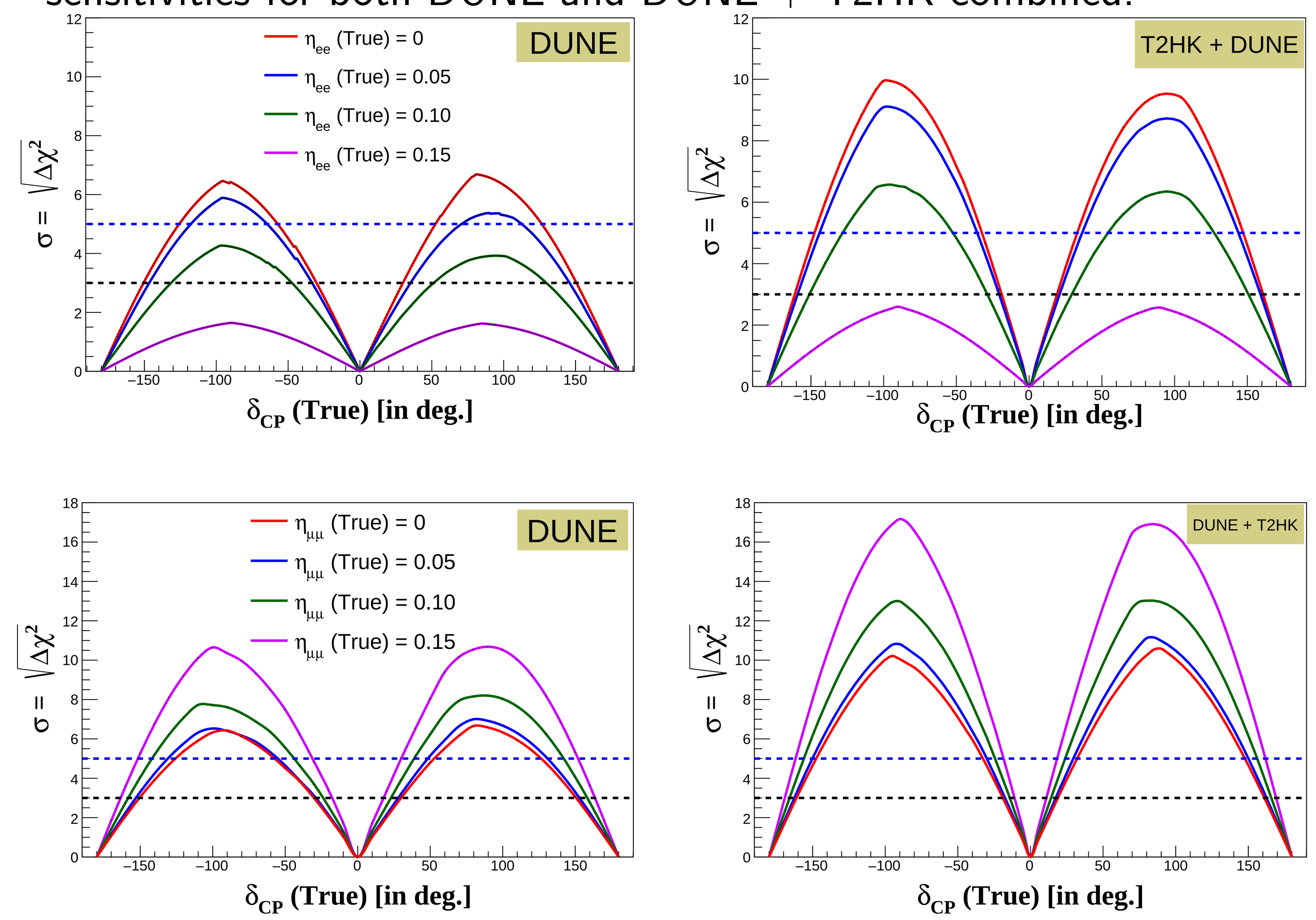

Figure 3: CPV sensitivities of DUNE and combined in presence of η_{ee} (upper) and $\eta_{\mu\mu}$ (lower) element considering NH as true hierarchy and HO as true octant.

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

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