Investigating Off-Diagonal Scalar NSI and the Impact on CP-Violation Sensitivities via ν-oscillations at DUNE

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XXXI International Conference on Neutrino Physics and Astrophysics, June 16-22,2024, Milan,Italy

1. INTRODUCTION

- Non-standard coupling of $\nu's$ with a scalar shows a promising possibility to probe BSM physics.
- Appear as a sub-dominant effect affecting the ν-oscillations in matter.
- It introduces a contribution directly to the ν-mass matrix in the interaction Hamiltonian.
- The linear scaling of the effects of scalar NSI (sNSI) with matter density also motivates its exploration in LBL experiments.
- We have explored the impact of off-diagonal sNSI and phases on the CP-violation (CPV) sensitivities at DUNE.
- We observe that the presence of off-diagonal sNSI elements ($\eta_{\alpha\beta}$) can significantly affect the sensitivities.
- The standard Hamiltonian can be written as,

$$\mathcal{H}_{\text{matter}} = \mathbf{E}_\nu + \frac{\mathbf{MM}^\dagger}{\mathbf{2E}_\nu} \pm \mathbf{V}_{\mathbf{SI}}. \tag{1}$$

2. FORMALISM

- The effective form of matter Hamiltonian with scalar NSI correction can be written as,

$$\mathcal{H}_{\mathbf{sNSI}} \equiv \mathbf{E}_\nu + \frac{\mathbf{M}_{\text{eff}}\mathbf{M}_{\text{eff}}^\dagger}{\mathbf{2E}_\nu} \pm \mathbf{V}_{\mathbf{SI}}. \tag{2}$$

With $M_{eff} = (M + \delta M)$ where, $\delta M \equiv \sum_f n_f y_f y_{\alpha\beta}/m_\phi^2$.
$y_f \rightarrow$ Yukawa coupling of the scalar mediator ϕ with the environmental fermion f and $y_{\alpha\beta} \rightarrow$ the coupling with $\nu's$.

- The contribution δM can be parameterized as,

$$\delta \mathbf{M} \equiv \mathbf{S_m} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{e\mu}^* & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{e\tau}^* & \eta_{\mu\tau}^* & \eta_{\tau\tau} \end{pmatrix}$$

where S_m is a rescaling factor.

- The effects of sNSI on numerically calculated ν-oscillation probabilities is explored by incorporating the effective Hamiltonian in the GLoBES Simulation framework.

3. EFFECTS OF SCALAR NSI ON PROBABILITIES

- Benchmark values of oscillation parameters used in the simulation.

Parameters	Values	Parameters	Values
θ_{12}	34.51°	Baseline	1300 km
θ_{13}	8.44°	$\triangle m_{12}^2$	$7.56\times10^{-5}eV^2$
θ_{23}	47°	$\lvert\triangle m_{13}^2\rvert$	$2.55\times10^{-3}eV^2$
δ_{CP}	$-\pi/2$	Runtime (yr)	$3\nu + 3\bar{\nu}$

Impact on $P_{\mu e}$ in the presence of $\eta_{e\mu}$, $\eta_{e\tau}$ & $\eta_{\mu\tau}$

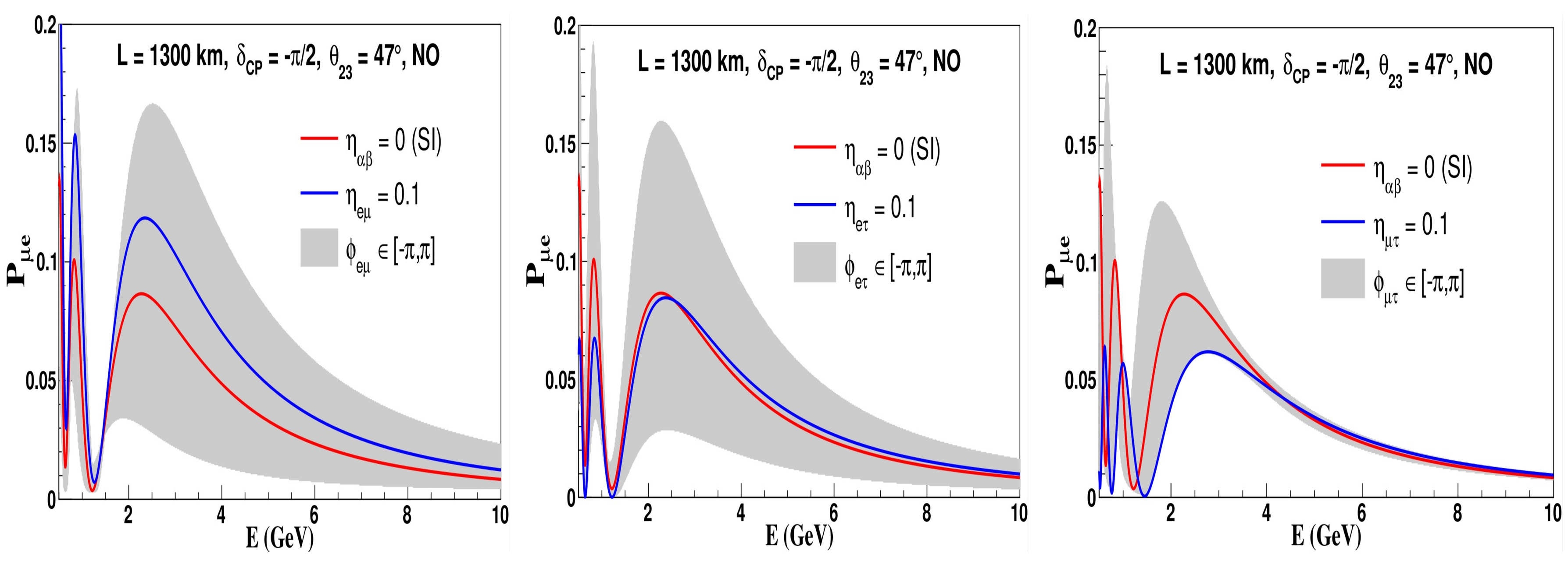

Figure 1: Impact on $P_{\mu e}$ for $\eta_{e\mu}$, $\eta_{e\tau}$ & $\eta_{\mu\tau}$ with band $\phi_{\alpha\beta} \in [-\pi, \pi]$.

- For $\eta_{e\mu}$, we observe enhancement in $P_{\mu e}$. Non-zero $\phi_{e\mu}$ phase can significantly modify the probabilities.
- Only nominal changes in the probabilities can be seen in the presence of $\eta_{e\tau}$. Although, $\phi_{e\tau}$ can considerably affect $P_{\mu e}$.
- For $\eta_{\mu\tau}$, we observe suppression in the $P_{\mu e}$ for $E < 4$ GeV. The phase $\phi_{\mu\tau}$ results in a narrower band in comparison to others.
- We define the statistical χ^2 as,

$$\chi^2 \equiv \min_{\eta} \sum_{\mathbf{i}} \sum_{\mathbf{j}} \frac{\left[\mathbf{N}_{\text{true}}^{\mathbf{i,j}} - \mathbf{N}_{\text{test}}^{\mathbf{i,j}}\right]^2}{\mathbf{N}_{\text{true}}^{\mathbf{i,j}}},$$

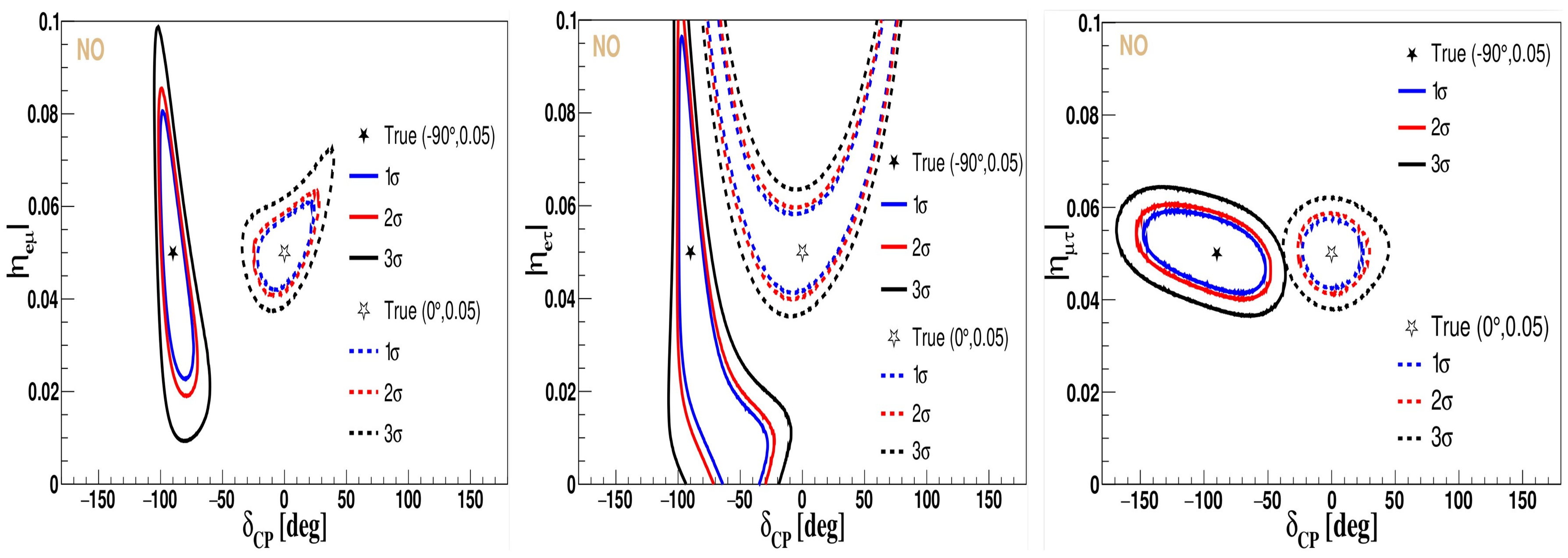

Figure 2: δ_{CP} constraining capability at DUNE for $\eta_{e\mu}$, $\eta_{e\tau}$ & $\eta_{\mu\tau}$.

- δ_{CP} is well constrained in presence of $\eta_{e\mu}$. For $\delta_{CP}^{true} = 0°$, we observe a relatively better constraint.
- δ_{CP} is better constrained for $|\eta_{\mu\tau}|$ compared to $|\eta_{e\mu}|$ & $|\eta_{e\tau}|$.

4. RESULTS

Impact on CP-Violation sensitivities at DUNE

- The CPV sensitivities can be defined as,

$$\boldsymbol{\Delta}\chi^2_{\text{CPV}}\,(\delta_{\text{CP}}) = \min\,\left[\chi^2\,(\boldsymbol{\delta}_{\mathbf{CP}}, \boldsymbol{\delta}_{\mathbf{CP}}^{\text{test}} = \mathbf{0}),\ \chi^2(\boldsymbol{\delta}_{\mathbf{CP}}, \boldsymbol{\delta}_{\mathbf{CP}}^{\text{test}} = \pm\pi)\right]. \tag{3}$$

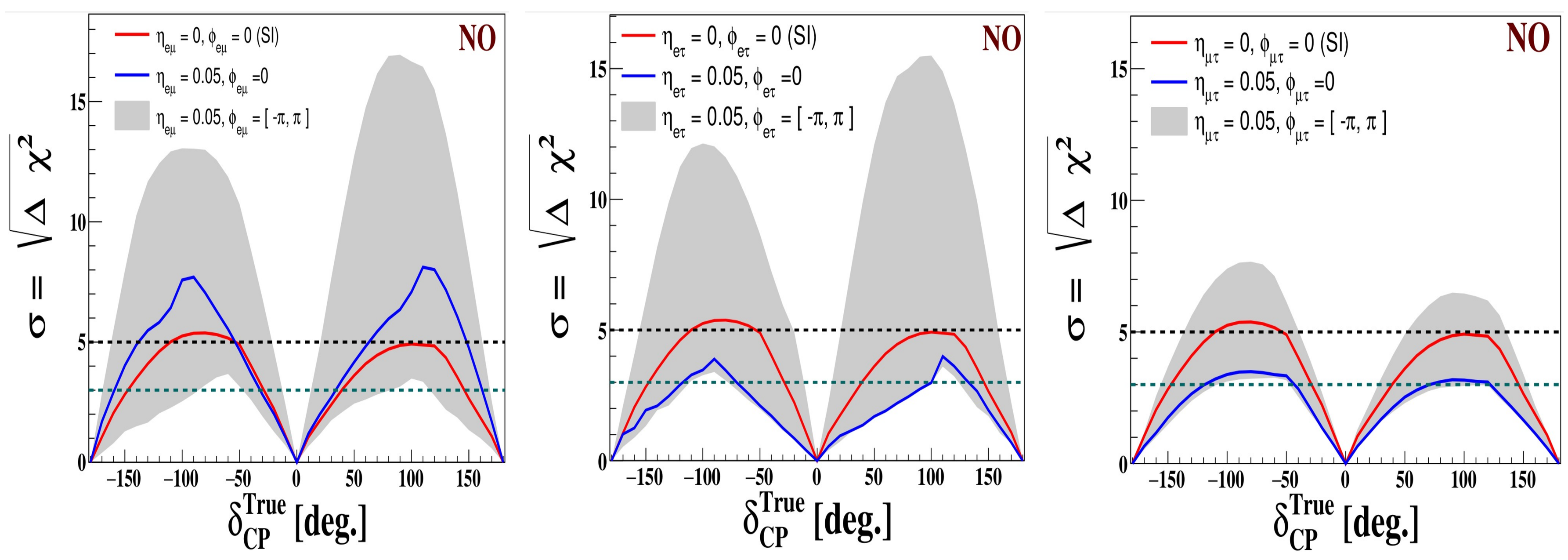

Figure 3: CPV sensitivities at DUNE for $\eta_{e\mu}$, $\eta_{e\tau}$ & $\eta_{\mu\tau}$.

- For $\eta_{e\mu}$, we observe an enhancement in the sensitivities. $\phi_{e\mu}$ can significantly alter the sensitivities depending on its value.
- $\eta_{e\tau}$ can deteriorate the CPV sensitivities. The phase $\phi_{e\tau}$ can enhance or suppress the sensitivities as also seen for $\phi_{e\mu}$.
- $\eta_{\mu\tau}$ also suppresses the sensitivities. Variation of sensitivities due to $\phi_{\mu\tau}$ is relatively small compared to $\phi_{e\mu}$ and $\phi_{e\tau}$.

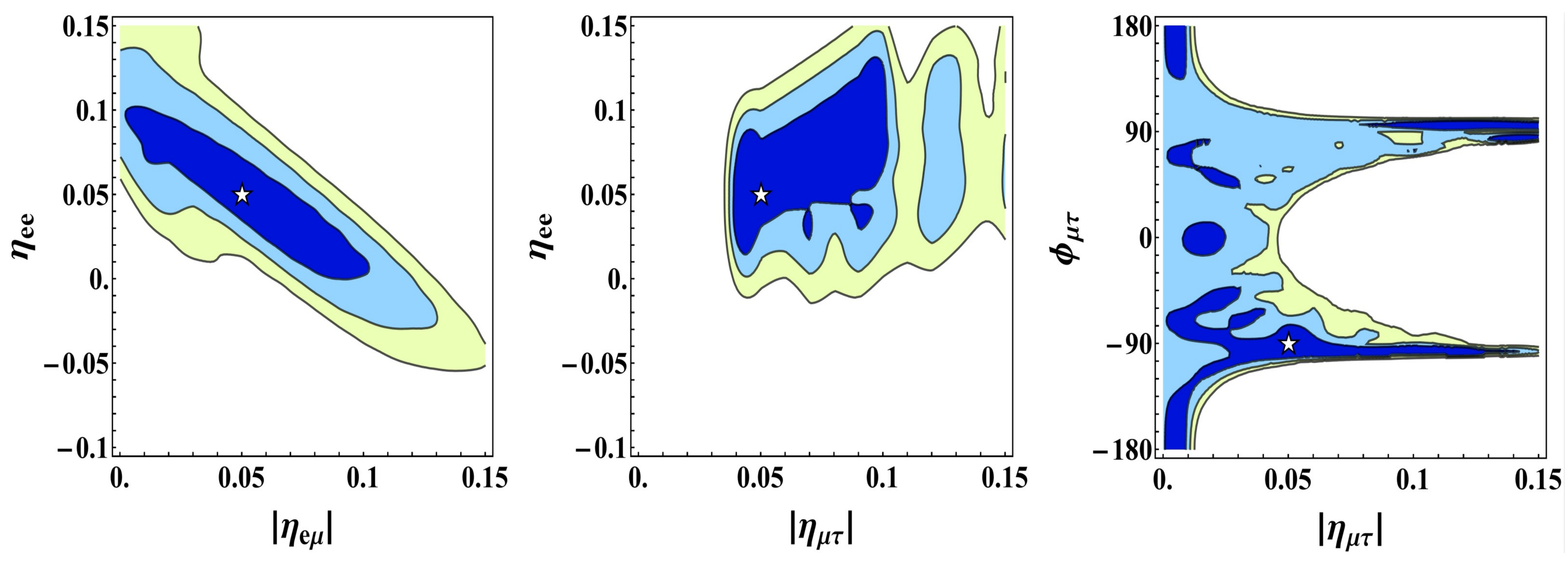

Figure 4: Correlation between different scalar NSI parameters.

- A correlation between the elements η_{ee} and $|\eta_{e\mu}|$ is seen. We also see a similar correlation between η_{ee} and $|\eta_{\mu\tau}|$.
- For $\phi_{\mu\tau}$ and $\eta_{\mu\tau}$, we observe a degeneracy for $\phi_{\mu\tau} \sim \pm 90°$.

5. CONCLUDING REMARKS

- The off-diagonal elements and their associated phases can modify the oscillation probabilities at DUNE.
- δ_{CP} constraining capability is affected in presence of sNSI.
- CPV sensitivities get significantly modified in presence of $\eta_{\alpha\beta}$ and corresponding phases $\phi_{\alpha\beta}$ at DUNE.
- We also explored potential degeneracies that may arise due to correlation among scalar NSI elements.

References

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Acknowledgement

We would like to thank the organizers of the NEUTRINO 2024 Conference. AS acknowledges the fellowship received from CSIR-SRF and travel fund provided by SERB-ANRF(ITS/2024/001704).