

Exploring new physics effects of scalar NSI at Long Baseline Experiments



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Outline

- 1 Introduction
- 2 Scalar Non Standard Interactions
- 3 Methodology
- 4 Results and Discussion
- 5 Conclusions

Introduction

- Neutrino oscillations essentially confirms neutrinos are massive.
- It provides the first firm experimental evidence of physics beyond Standard Model (BSM).
- The models describing BSM physics often comes with some additional unknown coupling of neutrinos.
- These new interactions are called Non Standard Interactions (NSIs), as it can't be explained within the framework of SM.

Non standard interactions in neutrinos

- NSI can introduce matter effect in neutrino oscillations.
- The impact of NSI on oscillation probability: an interesting sector to probe new physics.
- Neutrinos coupling with a scalar is an excellent probe to study new physics in Long Baseline experiments.

L. Wolfenstein, Phys. Rev. D 17 (1978)

Ge S.-F. and Parke S. J. , Phys. Rev. Lett. (2019)

Neutrino Oscillation in matter

- The weakly interacting neutrinos might interact with matter via **charged-current (CC)** or **neutral-current (NC)** when they pass through matter. [more](#)
- The Hamiltonian for neutrino oscillation in matter is given by :

$$\mathcal{H}_{\text{matter}} \approx U \frac{MM^\dagger}{2E_\nu} U^\dagger \pm V_{SI}.$$

Where

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

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

Scalar Non Standard Interactions

- The Lagrangian of such interactions can be formulated as :

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

- The corresponding neutrino Hamiltonian modifies as:

$$\mathcal{H}_{\text{NSI}} \approx \frac{(U M U^\dagger + \delta M)(U M U^\dagger + \delta M)^\dagger}{2E_\nu} \pm V_{\text{SI}},$$

where,

$$\delta M = \sum_f \frac{n_f y_f y_{\alpha\beta}}{m_\phi^2}$$

- The effect appears as correction/addition/perturbation to the neutrino mass term.

Methodology

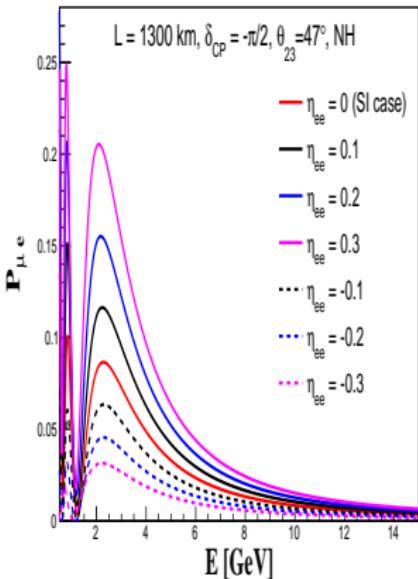
- The effect of scalar NSI can be parametrized as a 3×3 matrix :

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

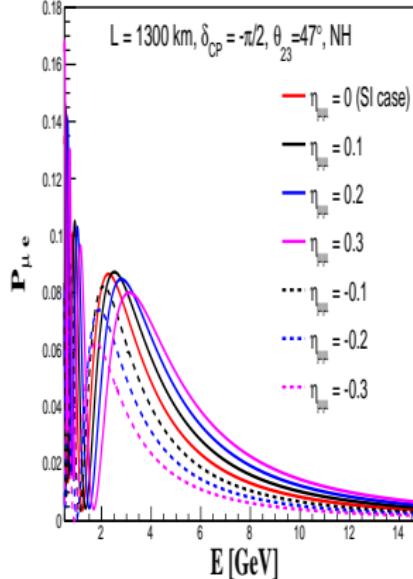
- $\eta_{\alpha\beta}$ elements are dimensionless and quantifies the size of scalar NSI.
- A framework is made with the modified Hamiltonian in GLoBES with different configuration of LBL experiments viz. DUNE, T2HK, and T2HKK.
- The values of mixing parameters used in the analysis :

$\sin^2 \theta_{12}$	$\sin^2 \theta_{13}$	$\sin^2 \theta_{23}$	δ_{CP}	$\Delta m_{21}^2 (\text{eV}^2)$	$\Delta m_{31}^2 (\text{eV}^2)$
0.308	0.0234	0.5348	$-\pi/2$	7.54×10^{-5}	2.43×10^{-3}

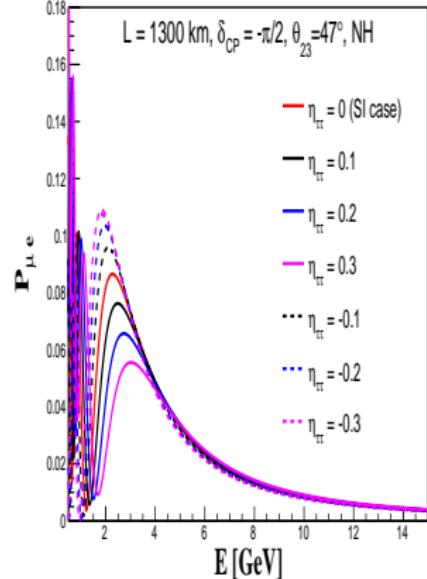
Results : $P_{\mu e}$ vs E with non zero $\eta_{ee}/\eta_{\mu\mu}/\eta_{\tau\tau}$



(a) $P_{\mu e}$ vs E for different
 η_{ee}



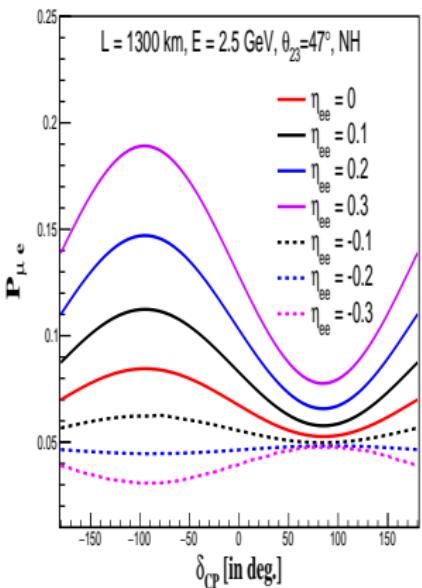
(b) $P_{\mu e}$ vs E for different
 $\eta_{\mu\mu}$



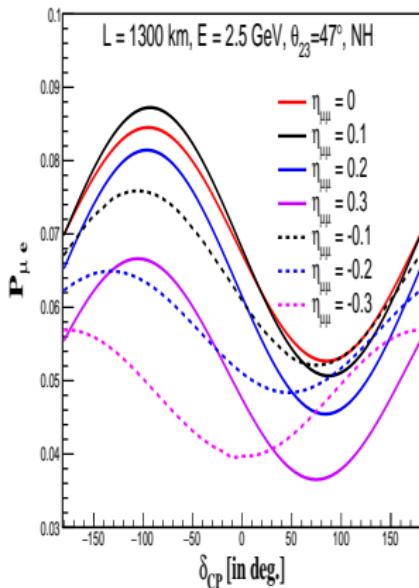
(b) $P_{\mu e}$ vs E for different
 $\eta_{\tau\tau}$

- η_{ee} and $\eta_{\tau\tau}$ affects the probability amplitude and $\eta_{\mu\mu}$ shifts the oscillation peaks.

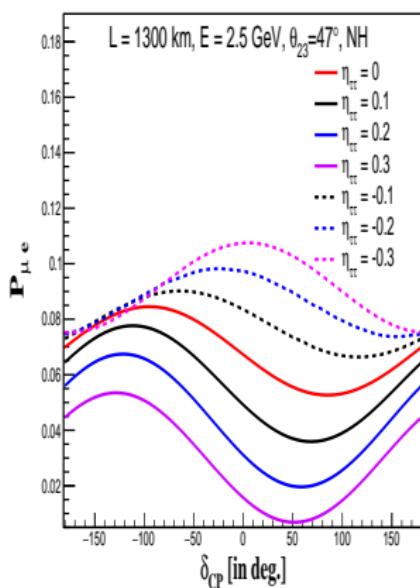
Results : $P_{\mu e}$ vs δ_{CP} with non zero $\eta_{ee}/\eta_{\mu\mu}/\eta_{\tau\tau}$



(a) $P_{\mu e}$ vs δ_{CP} for different η_{ee}



(b) $P_{\mu e}$ vs δ_{CP} for different $\eta_{\mu\mu}$

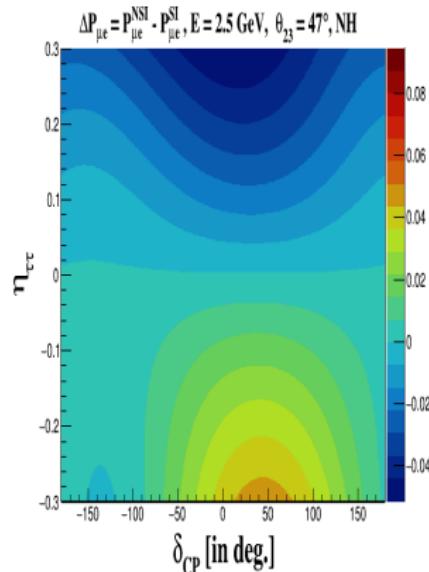
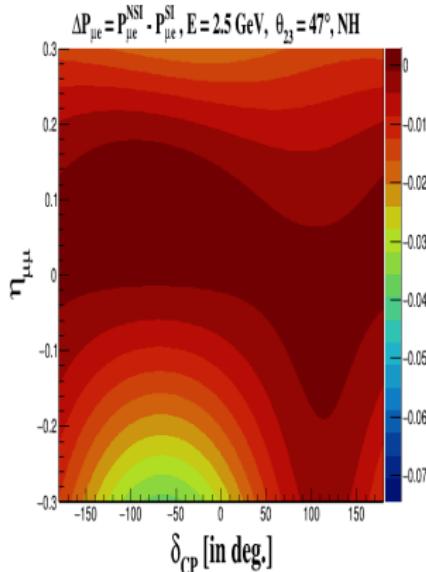
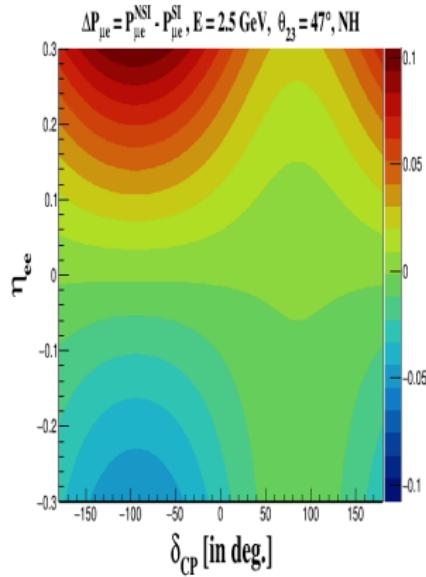


(b) $P_{\mu e}$ vs δ_{CP} for different $\eta_{\tau\tau}$

- Figures show the presence of various degeneracies with varied η and δ_{CP} values.

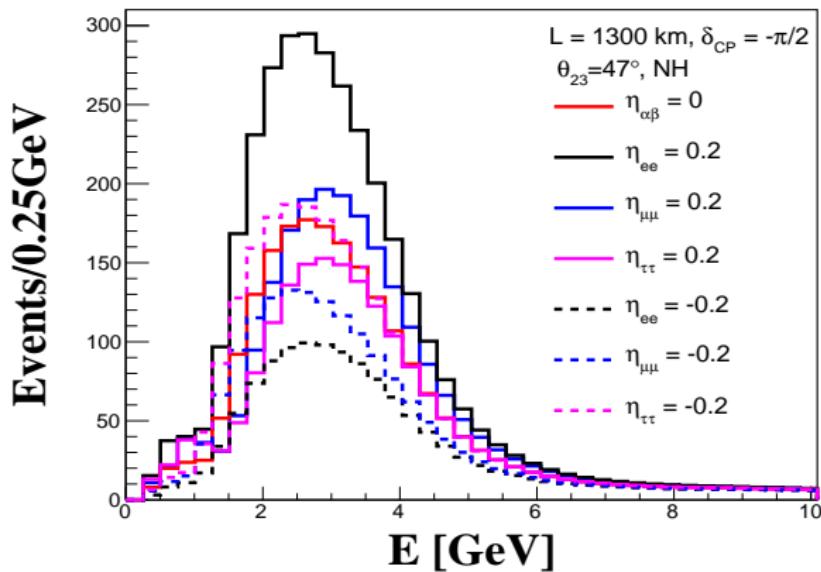
Results : $\Delta P_{\mu e}$ in δ_{CP} - $\eta_{\alpha\beta}$ plane

$$\Delta P_{\alpha\beta} = P_{\alpha\beta}(\text{with SNSI}) - P_{\alpha\beta}(\text{without SNSI})$$



- The impact of $\eta_{\mu\mu}$ is slightly milder as compared to η_{ee} and $\eta_{\tau\tau}$.

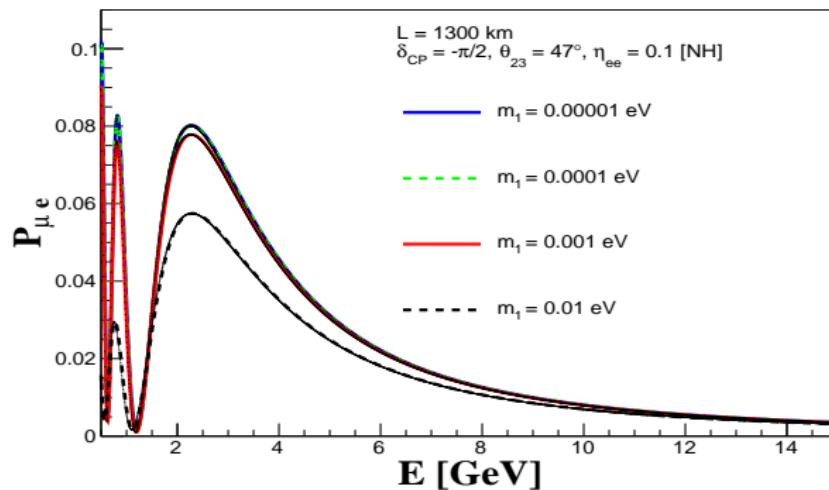
Results: Event rate in presence of scalar NSI



- The behavior of the binned events are in good agreement with the oscillation probabilities.

Results: $P_{\mu e}$ vs E for various test values of absolute ν -masses

- Scalar NSI brings in a dependence of ν -oscillations probability on the absolute ν -masses.



- Scalar NSI gives a possibility of probing it to various ν -mass models.

χ^2 -methodology

- We define the statistical χ^2 as,

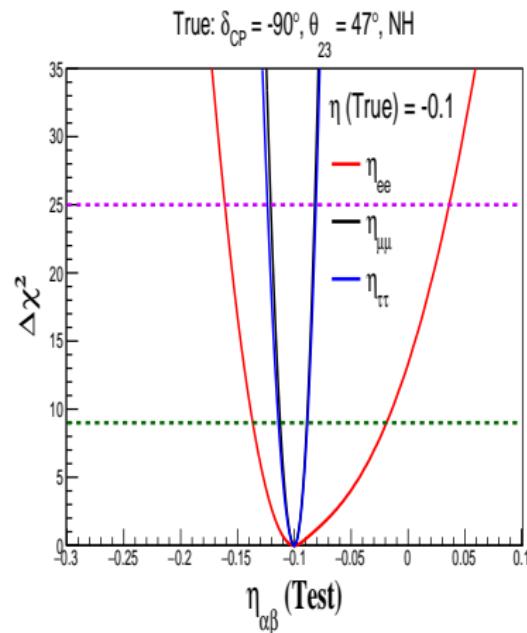
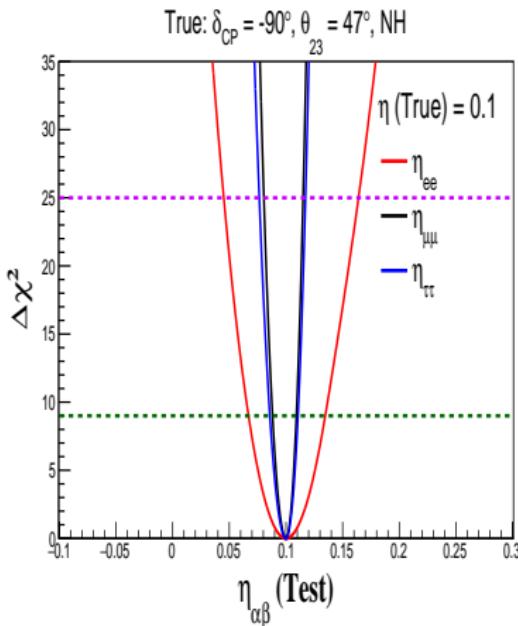
$$\Delta\chi^2 \equiv \min_{\eta} \sum_i \sum_j \frac{[N_{true}^{i,j}(\eta) - N_{test}^{i,j}(\eta)]^2}{N_{true}^{i,j}(\eta)}$$

$N_{true}^{i,j}$ ($N_{test}^{i,j}$) : number of true (test) events in the $\{i, j\}$ -th bin.

- This provides experiment's sensitivity towards distinguishing standard and non-standard effects.

Results : χ^2 vs test η elements

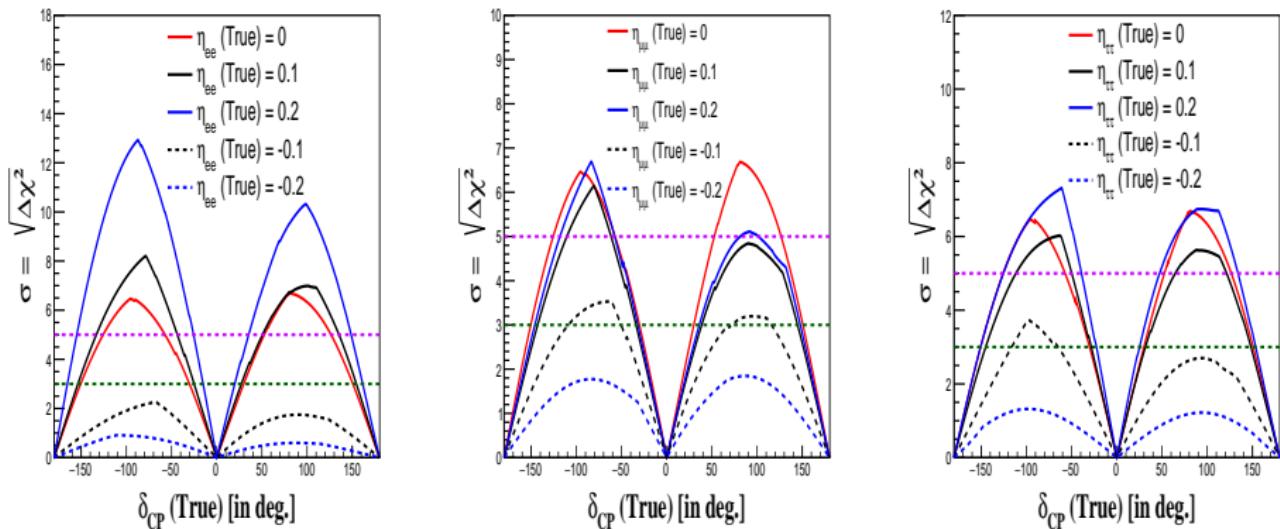
- DUNE: 5 years (ν) + 5 years ($\bar{\nu}$)



- Sensitivity towards constraining η_{ee} is less as compared to $\eta_{\mu\mu}$ or $\eta_{\tau\tau}$ cases.

Results : Effects on CP Violation sensitivity

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

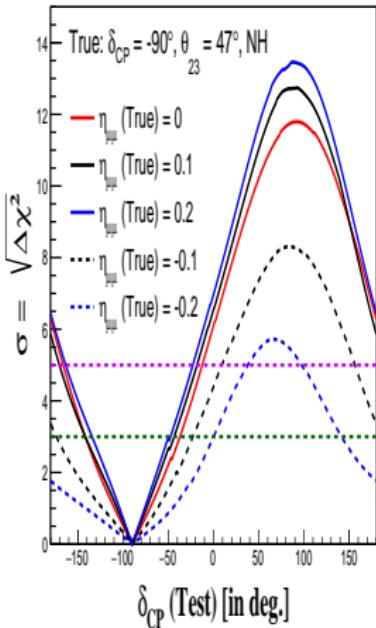
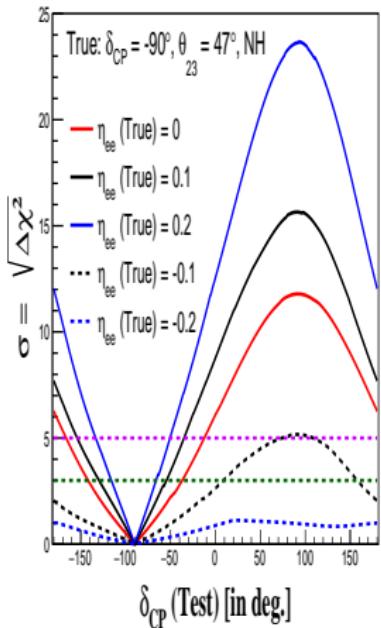


- Negative η deteriorates CP Violation sensitivity.

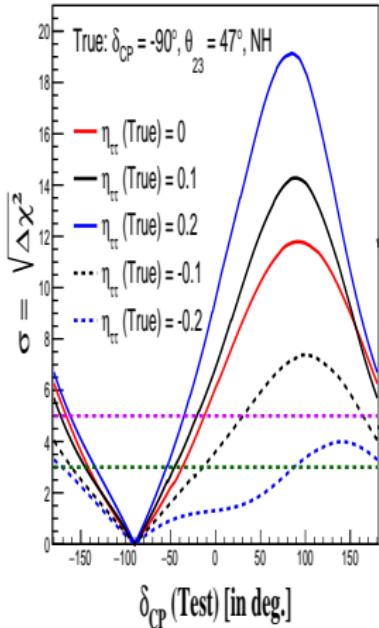
DUNE [5 (ν) + 5 ($\bar{\nu}$)]

Results : Effects on CP precision sensitivity

- True $\delta_{CP} = -90^\circ$



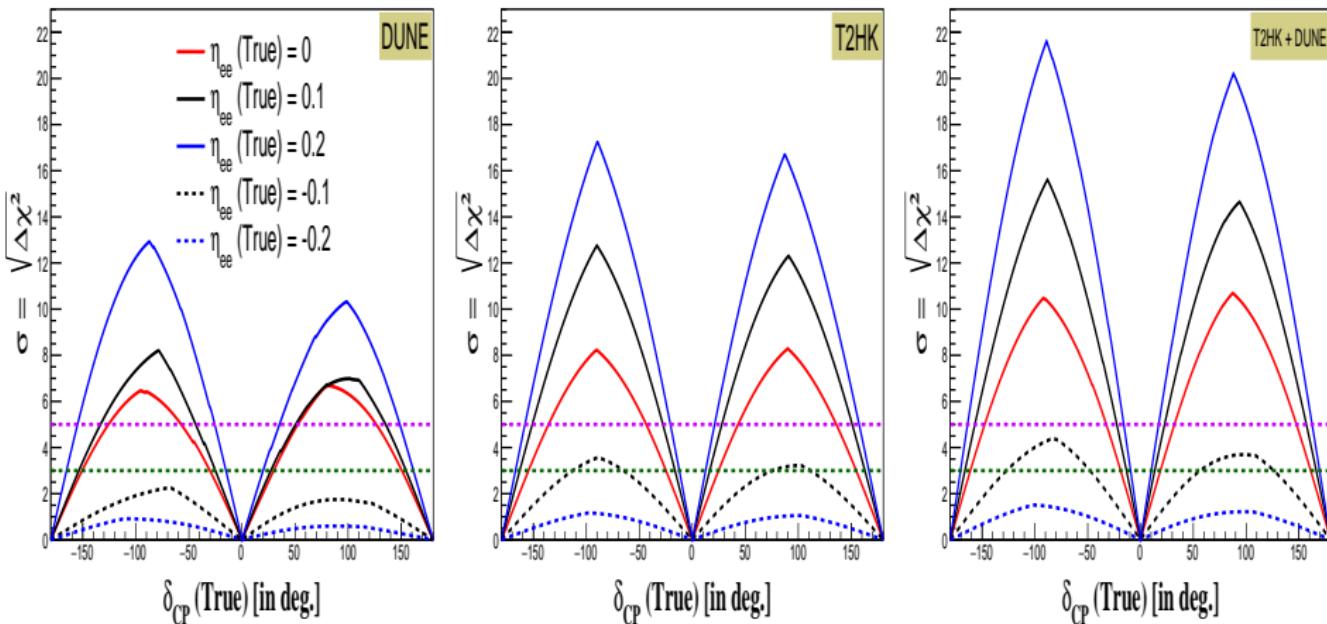
DUNE [5 (ν) + 5 ($\bar{\nu}$)]



- Positive (Negative) η enhances (deteriorates) CP precision sensitivity.

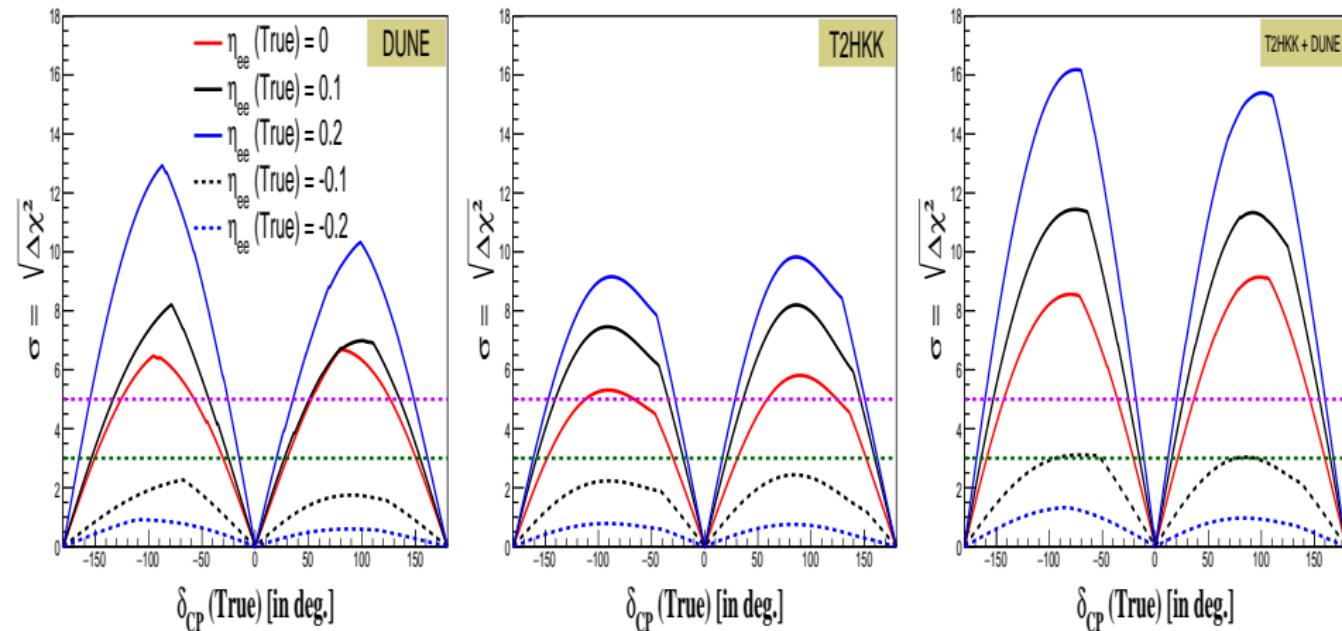
Synergy study with DUNE, T2HK, and T2HKK

Results : Effects on CP Violation sensitivity



- Negative η deteriorates CP Violation sensitivity.^{more}

Results : Effects on CP Violation sensitivity



- With T2HKK the sensitivities are better as compared to T2HK.

Concluding Remarks

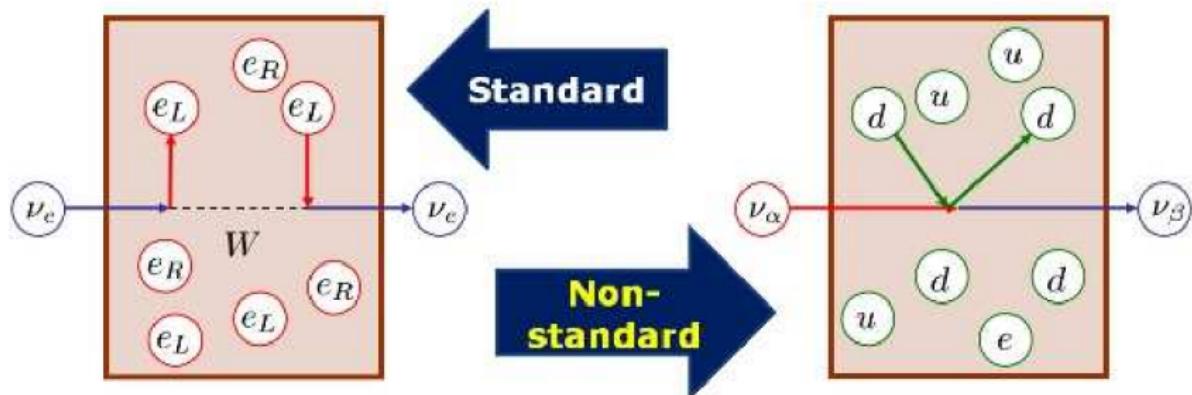
- Scalar NSI has a notable impact on the neutrino oscillations probabilities at LBL experiments.
- The CP sensitivity of DUNE gets spoiled in presence of scalar NSI.
- It is crucial to identify such subdominant effects of neutrino oscillations for accurate interpretation of data.
- A good window to study new physics beyond Standard Model (BSM).

Thank You for your kind attention !

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Back Up

Back up: Schematic representation



Schematic pictures of standard matter effects (left picture) and matter non-standard neutrino interactions (right picture).

Reference: DOI:10.1088/0034-4885/76/4/044201

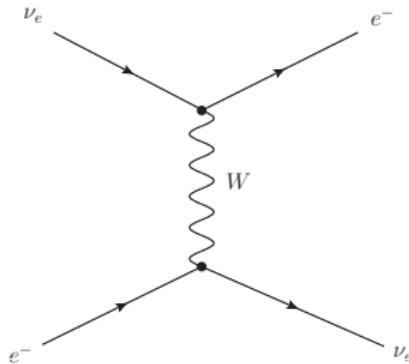
Back up

Baseline	1300 km
Target Mass	35 kton Liquid Argon TPC
Run time	5 years of ν mode and 5 years of $\bar{\nu}$ mode
Energy Window	0.375 GeV - 10.125 GeV
Profile type	single layer
Matter density	2.95 g/cm ³

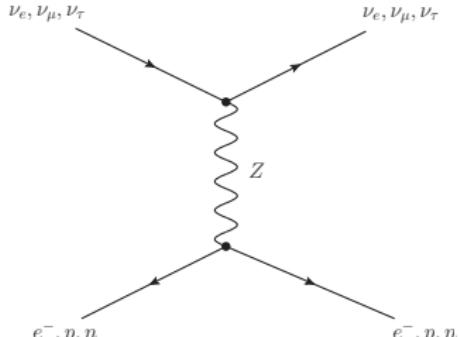
Table: Details of the detector configuration

Neutrino interaction with matter

- Neutrinos interact with matter via charged-current (CC) or neutral-current (NC) interactions.



(a) CC interactions
 $V_C = \pm \sqrt{2}G_F n_e$



(b) NC interactions
 $V_N = -\frac{G_F n_n}{\sqrt{2}}$

- Only ν_e participate in CC interactions.
- NC interactions are flavour blind.

return

Experimental set up

Experiment	Baseline (L in km)	Fiducial Volume (in kton)	Runtime
T2HK	295 km	187×2	$2.5 + 7.5$
T2HKK	295 km; 1100 km	$187(295 \text{ km}) + 187(1100 \text{ km})$	$2.5 + 7.5$
DUNE	1300 km	40	$5 + 5$

return