Probing scalar Non Standard Interactions at DUNE, T2HK, and T2HKK

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Outline

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 :

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

Where

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

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

Scalar Non Standard Interactions

- The Lagrangian of such interactions can be formulated as :

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

- The corresponding neutrino Hamiltonian modifies as:

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

where, δ 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

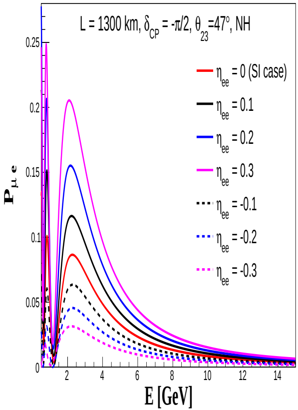
- The effect of scalar NSI can be parametrize as a 3×3 matrix :

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

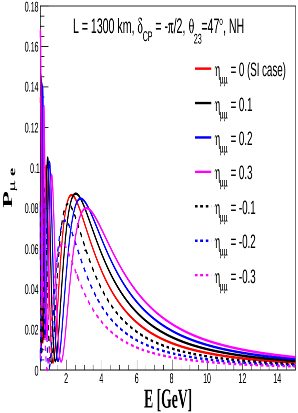
- $\eta_{\alpha\beta}$ elements are dimensionless and quantifies the size of scalar NSI.
- A framework is made with the modified Hamiltonian in GLoBES with different configuration of LBL experiments viz. DUNE, T2HK, and T2HKK.
- The values of mixing parameters used in the analysis :

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

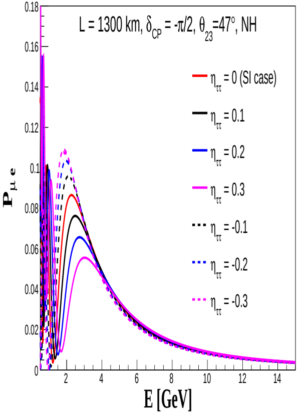
Results : $P_{\mu e}$ vs E with non zero $\eta_{ee}/\eta_{\mu\mu}/\eta_{\tau\tau}$



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



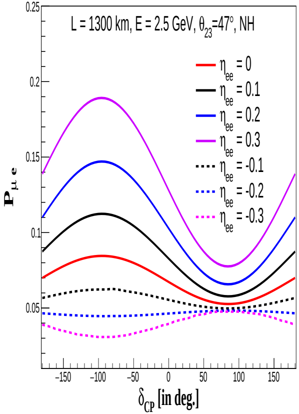
(b) $P_{\mu e}$ vs E for different $\eta_{\mu\mu}$



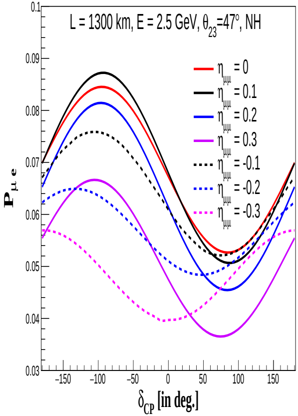
(b) $P_{\mu e}$ vs E for different $\eta_{\tau\tau}$

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

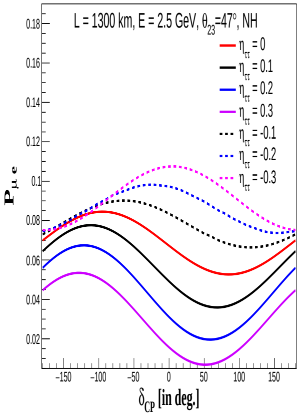
Results : $P_{\mu e}$ vs δ_{CP} with non zero $\eta_{ee}/\eta_{\mu\mu}/\eta_{\tau\tau}$



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



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

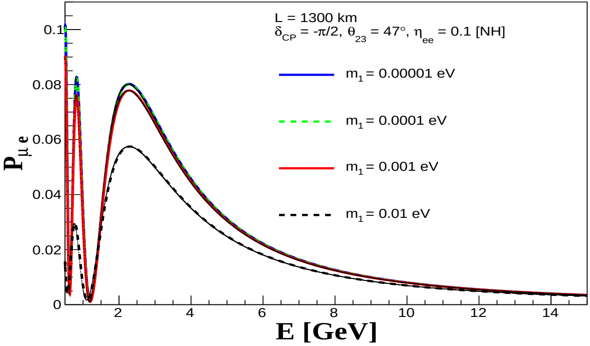


(b) $P_{\mu e}$ vs δ_{CP} for different $\eta_{\tau\tau}$

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

Results: $P_{\mu e}$ 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,

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

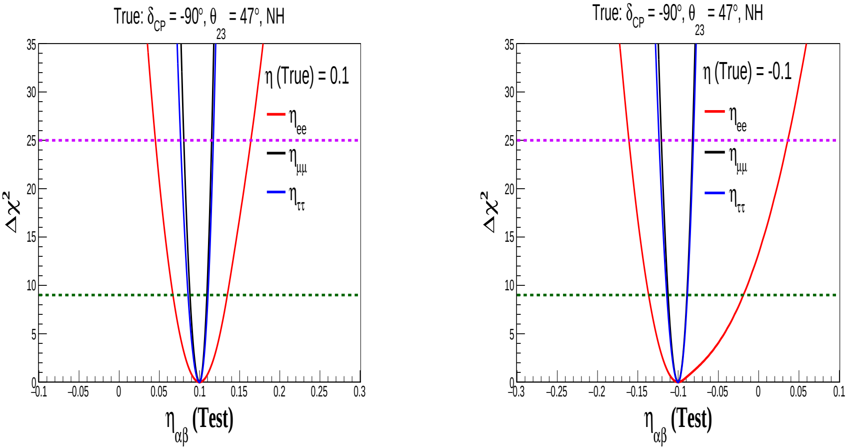
$N^{i,j}_{true}$ ($N^{i,j}_{test}$) : number of true (test) events in the $\{i, j\}$-th bin.

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

Huber, P., Lindner, M., Winter, W. Comput. Phys. Commun., (2005)

Results : χ^2 vs test η elements

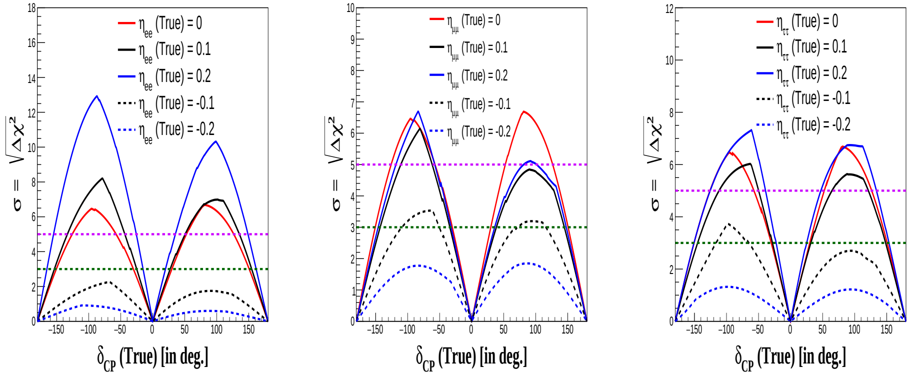
- DUNE: 5 years (ν) + 5 years ($\bar{\nu}$)



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

Results : Effects on CP Violation sensitivity

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



- Negative η deteriorates CP Violation sensitivity.

DUNE [5 (ν) + 5 ($\bar{\nu}$)]

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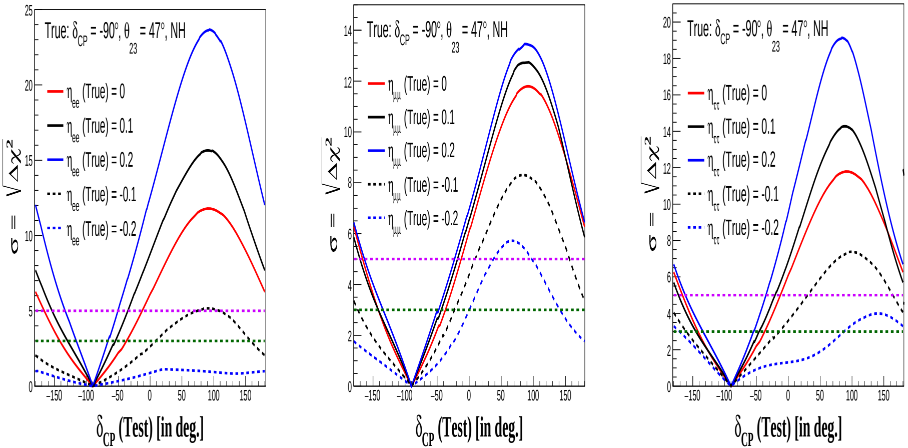
Results : Effects on CP precision sensitivity

- True δ_{CP} = -90°

DUNE [5 (ν) + 5 ($\bar{\nu}$)]



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

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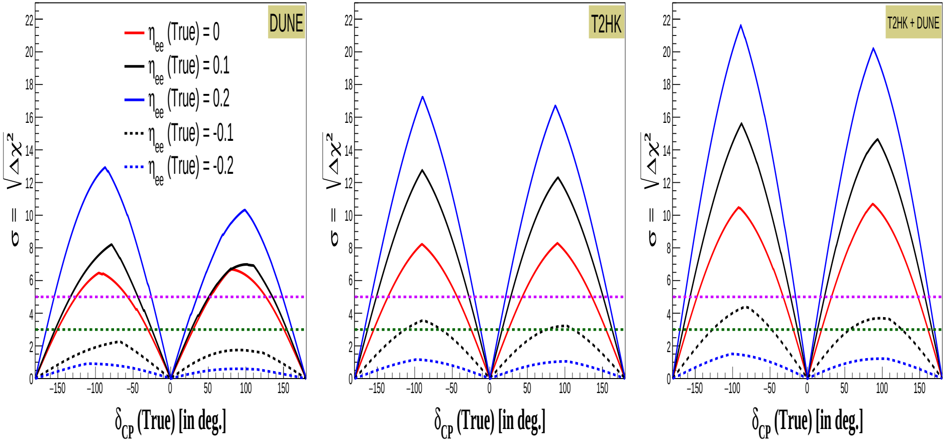
Synergy study with DUNE, T2HK, and T2HKK

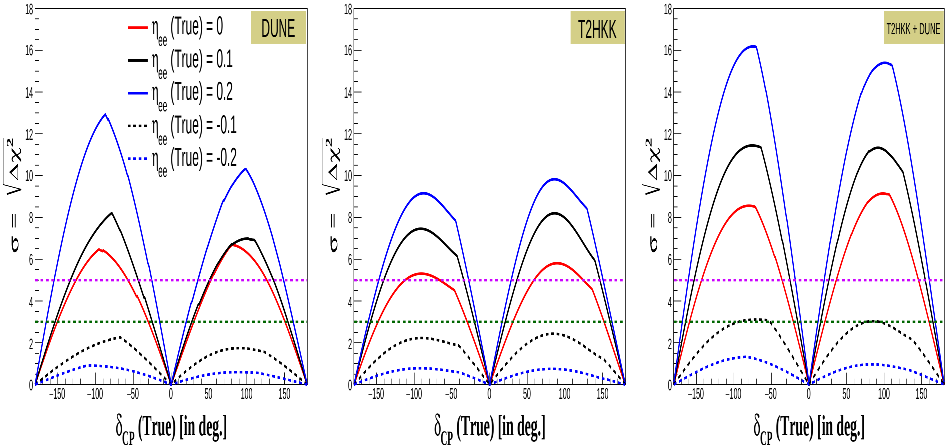
Results : Effects on CP Violation sensitivity



- Negative η deteriorates CP Violation sensitivity.more

Draft in preparation

Results : Effects on CP Violation sensitivity



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

Draft in preparation

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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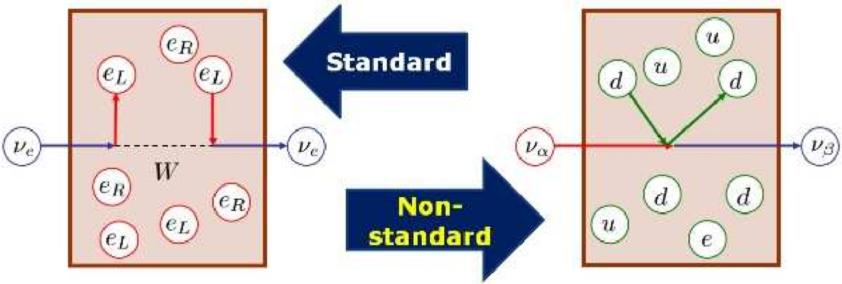
Back Up

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

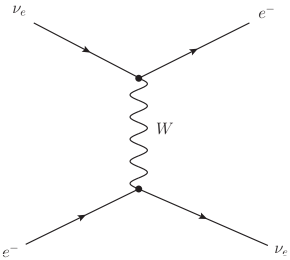
Back up

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

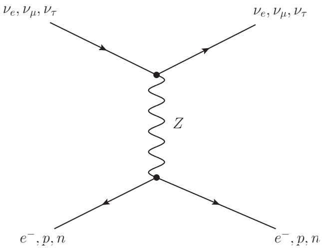
Neutrino interaction with matter

- 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 km) + 187(1100 km)	2.5 + 7.5
DUNE	1300 km	40	5 + 5

return