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Probing the effects of scalar Non Standard Interactions at Long Baseline Experiments

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Neutrino oscillations which essentially confirms neutrinos have non zero masses, is the first hint of physics beyond the Standard Model (SM). When neutrinos propagates through matter it interacts with the matter via weak interactions mediating a W or Z bosons. The study of Beyond Standard Model (BSM) physics often comes with some additional unknown coupling of neutrinos termed as non standard interactions(NSIs). Wolfenstein was the first to point out this type of NSIs of neutrinos with a vector field mediated by a vector boson namely vector NSI. There is also a possibility of neutrinos to couple with scalar field, which can offer rich phenomenology in neutrino oscillations. This scalar NSI effect the neutrino mass matrix instead of appearing as a matter potential, which makes its effect interesting to probe it further.

In this work, we have explored the effect of scalar NSI at Long Baseline (LBL) Experiment (DUNE). We found that the diagonal elements of scalar NSI matrix can have a significant impact on the oscillation probabilities of DUNE. Also, as it perturbs the neutrino mass term it can fake the CP effect in LBL experiments. As the mass correction due o scalar NSI scales linearly with the matter density scalar NSI can sense the matter density variation and LBL experiments are an excellent candidate to probe it. We found that indeed the impact of scalar NSI on LBL experiments is notable and it needs further exploration to put some constrain on the scalar NSI parameters.

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1. Introduction

The experimental observation of the phenomena of neutrino oscillations have provided a clear hint of physics beyond the Standard Model (SM). In spite of being the most successfully gauge theory, which has been tested rigorously in several experiments, SM needs an extension to accommodate the masses and mixing of neutrinos. Usually these extensions leads to some unknown coupling of neutrinos which are not incorporated by SM. These new interactions are termed as non standard interactions (NSIs). The idea of NSI was initially introduced in [1] where the authors discussed NSI may come in neutrino interactions from a vector mediated coupling. Later, the effects has been widely studied [2] in different experiments and it has been a well motivated approach to probe new physics in different neutrino experiments. It has been observed that the effects NSI is highly significant and constraining the NSI parameters are extremely crucial for understanding the results from various experiments. A global constrain on these parameters can be found in ref [2].

The non standard coupling neutrinos with a scalar is also an interesting prospect to study NSI [3]. These scalar type NSIs directly impact the neutrino mass matrix instead of adding as a matter potential term. So, it may impact the neutrino propagation differently than vector mediated NSIs. Hence, scalar NSI may impact the sensitivities of different neutrino experiments [6] differently. Moreover, the effects of scalar NSI is energy independent and it directly scales with the environmental matter density. This makes long baseline (LBL) experiments one of the suitable candidates to probe its effects. In this work we have studied the effects of scalar NSI on the LBL experiments taking DUNE [4] as a case study.

2. Scalar NSI

The coupling of neutrinos with a scalar is an interesting sector to probe NSI in neutrino oscillations. The Lagrangian for these types of coupling may be framed as,

$$\mathcal{L}_{\text{eff}}^{\text{S}} = \frac{y_f y_{\alpha\beta}}{m_\phi^2} (\bar{\nu}_\alpha(p_3)\nu_\beta(p_2))(\bar{f}(p_1)f(p_4)) \,. \tag{1}$$

Where, the subscript α, β refer to the neutrino flavours, f indicate the environmental matter fermions, and $\bar{f}$ is for corresponding anti fermions, $y_{\alpha\beta}$ is the Yukawa couplings of the neutrinos with the scalar mediator, ϕ, y_f is the Yukawa coupling of the mediator with the environmental fermions, and m_ϕ is the mass of the scalar mediator.

Here, the Lagrangian is composed of Yukawa terms and hence it can not be converted to vector currents unlike the vector mediated NSIs. As a result the effect of scalar NSI appears as a medium dependent correction to the neutrino mass matrix. The effective Hamiltonian in presence of scalar NSI can be formalised as,

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

Here, $\delta M \equiv \sum_f n_f y_f y_{\alpha\beta}/m_\phi^2$, where, n_f is the number density of the environmental fermions,

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$V_{SI} = \sqrt{2} G_F n_e$ is the matter potential due to charge current (CC) interactions of neutrinos. The scalar NSI matrix (δM) may be parameterized as,

$$\delta M \equiv \sqrt{\Delta m^2_{31}} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{pmatrix}, \quad (3)$$

where, $\eta_{\alpha\beta}$ are dimensionless parameters and it quantifies the size of the scalar NSI. Also, the hermicity of the neutrino Hamiltonian requires the diagonal elements to be real and the off-diagonal elements to be complex, which is represents as $\eta_{\alpha\beta} = |\eta_{\alpha\beta}| e^{i\phi_{\alpha\beta}}; \quad \alpha \neq \beta.$

3. Methodology

In this work we have considered the diagonal terms of NSI matrix to study the effects of scalar NSI at DUNE. First, we have studied its impact on the oscillation probabilities. The mixing parameter values used throughout the analysis are listed in Table 1. In Figure 1 and Figure 2, the

$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	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}

Table 1: Benchmark values of oscillation parameters.

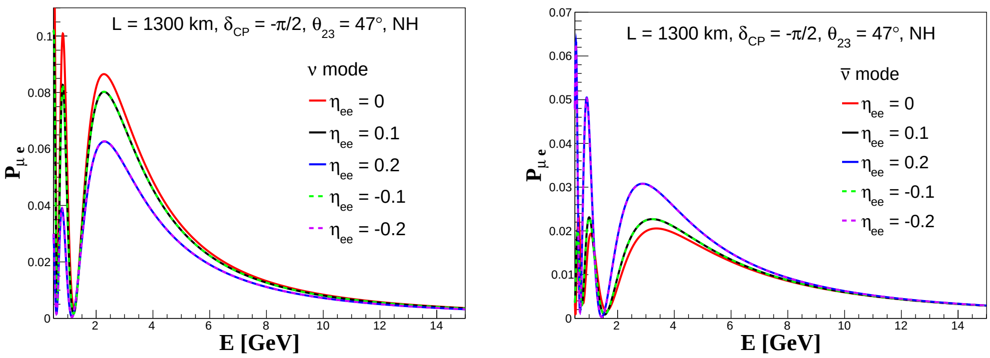

Figure 1: The effect of the scalar NSI element, η_{ee} on neutrino appearance probabilities ($P_{\mu e}$). The left (right) plot is for neutrino (antineutrino) case for fixed δ_{CP} = -π/2 and $\theta_{23} = 47°$.

effects of scalar NSI on the oscillation probability is shown for non zero η_{ee} and $\eta_{\mu\mu}$ respectively. The left (right) plot is for neutrino (antineutrino) case for both the figures. For neutrino case with increasing values of η_{ee} ($\eta_{\mu\mu}$ probability is suppressed (enhanced) around the oscillation maxima. Whereas for antineutrino case with increasing values of η_{ee} ($\eta_{\mu\mu}$ probability is enhanced (suppressed) around the oscillation maxima.

To check whether DUNE can distinguish between the CP conserving ($\delta_{CP} = 0, \pi$) and CP violating values ($\delta_{CP} \neq 0, \pi$), we have defined the χ^2 function as follows to check its CP violation sensitivity,

$$\chi^2 \equiv \min_{\eta} \sum_i \sum_j \frac{\left[N^{i,j}_{true} - N^{i,j}_{test}\right]^2}{N^{i,j}_{true}}, \quad (4)$$

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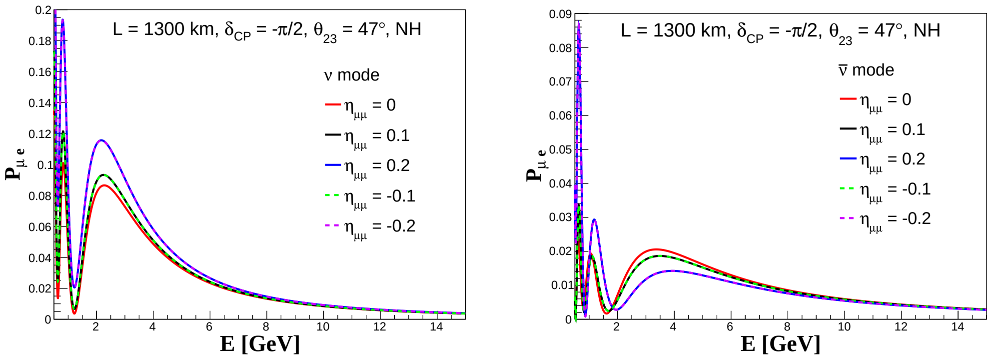

Figure 2: The effect of the scalar NSI element, $\eta_{\mu\mu}$ on neutrino appearance probabilities ($P_{\mu e}$). The left (right) plot is for neutrino (antineutrino) case for fixed δ_{CP} = $-\pi/2$ and θ_{23} = 47°.

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. We have used GLOBES [5] package to simulate our experiment. To probe the effects of scalar NSI we modified the Hamiltonain (Equation 2) accordingly to incorporate scalar NSI. The details of the experimental configuration and the systematic uncertainties taken in our simulations are listed in Table 2.

Detector details	Normalisation error		Energy calibration error	
	Signal	Background	Signal	Background
Baseline = 1300 km Runtime (yr) = 5 ν + 5 $\bar{\nu}$ 35 kton, LArTPC ε_{app} = 80%, ε_{dis} = 85% $R_e = 0.15/\sqrt{E}$, $R_\mu = 0.20/\sqrt{E}$	ν_e : 5% ν_μ : 5%	ν_e : 10% ν_μ : 10%	ν_e : 5% ν_μ : 5%	ν_e : 5% ν_μ : 5%

Table 2: Details of detector configurations, efficiencies, resolutions, and systematic uncertainties for DUNE.

4. Result and Discussion

Figure 3 shows the CP violation (CPV) sensitivities of DUNE in presence of scalar NSI. The left (right) plot represents the impact of scalar NSI on the CPV sensitivities in presence of non zero η_{ee} ($\eta_{\mu\mu}$) element. The solid red line is for SI case whereas other colours are for cases with NSI elements. It is observed that, η_{ee} suppresses the sensitivities whereas $\eta_{\mu\mu}$ enhances the CPV sensitivities of DUNE. In Figure 4 the CP precision measurement capability of DUNE in presence of scalar NSI is shown. The left (right) plot represents the cases with non zero η_{ee} ($\eta_{\mu\mu}$) element. The true value of the δ_{CP} is kept fixed at -90°. It is observed that in presence of η_{ee} the experiment's capability to constrain the δ_{CP} phase degrades as compared to the $\eta_{\mu\mu}$. With increasing values of $\eta_{\mu\mu}$ the precision measurement capability improves for DUNE.

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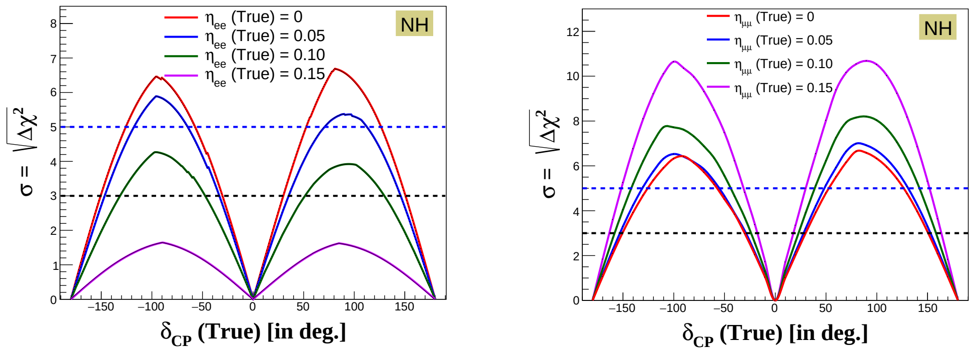

Figure 3: The plot represents CP violation sensitivity in presence of scalar NSI. The left (right) plot is for non zero η_{ee} ($\eta_{\mu\mu}$ case.

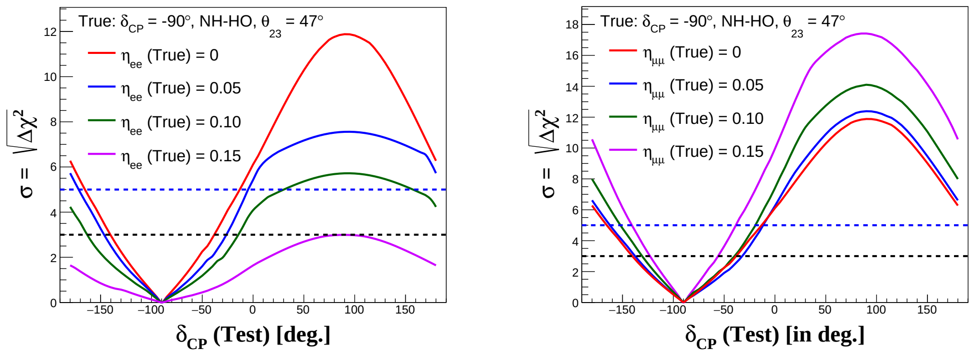

Figure 4: CP precision measurement in presence of diagonal scalar NSI element for true δ_{CP} = -π/2 and true θ_{23} = 47°. The left (right) plot is for non zero η_{ee} ($\eta_{\mu\mu}$) case.

5. Concluding Remarks

Currently, we are in the precision era of neutrino physics where the oscillation parameters are being measured with utmost accuracy. Looking at the precision of different ongoing and future LBL experiments it is equally important to study the impact of subdominant effects like NSIs on these experiments. In this study we found that the impact of scalar NSI on the oscillation probabilities is notable. Moreover, scalar NSI also effects the CP violation as well as CP precision measurement capability of DUNE significantly. Hence, a combined global analysis of all the LBL experiments is necessary to put some constrain on these scalar NSI parameters, which may improves the understanding of results from different neutrino experiments.

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