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Exploring the impact of LIV at Deep Underground Neutrino Experiment

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Lorentz Invariance Violation (LIV) is a fundamental violation of space-time symmetry, implying that physical laws vary under Lorentz transformation. The neutrinos are weakly interacting fundamental particles which can act as a probe for understanding the violation of Lorentz invariance symmetry. Here, we consider intrinsic LIV effects that can exist even in a vacuum. We use an effective field theory known as Standard Model Extension (SME) as a framework to treat the LIV as a small perturbation to the standard matter Hamiltonian. The effective Hamiltonian can be implemented to investigate how the presence of LIV parameters modifies the neutrino oscillation probabilities. We particularly study the effect of CPT-Violating LIV terms on the mass-induced neutrino oscillations. In this work, we explore the impact of LIV on neutrino oscillation probabilities in matter taking DUNE as a case study. We observe a significant effect on neutrino oscillations in the presence of a non-zero LIV parameter. We further investigate the impact of LIV parameters on the CP-measurement sensitivity at DUNE.

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1. Introduction

Neutrinos (ν's) interact with matter particles through weak interactions. The phenomenon of neutrino oscillations cannot be explained within the Standard Model (SM) framework as ν's are massless particles in SM. Therefore, ν-oscillations lead us to physics beyond the Standard Model (BSM). The major obstacles in neutrino physics are the precise measurements of CP-Violation in the leptonic sector, the determination of mass hierarchy of neutrinos and the octant of θ_{23}. The presence of non-standard effects like Lorentz invariance violation (LIV) and non-standard interactions (NSI) has the potential to affect the sensitivity of different ν-oscillation experiments in various measurements. Hence, it is important to quantify the impact of such sub-dominant effects on ν-oscillation probabilities.

Lorentz invariance is a fundamental symmetry that indicates the invariance under the Lorentz transformations. The breakdown of space-time symmetry can lead to a violation of Lorentz symmetry. The Charge-Parity-Time Reversal (CPT) symmetry violation may lead to LIV as shown in [1]. As neutrino oscillations are a sensitive interference phenomenon, the sub-dominant effect of LIV can be explored using long-baseline neutrino oscillation experiments. It should be noted that LIV is intrinsic and can exist even in a vacuum. The presence of LIV can be incorporated using the Standard Model Extension (SME) framework that treats LIV as a sub-dominant effect on ν-oscillations. In this work, we have focused on exploring the effects of LIV on long-baseline (LBL) ν experiments taking the DUNE experiment [2] as a test case.

2. Formalism

In SM, the ν's interact with matter particles via charge-current and neutral-current weak interactions, where the standard Hamiltonian can be written as,

$$\begin{aligned} H_{SI} &= H_\nu + H_m \\ &= \frac{1}{2E} U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger + \sqrt{2} G_f N_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \end{aligned} \tag{1}$$

where, H_ν is the vacuum Hamiltonian, H_m is matter potential and U is the PMNS mixing matrix [5, 6]. A time-dependent perturbation theory can be used to describe Lorentz symmetry violation in ν-oscillations as shown in [3, 4]. In the neutrino sector, the effects of LIV can be incorporated as a small perturbation to H_{SI} by following the minimal Standard Model Extension framework (SME) [7]. The effective Hamiltonian in the presence of LIV can be framed as [8],

$$\begin{aligned} H_{eff} &= H_{SI} + \left[H_{LIV}^{CPT-} + H_{LIV}^{CPT+} \right], \\ &= H_{SI} + \left[\begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a_{e\mu}^* & a_{\mu\mu} & a_{\mu\tau} \\ a_{e\tau}^* & a_{\mu\tau}^* & a_{\tau\tau} \end{pmatrix} - \frac{4}{3} E \begin{pmatrix} c_{ee} & c_{e\mu} & c_{e\tau} \\ c_{e\mu}^* & c_{\mu\mu} & c_{\mu\tau} \\ c_{e\tau}^* & c_{\mu\tau}^* & c_{\tau\tau} \end{pmatrix} \right]. \end{aligned} \tag{2}$$

The $H_{LIV}^{CPT_-}$ and $H_{LIV}^{CPT_+}$ matrix corresponds to the CPT-odd and CPT-even contributions where, $a_{\alpha\beta}$ are CPT-odd and $c_{\alpha\beta}$ are CPT-even parameters. The standard Sun-centered celestial equatorial

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frame is taken as the reference frame as it is roughly inertial over the run time of most earth-based experiments [9, 10]. These parameters will quantify the effects of LIV on oscillation probabilities. From equation 2, we observe that LIV can be present due to CPT-odd/CPT-even parameters. In this work, we have focused on the off-diagonal CPT-odd LIV elements, $a_{\alpha\beta} = |a_{\alpha\beta}|e^{i\phi_{\alpha\beta}}$. We explore the effect of $a_{\alpha\beta}$ on the neutrino oscillation probabilities and study its impact on the CP-Violation and CP-Precision sensitivity at DUNE [13].

3. Methodology

In this work, we explore the impact of off-diagonal LIV parameters on the ν-oscillation probabilities, by taking the normal mass ordering as the true ordering. We have used the GLoBES [11] framework to implement the effective LIV Hamiltonian for the DUNE experiment. The values of ν-mixing parameters used for this study are tabulated in 1.

Parameters	Values	Parameters	Values
$\theta_{12}[°]$	34.51	$L[km]$	1300
$\theta_{13}[°]$	8.44	δ_{CP}	$-\pi/2$
$\theta_{23}[°]$	47	Hierarchy	Normal
$\triangle m^2_{21}\ [10^{-5}eV^2]$	7.56	$\triangle m^2_{31}\ [10^{-3}eV^2]$	2.55

Table 1: The values of ν-mixing parameters that are used for GLoBES simulation [12].

In order to quantify the CP-measurement sensitivity at DUNE, we define a statistical χ^2 as,

$$\chi^2 \equiv \min_{\eta} \sum_i \sum_j \frac{\left[N^{i,j}_{true} - N^{i,j}_{test}\right]^2}{N^{i,j}_{true}}, \tag{3}$$

where, $N^{i,j}_{true}$ and $N^{i,j}_{test}$ represents the count of true and test events in the $\{i, j\}$-th bin respectively. This helps in quantifying the experiment's capability of distinguishing between CP-conserving and CP-violating values.

4. Results and Discussion

In this subsection 4.1, we first explore the effect of $a_{\alpha\beta}$ and $\phi_{\alpha\beta}$ on the appearance ($P_{\mu e}$) & disappearance ($P_{\mu\mu}$) probabilities for DUNE). We then study the impact of $a_{\alpha\beta}$ on $P_{\mu e}$ and $P_{\mu\mu}$ for varying δ_{CP}. In subsections 4.2 and 4.3, we study the impact of $a_{\alpha\beta}$ on CP-Violation and CP-Precision sensitivities at DUNE.

4.1 Effect of LIV on ν-oscillation probabilities

In Figure 1, we have plotted $P_{\mu e}$ and $P_{\mu\mu}$ for the LIV parameters $a_{e\mu}$, $a_{e\tau}$ and $a_{\mu\tau}$ respectively by varying energy in the range 0.5-10GeV. The red (black) line represents the $a_{\alpha\beta} = 2, \phi_{\alpha\beta} = 0$ case (SI case). The grey band represents the variation of LIV phase $\phi_{\alpha\beta} \in [-\pi, \pi]$. The parameters $a_{e\mu}$, $a_{e\tau}$ and $a_{\mu\tau}$ have the most impact on the ν-oscillation probabilities. In presence of $a_{e\mu}$, the

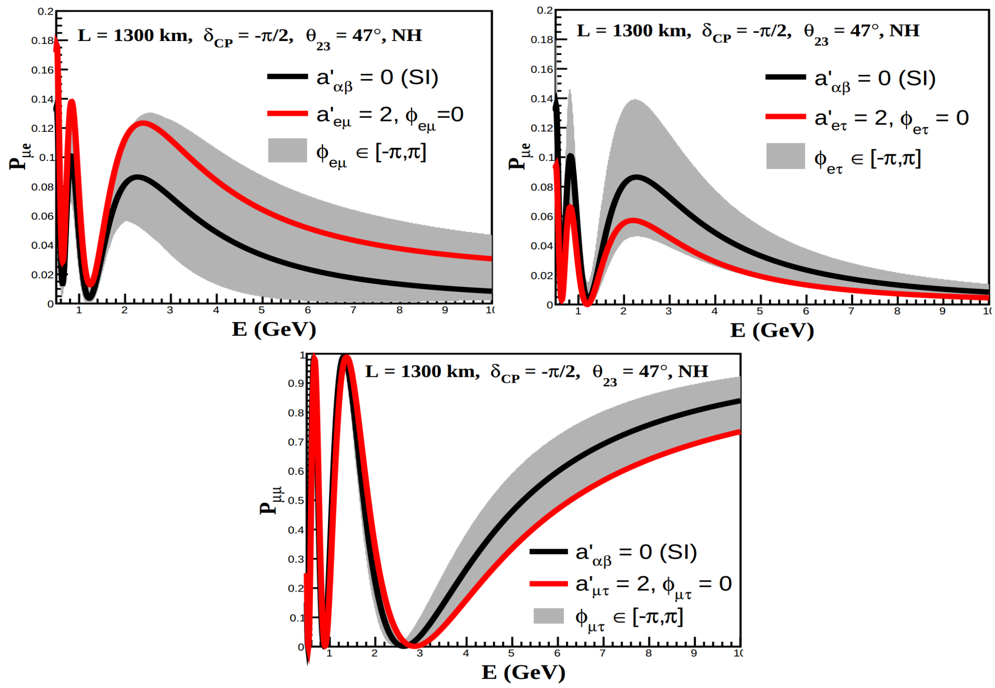

Figure 1: Effect of LIV on $P_{\mu e}$ & $P_{\mu\mu}$ in presence of $a_{e\mu}$(top-left), $a_{e\tau}$(top-right) and $a_{\mu\tau}$(bottom).

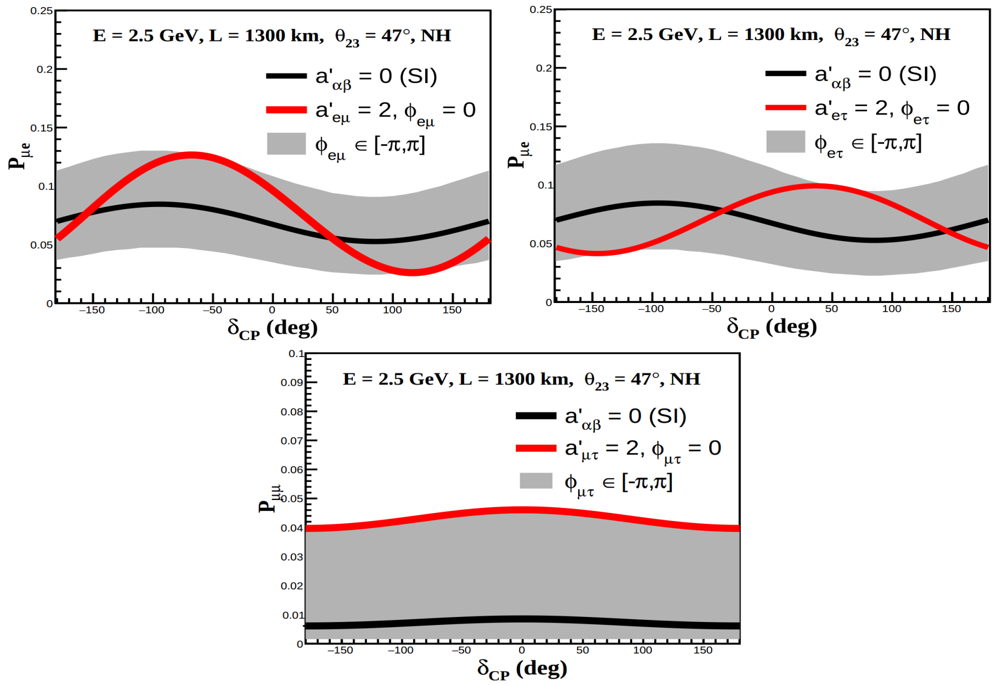

Figure 2: Effects of LIV $a_{e\mu}$(top-left), $a_{e\tau}$(top-right) and $a_{\mu\tau}$(bottom) for varying δ_{CP}.

appearance probabilities get enhanced for energies beyond the second oscillation peak. However, the presence of corresponding LIV phase $\phi_{e\mu}$ can suppress the probability values. For $a_{e\tau}$, a suppression of $P_{\mu e}$ can be seen at higher energies. We also see that the effect of $a_{e\mu}$ and $a_{e\tau}$ are complimentary to each other. And the presence of an off-diagonal phase can significantly affect the ν-oscillation probabilities.

In Figure 2, we study the effects of $a_{\alpha\beta}$ on ν-oscillation probabilities for a varying δ_{CP} value. We have plotted the oscillation probabilities for the complete δ_{CP} space i.e. $[-\pi, \pi]$. The red (black) line represents the $a_{\alpha\beta} = 2, \phi_{\alpha\beta} = 0$ case (SI case). The grey band represents the variation of LIV phase $\phi_{\alpha\beta} \in [-\pi, \pi]$. We see that for all the off-diagonal parameters $a_{\alpha\beta}$ the enhancement/suppression of oscillation probabilities depends majorly on the $\delta_{CP} - \phi_{\alpha\beta}$ combinations. We also note that $\phi_{\alpha\beta}$ may bring degeneracy in the measurement of δ_{CP}.

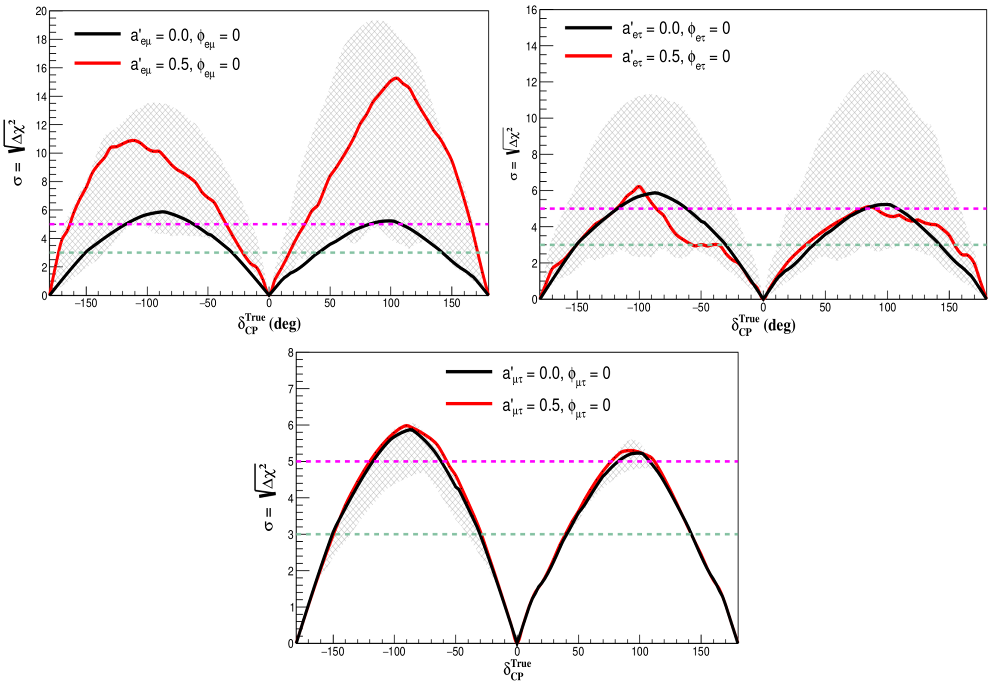

Figure 3: CP-Violation Sensitivities for $a_{e\mu}$(top-left), $a_{e\tau}$(top-right) and $a_{\mu\tau}$(bottom) at DUNE.

4.2 Impact of LIV on CP-Violation Sensitivities

In Figure 3, we have studied the effects of off-diagonal parameters $a_{\alpha\beta}$ on the CP-Violation sensitivities at DUNE. The red (black) line implies the $a_{\alpha\beta} = 2, \phi_{\alpha\beta} = 0$ case (SI case). In all panels, the grey region represents the effects of varying LIV phase $\phi_{\alpha\beta} \in [-\pi, \pi]$. It can be seen that the presence of $\phi_{\alpha\beta}$ may bring degeneracy in δ_{CP}-measurement. In presence of $a_{e\mu}$ & $a_{e\tau}$, sensitivity depends on the combinations of $\phi_{\alpha\beta}$ and $a_{\alpha\beta}$. For non-zero $\phi_{\mu\tau}$, the sensitivity deteriorates in the presence of $a_{\mu\tau}$.

4.3 Impact of LIV on CP-Precision Sensitivities

In Figure 4, we study the δ_{CP} constraining capability of DUNE given that the true δ_{CP} value is known. In presence of $a_{e\mu}$, $\phi_{e\mu}$ dependent enhancement/suppression is seen. For $a_{e\tau}$ with $\phi_{e\tau} = 0$, the sensitivity is at base of the grey region. For some values of $\phi_{e\tau}$, an enhancement in the CP-Precision sensitivities can be seen. The effect on sensitivities for $a_{\mu\tau}$ is nominal, though the presence of phase can lead to an enhancement.

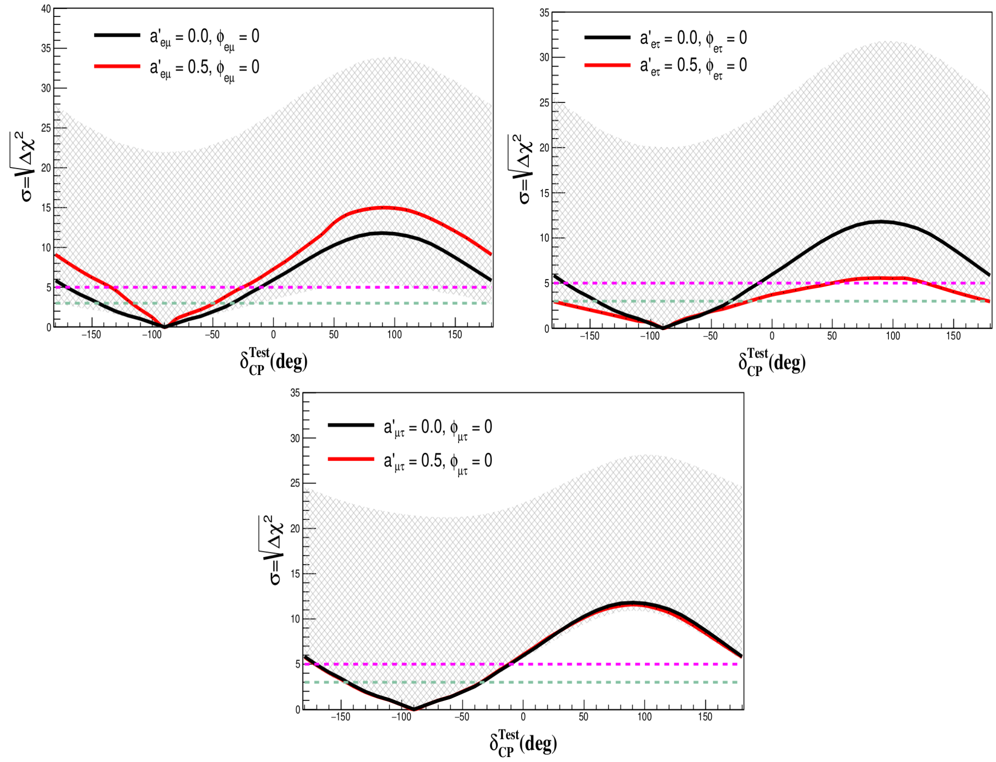

Figure 4: CP-Precision Sensitivities for $a_{e\mu}$(top- left), $a_{e\tau}$(top-right) and $a_{\mu\tau}$(bottom) at DUNE.

5. Conclusion

The different ongoing and upcoming LBL ν-oscillation experiments are focused on the precise measurements of ν-oscillation parameters with utmost accuracy. The study of sub-dominant effects like LIV is very important as it can affect the measurement capabilities of such experiments. We find that LIV can significantly modify the ν-oscillation probabilities. We also see that it can enhance/suppress the CP measurement capabilities at DUNE.

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