Impact of Lorentz Invariance Violation at DUNE

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Arnab Sarker[a], Abinash Medhi[b], **Moon Moon Devi**[c]

Department of Physics, Tezpur University, India, Email:[c] devimm@tezu.ernet.in,

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Abstract

Neutrinos are fundamental particles that can act as a probe for exploring violations of fundamental symmetries such as Lorentz Invariance. Lorentz symmetry breaking is a fundamental violation of space-time symmetry which implies that physical laws vary under Lorentz transformation.

In this work, we explore the impact of LIV parameters on the neutrino oscillation probabilities, particularly the oscillation channel $P_{\mu e}$ which is the most significant channel for DUNE.

1. Introduction

- Oscillation of $\nu's$ provides strong evidence for non-zero ν-mass.
- Lorentz Invariance is a space-time symmetry. All physical laws are invariant under Lorentz transformations.
- ν-Oscillation (BSM physics) $\rightarrow$ A possible way to probe LIV. The LIV Effect considered is inherent in nature, and its effects will be noticeable even in a vacuum.
- LIV effect treated as a perturbation to the standard Hamiltonian. Most Prominent Contribution to $P_{\alpha\beta}$.
  - $\boldsymbol{P_{\mu e}}$ oscillation channel is affected mostly by the LIV parameters $\boldsymbol{a_{ee}}$, $\boldsymbol{a_{e\mu}}$ and $\boldsymbol{a_{e\tau}}$.
  - Contribution to $\boldsymbol{P_{\mu\mu}}$ oscillation channel is maximum for the LIV parameters $\boldsymbol{a_{\mu\mu}}$, $\boldsymbol{a_{\tau\tau}}$ and $\boldsymbol{a_{\mu\tau}}$.
- CPT Violation is closely related to LIV. LBL experiments may be able to probe such effects through ν-oscillations.

3. Impact of LIV on $P_{\mu e}$ and $P_{\mu\mu}$

Parameters	Values	Parameters	Values
θ_{12}	34.51°	L	1300 km
θ_{13}	8.44°	δ_{CP}	-90°
θ_{23}	47°	Hierarchy	Normal
$\triangle m^2_{12}$	$7.56\times10^{-5}eV^2$	Density	2.8g/cm3
$\triangle m^2_{13}$	$2.55\times10^{-3}eV^2$		

a) Variation of $P_{\mu e}$ in the presence of a_{ee}, $a_{e\mu}$ and $a_{e\tau}$

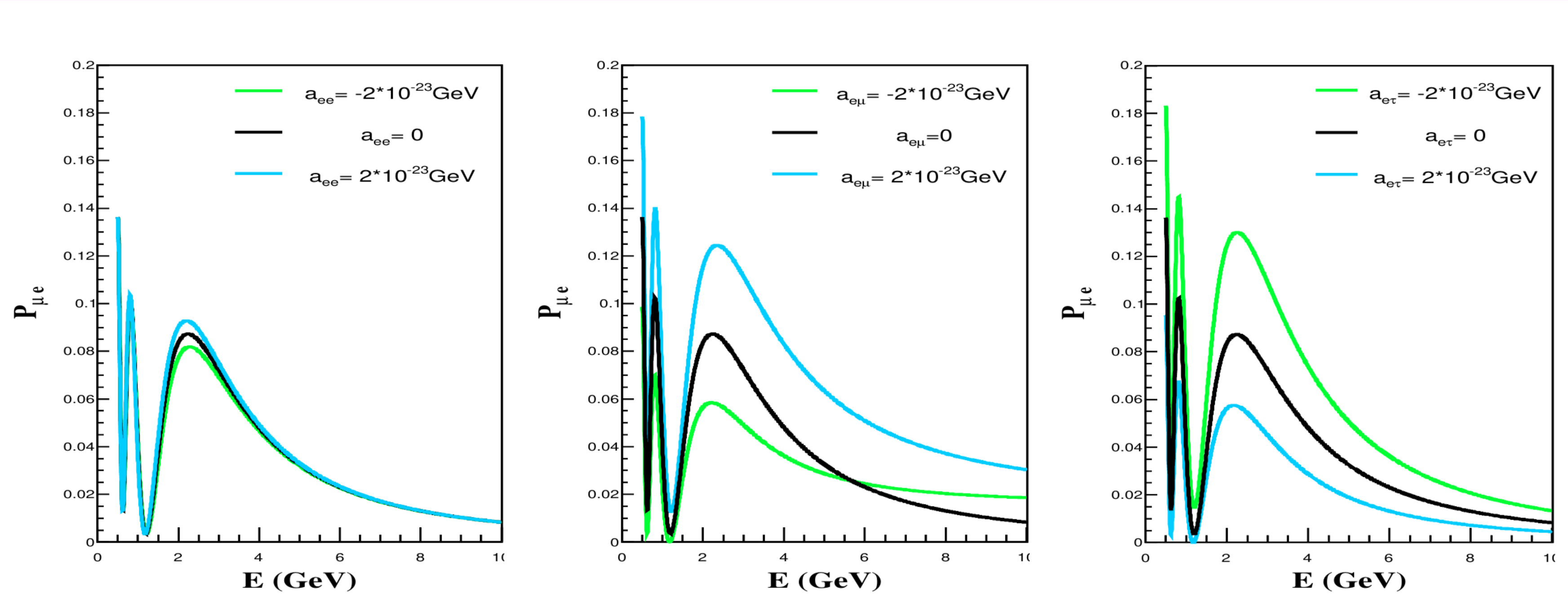

Figure 1: $P_{\mu e}$ Plots for a_{ee} (Left), $a_{e\mu}$ (Middle) and $a_{e\tau}$ (Right)

- $\boldsymbol{P_{\mu e}}$ is more affected by $\boldsymbol{a_{e\mu}}$ and $\boldsymbol{a_{e\tau}}$ at energy beyond the peak energy and their effects appears to be opposite of one another.

b) Variation of $P_{\mu\mu}$ in the presence of $a_{\mu\mu}$, $a_{\mu\tau}$ and $a_{\tau\tau}$

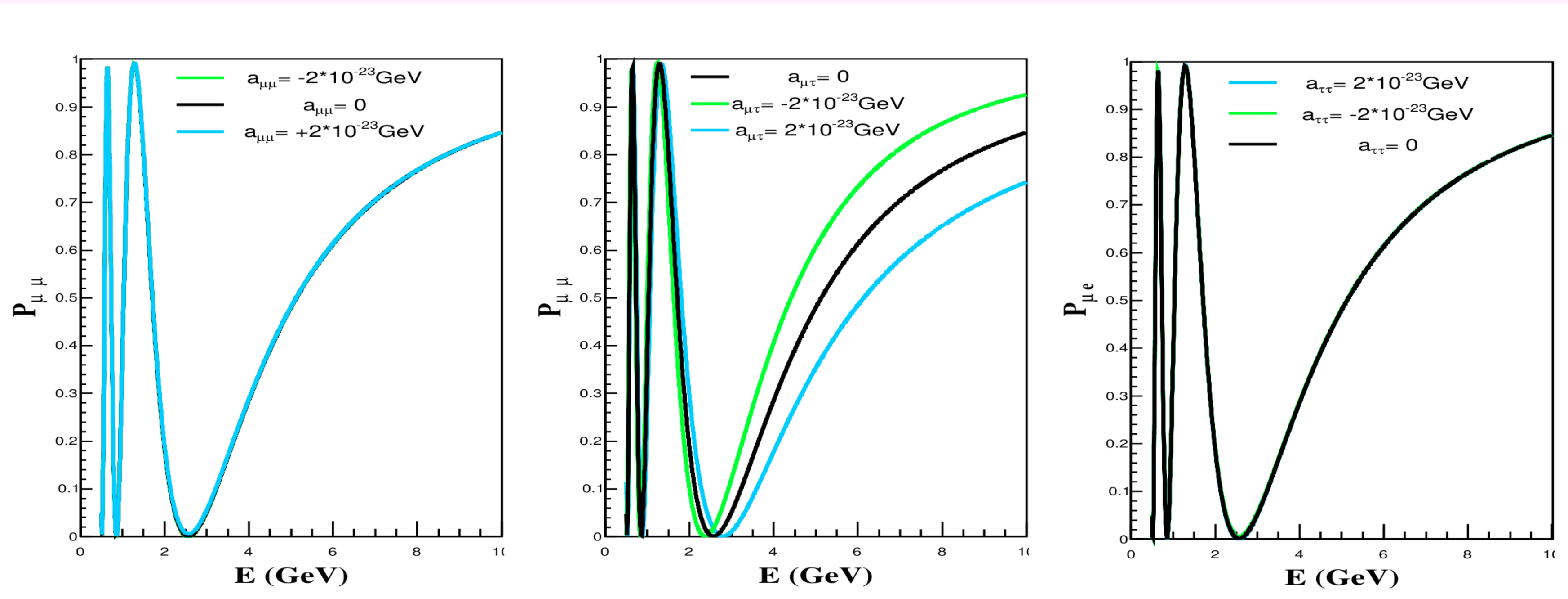

Figure 2: $P_{\mu\mu}$ Plots for $a_{\mu\mu}$ (Left), $a_{\mu\tau}$ (Middle) and $a_{\tau\tau}$ (Right)

- $\boldsymbol{P_{\mu\mu}}$ is affected only by $\boldsymbol{a_{\mu\tau}}$, the effects due to $\boldsymbol{a_{\mu\mu}}$ and $\boldsymbol{a_{\tau\tau}}$ is quite nominal for $\boldsymbol{P_{\mu\mu}}$.

2. Formalism

- Effect of LIV can be treated as a perturbation to the standard description of neutrino oscillations.
- Hamiltonian for $\nu's$, taking into the LIV effect,

$$\boldsymbol{H = H_{vac} + H_{mat} + H_{LIV}}$$

where $H_{vac} \rightarrow$ Vacuum Hamiltonian, $H_{mat} \rightarrow$ Matter potential.

- LIV effect as a perturbation to standard Hamiltonian $\rightarrow$ We use the Standard Model Extension(SME) framework to analyse LIV.
- $\boldsymbol{H_{LIV}} \rightarrow$ LIV Hamiltonian in the form

$$\boldsymbol{H_{LIV}} = \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & a^*_{\tau\tau} \end{pmatrix} - \frac{4}{3}E \begin{pmatrix} c_{ee} & c_{e\mu} & c_{e\tau} \\ c^*_{e\mu} & c_{\mu\mu} & c_{\mu\tau} \\ c^*_{e\tau} & c^*_{\mu\tau} & c^*_{\tau\tau} \end{pmatrix}$$

where $a_{\alpha\beta}$ are CPT-odd terms and $c_{\alpha\beta}$ are CPT-even terms.

- In the presence of LIV parameters, the modified Hamiltonian can be used to investigate the effect of LIV on ν-oscillations.

In this work, we have explored how LIV affects $\nu-$propagation through the CPT-odd (LIV terms).

4. Results: Sensitivity studies

iii) CPV sensitivities at DUNE

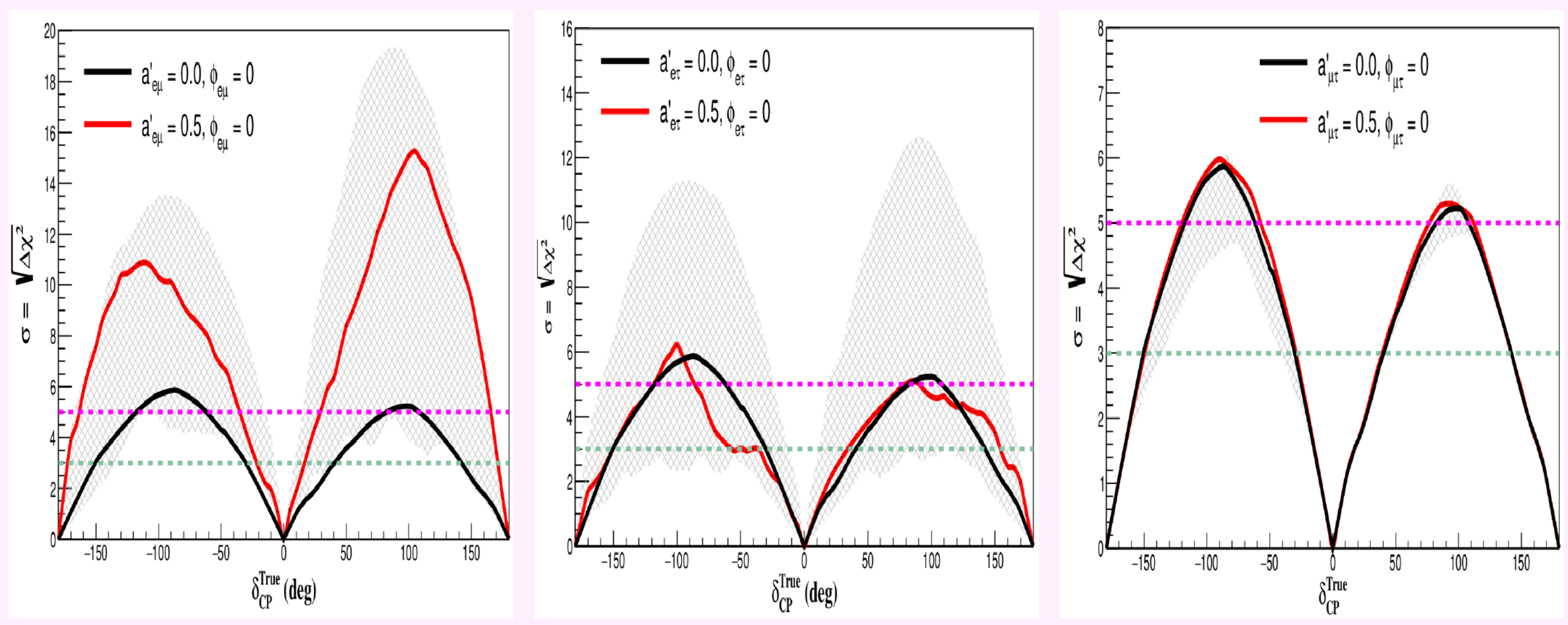

Figure 3: CPV sensitivities at DUNE for $a_{e\mu}$(left), $a_{e\tau}$(middle) and $a_{\mu\tau}$(right).

- LIV phases may pose degeneracy in the measurement of $\boldsymbol{\delta_{CP}}$.
- For $\boldsymbol{a_{e\mu}}$ & $\boldsymbol{a_{e\tau}}$, sensitivity depends on the combinations of $\boldsymbol{\phi_{\alpha\beta}}$.
- The sensitivity deteriorates in the presence of $\boldsymbol{a_{\mu\tau}}$.

iv) CP-Precision Sensitivites at DUNE

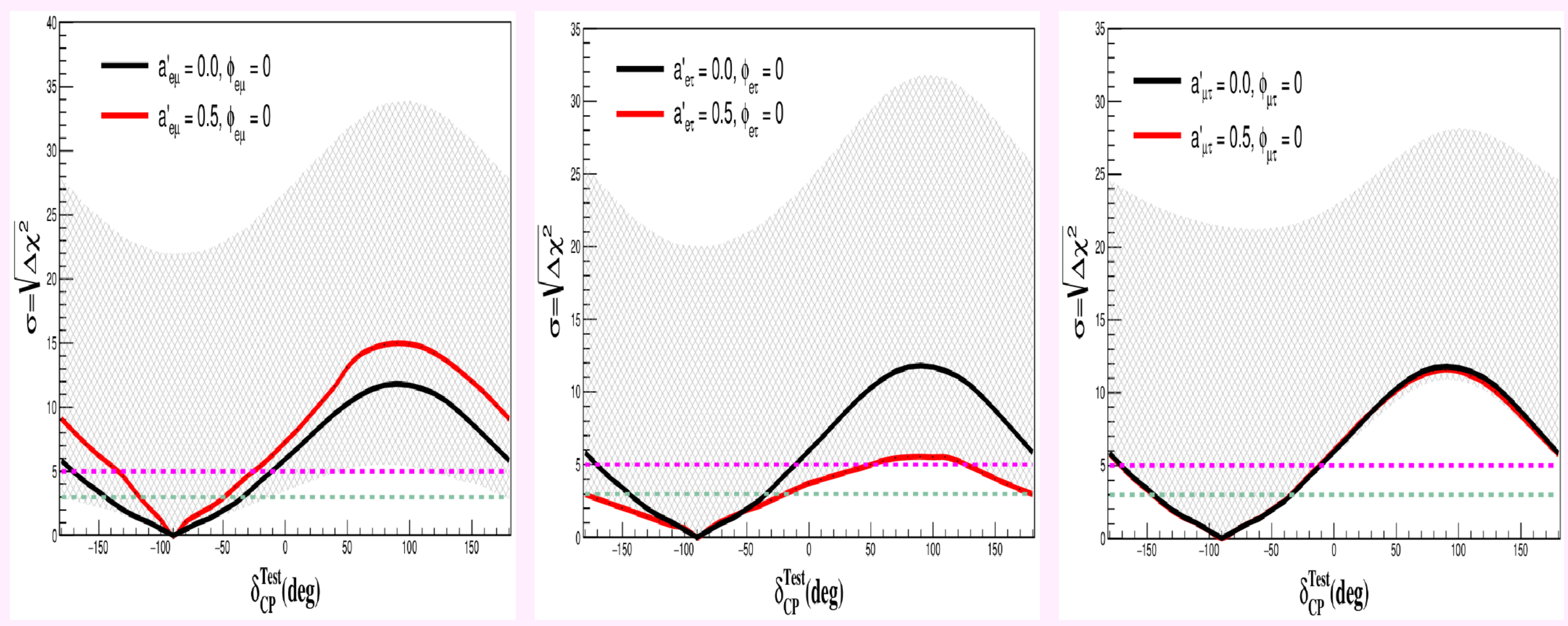

Figure a: CP-Precision Sensitivites for $a_{e\mu}$(left), $a_{e\tau}$(middle) and $a_{\mu\tau}$(right).

- For $\boldsymbol{a_{e\mu}}$, $\boldsymbol{\phi_{e\mu}}$ dependent enhancement/suppression can be seen.
- For $\boldsymbol{a_{e\tau}}$ with $\boldsymbol{\phi_{e\tau} = 0}$, the sensitivity lies in the bottom of the band.
- The presence of $\boldsymbol{\phi_{\mu\tau}}$ enhances the CP–Precision sensitivities.

Concluding Remarks

- Effect of $\boldsymbol{a_{e\mu}}$, $\boldsymbol{a_{e\tau}}$ on $\boldsymbol{P_{\mu e}}$; $\boldsymbol{a_{\mu\tau}}$ on $\boldsymbol{P_{\mu\mu}}$ is quite significant. LIV can also affect the CP-measurement sensitivities.

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