Differentiating Lorentz Invariance Violation and Non-Standard Interaction at Protvino to Super-ORCA experiment

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Introduction

- Non-standard interactions (NSIs) between neutrinos and matter have the potential to influence neutrino oscillation.
- These interactions can manifest via both charge-current (CC) and neutral-current (NC) processes.
- Our focus has been on neutral-current NSI that occurs as neutrinos propagate through the Earth.
- Lorentz Invariance is a key symmetry of Quantum Field Theory concerning space and time, and deviations from it may be detectable in theories at low energies.
- Additionally, violations of Lorentz invariance (LIV) could result in a breach of CPT symmetry.
- The effects of LIV parameters can be analyzed via long-baseline experiments.

Objectives

There exists a fundamental distinction in the source of NSI and LIV, with NSI being a property dependent on exotic matter while LIV is independent of matter.

The impact of NSI and LIV on the neutrino propagation Hamiltonian is quite analogous. Differentiating between the impacts of NSI and LIV holds significance in the context of investigations into neutrino oscillations. One can distinguish NSI and LIV based on:

(i) ***Matter density variation over different baseline lengths.***

(ii) ***Current and future bounds of the NSI and LIV parameters at long-baseline experiments.***

- In the present work, we have tried to differentiate between these two scenarios at Deep Underground Neutrino Experiment (DUNE) and Protvino to Super-ORCA (P2SO) experiments.

Simulation Details

- We have used GLoBES [3, 4] software package for simulation.
- We utilize Ref.[5] for the P2SO experiment simulation, and we use the configuration from the technical design report [6] for DUNE.
- Neutrino oscillation parameters are taken from Nufit 5.1.

Conclusion

1. DUNE and P2SO experiments are capable of distinguishing the effects of LIV from NSI parameters.
2. The $\mu\mu$ sector had the best discriminating sensitivity, whereas the ee and $\tau\tau$ sectors had the weakest sensitivity.

Theoretical Background

In the presence of NC NSI, the effective Hamiltonian for neutrinos [1] is

$$\mathcal{H}_{NSI} = \sqrt{2}G_F N_e \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}, \quad (1)$$

where $\epsilon_{\alpha\beta}$ are the effective NSI parameters.

Considering the CPT violating LIV parameters, the effective hamiltonian takes the form [2]

$$\mathcal{H}_{LIV} = \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a_{e\mu}^* & a_{\mu\mu} & a_{\mu\tau} \\ a_{e\tau}^* & a_{\mu\tau}^* & a_{\tau\tau} \end{pmatrix}, \quad (2)$$

where $a_{\alpha\beta}$ are the effective LIV parameters.
From Eqns. (1) and (2), one can correlate NSI parameters with LIV parameters as

$$a_{\alpha\beta} = \sqrt{2}G_F N_e \epsilon_{\alpha\beta} = 3.75 \frac{\rho \times 10^{-23}}{(\mathrm{g/cm^3})} \epsilon_{\alpha\beta}\ \mathrm{GeV}, \quad (3)$$

where ρ is the matter density.

★ The constraints on the LIV and NSI parameters deviate from Eqn. 3 and are not equal. As a result, it is possible to distinguish between NSI and LIV.

Differentiation at Probability Levels

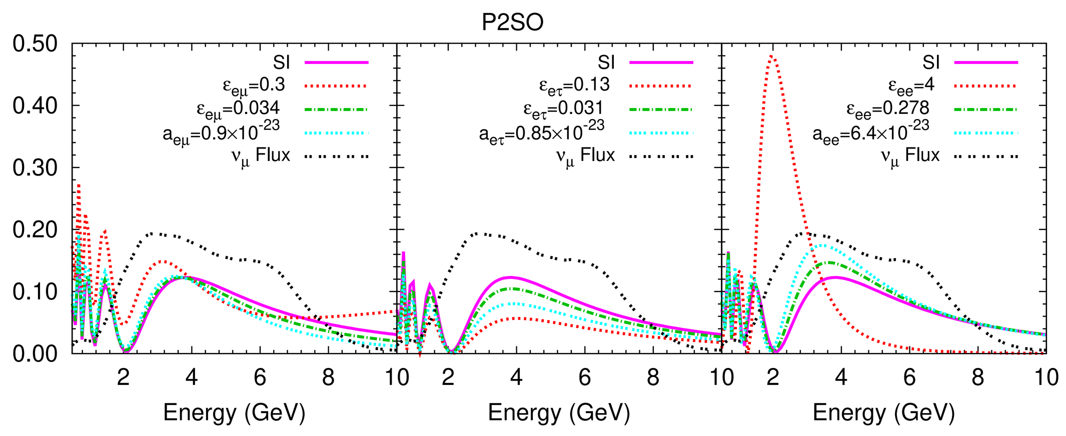

Figure 1: Appearance probability as a function of Neutrino Energy for P2SO experiment in presence of NSI and LIV parameters.

- Cyan curve is always sandwiched between the magenta and red curves but it is mostly outside the region between the magenta and green curves.
- For the present (future) bound of the NSI parameters, the difference between SI and NSI is larger (smaller) than the difference between SI and LIV.
- Distinction between NSI and LIV would be higher for future bounds of NSI parameters compared to their current bounds.

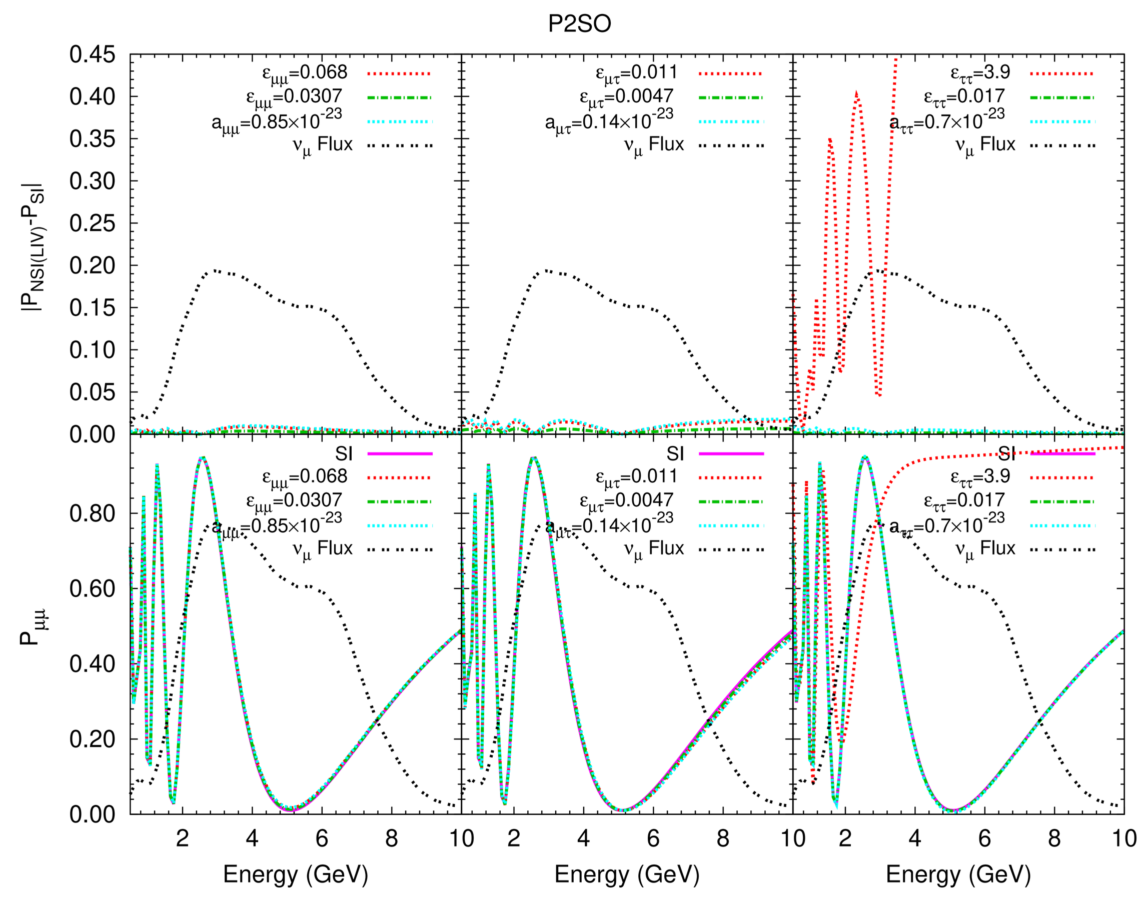

Figure 2: Survival probability as a function of Neutrino Energy for P2SO experiment in presence of NSI and LIV parameters.

★ For disappearance channel, we anticipate greater separation between LIV and NSI for the future bound of NSI compared to their current bound.

Elimination of Degeneracies

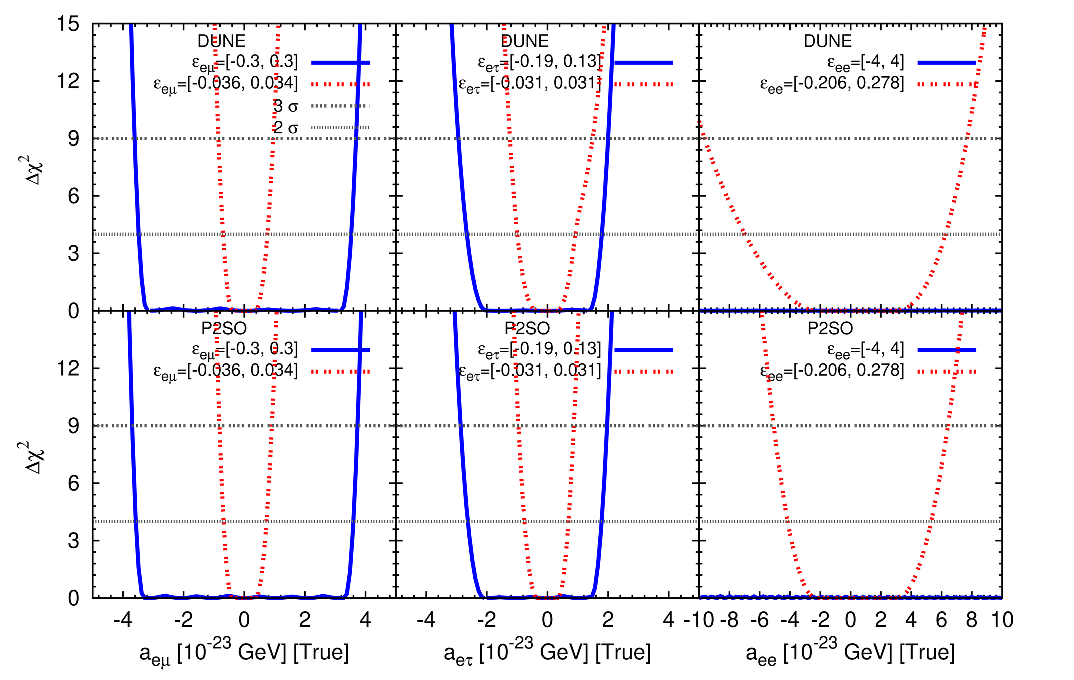

Figure 3: Sensitivity as a function of true LIV parameters $a_{e\mu}$, $a_{e\tau}$ and a_{ee} for P2SO and DUNE experiments.

- Assuming LIV existing in nature and NSI serving as the test hypothesis, we computed $\chi^2_{\min}$ using Poisson log-likelihood method

$$\chi^2 \sim N^{\text{test}}(\epsilon^{\text{test}}_{\alpha\beta} \neq 0, a^{\text{test}}_{\alpha\beta} = 0) - N^{\text{true}}(\epsilon^{\text{true}}_{\alpha\beta} = 0, a^{\text{true}}_{\alpha\beta} \neq 0).$$

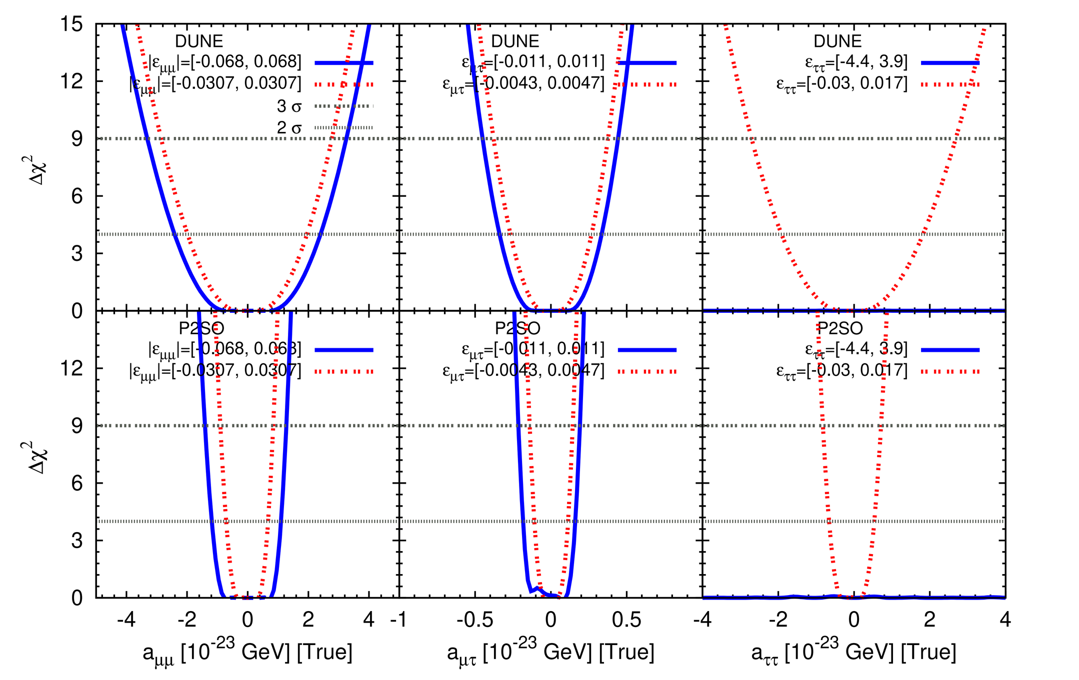

Figure 4: Sensitivity as a function of true LIV parameters $a_{\mu\mu}$, $a_{\mu\tau}$ and $a_{\tau\tau}$ for P2SO and DUNE experiments.

★ For the $\mu\mu$ sector, the best discrimination between LIV and NSI is achievable, but the ee and $\tau\tau$ sectors have the lowest sensitivity.

★ Discrimination occurs for current limits of LIV parameters but beyond their future bounds for $a_{e\mu}$, $a_{e\tau}$, and $a_{\mu\tau}$ sectors.

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