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Impact of Lorentz Invariance Violation at DUNE

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Introduction

- DUNE will play a crucial role in establishing ν oscillation over a wide range of energies by determining the oscillation parameters with utmost precision
- DUNE is potentially sensitive to Beyond the Standard Model Physics: Lorentz Invariance Violation (LIV), Non-Standard Interaction (NSI), presence of light eV-scale sterile neutrino….
- Baseline:1300 km Detector: 40 kt (fiducial) LiArTPC
  Runtime: 3.5 yrs. in ν mode + 3.5 yrs. in $\bar{\nu}$ mode
  Exposure : 300 kt.MW.yrs.

Lorentz Invariance Violation

- Possible LIV at a higher scale (Planck Mass M_P) can manifest itself as perturbation at a low energy theory such as Standard Model and is suppressed by M_P.
- $$H = \frac{1}{2E} U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger + \sqrt{2} G_F N_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a_{e\mu}^* & a_{\mu\mu} & a_{\mu\tau} \\ a_{e\tau}^* & a_{\mu\tau}^* & a_{\tau\tau} \end{pmatrix}$$
- Difference of probabilities between Higher Octant (HO) and Lower Octant (LO) of θ_{23} in presence of $a_{e\mu}$ and/or $a_{e\tau}$:

$\Delta P = \Delta P_{\mu e}(SI) + \Delta P_{\mu e}(a_{e\beta})$;

$\Delta P_{\mu e}(SI)$: Contribution of Standard matter interaction (SI)

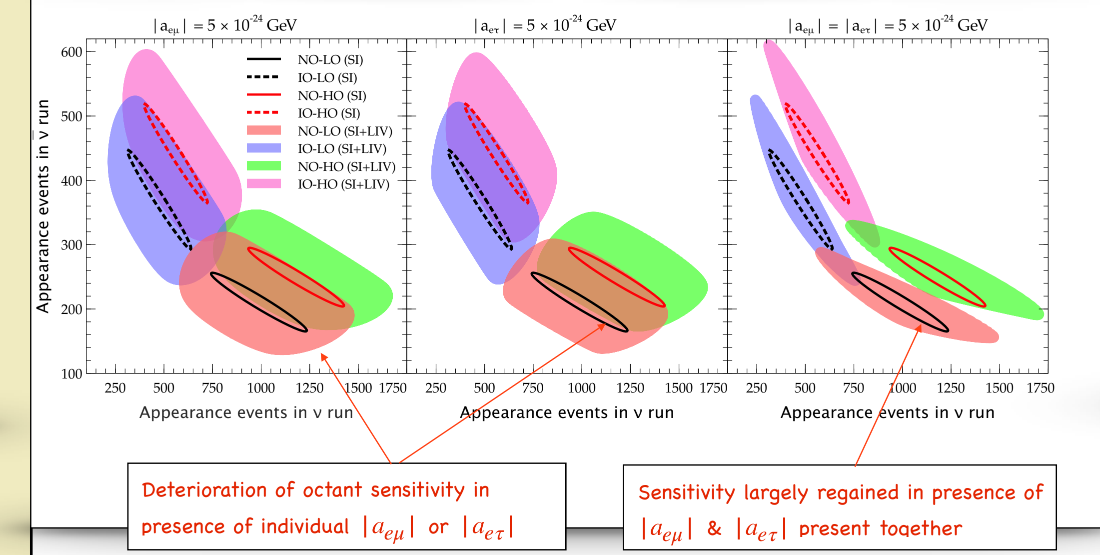
$$\Delta P_{\mu e}(a_{e\beta}) \simeq \left[\frac{|a_{e\beta}| \mathrm{GeV}^{-1}}{5\times 10^{-24}}\right]\Big[\mp 0.67\times 10^{-2}\Big\{\sin(\delta^{\rm HO}+\varphi_{e\beta}^{\rm HO}) - \sin(\delta^{\rm LO}+\varphi_{e\beta}^{\rm LO})\Big\} + 0.42\times 10^{-2}\Big\{\cos(\delta^{\rm HO}+\varphi_{e\beta}^{\rm HO}) - \cos(\delta^{\rm LO}+\varphi_{e\beta}^{\rm LO})\Big\}\Big]$$

where $-(+)$ sign is for $\beta = \mu(\tau)$.

Methodology

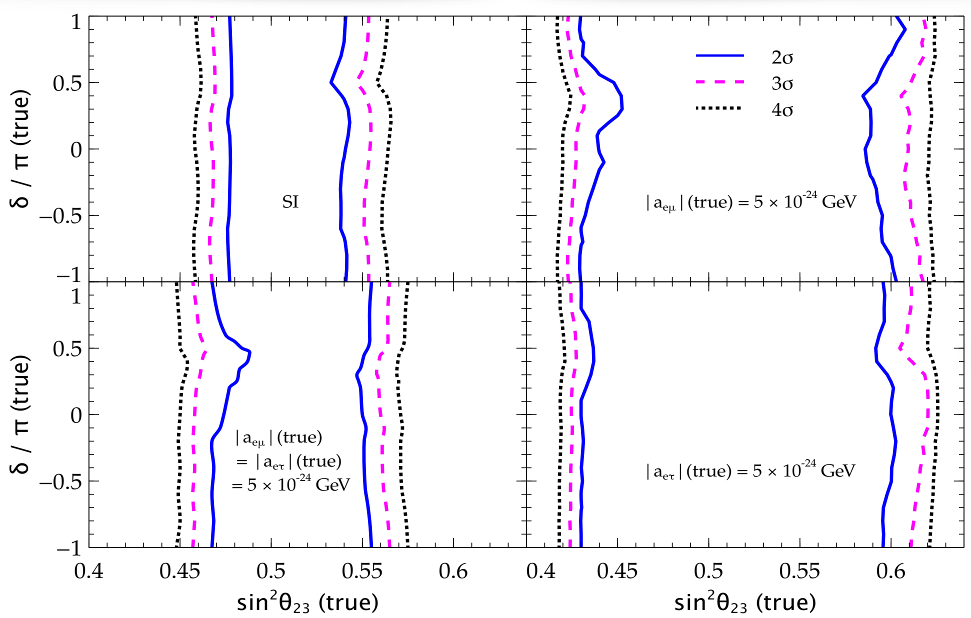
- Events corresponding to true and test octant at DUNE are simulated using GLoBES package with LIV implementation
- We numerically estimate $\Delta\chi^2_{\rm octant}$ between the true and test events to obtain the octant sensitivity of DUNE:
  $\Delta\chi^2_{\rm octant} \propto \Delta P$
- In calculating $\Delta\chi^2_{\rm octant}$, we marginalise over θ_{23} in the opposite octant, $\delta \in [-\pi,\pi]$, $\varphi_{e\beta} \in [-\pi,\pi]$.
- In simulation, we use the flux, cross-section, energy smearing, efficiencies, signal, and background systematics as provided by the DUNE collaboration (T. Alion et. al.: arXiV 1606.09550)

Origin of Octant Sensitivity: Bi-event Plot



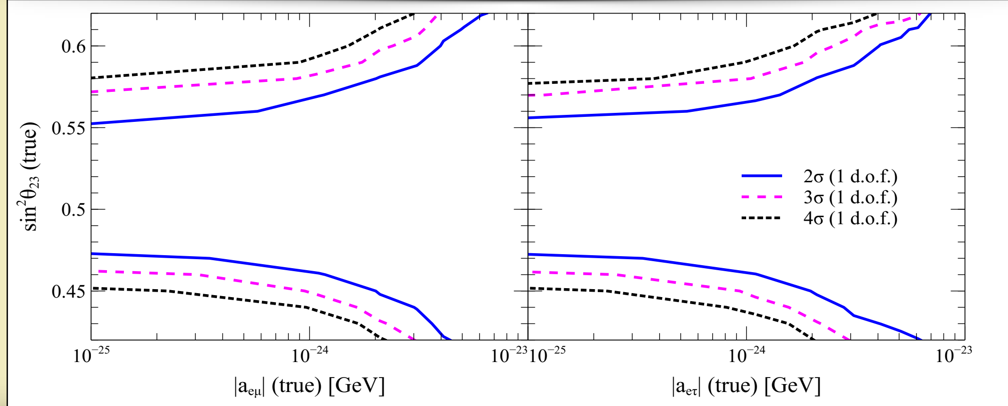
- Solid and dashed ellipses (SI): Generated by varying the standard CP phase $\delta \in [-\pi,\pi]$
- Coloured blobs (LIV): Generated by varying the CP phases $\delta, \varphi_{e\beta} \in [-\pi,\pi]$

Octant Discovery with $|a_{e\beta}|(\text{true}) = 5\times10^{-24}$ GeV



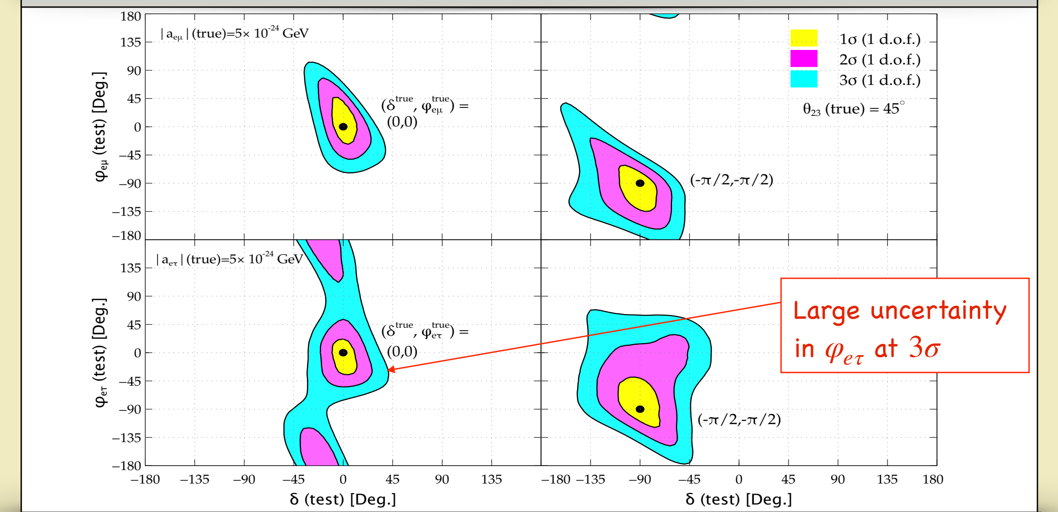
- Estimation of $\Delta\chi^2_{\rm octant}$ after marginalising over test δ, test θ_{23}, test $|a_{e\beta}|$, test and true $\varphi_{e\beta}$.
- Presence of individual $|a_{e\mu}|$ and $|a_{e\tau}|$ spoils the octant sensitivity:
  octant can only be resolved at 3σ if $\sin^2\theta_{23} \lesssim 0.42$ or $\sin^2\theta_{23} \gtrsim 0.62$ for any choice of true δ, true $\varphi_{e\beta}$ and true $\sin^2\theta_{23}$.
- Simultaneous presence of $|a_{e\mu}|$ and $|a_{e\tau}|$ restores the sensitivity closer to SI case.

Octant Discovery with Varying LIV



- $\Delta\chi^2_{\rm octant}$ after marginalising over test δ, test and true θ_{23}, test and true $\varphi_{e\beta}$, and test $|a_{e\beta}|$
- As the strength of true $|a_{e\beta}|$ decreases, the sensitivity becomes a plateau and

Reconstruction of the CP Phases



- Shows the capability of DUNE to reconstruct the CP phases: $[\delta, \varphi_{e\mu}]$ (top row) and $[\delta, \varphi_{e\tau}]$ (bottom row).
- True CP phases are CP conserving (left column) and maximally CP violating (right column).

Summary

- LIV induces new interference terms in $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ transition
- Individual LIV ($a_{e\mu}$ or $a_{e\tau}$) with new CP phases ($\varphi_{e\mu}$ or $\varphi_{e\tau}$) spoil the octant sensitivity of DUNE. But when they are present together the sensitivity is largely retrieved due to partial cancellation of the interference terms.
- The typical 1σ uncertainty on δ is $10^\circ - 15^\circ$ and on $\varphi_{e\mu}/\varphi_{e\tau}$ is $25^\circ - 30^\circ$

Reference: S.K. Agarwalla, M.Masud. *Can Lorentz Invariance Violation affect the Sensitivity of Deep Underground Neutrino Experiment?* arXiV: hep-ph 1912.13306