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Constraining Lorentz Invariance Violation with Future Long-Baseline Experiments

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Sanjib Kumar Agarwalla[a,b,c], Sudipta Das[a,b], Sadashiv Sahoo[a,b], Pragyanprasu Swain[a,b]

[a] Institute of Physics, Bhubaneswar, India, [b] Homi Bhaba National Institute, India, [c] Department of Physics & WIPAC, UW Madison, USA

Introduction

Lorentz Invariance Violation (LIV) is a Planck-scale ($M_P \sim 10^{19}$ GeV) effect that can be studied at low energies using the so-called Standard Model Extension Lagrangian given by,

$$\mathscr{L}' \supseteq \frac{\lambda}{(M_p)^k}\langle T\rangle \overline{\psi}\Gamma(i\partial)^k\psi + h.c.$$

$M_p \rightarrow$ Planck-mass (10^{19} GeV)

k = 0 $\rightarrow$ CPT-conserving LIV parameters

k = 1 $\rightarrow$ CPT-violating LIV parameters

$$\mathscr{L}_{\rm LIV} = -\frac{1}{2}\left[a^{\mu}_{\alpha\beta}\,\overline{\psi}_\alpha\gamma_\mu P_L\psi_\beta - ic^{\mu\nu}_{\alpha\beta}\,\overline{\psi}_\alpha\gamma_\mu\partial_\nu P_L\psi_\beta\right] + h.c.$$

We probe the time-like components ($\mu, \nu = 0$) of both the CPT-violating and CPT-conserving LIV parameters with standalone DUNE, Hyper-K, and their combination.

$(a^0_L)_{\alpha\beta} \equiv a_{\alpha\beta}$ $\quad$ $(c^{00}_L)_{\alpha\beta} \equiv c_{\alpha\beta}$

Neutrino propagation with LIV

$$\mathscr{H}_{\rm eff} = \underbrace{\frac{1}{2E}U\begin{pmatrix}0&0&0\\0&\Delta m^2_{21}&0\\0&0&\Delta m^2_{31}\end{pmatrix}U^\dagger}_{H_{\rm vac}} + \underbrace{\sqrt{2}G_F N_e\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix}}_{H_{\rm SI}}$$

$$\underbrace{+\underbrace{\begin{pmatrix}a_{ee}&a_{e\mu}&a_{e\tau}\\a^*_{e\mu}&a_{\mu\mu}&a_{\mu\tau}\\a^*_{e\tau}&a^*_{\mu\tau}&a_{\tau\tau}\end{pmatrix}}_{\rm CPT-violating} - \underbrace{\frac{4}{3}E\begin{pmatrix}c_{ee}&c_{e\mu}&c_{e\tau}\\c^*_{e\mu}&c_{\mu\mu}&c_{\mu\tau}\\c^*_{e\tau}&c^*_{\mu\tau}&c_{\tau\tau}\end{pmatrix}}_{\rm CPT-conserving}}_{H_{\rm LIV}}$$

$P_{\mu e} \simeq P_{\mu e}({\rm SI}) + P_{\mu e}(a_{e\beta}/c_{e\beta})$ & $P_{\mu\mu} \simeq P_{\mu\mu}({\rm SI}) + P_{\mu\mu}(a_{\mu\tau}/c_{\mu\tau})$

$P_{\mu e}$(SI), $P_{\mu\mu}$(SI) $\rightarrow$ probabilities in presence of the standard interactions only.

$$P_{\mu e}(a_{e\beta}) \simeq 2|a_{e\beta}|\,\boxed{L}\,\sin\theta_{13}\sin 2\theta_{23}\sin\Delta\left[\mathbb{Z}_{e\beta}\sin(\delta_{\rm CP}+\varphi_{e\beta}) + \mathbb{W}_{e\beta}\cos(\delta_{\rm CP}+\varphi_{e\beta})\right]$$

$$P_{\mu e}(c_{e\beta}) \simeq \frac{-8}{3}|c_{e\beta}|\,\boxed{EL}\,\sin\theta_{13}\sin 2\theta_{23}\sin\Delta\left[\mathbb{Z}_{e\beta}\sin(\delta_{\rm CP}+\varphi_{e\beta}) + \mathbb{W}_{e\beta}\cos(\delta_{\rm CP}+\varphi_{e\beta})\right]$$

$$P_{\mu\mu}(a_{\mu\tau}/c_{\mu\tau}) = \frac{\sin^2 2\theta_{23}}{2}\left[2\sin^2\theta_{13}\Delta - \mathbb{S}\right]\sin 2\Delta$$

Notations

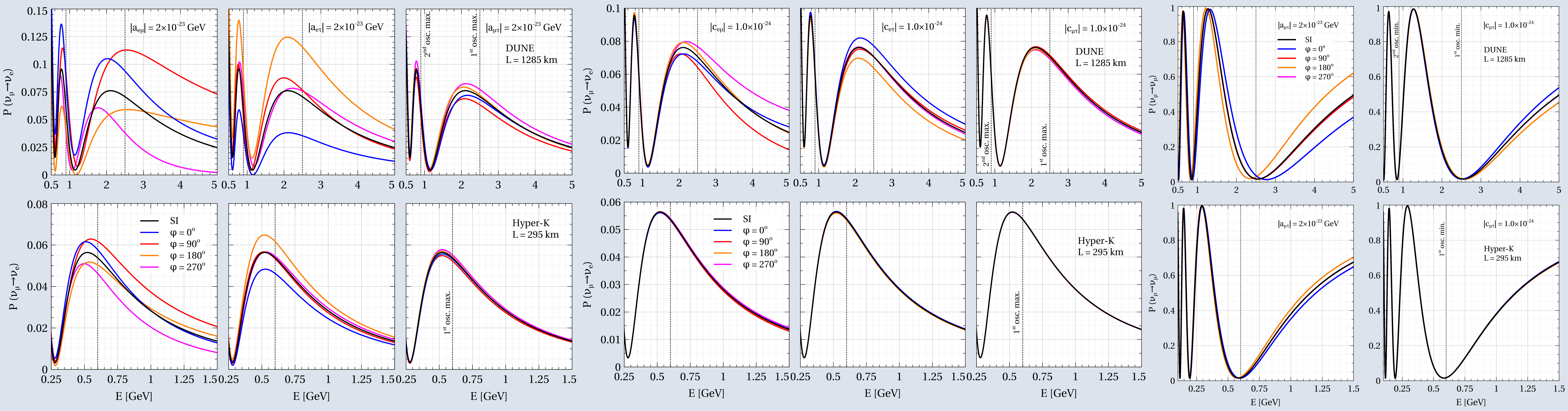
$$\mathbb{Z}_{e\beta} = \begin{cases}-c_{23}\sin\Delta, & \text{if } \beta = \mu.\\ s_{23}\sin\Delta, & \text{if } \beta = \tau.\end{cases}$$

$$\mathbb{W}_{e\beta} = \begin{cases}c_{23}\left(\frac{s^2_{23}\sin\Delta}{c^2_{23}\Delta} + \cos\Delta\right), & \text{if } \beta = \mu.\\ s_{23}\left(\frac{\sin\Delta}{\Delta} - \cos\Delta\right), & \text{if } \beta = \tau.\end{cases}$$

$$\mathbb{S}(a_{\mu\tau}) = 2\underline{L}\sin 2\theta_{23}|a_{\mu\tau}| \times \cos\phi_{\mu\tau}$$

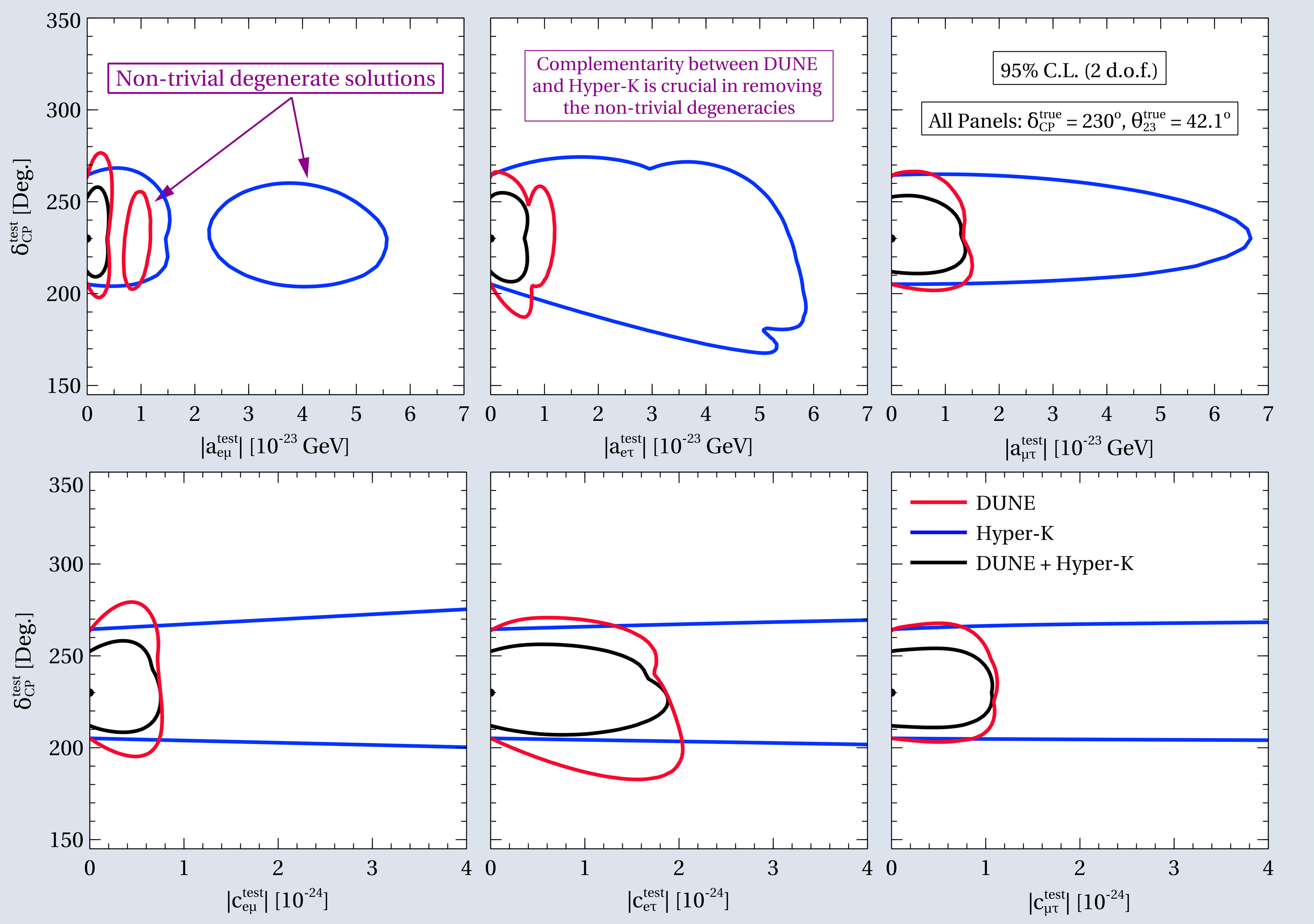
$$\mathbb{S}(c_{\mu\tau}) = -\frac{8}{3}\underline{EL}\sin 2\theta_{23}|c_{\mu\tau}| \times \cos\phi_{\mu\tau}.$$

Neutrino oscillation probability in the presence of LIV

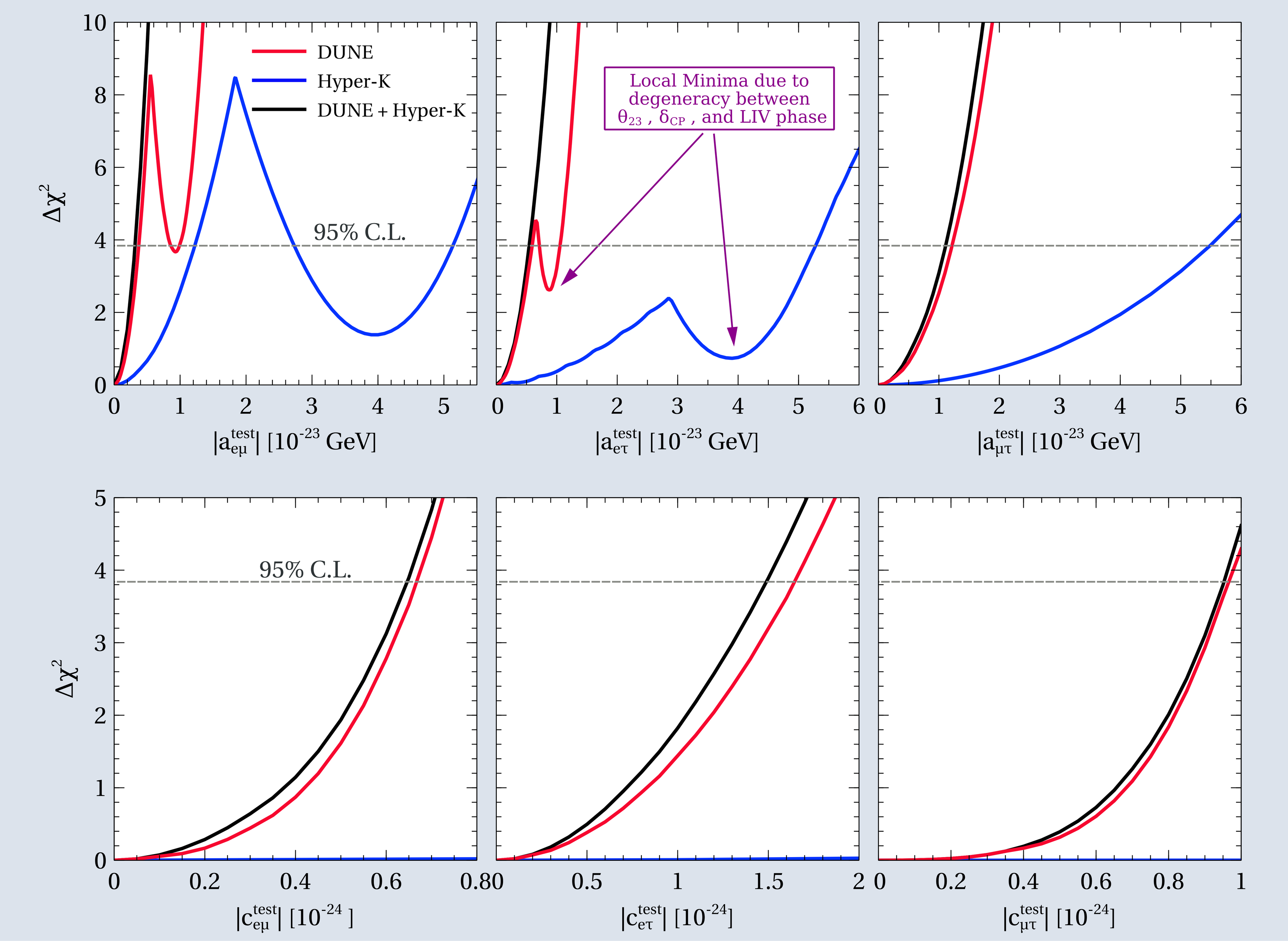


- Appearance probability is affected maximally by $a_{e\mu}$ ($c_{e\mu}$) followed by $a_{e\tau}$ ($c_{e\tau}$)
- $a_{\mu\tau}$ ($c_{\mu\tau}$) impacts the appearance probability marginally compared to $a_{e\mu}$ ($c_{e\mu}$) and $a_{e\tau}$ ($c_{e\tau}$)
- The effects of LIV phases are significant in DUNE compared to Hyper-K
- $a_{\mu\tau}$ ($c_{\mu\tau}$) mostly affects the disappearance probability
- The effects of $c_{\alpha\beta}$ are opposite in comparison to those of $a_{\alpha\beta}$
- Hyper-K is almost blind to the CPT-conserving LIV parameters

Correlations in ($\delta_{\rm CP} - |a_{\alpha\beta}|/|c_{\alpha\beta}|$) plane



Constraints on the LIV parameters



95% C.L. bounds

	DUNE	Hyper-K	DUNE+Hyper-K	T2K+NOνA
$\lvert a_{e\mu}\rvert$ [10^{-23} GeV]	< 1.0	< 5.15	< 0.32	< 6.1
$\lvert a_{e\tau}\rvert$ [10^{-23} GeV]	< 1.05	< 5.3	< 0.55	< 7.0
$\lvert a_{\mu\tau}\rvert$ [10^{-23} GeV]	< 1.26	< 5.5	< 1.1	< 8.3
$\lvert c_{e\mu}\rvert$ [10^{-24}]	< 0.66	< 17.1	< 0.64	< 11.0
$\lvert c_{e\tau}\rvert$ [10^{-24}]	< 1.65	< 71.1	< 1.49	< 37.5
$\lvert c_{\mu\tau}\rvert$ [10^{-24}]	< 0.97	< 42.4	< 0.95	< 29.0

Conclusions

- Due to longer baseline and access to multi-GeV energies, DUNE has a better reach in probing both CPT-violating and CPT-conserving LIV parameters
- Hyper-K, which mostly deals with sub-GeV neutrinos, is almost insensitive to the CPT-conserving LIV parameters
- The degeneracy between θ_{23}, $\delta_{\rm CP}$, and the LIV phases lead to the deterioration of the bounds for the individual setups; however, when we add the data from both, these degeneracies disappear

References

Agarwalla et al., Constraining Lorentz invariance violation with next-generation long-baseline experiments, arXiv: 2302.12005, **JHEP 07 (2023) 216**

For queries, please write to: pragyanprasu.s@iopb.res.in