Effect of torsion in long-baseline neutrino oscillation experiments

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Introduction

- The presence of curved spacetime affects the characteristics of the fermions. In a curved spacetime, the effect of curvature on fermionic fields is represented by spin connection.
- The spin connection consists of two terms; one is solely the gravitational part, and the other is the non-universal "contorsion" part. The contraction of contorsion part with the tetrad fields is known as torsion.
- In a scenario where neutrino travels through background of fermionic matter at ordinary densities in a curved spacetime, the additional interaction term contributing to the effective Hamiltonian can be written as:

$$H_{\text{tor}} = \left(\sum_{f=e,p,n} \lambda_f n_f\right)\left(\sum_{i=1,2,3} \lambda_i \bar{\nu}_i \gamma^0 \nu_i\right) = \sum_{i=1,2,3} \left(\lambda_i \nu_i^{\dagger} \mathbb{P}_{\mathbb{L}} \nu_i\right) \tilde{n}\,, \tag{1}$$

  where n_f: number density of the background fermion and λ_i: torsional couplings for vector charge densities of neutrinos, $\tilde{n} = \sum_{f=e,p,n} (\lambda_f n_f)$ and $\mathbb{P}_{\mathbb{L}} = (1-\gamma_5)/2$.
- In this work [3], we study the effect of curved spacetime on neutrino oscillation.

Modified probability expressions

- We adopt the Einstein-Cartan-Sciama-Kibble (ECSK) [2] formalism in our work which represents a first-order formulation of gravity, employing tetrad fields.
- The time evolution of mass eigenstates in presence of torsion is [1]

$$i\frac{d}{dt}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = \left[E\mathbb{I} + \frac{1}{2E}\begin{pmatrix} m_1^2 & 0 & 0\\ 0 & m_2^2 & 0\\ 0 & 0 & m_3^2\end{pmatrix} + \begin{pmatrix}\lambda_1 & 0 & 0\\ 0 & \lambda_2 & 0\\ 0 & 0 & \lambda_3\end{pmatrix}\tilde{n} - \frac{G_F}{\sqrt{2}} n_n \mathbb{I} + U^T \begin{pmatrix}\sqrt{2}G_F n_e & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix} U^*\right]\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}, \tag{2}$$

  where n_n and n_e: nucleon and electron number densities, U: PMNS mixing matrix.
- In presence of torsion, the appearance and disappearance probabilities can be expressed as:

$$\begin{aligned} P_{\nu_\mu\to\nu_e} &= 4\sin^2\theta_{13}\sin^2\theta_{23}\frac{\sin^2(\tilde{A}-1)\tilde{\Delta}}{(\tilde{A}-1)^2} \\ &\quad + 2\tilde{\alpha}\sin\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos(\tilde{\Delta}+\delta_{CP})\frac{\sin\tilde{A}\tilde{\Delta}}{\tilde{A}}\frac{\sin(\tilde{A}-1)\tilde{\Delta}}{(\tilde{A}-1)} \\ &\quad + \tilde{\alpha}^2\sin^2 2\theta_{12}\cos^2\theta_{23}\frac{\sin^2\tilde{A}\tilde{\Delta}}{\tilde{A}^2} \equiv P_1 + P_2 + P_3\,, \end{aligned} \tag{3}$$

$$P_{\nu_\mu\to\nu_\mu} = 1 - \sin^2 2\theta_{23}\sin^2\tilde{\Delta} + \text{higher order terms}\,, \tag{4}$$

  where $\tilde{\Delta} = \frac{\Delta\tilde{m}^2_{31}L}{4E}$, $\tilde{\alpha} = \frac{\Delta\tilde{m}^2_{21}}{\Delta\tilde{m}^2_{31}}$ and $\tilde{A} = \frac{2\sqrt{2}G_F n_e E}{\Delta\tilde{m}^2_{31}}$.

Experimental setup

Experiment	DUNE	P2SO
Runtime	$6.5\nu : 6.5\bar{\nu}$	$3\nu : 3\bar{\nu}$
Baseline	1300 km	2595 km
First oscillation peak	2.5 GeV	4.5 GeV
Detector material	LArTPC	Water Cherenkov
Fiducial volume	40 kt	few Mega ton

Table 3: Experimental setup and their details.

Results

0.1 Probability in presence of torsion

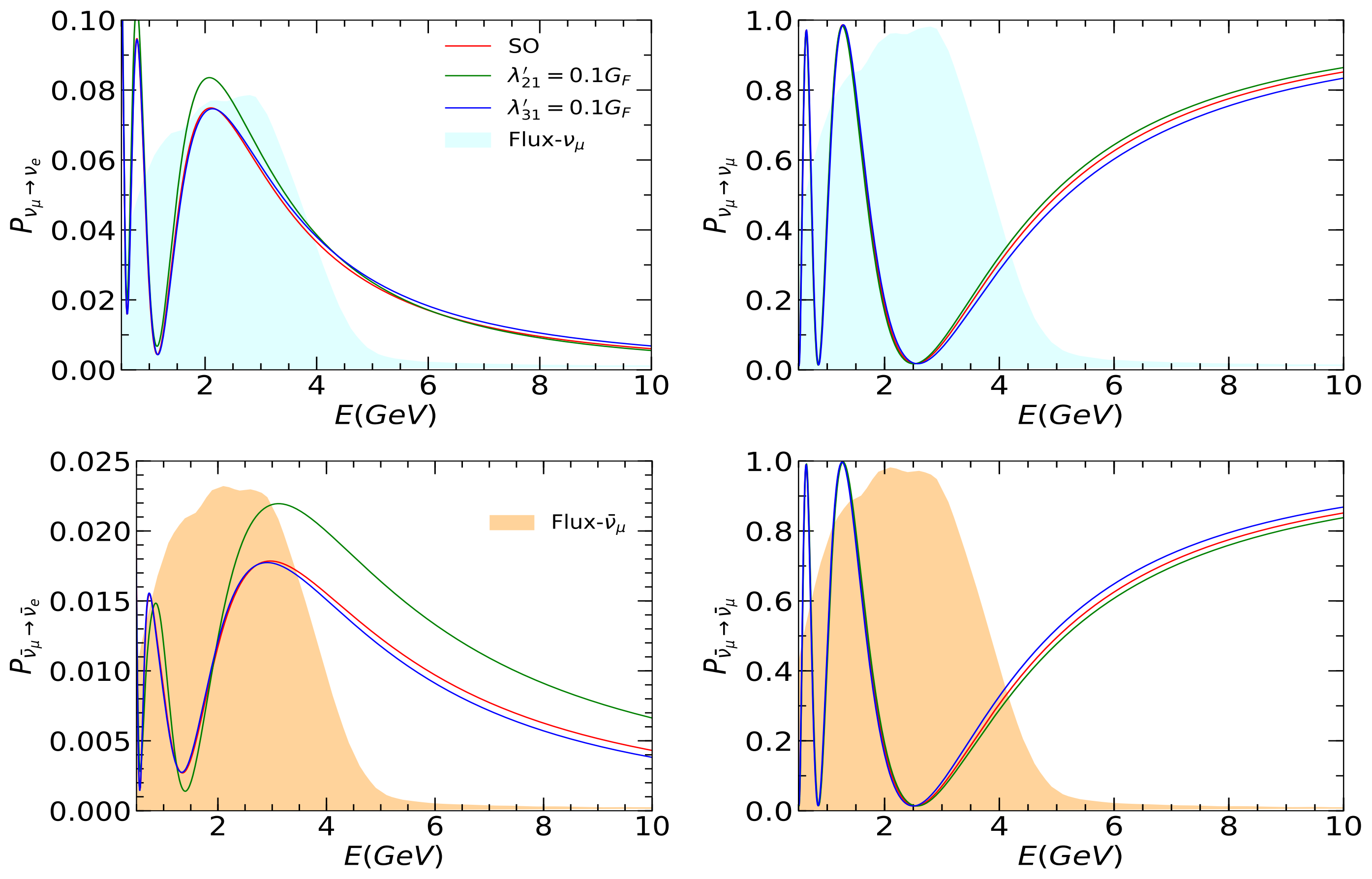

Fig. 1: Upper (lower) row shows the appearance (disappearance) probability for DUNE. Left (right) column is for neutrino (antineutrino) mode.

0.2 Bounds on torsional couplings

Experimental Setup	λ'_{21} bound [2σ (3σ)] (when $\lambda'_{31}=0$)	λ'_{31} bound [2σ (3σ)] (when $\lambda'_{21}=0$)	λ'_{21} bound (when $\lambda'_{31}\neq 0$)	λ'_{31} bound (when $\lambda'_{21}\neq 0$)
DUNE	-0.039 (-0.057)	-0.043 (-0.064)	-0.060	-0.070
	0.040 (0.060)	0.043 (0.063)	0.080	0.080
P2SO	-0.022 (-0.032)	-0.016 (-0.024)	-0.080	-0.060
	0.022 (0.032)	0.016 (0.024)	0.130	0.100

Table 1: λ'_{21} and λ'_{31} bounds (in the units of G_F) for DUNE and P2SO.

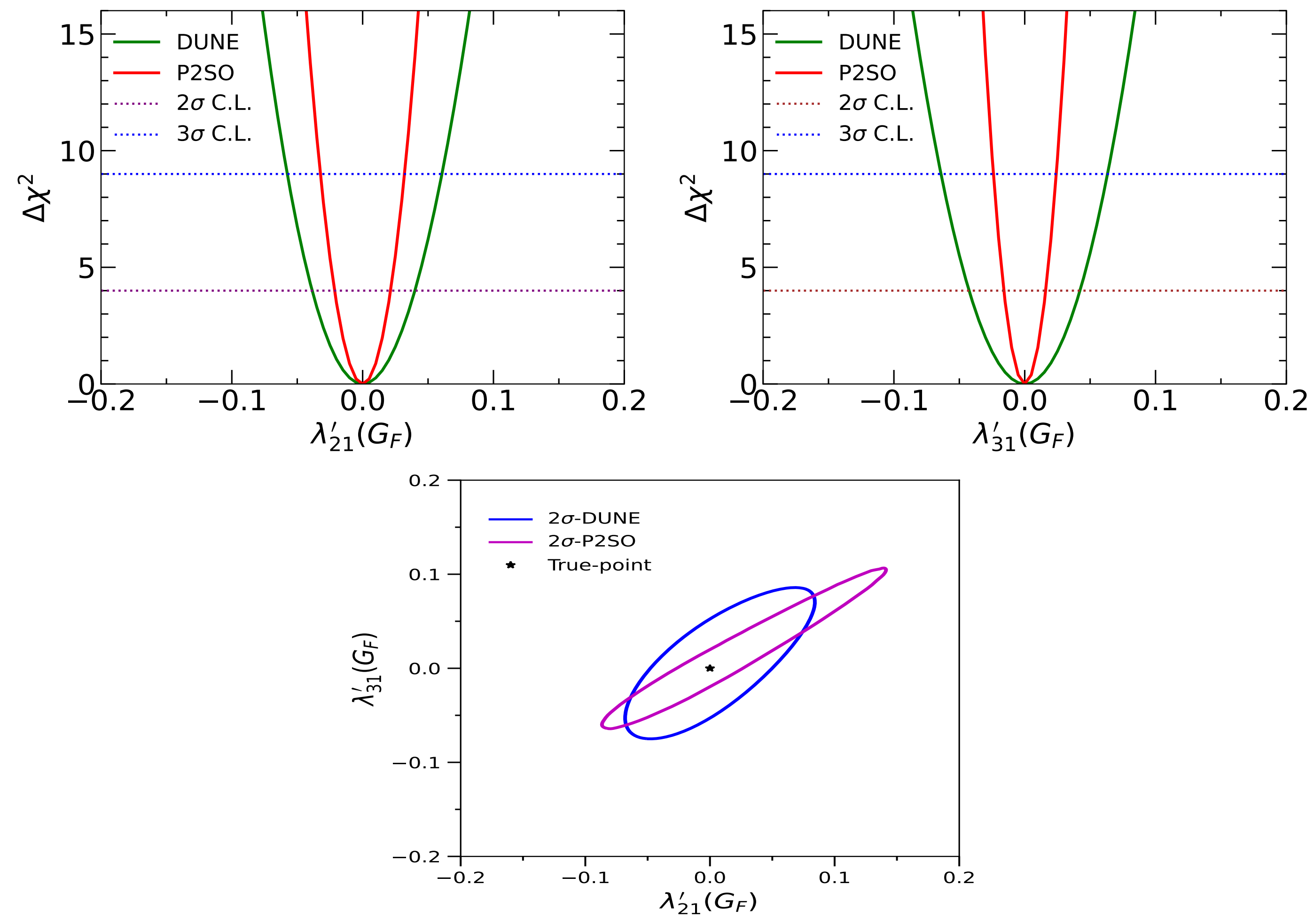

Fig. 2: Upper row: Left (right) panel shows the bounds of λ'_{21} (λ'_{31}) in DUNE and P2SO. Lower panel: 2-D bound plot of λ'_{21} and λ'_{31} for two experiments at 2σ C.L.

0.3 Physics sensitivity in presence of torsion

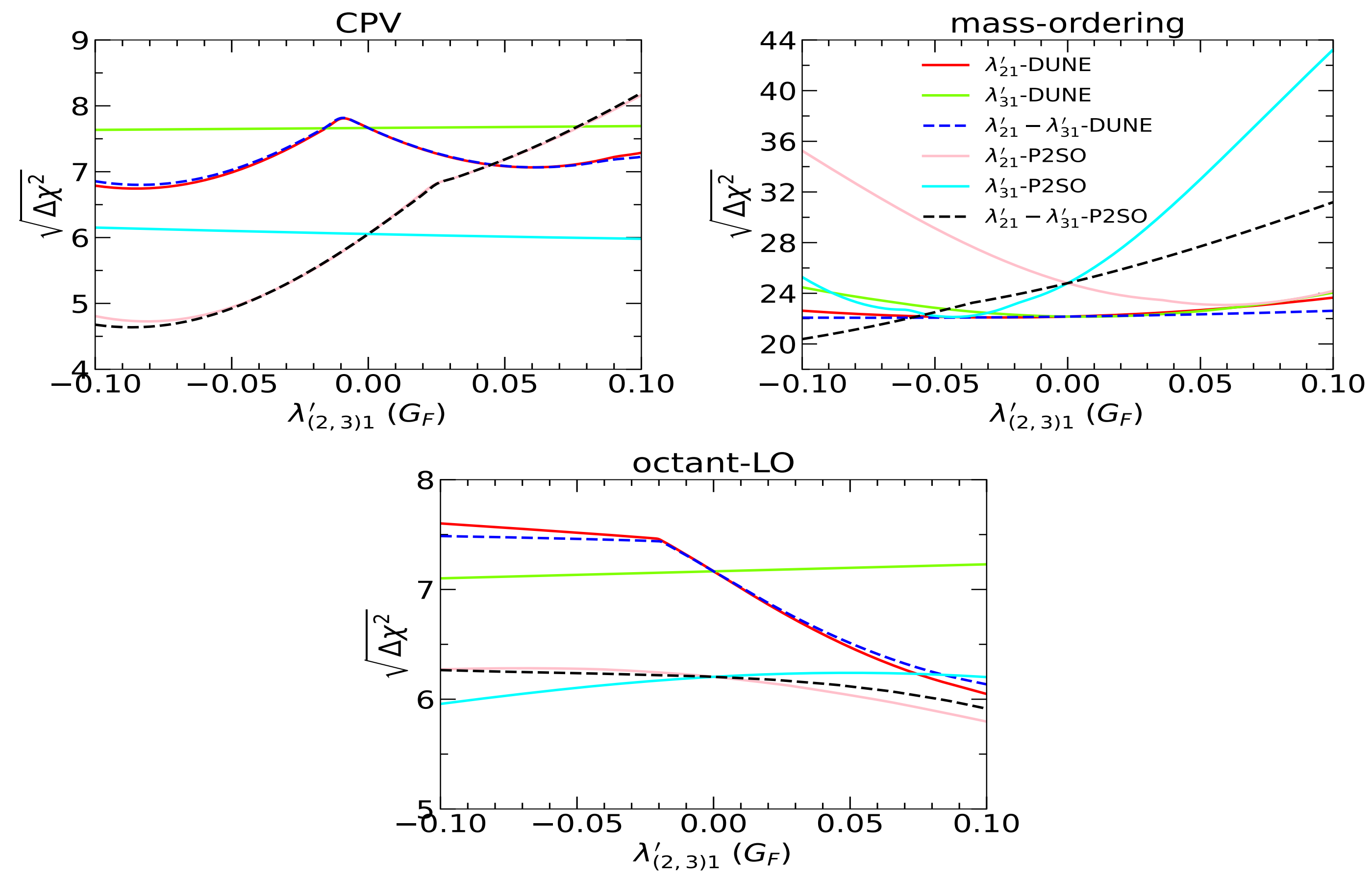

Fig 3: Left (right) panel of upper row: CPV (mass-ordering) sensitivity as a function of $\lambda'_{(2,3)1}$ in units of G_F. Lower row: the octant sensitivity of atmospheric mixing angle θ_{23} in variation with $\lambda'_{(2,3)1}$.

Summary and conclusion

- For one parameter at a time, P2SO gives more stringent bound on both the parameters λ'_{21}, λ'_{31} than DUNE. When both parameters are present at the same time, DUNE provides similar bounds on both the couplings and its sensitivity is better than P2SO. Results can be seen from Table 1.
- The variation of CP violation sensitivity is more for λ'_{21}, whereas the change is marginal for λ'_{31}.
- The change in mass ordering sensitivity with respect to both the torsional coupling constants are marginal in DUNE, whereas it is significant for P2SO.
- Regarding octant, the sensitivity of DUNE and P2SO are affected by λ'_{21} whereas change in the sensitivity due to λ'_{31} is marginal.

References

[1] R. Barick, I. Ghose, and A. Lahiri. Effect of spacetime geometry on neutrino oscillations. *Eur. Phys. J. Plus*, 139(6):461, 2024.

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