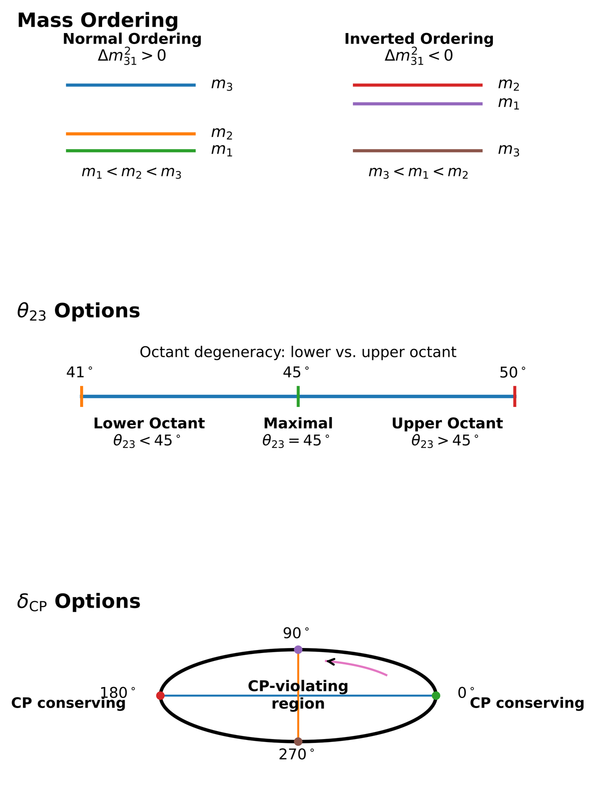
Complementarity between neutrinos from Atmospheric, Accelerator, and Reactor in the study of Lorentz Invariance Violation

Supriya Pan [1] Tatiana Araya-Santander [1] Cesar Bonilla [1] Omar G. Miranda [2]

[1]Universidad Católica del Norte, Antofagasta, Chile [2]Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional, México

Motivation and Major Features

- The neutrino mass ordering (MO), the octant of θ_{23}, and the value of δ_{CP} remain key unknowns in three-flavor neutrino oscillation physics.
- Beyond-standard-model effects can affect neutrino oscillations and make **the determination of these quantities more difficult through new degeneracies.**
- **We explore the effects of CPT-even** Lorentz-invariance-violating potentials in the determination of unknown neutrino oscillation parameters.
- **Can the combined analysis of accelerator, atmospheric, and reactor** neutrinos help when LIV potentials are present?
- **We consider DUNE (accelerator, atmospheric) and JUNO (reactor)** simulated data for the analysis.



Key unknowns in three-flavor oscillations

Neutrinos under Lorentz Invariance Violations (LIV)

The total Hamiltonian in the presence of LIV is given by

$$H = \frac{1}{2E}\left[U\begin{pmatrix}0&0&0\\0&\Delta_{21}&0\\0&0&\Delta_{31}\end{pmatrix}U^\dagger + \begin{pmatrix}A&0&0\\0&0&0\\0&0&0\end{pmatrix}\right] + \begin{bmatrix}a_{ee}&a_{e\mu}&a_{e\tau}\\a^\star_{e\mu}&a_{\mu\mu}&a_{\mu\tau}\\a^\star_{e\tau}&a^\star_{\mu\tau}&a_{\tau\tau}\end{bmatrix} - \frac{4}{3}E\begin{bmatrix}\mathbf{c_{ee}}&\mathbf{c_{e\mu}}&\mathbf{c_{e\tau}}\\c^\star_{e\mu}&c_{\mu\mu}&c_{\mu\tau}\\c^\star_{e\tau}&c^\star_{\mu\tau}&c_{\tau\tau}\end{bmatrix}, \quad (1)$$

$A = 2E\sqrt{2}G_F N_e = 7.6\times10^{-5}\rho(\mathrm{g/cc})\mathrm{E(GeV)}\,\mathrm{eV}^2$, G_F: Fermi Constant, N_e: No. density of e^- in matter, ρ: matter density, $a_{\alpha\beta}$: CPT odd, $c_{\alpha\beta}$: CPT even. $\hat{A} = A/\Delta m^2_{31}$, $\Delta = \Delta m^2_{31}L/4E$

$$P_{\bar\nu_e\to\bar\nu_e}[4] \simeq 1 - \cos^2\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E} + f_{21}\right) - \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}L}{4E} + f_{31}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32}L}{4E} + f_{31}\right)\right], \quad (2)$$

$$P_{\nu_\mu\to\nu_e}[1] \simeq 2\alpha s_{13}\sin 2\theta_{12}\sin 2\theta_{23}\frac{\sin[\hat{A}\Delta]}{\hat{A}}\frac{\sin[(\hat{A}-1)\Delta]}{\hat{A}-1}\cos(\Delta+\delta_{CP}) + 4s^2_{13}s^2_{23}\frac{\sin^2[(\hat{A}-1)\Delta]}{(\hat{A}-1)^2} - \frac{8EL\Delta s_{13}\sin 2\theta_{23}\sin\Delta}{3}\sum_{\beta}^{\mu,\tau}[|c_{e\beta}|Z_{e\beta}\sin(\psi_{e\beta}+\delta_{CP}) + |c_{e\beta}|W_{e\beta}\cos(\psi_{e\beta}+\delta_{CP})] \quad (3)$$

The functions f_{21}, f_{31}[4] depend on LIV. $Z_{e\beta}, W_{e\beta}$[1] depend on $\theta_{23}, \sin\Delta, \cos\Delta$.

Details of Experiments

We consider two experiments **DUNE**, **JUNO** and three different sources of neutrinos **accelerator, atmospheric** ($P_{\mu e}$, $P_{\mu\mu}$), and reactor ($\bar{P}_{ee}$).

Characteristic	DUNE acc.	DUNE atm.	JUNO reactor
Source	Beam neutrinos	Atmospheric neutrinos	Reactor $\bar\nu_e$
Channel	$\nu_\mu\to\nu_e, \nu_\mu\to\nu_\mu$	$\nu_\mu\to\nu_e, \nu_\mu\to\nu_\mu$	$\bar\nu_e\to\bar\nu_e$
Baseline	1300 km	10–10^4 km	52.5 km
Energy	$1-9$ GeV	0.5–10.5 GeV	1.8–9.8 MeV
Exposure	40 kt $\times$ (1.5 + 1.5) yr	40 kt $\times$ 3 yr	20 kt $\times$ 3 yr
Energy resolution	DUNE smearing matrices	$\sigma_E = 15\%$	$\sigma_E = 3\%$
Angular resolution	–	$\sigma_\theta = 15°$	–
Systematics	Signal/background norm., calibration	Flux 20%, zenith 5%, xsec 10%, syst. 5%, tilt	Flux norm., detector norm., energy scale, backgrounds
Physics role	MO, δ_{CP} and θ_{23}	MO, θ_{23}	MO, precision of θ_{13}, θ_{12}

Sensitivity to $\theta_{23} - \delta_{CP}$ (same Mass Ordering)

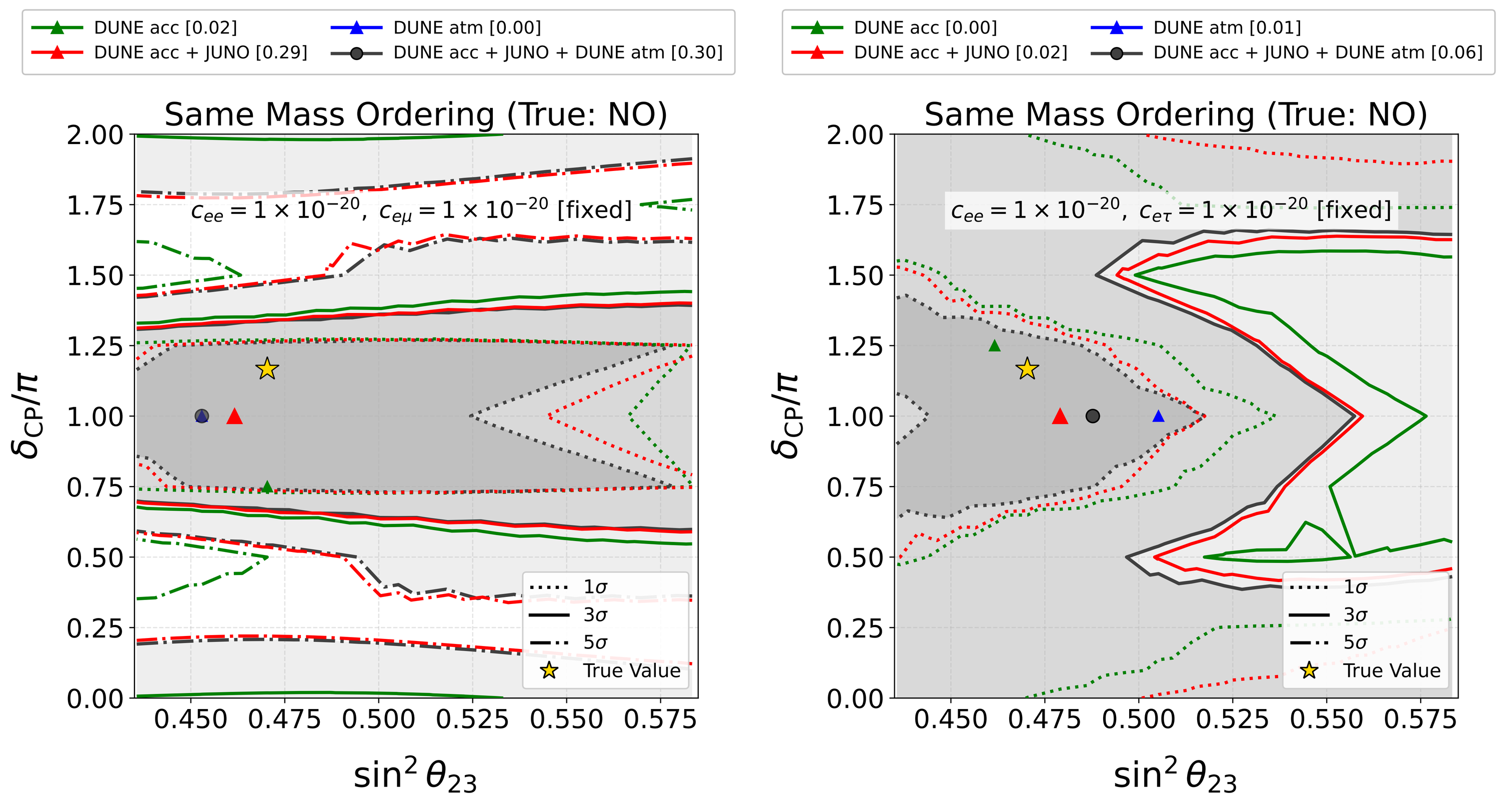


Figure 1. Sensitivity to NO for true NO in test $\sin^2\theta_{23} - \delta_{CP}$ with fix $c_{ee} - c_{e\mu}$[left], $c_{ee} - c_{e\tau}$[right]

1. **Sensitivity improves significantly with the addition of JUNO and atmospheric ν's over only the DUNE accelerator**, as seen from shaded contours.
2. **Degeneracies in $\sin^2\theta_{23} - \delta_{CP}$ plane still remain.**. Degeneracy in δ_{CP} is more in presence of $c_{ee} - c_{e\tau}$, whereas degeneracy in θ_{23} is greater in presence of $c_{ee} - c_{e\mu}$.
3. **More exposure of accelerator, atmospheric, and reactor neutrinos is needed** to overcome the degeneracies.

Sensitivity to Opposite Mass Ordering

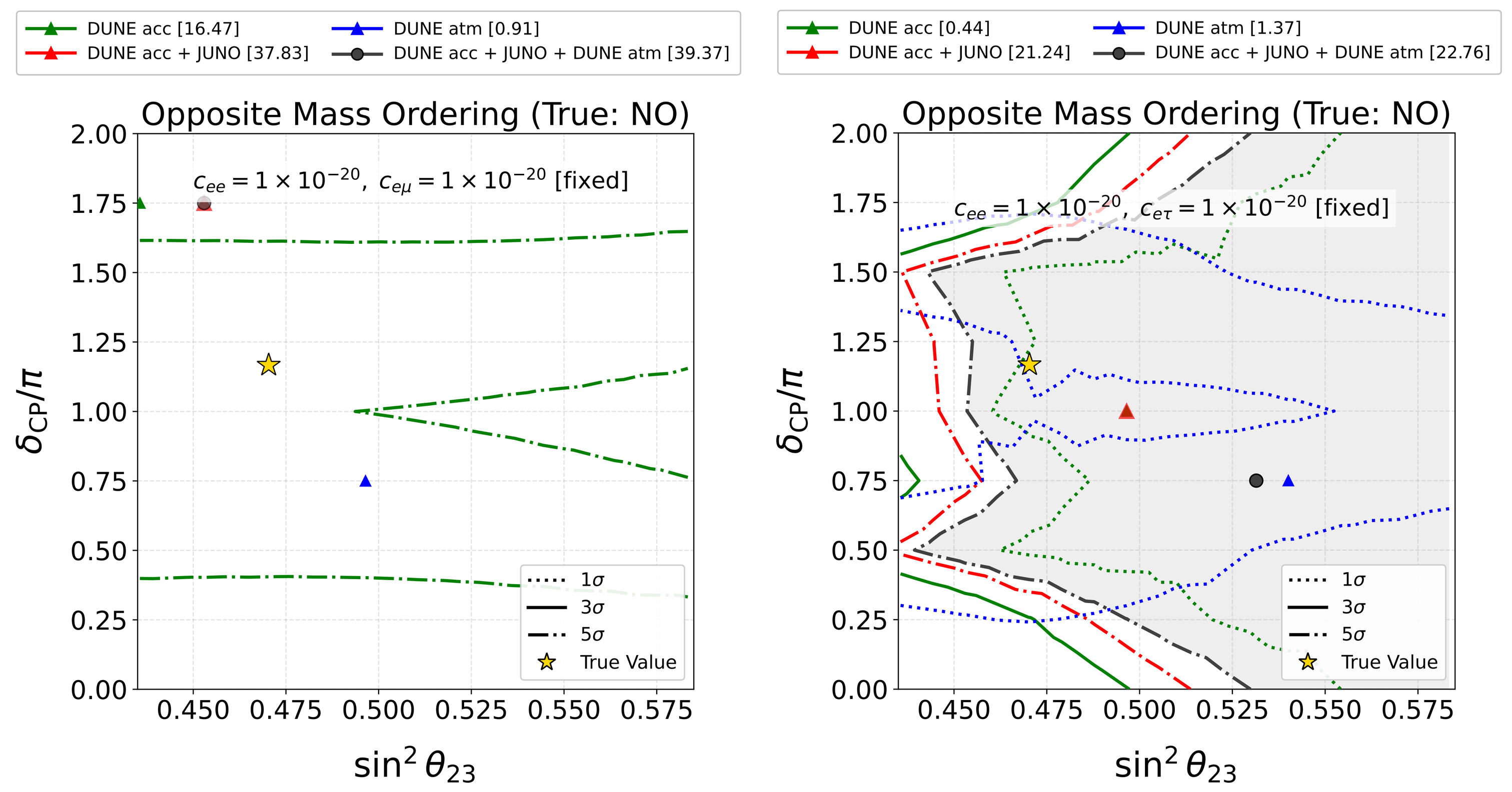


Figure 2. Sensitivity to IO for true NO in test $\sin^2\theta_{23} - \delta_{CP}$ with fix $c_{ee} - c_{e\mu}$[left], $c_{ee} - c_{e\tau}$[right]

1. $c_{ee} - c_{e\tau}$(right) **affects the sensitivity to mass ordering more than** $c_{ee} - c_{e\mu}$(left).
2. **The addition of different channels helps in overcoming the MO degeneracy completely** in the presence of $c_{ee} - c_{e\mu}$ (left) in 5σ significance (as we don't see shaded contours bordered by black curves) with the lowest $\chi^2 = 39.37$.
3. In the $c_{ee} - c_{e\tau}$ (right) case, **only a small portion of the parameter space (on the left of the shaded contours bordered by black curves) has more than** 5σ **sensitivity** to the opposite MO with a minimum $\chi^2 = 22.76$ in the combined scenario.
4. To overcome MO degeneracy in the **presence of** $c_{ee} - c_{e\tau}$, **will need more exposure from all the channels.**

Sensitivity in $\theta_{13} - \Delta m^2_{31}$

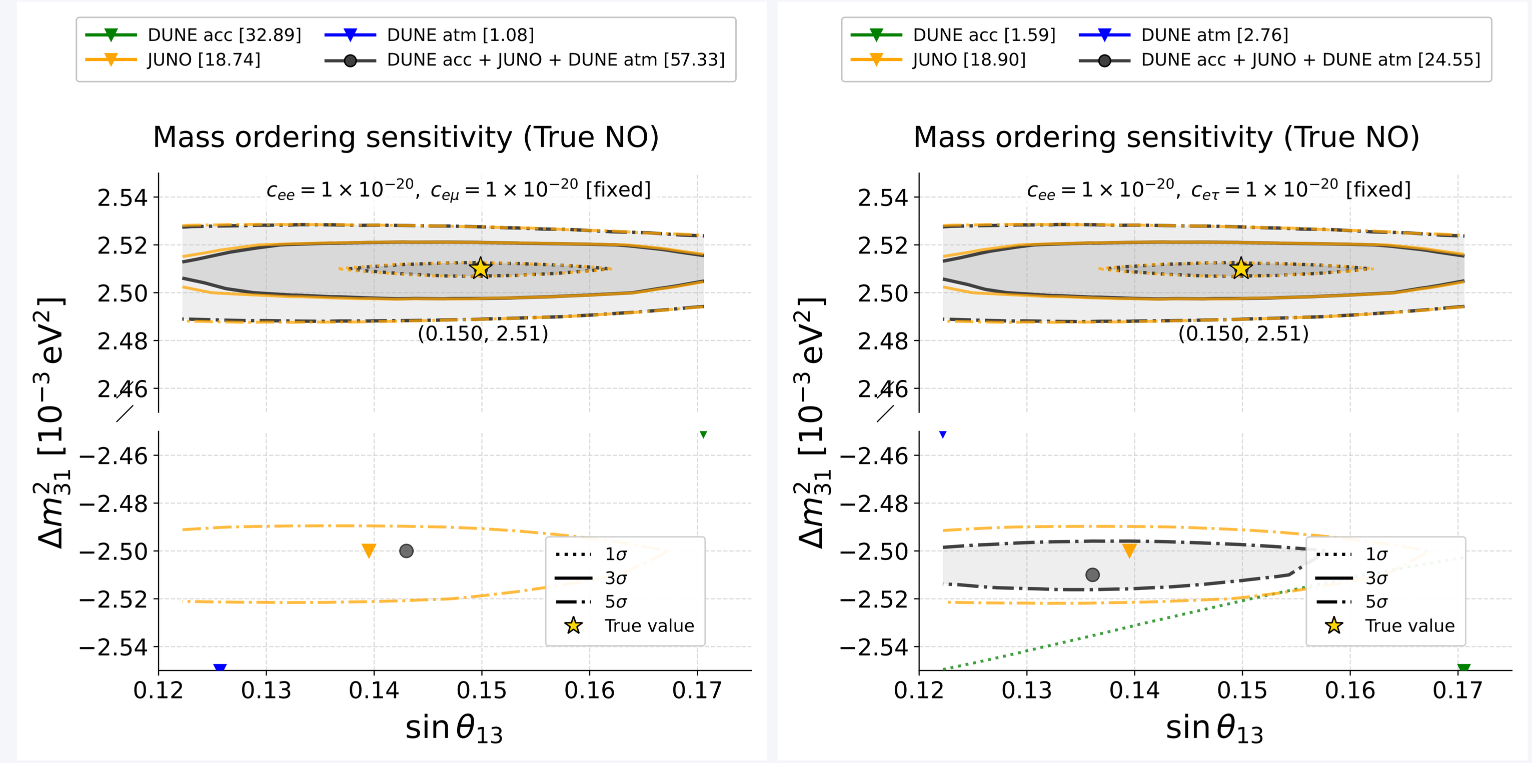


Figure 3. Sensitivity to MO for true NO in test $\sin\theta_{13} - \Delta m^2_{31}$ with fix $c_{ee} - c_{e\mu}$[left], $c_{ee} - c_{e\tau}$[right]

1. $c_{ee} - c_{e\tau}$(right) **affects the sensitivity to MO (bottom panels)** more than $c_{ee} - c_{e\mu}$(left).
2. Sensitivity in $\theta_{13} - \Delta m^2_{31}$ (top panels) **is narrower in the combined case** but needs to be improved with more exposure from different channels when LIV ($c_{ee}, c_{e\mu}, c_{e\tau}$) is present.

Numerical Analysis

We perform pulled chi-square analyses using GLoBES[2, 3] for the DUNE accelerator and JUNO reactor analyses, and use an in-house code for atmospheric neutrinos at DUNE. The total χ^2 is obtained by marginalizing over the oscillation parameters ω and the systematic pull variables ξ,

$$\chi^2 = \min\left[2\sum_i\left[N_i^{\text{test}} - N_i^{\text{true}} + N_i^{\text{true}}\ln\left(\frac{N_i^{\text{true}}}{N_i^{\text{test}}}\right)\right] + \sum_{r=1}^{4}\xi_r^2\right]. \quad (4)$$

Parameter	True Value	Test Values
θ_{12}	33.76°	33.76°
θ_{13}	8.62°	7.0° − 10.0°
θ_{23}	43.3°	41.3° − 49.8°
δ_{CP}	210°	0° − 360°
Δm^2_{21}	7.54×10^{-5} eV^2	7.54×10^{-5} eV^2
Δm^2_{31} (same MO)	2.51×10^{-3} eV^2	$[2.45-2.55]\times10^{-3}$ eV^2
Δm^2_{31} (opposite MO)	2.51×10^{-3} eV^2	$-[2.55-2.45]\times10^{-3}$ eV^2
$c_{ee}, c_{e\mu}, c_{e\tau}$	1×10^{-20}	1×10^{-20}

Table 1. True and test values of the parameters

Take-home Message

- LIV can create degeneracies in θ_{23}, δ_{CP}, and MO determination.
- JUNO improves the combined analysis through **strong sensitivity in** Δm^2_{31} **and MO.**
- DUNE accelerator neutrinos provide strong constraints on δ_{CP} **and** θ_{23} **through** $P_{\mu e}$ **and** $P_{\mu\mu}$.
- Atmospheric neutrinos provide events through their **wide energy and baseline coverage.**
- **Complementarity between different channels allows robust sensitivity when combined.**

References

[1] Sanjib Kumar Agarwalla, Sudipta Das, Sadashiv Sahoo, and Pragyanprasu Swain. Constraining Lorentz invariance violation with next-generation long-baseline experiments. *JHEP*, 07:216, 2023.

[2] Patrick Huber et al. Simulation of long-baseline neutrino oscillation experiments with GLoBES. *Comput. Phys. Commun.*, 167:195, 2005.

[3] Patrick Huber et al. New features in the simulation of neutrino oscillation experiments with GLoBES 3.0. *Comput. Phys. Commun.*, 177:432–438, 2007.

[4] Hai-Xing Lin, Jie Ren, and Jian Tang. Anisotropic Lorentz invariance violation in reactor neutrino experiments. *Front. Phys. (Beijing)*, 21(1):16200, 2026.