Probing Lorentz Invariance Violation with Atmospheric Neutrinos at INO-ICAL

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1. Introduction

- Iron Calorimeter (ICAL) Detector at INO plays a crucial role to establish three-flavour neutrino oscillation in the multi-GeV energy range and over a wide range of baselines by observing atmospheric neutrinos and antineutrinos separately.
- The primary goals of ICAL are to determine Mass Ordering (MO) and precise measurement of neutrino oscillation parameters at 2-3 sector.
- This is also sensitive to probe Beyond the Standard Model (BSM) Physics, such as Lorentz Invariance Violation (LIV), Non Standard Interaction (NSI) with matters, search of Sterile Neutrinos (SNs) ...
- It has unique capability of Charge Identification (CID) of muons (μ^- / μ^+) by magnetizing 50kt of Iron Calorimeter of strength ~1.3 Tesla
- It has ~10% resolution of muon momentum ranging 1-25 GeV and ~1° zenith angle resolution over 15-12800 km range of baselines

2. Lorentz Invariance Violation

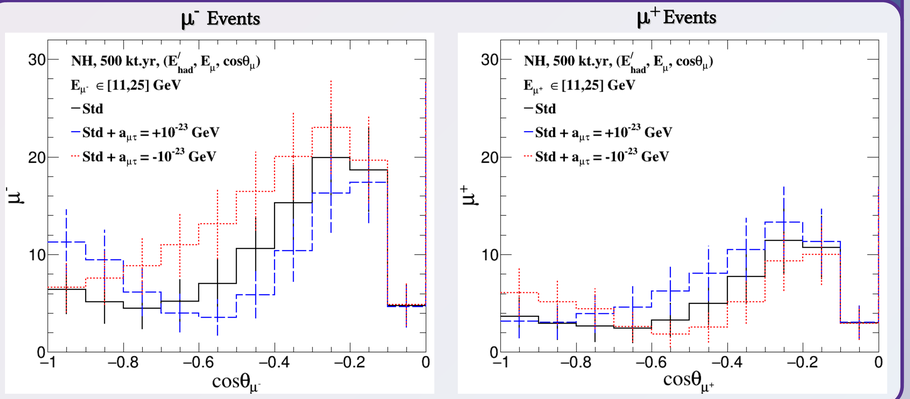
$$\mathcal{L}' \supset \frac{\lambda}{M^k} \langle T \rangle \overline{\psi} \Gamma (i\partial)^k \psi + H.c. \qquad (k = 0, 1, 2...)$$

$$\mathcal{L} = i\frac{1}{2}\overline{\psi}\gamma^\mu \overleftrightarrow{\partial_\mu}\psi - a_\mu \overline{\psi}\gamma^\mu\psi - b_\mu \overline{\psi}\gamma_5\gamma^\mu\psi - m\overline{\psi}\psi; \qquad (k = 0) \text{ CPTV}$$

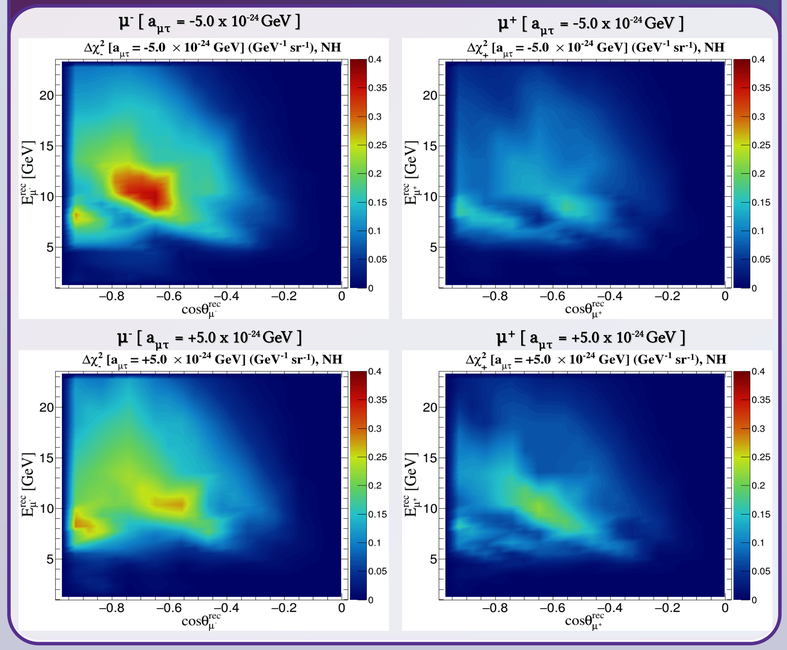
$$\mathcal{H}^{eff}_{ij} = \frac{1}{2E}\left[U.m^2.U^\dagger\right]_{ij} + \frac{1}{E}\left[a^\mu p_\mu\right]_{ij} \qquad a(\overline{\nu}_R) = -a(\nu_L)$$

- NUANCE MC Generator using Neutrino Flux (Honda) at INO site
- Three-Flavour Oscillation Framework; PREM profile; 500 kt.yr (10 yr data)
- Migration matrices from ICAL-Geant4 simulation [arXiv:1304.5115, 1405.7243]
- $\Delta\chi^2$ marginalized over Systematics and Osc. Parameters (Δm^2_{32} , $\sin^2\theta_{23}$, MO)

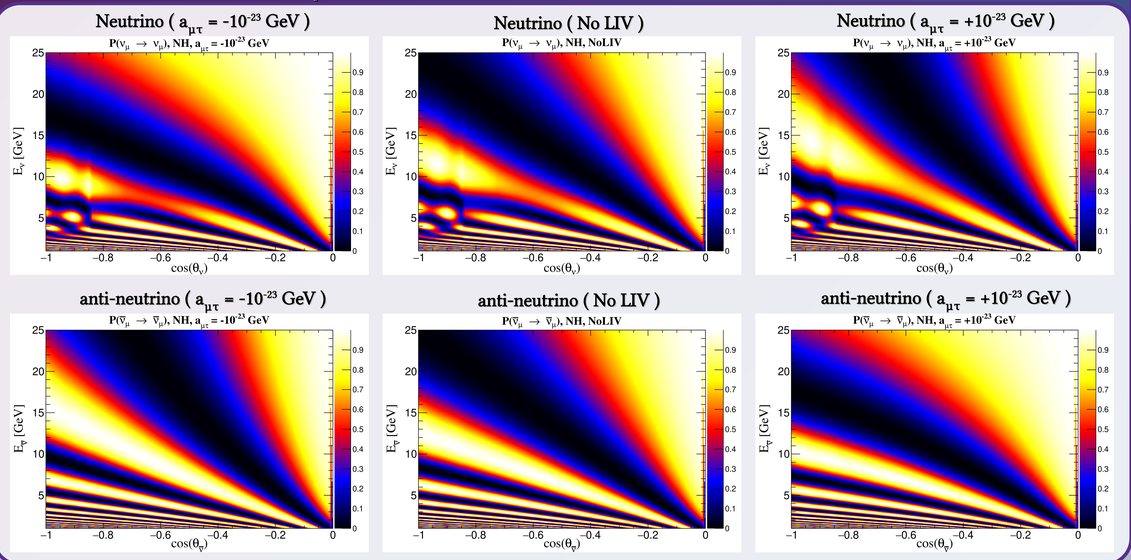
4. Reconstructed Event Distribution



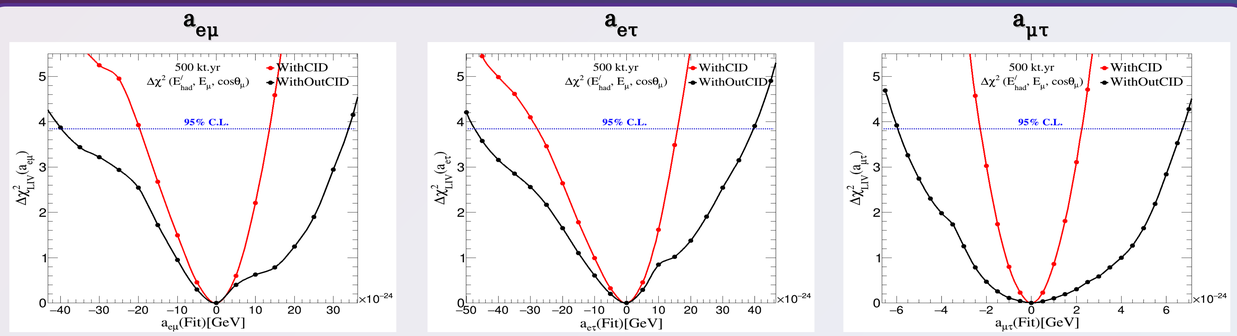
5. $\Delta\chi^2_{LIV}$ [GeV^{-1} sr^{-1}] Distribution



3. Effect of $|a_{\mu\tau}| = 10^{-23}$ GeV on Muon Survival Channel



6. Result & Conclusion



95% C. L. Constraints on CPT-Violating parameters using 50 kt INO-ICAL			
Observable	$a_{e\mu}$ (10^{-23} GeV)	$a_{e\tau}$ (10^{-23} GeV)	$a_{\mu\tau}$ (10^{-23} GeV)
$(E_\mu, \cos\theta_\mu, E'_{had})$ w/o CID	$-3.97 < a_{e\mu} < 3.40$	$-4.71 < a_{e\tau} < 3.96$	$-0.59 < a_{\mu\tau} < 0.67$
$(E_\mu, \cos\theta_\mu, E'_{had})$ w/ CID	$-1.97 < a_{e\mu} < 1.34$	$-2.80 < a_{e\tau} < 1.58$	$-0.22 < a_{\mu\tau} < 0.22$

* Marginalized over systematic uncertainties and oscillation parameters (Δm^2_{32} , $\sin^2\theta_{23}$, MO)

Comparison with Super-K (SK) and ICE CUBE (I.C) Constraints			
	$a_{e\mu}$ (10^{-23} GeV)	$a_{e\tau}$ (10^{-23} GeV)	$a_{\mu\tau}$ (10^{-23} GeV)
†SK (95% C.L.)	$\lvert a_{e\mu}\rvert < 2.55$	$\lvert a_{e\tau}\rvert < 4.96$	$\lvert a_{\mu\tau}\rvert < 0.82$
‡I.C (90% C.L.)	–	–	$\lvert a_{\mu\tau}\rvert < 0.35$

†Phys.Rev. D 91, 052003 ‡Nature Physics 14(9) 2018, pp. 961966

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