Exploring CP sensitivity in the presence of Lorentz invariance violations at T2HK/T2HKK

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Abstract

- Breaching of Lorentz invariance can lead to CPT violations.
- Conservation/violation of CP symmetry in leptonic sector is essential in understanding the universe's evolution.
- We examine how CPT-violating LIV parameters $a_{e\mu}, a_{e\tau}, a_{\mu\tau}$ impact CP violation within two proposed setups for the forthcoming T2HK experiment: (i) individual detectors placed at 295 km and 1100 km [T2HKK], and (ii) a detector with double capacity positioned at 295 km [T2HK].
- We explore[1] the role of different beam channels and baseline and their synergy in the context of CP sensitivity.

Lorentz Invariance Violations (LIV)

The total Hamiltonian in presence of LIV is given by,

$$H = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta_{21} & 0\\ 0 & 0 & \Delta_{31}\end{pmatrix}U^\dagger + \begin{pmatrix}A & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right] + H_{LIV}, \quad (1)$$

$A = 2E\sqrt{2}G_F N_e = 7.6\times 10^{-5}\rho(\text{g/cc})\text{E(GeV)}\,\text{eV}^2$, G_F: Fermi Constant, N_e: No. density of e^- in matter, ρ: matter density.

$$H_{LIV} = \begin{bmatrix} a_{ee} & \mathbf{a}_{e\mu} & \mathbf{a}_{e\tau}\\ a^\star_{e\mu} & a_{\mu\mu} & \mathbf{a}_{\mu\tau}\\ a^\star_{e\tau} & a^\star_{\mu\tau} & a_{\tau\tau}\end{bmatrix} - \frac{4}{3}E\begin{bmatrix} c_{ee} & c_{e\mu} & c_{e\tau}\\ c^\star_{e\mu} & c_{\mu\mu} & c_{\mu\tau}\\ c^\star_{e\tau} & c^\star_{\mu\tau} & c_{\tau\tau}\end{bmatrix} \quad (2)$$

$a_{\alpha\beta}$: CPT violating, $c_{\alpha\beta}$: CPT conserving.

Oscillation Probability

$$P_{\mu e} = 2\alpha s_{13}\sin 2\theta_{12}\sin 2\theta_{23}\frac{\sin[\hat{A}\Delta]}{\hat{A}}\frac{\sin[(\hat{A}-1)\Delta]}{\hat{A}-1}\cos(\Delta+\delta_{13})$$

$$+ 4s^2_{13}s^2_{23}\frac{\sin^2[(\hat{A}-1)\Delta]}{(\hat{A}-1)^2} + P^{a_{e\mu}}_{\mu e} + P^{a_{e\tau}}_{\mu e} \quad (3)$$

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23}\sin^2\Delta + P^{a_{\mu\tau}}_{\mu\mu} \quad (4)$$

$$P^{a_{e\mu}}_{\mu e} \simeq \frac{4|a_{e\mu}|\hat{A}\Delta s_{13}\sin 2\theta_{23}\sin\Delta}{\sqrt{2}G_F N_e}[Z_{e\mu}\sin\psi_{e\mu} + W_{e\mu}\cos\psi_{e\mu}] \quad (5)$$

$$P^{a_{e\tau}}_{\mu e} \simeq \frac{4|a_{e\tau}|\hat{A}\Delta s_{13}\sin 2\theta_{23}\sin\Delta}{\sqrt{2}G_F N_e}[Z_{e\tau}\sin\psi_{e\tau} + W_{e\tau}\cos\psi_{e\tau}] \quad (6)$$

$$P^{a_{\mu\tau}}_{\mu\mu} = \frac{4|a_{\mu\tau}|\hat{A}\Delta\sin 2\theta_{23}\sin\Delta}{\sqrt{2}G_F N_e}[Z_{\mu\tau}\cos\phi_{\mu\tau} + W_{\mu\tau}\cos\phi_{\mu\tau}] \quad (7)$$

where $\Delta = \Delta_{31}L/4E$, $\alpha = \Delta_{21}/\Delta_{31}$, $\hat{A} = 2\sqrt{2}G_F N_e E/\Delta_{31}$, $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$, $\psi_{e\mu} = \delta_{13} + \phi_{e\mu}$, $\psi_{e\tau} = \delta_{13} + \phi_{e\tau}$

$$Z_{e\mu} = -\cos\theta_{23}\sin\Delta,\ W_{e\mu} = c_{23}\left(\frac{s^2_{23}\sin\Delta}{\Delta.c^2_{23}} + \cos\Delta\right) \quad (8)$$

$$Z_{e\tau} = \sin\theta_{23}\sin\Delta,\ W_{e\tau} = s_{23}\left(\frac{\sin\Delta}{\Delta} - \cos\Delta\right) \quad (9)$$

$$Z_{\mu\tau} = -\sin^2 2\theta_{23}\cos\Delta,\ W_{\mu\tau} = \frac{-\cos^2 2\theta_{23}\sin\Delta}{\Delta} \quad (10)$$

- $P_{\mu e}$[2] depends on $a_{e\mu}, a_{e\tau}$ and their respective phases.
- $P_{\mu\mu}$[2, 3] depends on $a_{\mu\tau}$ and $\phi_{\mu\tau}$ at leading order.

Tokai to Hyper-Kamiokande (T2HK) and Tokai to Hyper-Kamiokande and Korea (T2HKK)

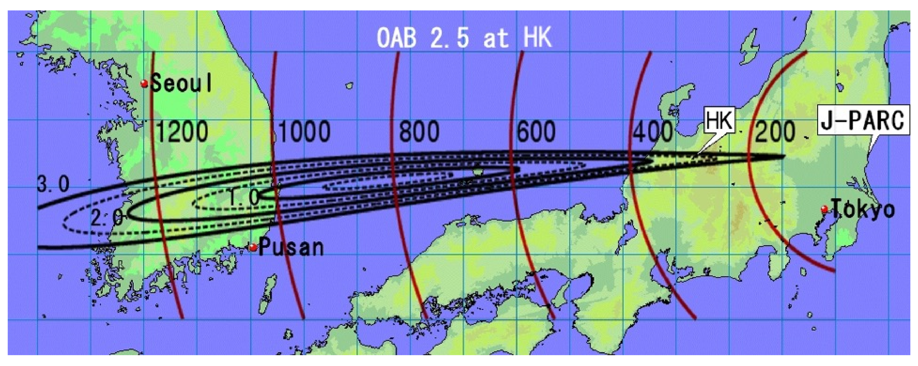

Figure 1. Schematic of T2HK and T2HKK experiment [neutrino.skku.edu]

- T2HK[4]: Detector of 374 kt at 295 km (2.5° off-axis beam) in Hyper-K site. The 1^{st} oscillation maxima is at 0.6 GeV.
- T2HKK[5]: One Detector of 187 kt at 295 km in Hyper-K site and another similar detector in Korea at 1100 km (1.5° off-axis beam), the 2^{nd} oscillation maxima is at 0.6 GeV.
- 1.3 MW beam with an exposure of 27×10^{21} POT.

Channel	295 km	1100 km
ν_e Appearance	3.2%(5%)	3.8%(5%)
ν_μ Disappearance	3.6%(5%)	3.8%(5%)
$\bar{\nu}_e$ Appearance	3.9%(5%)	4.1%(5%)
$\bar{\nu}_\mu$ Disappearance	3.6%(5%)	3.8%(5%)

Table 1. The signal (background) normalization uncertainties

Numerical Analysis

GLoBES[6, 7] has been used with the values in tables 1,2.

Parameter	True Value	Marginalization Range
θ_{12}	33.4°	N.A.
θ_{13}	8.62°	N.A.
θ_{23}	49°	(39°, 51°)
δ_{13}	(−180°, 180°)	0°, 180°
Δ_{21}	7.4×10^{-5} eV^2	N.A.
$\|\Delta_{31}\|$	2.5×10^{-3} eV^2	$(2.4, 2.6)\times 10^{-3}$ eV^2
$a_{\alpha\beta}$	10^{-23} GeV	$(10^{-22}, 10^{-24})$ GeV
$\phi_{\alpha\beta}$	(−180°, 180°)	0°, 180°

Table 2. True values and range of marginalization of all the parameters

Single Detector Analysis

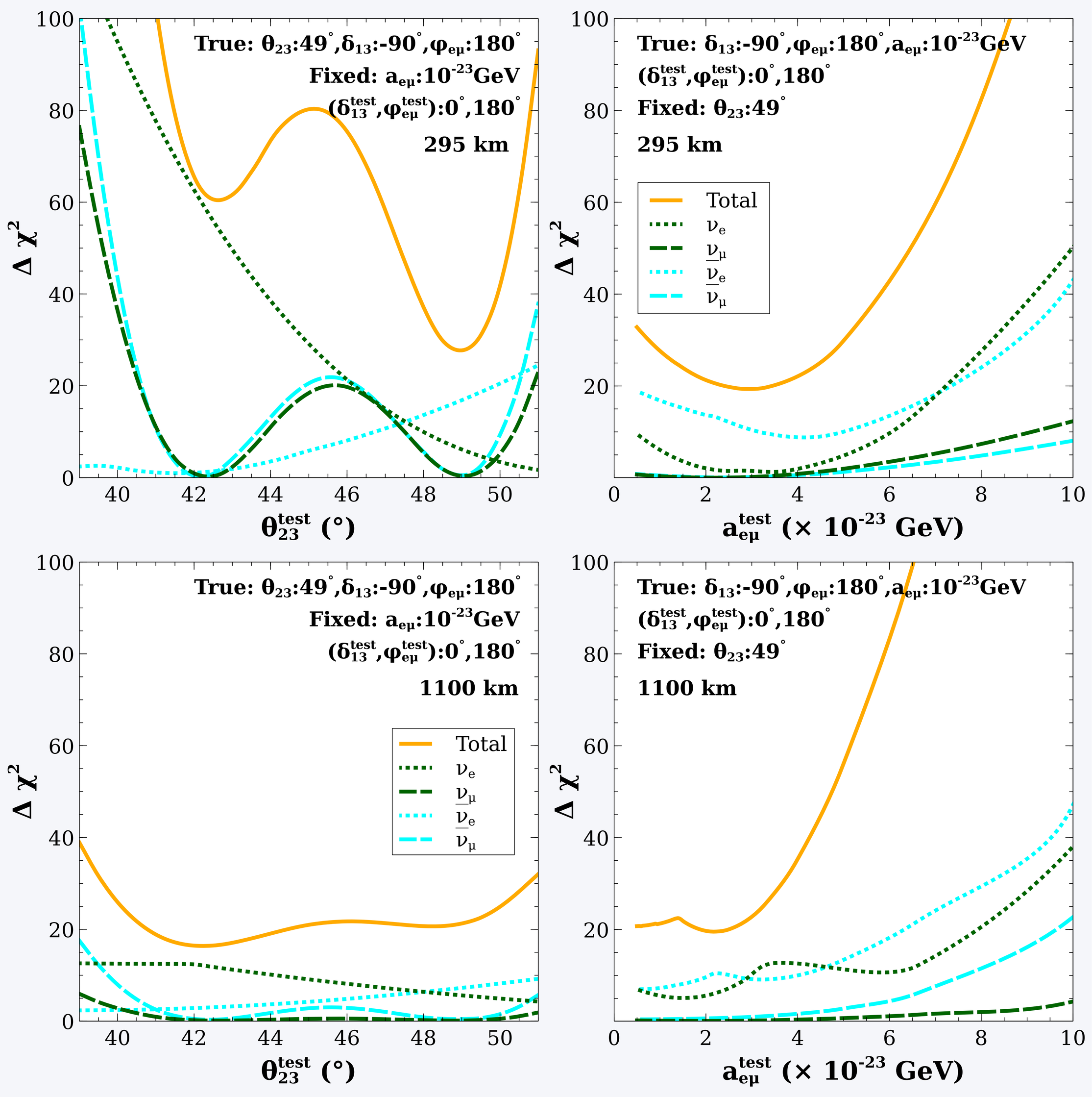

Figure 2. Sensitivity of CP conservation versus $\theta^{\text{test}}_{23}$ (left) and $a^{\text{test}}_{e\mu}$ (right)

- The marginalization in $\theta_{23}, a_{\alpha\beta}$ enhances sensitivity.
- Major contribution of χ^2 comes from $\nu_e, \bar{\nu}_e$ channels and $\nu_\mu, \bar{\nu}_\mu$ channels dictate the nature of total χ^2 curve.

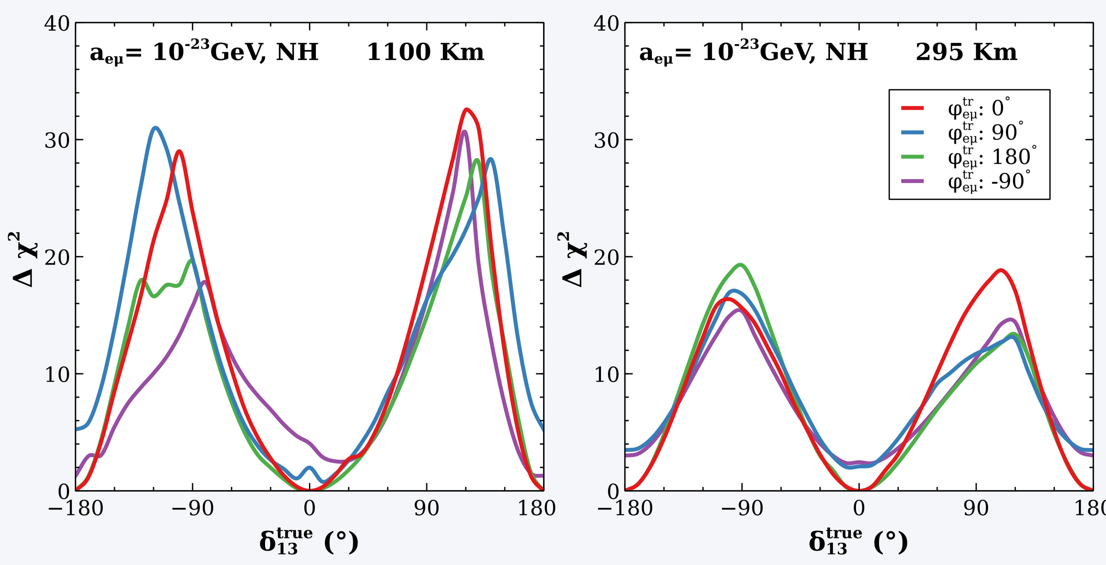

Figure 3. Sensitivity of CP conservation versus $\delta^{\text{true}}_{13}$ in presence of $a_{e\mu} = 10^{-23}$ GeV at 295 km (left) and 1100 km (right)

- The sensitivity at 1100 km is better than 295 km as variation in probability is higher at 2^{nd} osc. maxima.
- At 1100 km and 295 km, the nature of sensitivity is different for the same values of $\phi^{\text{true}}_{e\mu}$.

Comparison between T2HK and T2HKK

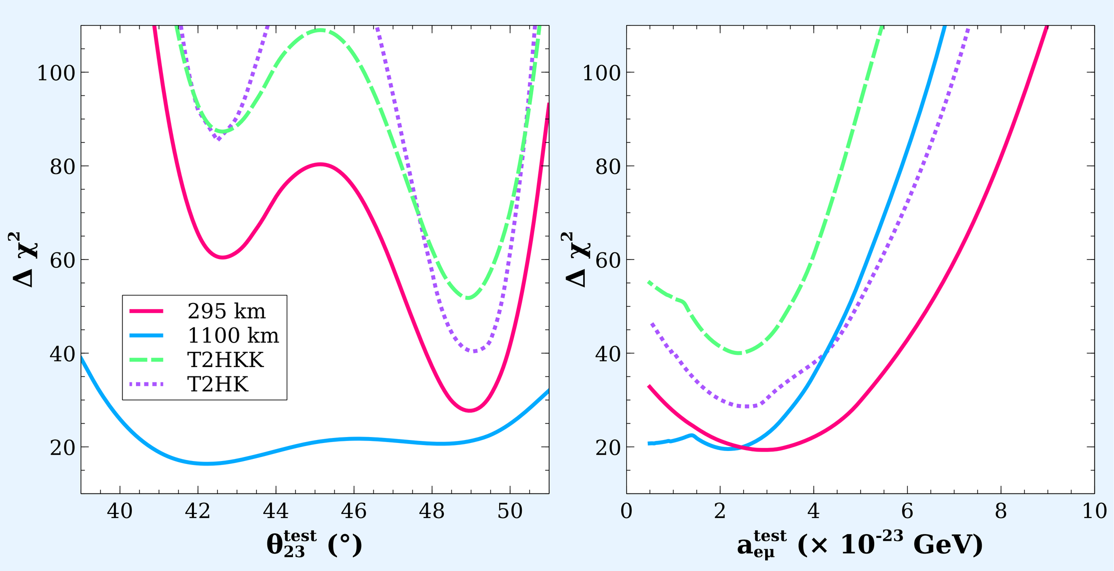

Figure 4. Sensitivity of CP versus $\theta^{\text{test}}_{23}$ (left) and $a^{\text{test}}_{e\mu}$ (right)

Due to minima of χ^2 occurring at different test values of $\theta_{23}, a_{e\mu}$ at 295 km and 1100 km baseline, in T2HKK, minimum χ^2 is higher than in T2HK (only 295 km contributes).

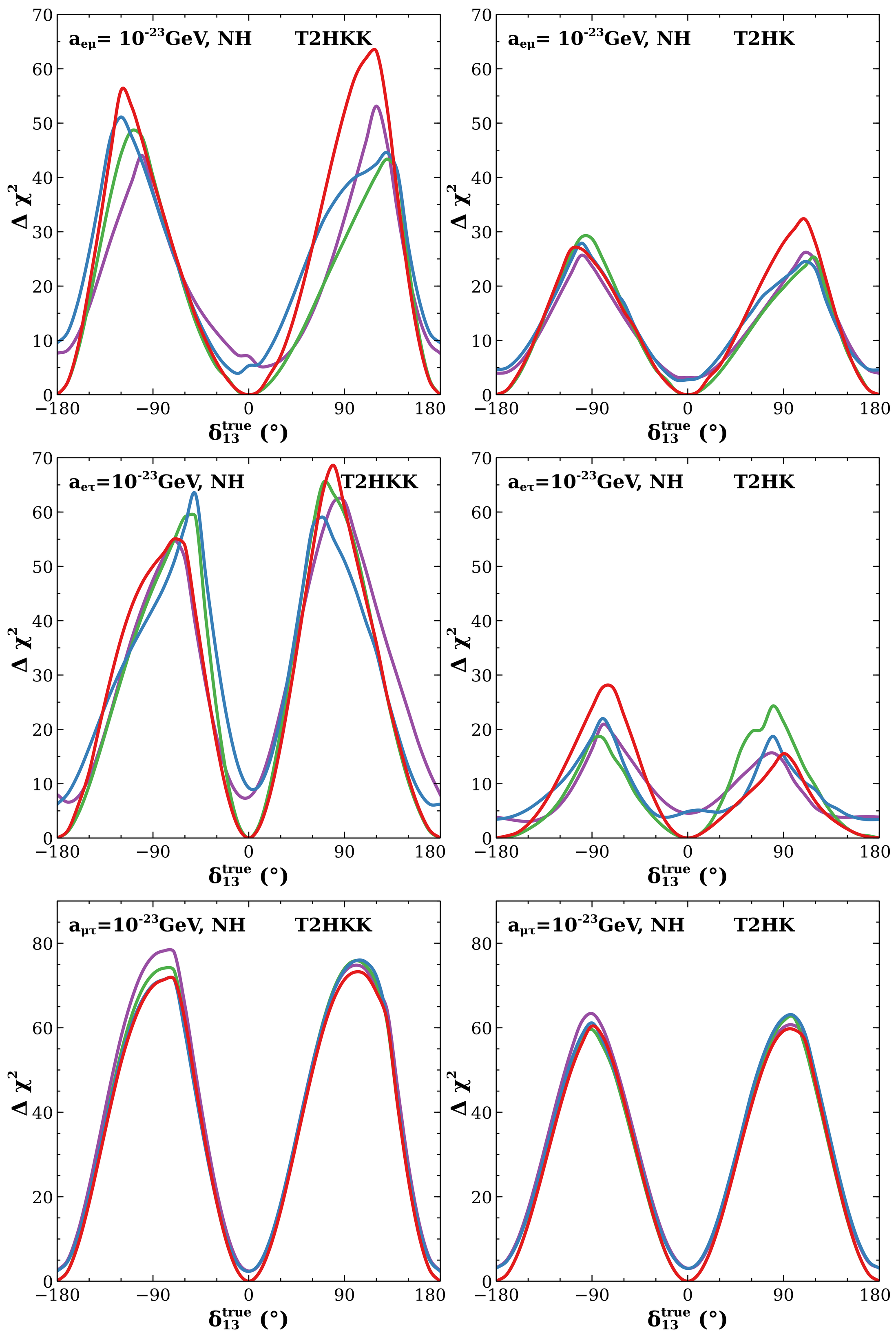

Figure 5. χ^2 as a function of δ^{true}_{13} for true values of $\theta_{23} = 49°$ with $a_{e\tau} = 10^{-23}$ GeV for T2HKK (left) and T2HK (right)

- In presence of $a_{e\mu}, a_{e\tau}$ CP sensitivity is double in T2HKK w.r.t. T2HK due to synergy between 1100 km & 295 km.
- The sensitivity is slightly higher in T2HKK when $a_{\mu\tau}$ is present as no contribution from $\nu_e, \bar{\nu}_e$ channels.

Precision analysis of $\delta_{CP}, \phi_{e\mu}, \phi_{e\tau}$

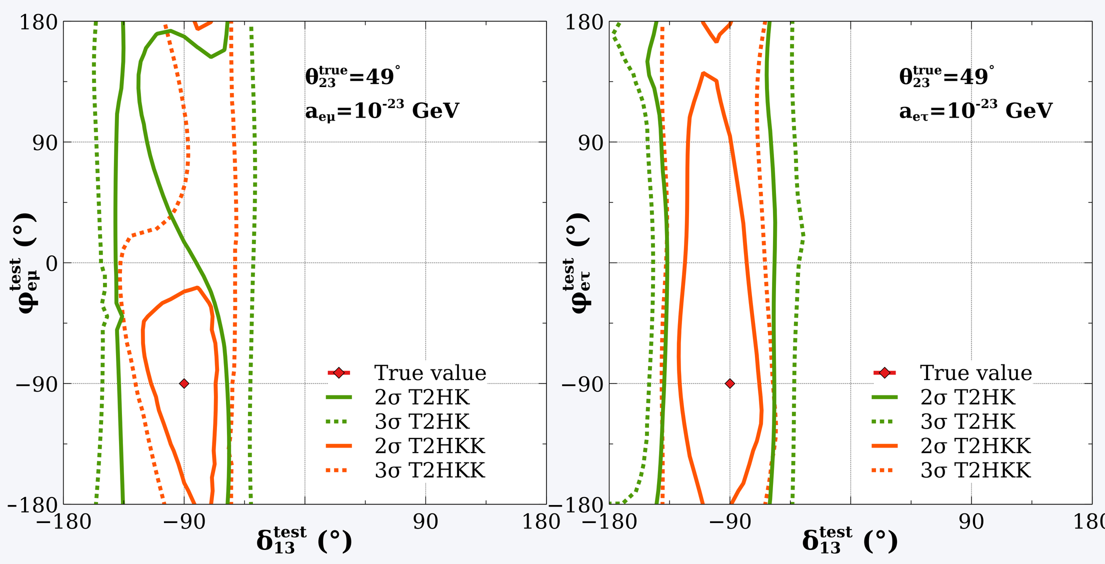

Figure 6. 2σ(solid), 3σ(dotted) contours[2 d.o.f.] for true LIV parameter $a_{e\mu}$ (left), $a_{e\tau}$ (right) having value of 10^{-23} GeV for T2HK(green), T2HKK (orange) configuration for true values of $\delta_{13} = \phi_{e\mu} = \phi_{e\tau} = -90°$.

Summary

1. At a fixed baseline, CP sensitivity increases due to the synergy between appearance and disappearance channels.
2. Addition of 295 km with 1100 km significantly enhances the CP sensitivity in T2HKK, making it a better choice. Two different baselines provide synergy while marginalization.
3. Sensitivity of the LIV phases is poor, as seen from fig.6. But, sensitivity to δ_{13} is better at T2HKK.

References

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