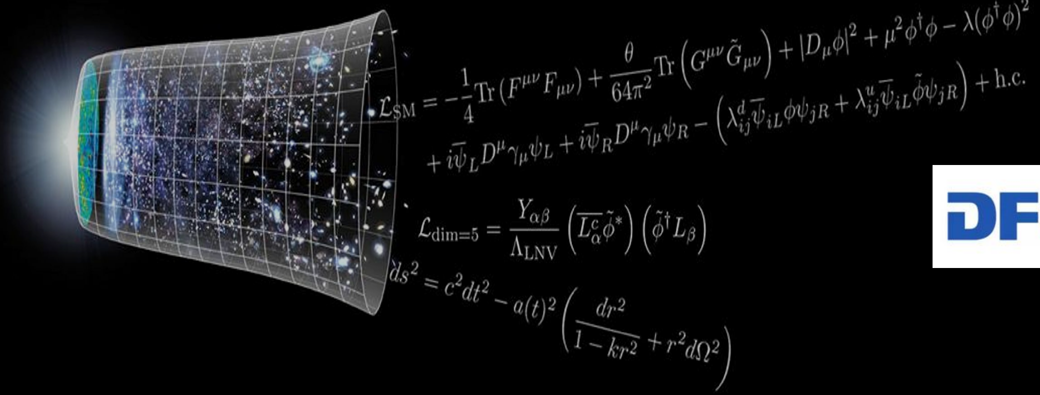
# Searches for T violation in neutrino oscillations with T2HK and DUNE



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arXiv:2408.06419

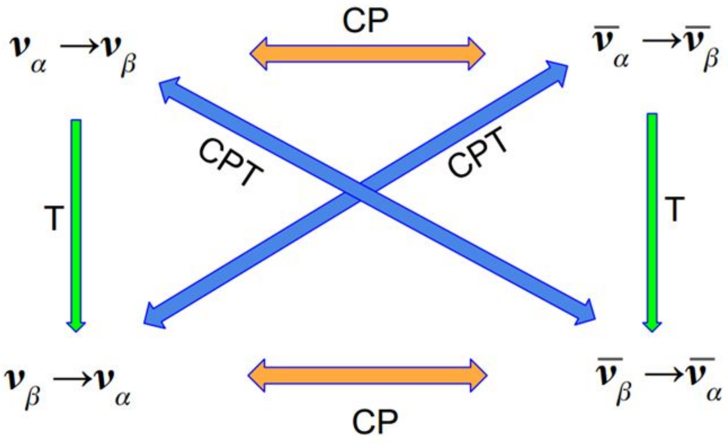
**Kiran Sharma, ISAPP, KIT / Bad Liebenzell, 16–27 Sept 2024**

# Outline

- **CP and T violation**
- **Model Independent Approach**
- **T violation test with New Physics**

# CP and T violation in neutrino oscillations

- In two flavor picture, no fundamental CP and T violation.
- In three flavor picture, fundamental CP violation due to leptonic phase.
- Normal matter (no. of particles is not equal to no. of antiparticles) induces extrinsic(fake) CP violation.
- Matter with symmetric density profiles don’t induce fake T violation, asymmetric profiles do.



$$
\begin{aligned}
\Delta P^{CP}_{\alpha\beta} &= P_{\alpha\beta} - \bar{P}_{\alpha\beta}\,, \\
\Delta P^{T}_{\alpha\beta} &= P_{\alpha\beta} - P_{\beta\alpha}\,, \\
\Delta P^{CPT}_{\alpha\beta} &= P_{\alpha\beta} - \bar{P}_{\beta\alpha}\,.
\end{aligned}
$$

# Model Dependent Approach in SM

- Standard approach is to perform a model dependent fit to data (combining accelerator and reactor data).
- Not possible to construct model-independent CP asymmetric observables.
- CPV signature in neutrino oscillation experiments is rather indirect.
- Observation of CPV is equivalent to establishing $\delta$ different from 0 and $\pi$ at a certain confidence level.
- T violation is rather hard by exchanging the source and detector.

# Model Independent Test for T violation

- Standard Approach is to perform a **model-dependent fit** to data, which assumes only 3 standard model neutrinos exist.
- However, new physics scenarios like non-unitary mixings, non-standard neutrino interactions, presence of sterile neutrinos act as **New Source of CP and T violation.**
- Develop a largely **model-independent test** covering a wide class of non-standard scenarios.

Schwetz, Segarra, On T violation in non-standard neutrino oscillation scenarios [2112.08801 ]
Schwetz, Segarra, Model-independent test of T violation in neutrino oscillations [2106.16099]

# Assumptions of Model

- The evolution of the flavor state is described :

$$i\partial_t|\psi\rangle = H(E_\nu)|\psi\rangle \,.$$

- Allow for non-unitary mixing among energy eigenstates and flavor states at detection and production:

$$|\nu_\alpha^{s,d}\rangle = \sum_{i=1}^{3}(N_{\alpha i}^{s,d})^*|\nu_i\rangle$$

- Medium effects are defined by constant matter density approximately.

- The eigenvalues and their energy dependence resembles approximately the one following from the effective neutrino mass squared differences in matter in the SM.

# Appearance Probability

- The appearance probability is defined as :

$$P = \left| \sum_{i=1}^{3} c_i e^{-i\lambda_i L} \right|^2 , \qquad c_i \equiv N^{s*}_{\mu i} N^{d}_{ei} ,$$

- Expanding it out, in terms of new variable, ε that describes deviation from unitarity and leads to a "zero distance effect".

$$P = \left| c_2(e^{-i(\lambda_2-\lambda_1)L} - 1) + c_3(e^{-i(\lambda_3-\lambda_1)L} - 1) + \epsilon \right|^2 ,$$

$$\epsilon \equiv \sum_{i=1}^{3} c_i . \qquad P^{\mathrm{ND}} \equiv P(L \to 0) = |\epsilon|^2 .$$

# T violation Test for 2 experiments

$$P_{\text{even}} = \gamma_2 c_2 (c_2 - \epsilon) + \gamma_3 c_3 (c_3 - \epsilon) + \gamma_{23} c_2 c_3 + \epsilon^2$$

With the abbreviations

$$\gamma_i = 4 \sin^2 \phi_{i1} \quad (i = 2, 3)\,,$$
$$\gamma_{23} = 8 \sin \phi_{21} \sin \phi_{31} \cos(\phi_{31} - \phi_{21})\,.$$

$$\left\{ \quad \phi_{ij} \approx \frac{\Delta m^2_{ij,\text{eff}}(E_\nu) L}{2 E_\nu} \right.$$

- There is always a fit for two experiments plus a near detector, which provide three data points.
- Under certain conditions the quadratic nature of the parameter dependence does not provide a solution for three data points.

Define a model-independent observable $X_T$, built out of the observed probabilities $P_{\nu_\mu \to \nu_e}(L)$ at two baselines $L_1$, $L_2$ and at a near detector.

$$X_T \equiv P_{\mathrm{even}}(L_2) - P_{\mathrm{even}}(L_1) - \epsilon^2 \delta_0 = \delta_2 c_2^2 + \delta_3 c_3^2 + \delta_{23} c_2 c_3$$

With,

$$\delta_0 = \frac{\delta_2 + \delta_3 - \delta_{23}}{\delta_{23}^2/(\delta_2 \delta_3) - 4} \, .$$

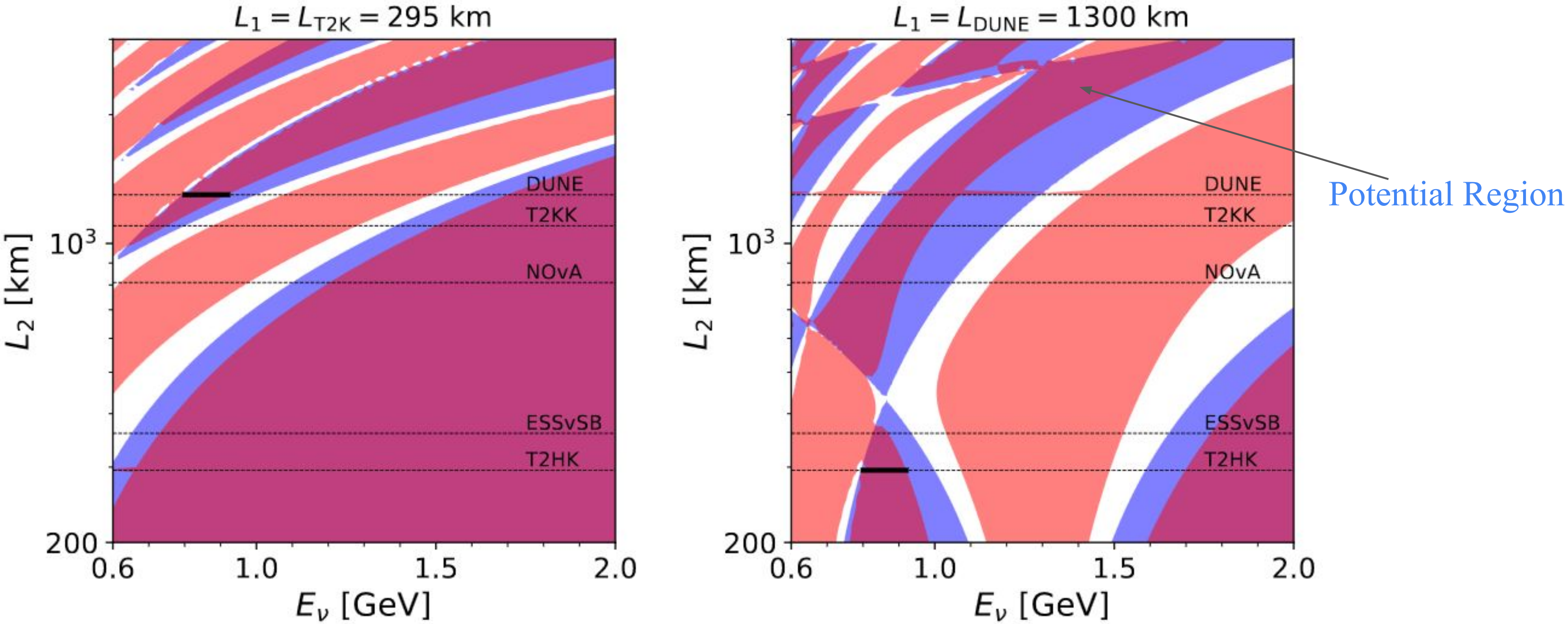
The right-hand side of eq. is a non-negative function of $c_2$ and $c_3$ if

$$\delta_3 > 0 \quad \text{and} \quad \delta_2 > 0 \, , \quad \text{and}$$

$$|\alpha| < 2 \quad \text{with} \quad \alpha \equiv \frac{\delta_{23}}{\sqrt{\delta_2 \delta_3}} \, .$$

$$X_T^{\mathrm{obs}} = P^{\mathrm{obs}}_{\nu_\mu \to \nu_e}(L_2) - P^{\mathrm{obs}}_{\nu_\mu \to \nu_e}(L_1) - \delta_0 P^{\mathrm{ND,obs}}_{\nu_\mu \to \nu_e}$$

If it can be established within experimental uncertainties that $X_T^{\mathrm{obs}} < 0$ and the conditions are fulfilled then T has to be violated in Nature.



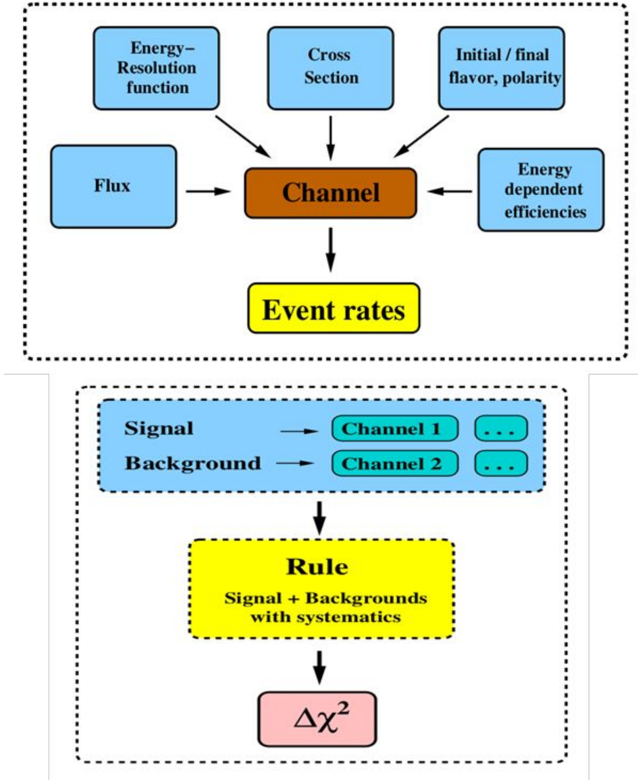
Potential Region

$$E_\nu \in [0.80, 0.92]\,\mathrm{GeV} \qquad \text{(neutrinos/NO, anti-neutrinos/IO)}$$
$$E_\nu \in [0.86, 0.99]\,\mathrm{GeV} \qquad \text{(neutrinos/IO, anti-neutrinos/NO)}$$

# Simulation Details

- Modified Probability engine for new physics
- Flux Spectrum
- Cross-Sections
- Event-Rates
- Bin-based energy smearing
- Detector Resolution
- Systematics

GLoBES Toolkit



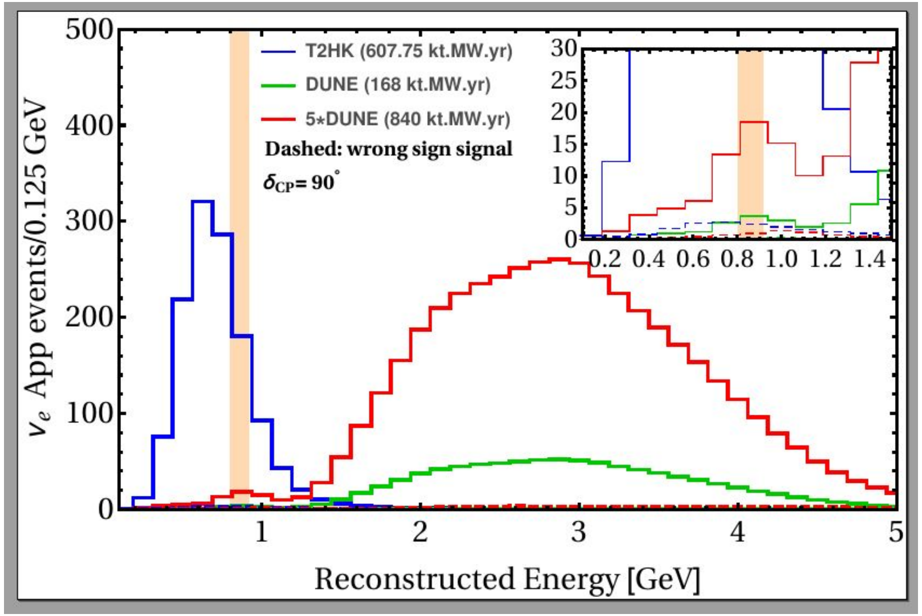
# Hypothesis testing

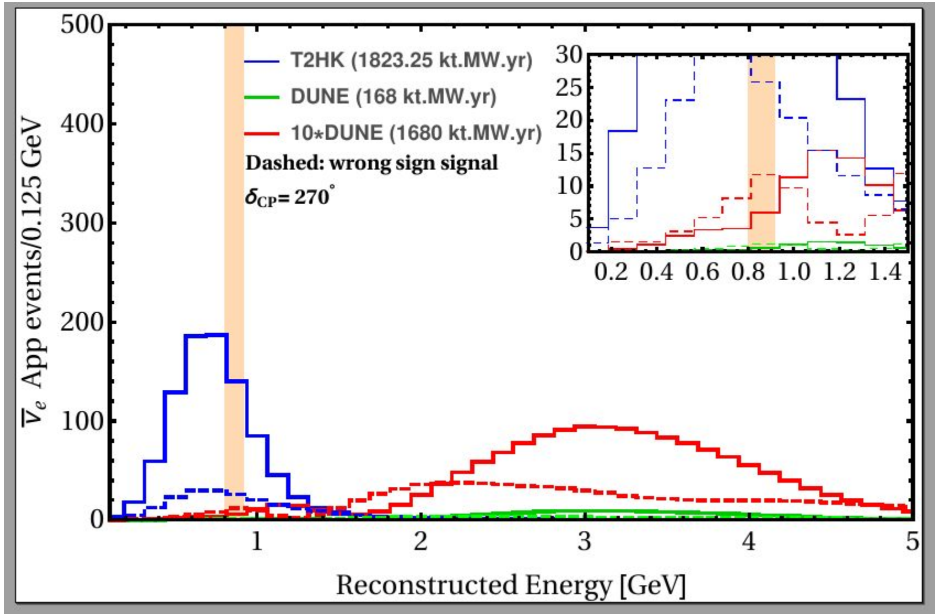
$$\chi^2_{\text{even}}(E;\theta) = \sum_{a=1}^{N_L} \left[ \frac{P^{\text{even}}_{\mu e}(L_a, E;\theta) - p^{\text{app}}_a}{\sigma^{\text{app}}_a} \right]^2$$

where, $P_a^{\text{app}}$ is calculated in the standard three flavor scenario.

The value of $\chi 2$ min (E) is an indication of T violation by data.

# Event Spectra





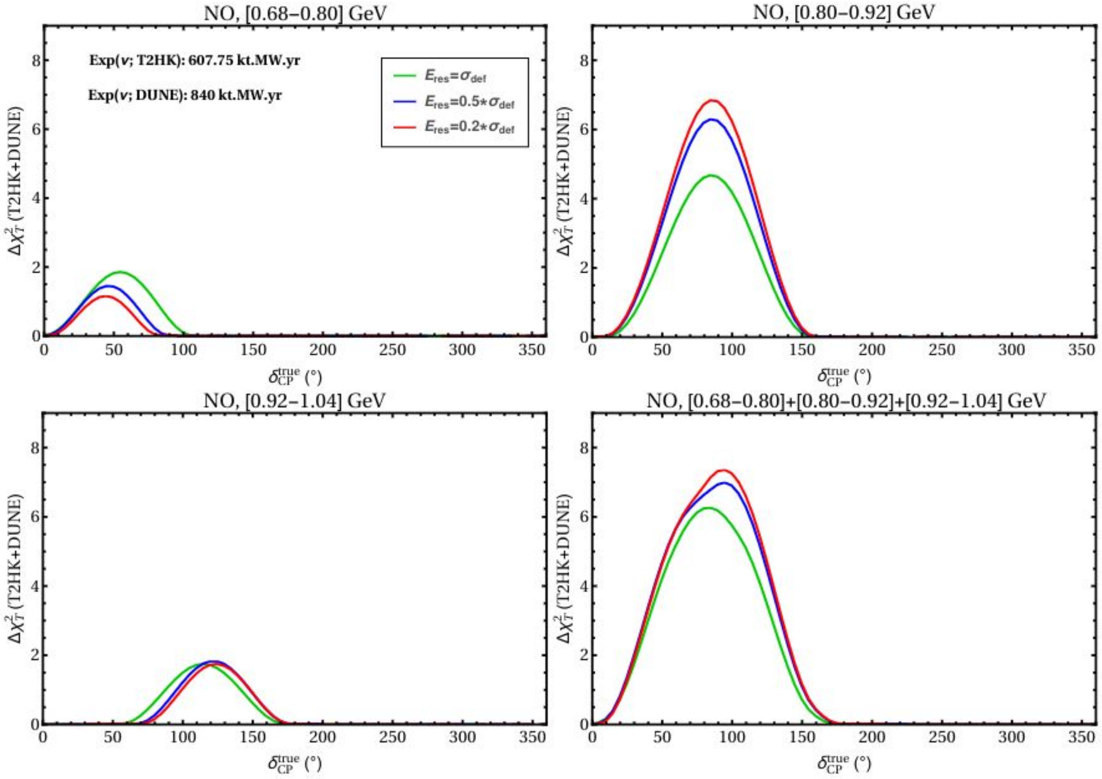
# Hypothesis testing

Default Configuration:

T2HK[L=295 km]:
Runtime(neutrino mode): 2.5 yrs
Detector mass: 187 kton

DUNE[L=1300 km]:
Runtime(neutrino mode): 3.5 yrs
Detector mass: 40 kton

*5 times of actual runtime for Dune.

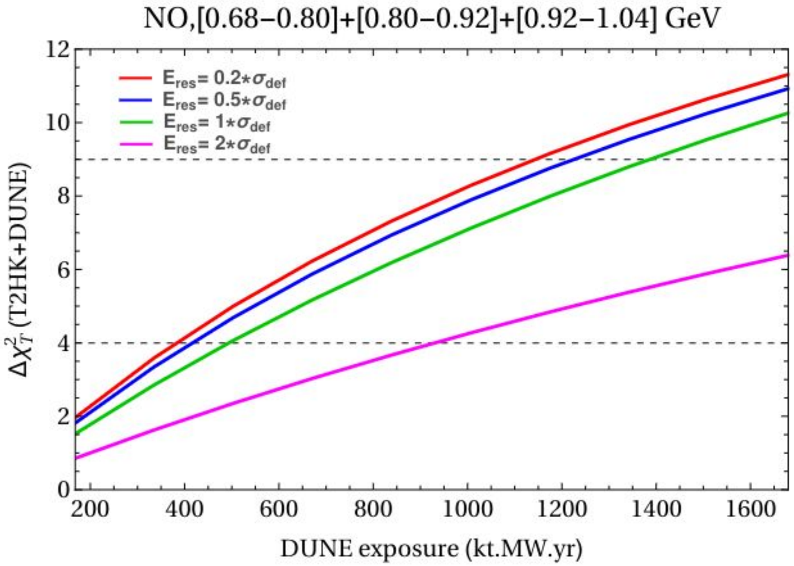


# Exposure and Resolution Effect

Standard Resolution:
T2HK~16%
DUNE~8.5% (better than CDR and TDR files)

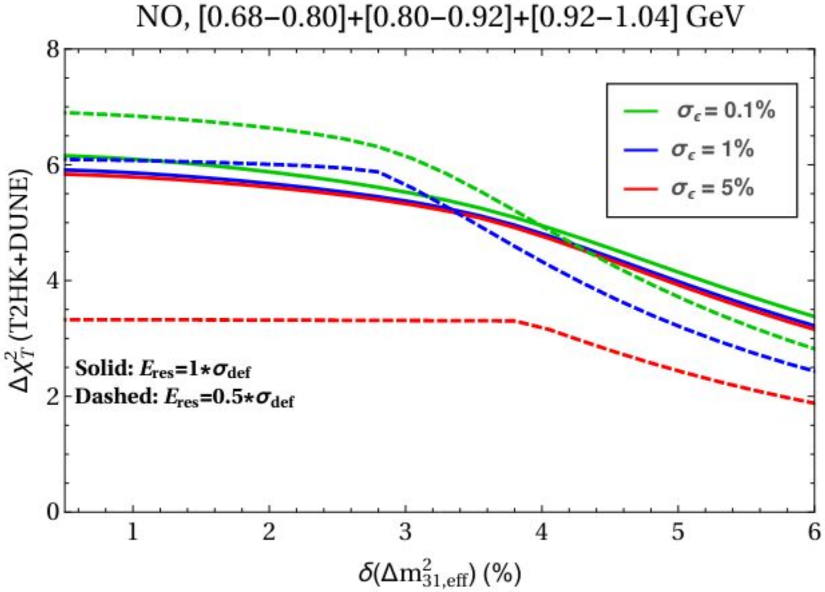
$$E_{res} = \alpha.E+\beta.\sqrt{E}+\gamma$$

$\sigma_{def}(\text{T2HK},\nu)$: $\{\alpha, \beta,\gamma\}=\{0.12,0.07,0.0\}$
$\sigma_{def}(\text{T2HK},\bar{\nu})$: $\{\alpha, \beta,\gamma\}=\{0.12,0.0,0.09\}$
$\sigma_{def}(\text{DUNE},\nu)$: $\{\alpha, \beta,\gamma\}=\{0.045,0.001,0.048\}$
$\sigma_{def}(\text{DUNE},\bar{\nu})$: $\{\alpha, \beta,\gamma\}=\{0.026,0.001,0.085\}$



Chatterjee, et.al , Impact of Improved Energy Resolution on DUNE sensitivity to Neutrino Non-Standard Interactions [2106.04597]

# Zero-distance effect and prior on oscillation frequencies



# Conclusions

- The variable $X_T$ depending solely on oscillation probabilities provides an efficient way to probe T violation signature experimentally.
- We find the potential region for studying T violation with T2HK and DUNE at low energies.
- The improved statistics and better detector resolution, particularly for **DUNE**, plays a crucial role in improving sensitivities.
- There is a possibility of finding the potential region at higher energies and longer baselines.

# Thank You ☺