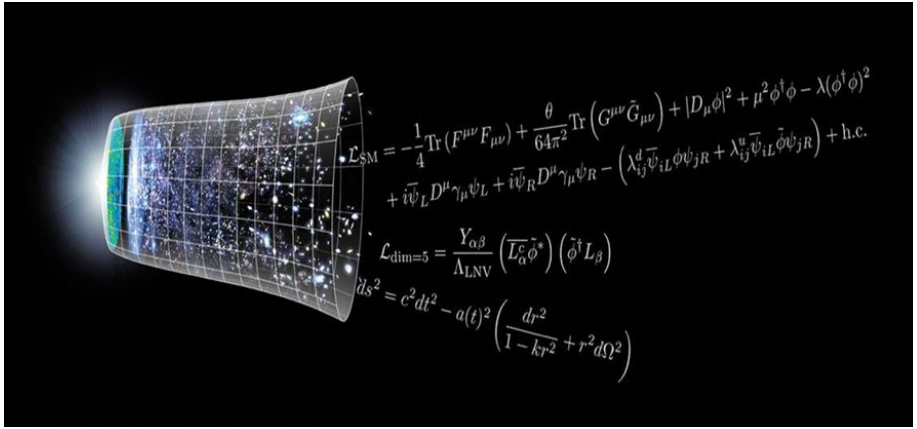
Model Independent test for T-violation with T2HK and DUNE



Sabya Sachi Chatterjee, Thomas Schwetz, Kiran Sharma*

Kiran Sharma, Invisibles Workshop 2024, Bologna Italy, July 01-05, 2024

Appearance Probability

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

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

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

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

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

$$\begin{aligned} \gamma_i &= 4 \sin^2 \phi_{i1} \quad (i = 2, 3) , \\ \gamma_{23} &= 8 \sin \phi_{21} \sin \phi_{31} \cos(\phi_{31} - \phi_{21}) \end{aligned} \quad \left\{ \phi_{ij} \approx \frac{\Delta m^2_{ij,\mathrm{eff}}(E_\nu) L}{2 E_\nu} \right.$$

$$\delta_i = \gamma_i(L_2) - \gamma_i(L_1) \quad (i = 2, 3, 23)$$

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,

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

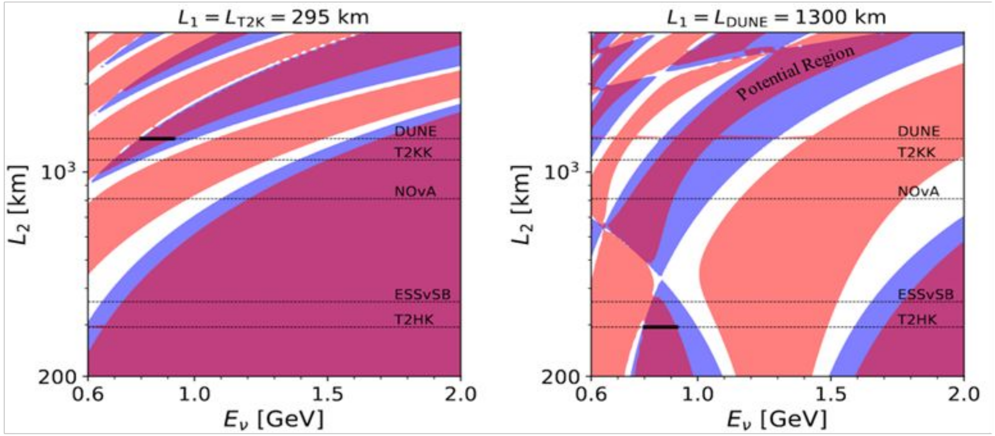
The right-hand side of eq. is a non-negative function of c_2 and c_3 if

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

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

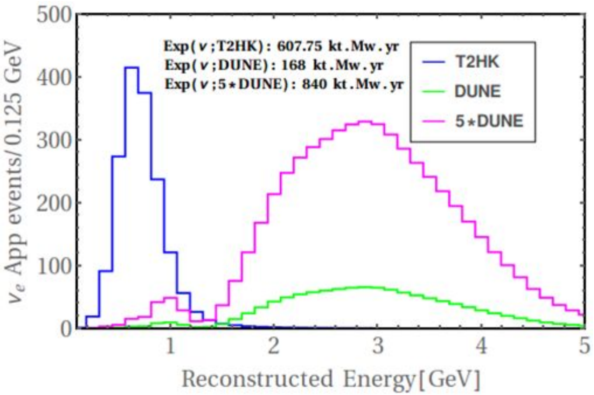
$$X_T^{\text{obs}} = P^{\text{obs}}_{\nu_\mu \to \nu_e}(L_2) - P^{\text{obs}}_{\nu_\mu \to \nu_e}(L_1) - \delta_0 P^{\text{ND,obs}}_{\nu_\mu \to \nu_e}$$

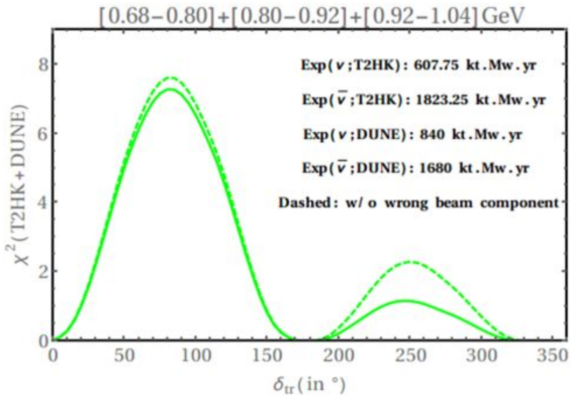
If it can be established within experimental uncertainties that $X_T^{\text{obs}} < 0$ and the conditions are fulfilled then T has to be violated in nature

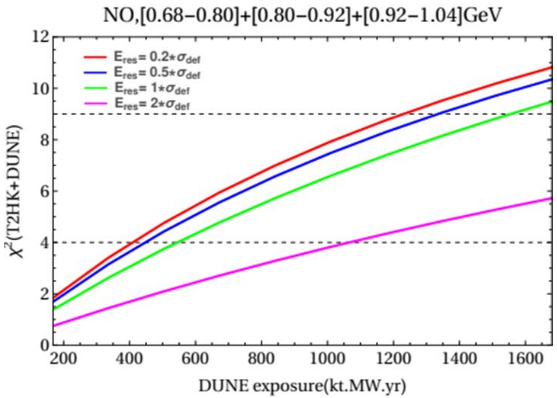


$$E_\nu \in [0.80, 0.92]\,\text{GeV} \qquad (\text{neutrinos/NO, anti-neutrinos/IO})$$
$$E_\nu \in [0.86, 0.99]\,\text{GeV} \qquad (\text{neutrinos/IO, anti-neutrinos/NO})$$

Results







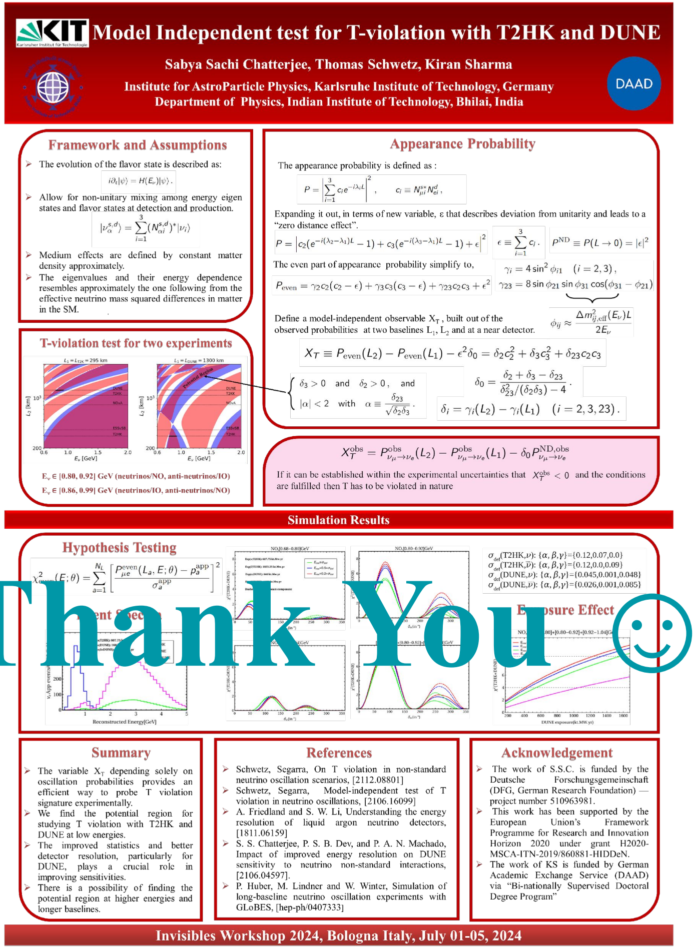
$$\chi^2_{\text{even}}(E;\theta) = \sum_{a=1}^{N_L}\left[\frac{P^{\text{even}}_{\mu e}(L_a,E;\theta) - p^{\text{app}}_a}{\sigma^{\text{app}}_a}\right]^2$$

Where, P_a^{app} is calculated in the standard three flavor scenario.

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

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

Thank You ☺



Model Independent test for T-violation with T2HK and DUNE

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Framework and Assumptions

- The evolution of the flavor state is described as:

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

- Allow for non-unitary mixing among energy eigen states 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.

T-violation test for two experiments

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

Appearance Probability

The appearance probability is defined as :

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

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

$$P = \left|c_2(e^{-i(\lambda_2-\lambda_1)L} - 1) + c_3(e^{-i(\lambda_3-\lambda_1)L} - 1) + \epsilon\right|^2 \qquad \epsilon \equiv \sum_{i=1}^{3} c_i\,. \qquad P^{\rm ND} \equiv P(L \to 0) = |\epsilon|^2$$

The even part of appearance probability simplify to,

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

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

Define a model-independent observable X_T, built out of the observed probabilities at two baselines L_1, L_2 and at a near detector.

$$\phi_{ij} \approx \frac{\Delta m^2_{ij,\rm eff}(E_\nu)L}{2E_\nu}$$

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

$$\begin{cases} \delta_3 > 0 \quad \text{and} \quad \delta_2 > 0\,, \quad \text{and} \\ |\alpha| < 2 \quad \text{with} \quad \alpha \equiv \dfrac{\delta_{23}}{\sqrt{\delta_2\delta_3}}\,. \end{cases} \qquad \delta_0 = \frac{\delta_2 + \delta_3 - \delta_{23}}{\delta_{23}^2/(\delta_2\delta_3) - 4}\,.$$

$$\delta_i = \gamma_i(L_2) - \gamma_i(L_1) \quad (i = 2, 3, 23)\,.$$

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

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

Simulation Results

Hypothesis Testing

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

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

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Exposure Effect

Summary

- 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.

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