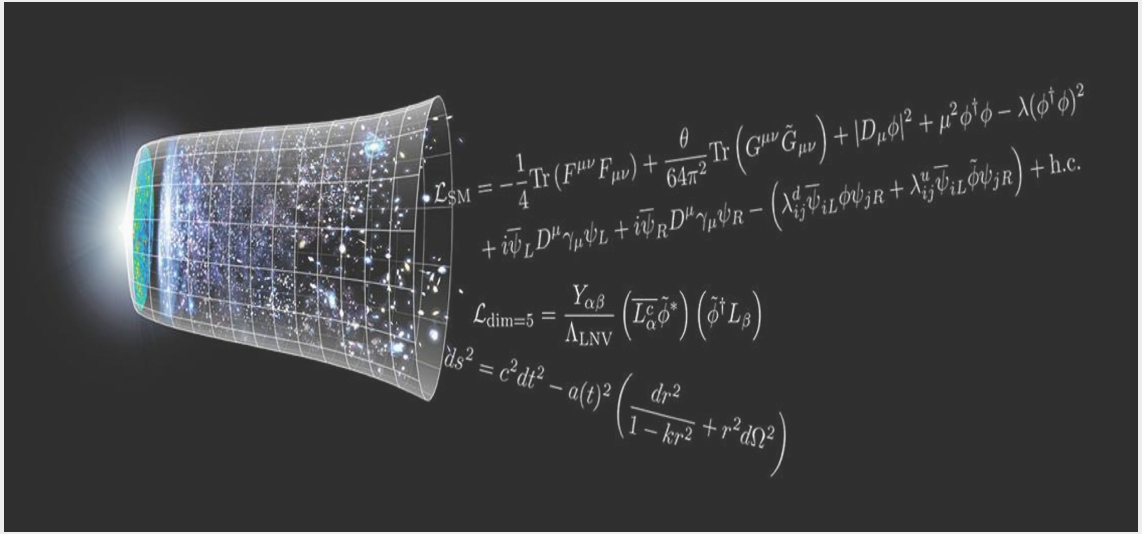
T violation searches with DUNE and T2HK

Karlsruher Institut für Technologie



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Sabya Sachi Chatterjee, Sudhanwa Patra, Thomas Schwetz, Kiran Sharma*

Kiran Sharma, NuFact 2025, Spine, Liverpool, 1-6 September

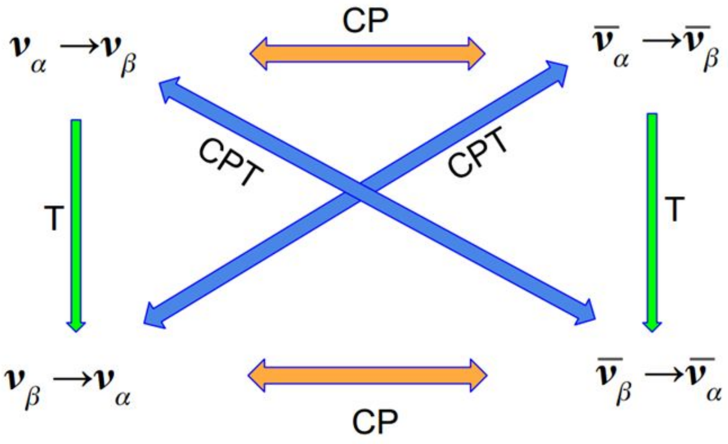
Outline

- **CP and T violation.**
- **Model Independent T violation test with New Physics.**
- **T -violation test with 3 flavor scenario only.**

Schwetz, Sharma et.al, Model-independent search for T violation with T2HK and DUNE [2408.06419]
Schwetz, Sharma et.al, T versus CP effects in DUNE and T2HK [2508.04766]

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.



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

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 δ different from 0 and π at a certain confidence level.

  → Appears in Unitary Parameterization(U_{PMNS})
- 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 new physics is a sub-leading contribution to the standard framework.

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".

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

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

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

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

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

- One may think there is always a fit for two experiments plus a near detector, which provide three data points.
- However, 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.

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

With,

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

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

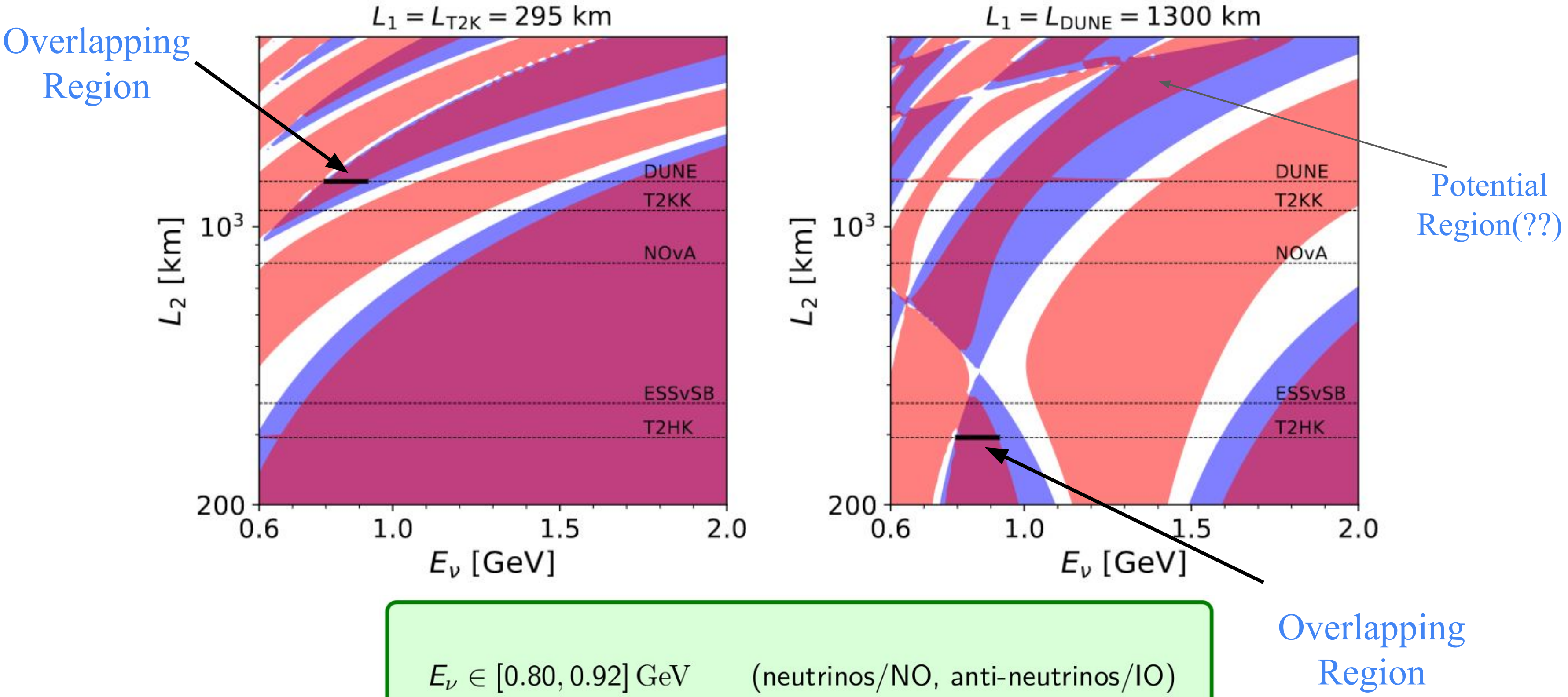
The right-hand side of eq. is a non-negative function of c_2 and c_3 if

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

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

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

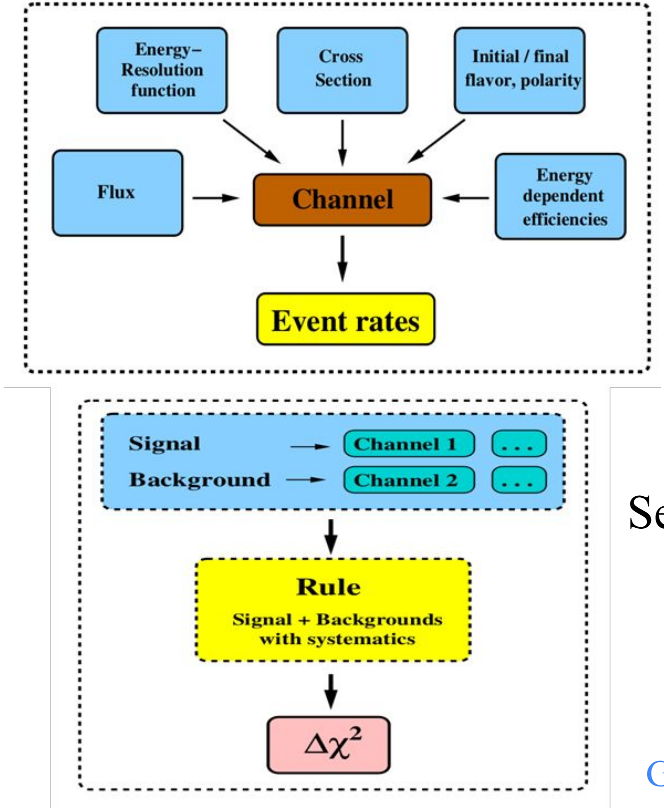
If it can be established within experimental uncertainties that $X_T^{\text{obs}} < 0$ and the conditions are fulfilled then T has to be violated in Nature.

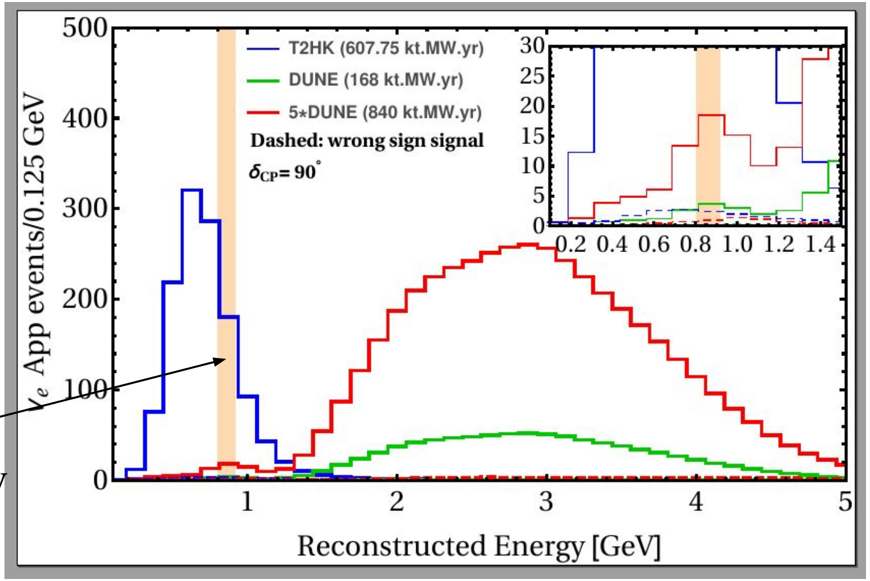


$E_\nu \in [0.80, 0.92]$ GeV (neutrinos/NO, anti-neutrinos/IO)

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

Simulation Details





T2HK: 180 events

DUNE: 18 events

GLoBES Toolkit

We work with neutrino running mode

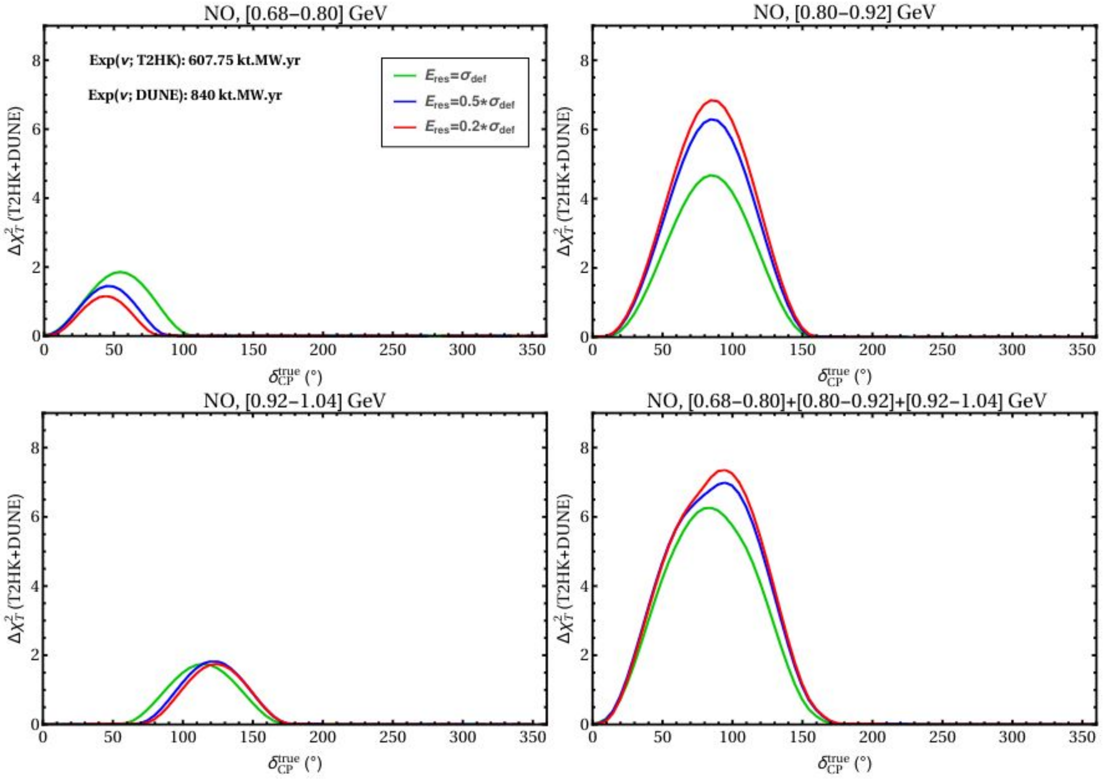
Hypothesis testing

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

DUNE exposure: achieved roughly after 13 years of operation

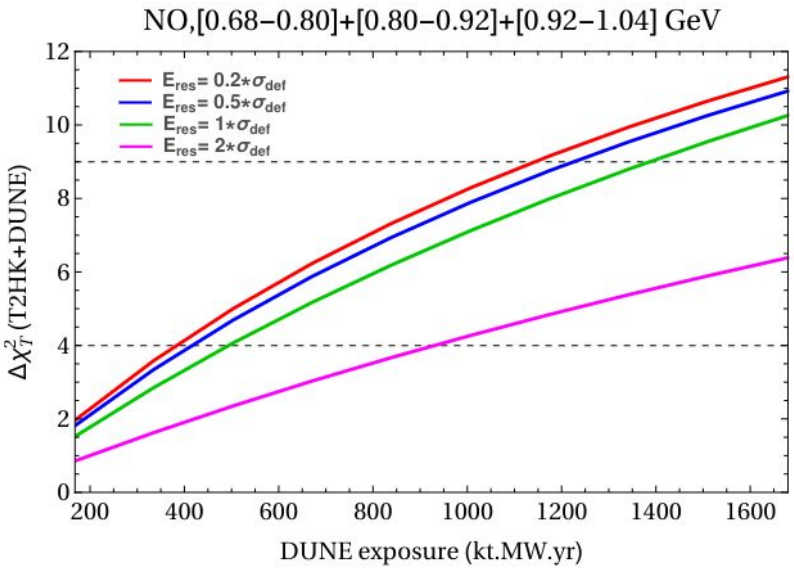


Exposure and Resolution Effect

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

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

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,$\bar{\nu}$): $\{\alpha, \beta,\gamma\}=\{0.026,0.001,0.085\}$



A. Friedland, et.al, Understanding the energy resolution of liquid argon neutrino detectors [1811.06159]
Chatterjee, et.al, Impact of Improved Energy Resolution on DUNE sensitivity to Neutrino Non-Standard Interactions [2106.04597]

Key Results of Model-independent Approach

- 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.
- A sufficiently strong constraint on $\nu_\mu \rightarrow \nu_e$ transitions at zero distance is required, at least at the $\lesssim 1\%$ level.

3 Flavor Scenario

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Model-Independent vs. 3-Flavor Analysis

Model-Independent:

- Uses **X_T observable** (probability difference at two baselines).
- No assumptions on c_i coefficients (includes the various possible scenarios of new physics).
- High exposure: **840 kton (DUNE)(**~ 13 yrs runtime).

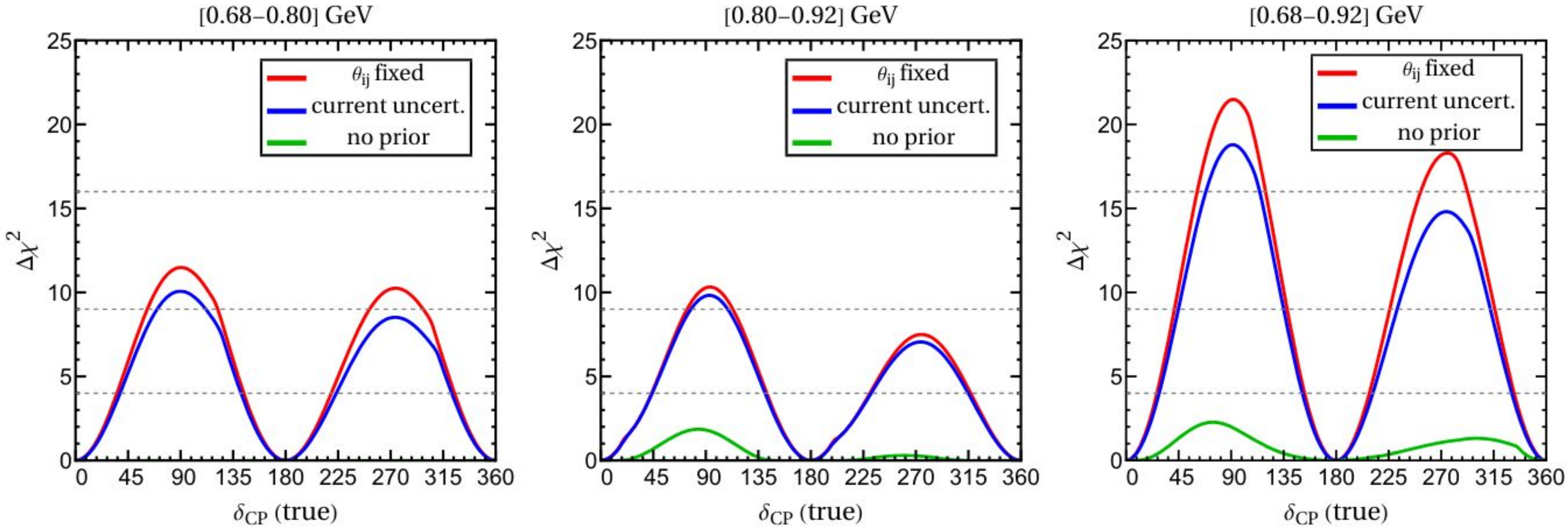
3-Flavor Framework:

- Based on **L-odd component** of transition probabilities at fixed energy.
- c_i coefficients tied to mixing-angle uncertainties (restricted to unitarity mixing).
- Realistic exposure: **300 kton (**~ 7 yrs runtime**).**

A complimentary analysis using X_T observable within 3 flavor scenario is also performed (see Backup)

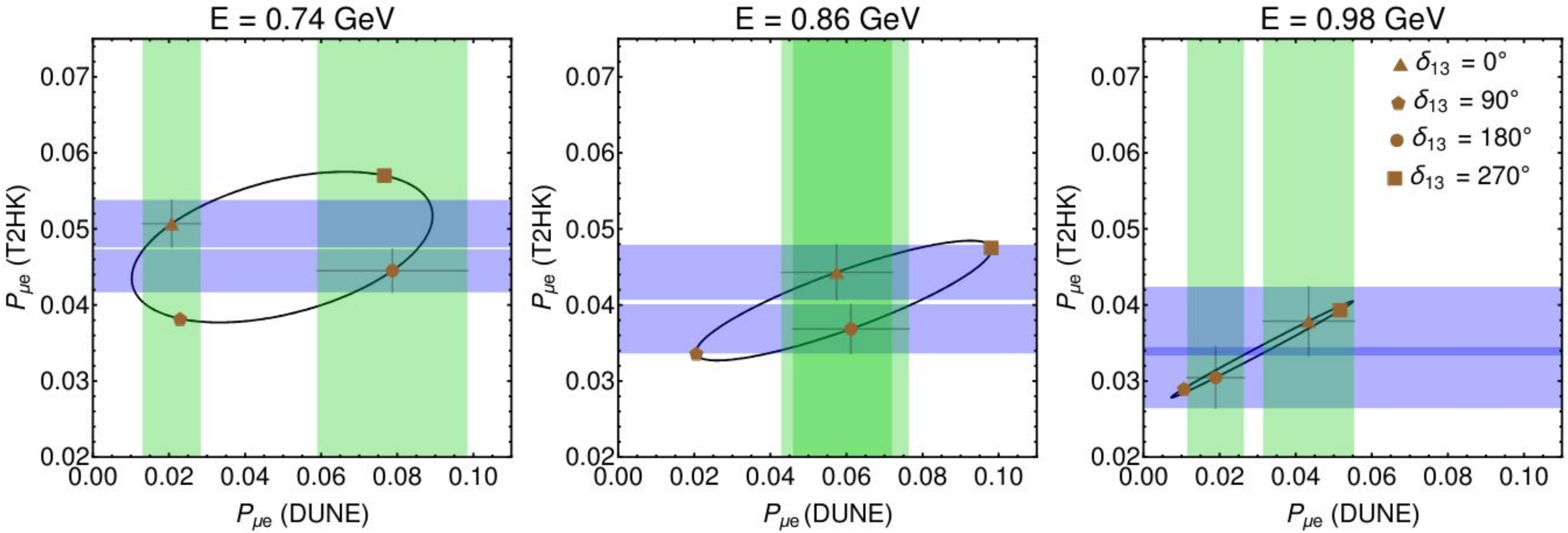
T violation from L dependence

Assume a Gaussian prior on $\sin^2\theta_{ij}$,sensitivity to T violation by evaluating $\Delta\chi^2$ for 1 degree of freedom using **neutrino beam mode only**.



No prior information on the mixing angles is similar to model-independent approach.

Bi-Probability Analysis



- For low bin, sensitivity emerges from a synergy between the two experiment.
- For middle bin, DUNE dominates the sensitivity and T2HK gives only a sub-leading contribution.
- For higher bin, there is the absence of sensitivity.

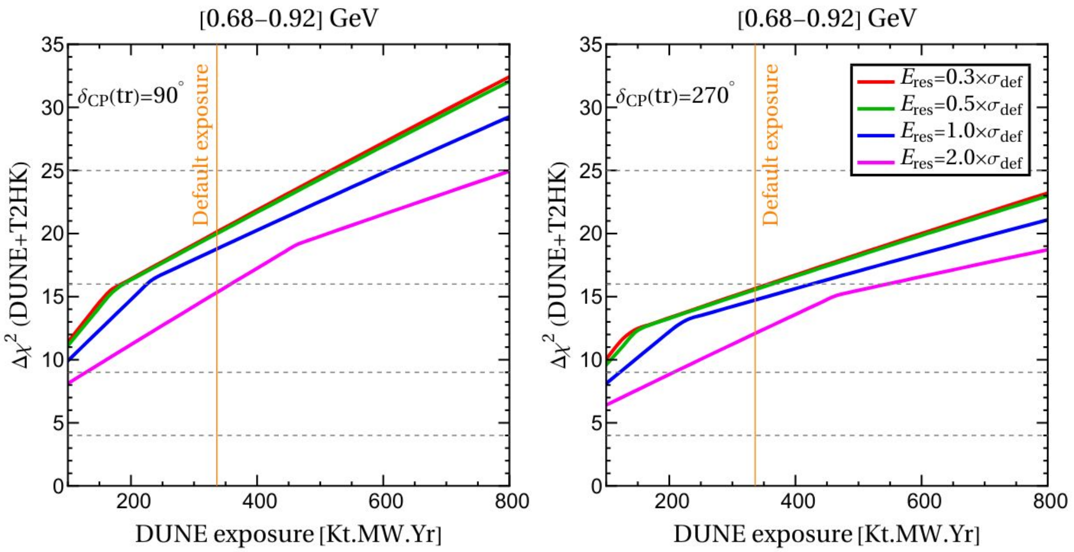
Exposure and Resolution Effect

- DUNE[L=1300 km]:
  336 kt MW yr, (neutrino-beam mode only)
  ~roughly 7 years of run time.

- The kink in the sensitivity curves is related to the lower energy bin [0.68, 0.8] GeV. For small enough DUNE errors, the sensitivity is determined by T2HK error bars which are kept fixed.

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

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



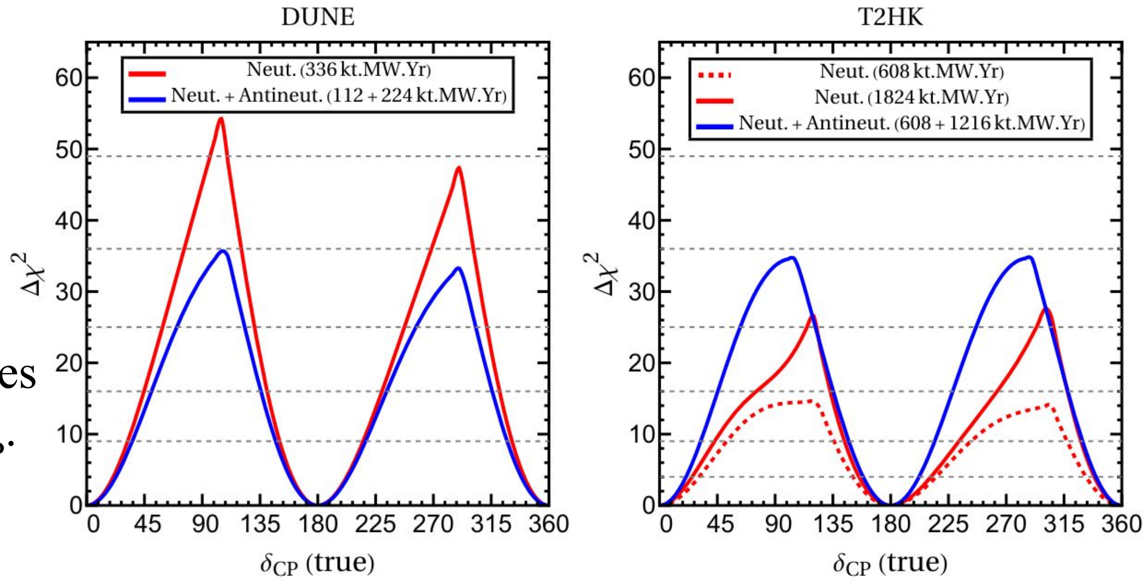
T versus CP

Neutrino Data only: **T Violation**

Neutrino and Antineutrino Data:
CP Violation

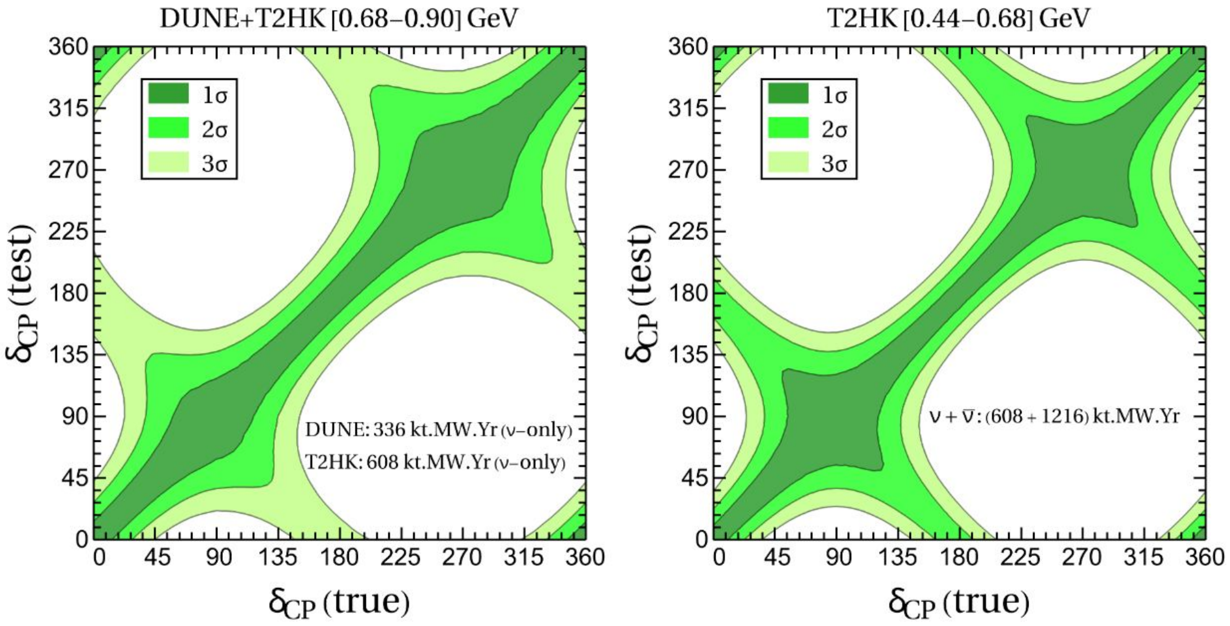
For **DUNE**: 336 kt MW yr
For **T2HK**: 1824 kt MW yr

- For DUNE, T violation provides dominating information on δ_{CP}.
- For T2HK, CP-asymmetric observable is more powerful.



Note: Results apply not only for the sensitivity of the full spectrum but for each energy bin separately.

Comparison (Test of the CPT symmetry)



Two independent determinations of δ_{CP} from T and CP violating observables.

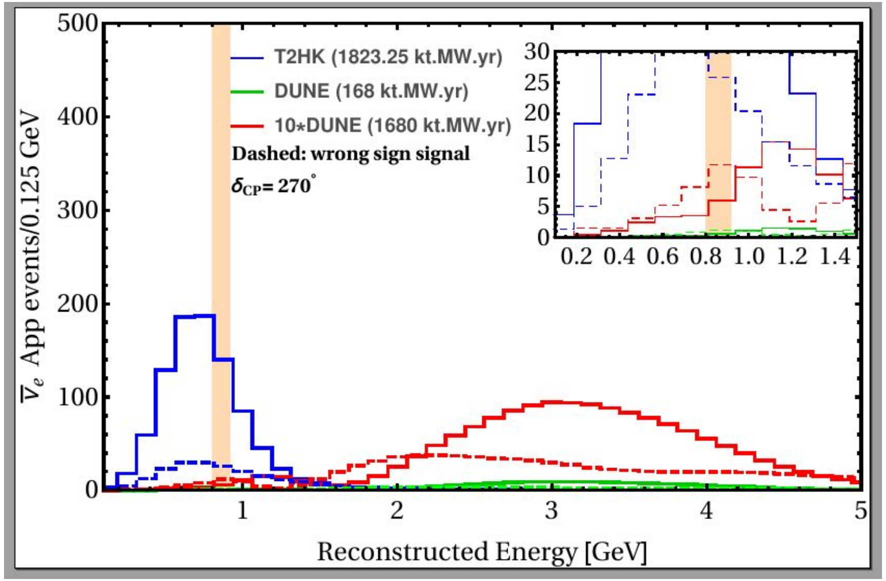
Conclusions

- We find that the model-independent requirements on exposure/resolution are more demanding than for the 3-flavour case, which offers very good sensitivity even with standard exposures.
- We find that L-odd component in the transition probability, appears as a direct consequence of fundamental T violation.
- We distinguish T violation in the sense of an L-odd component of the transition probability (for a neutrino beam only) as contrasted to CP violation from the comparison of neutrino and antineutrino transition probabilities.
- Sensitivity depends on the available exposure as well as on prior knowledge on the mixing angles, including the octant degeneracy of θ_{23}
- DUNE offers better sensitivity in the neutrino-only mode, whereas T2HK performs better in the split neutrino/anti-neutrino configuration.

Thank You ☺

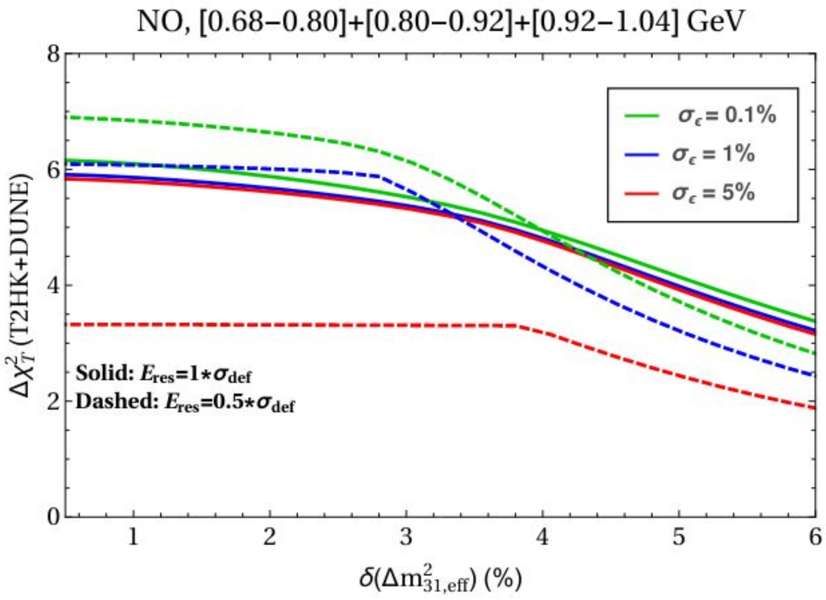
Backup Slides

Anti-Neutrino Event Spectra

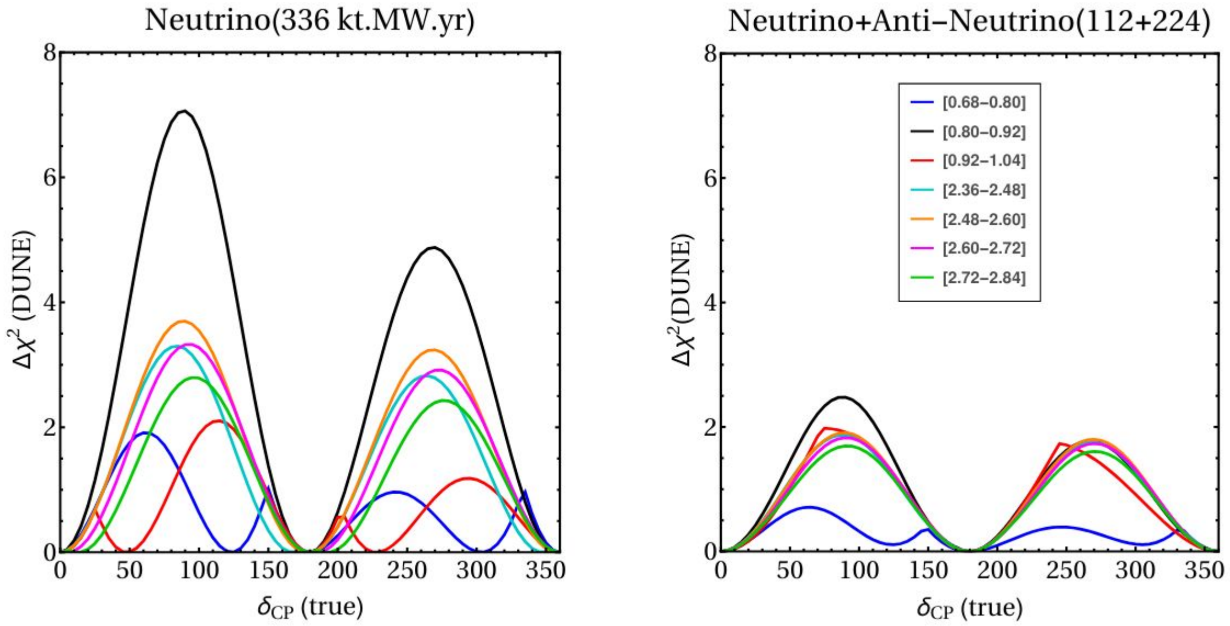


Zero-distance effect and prior on oscillation frequencies

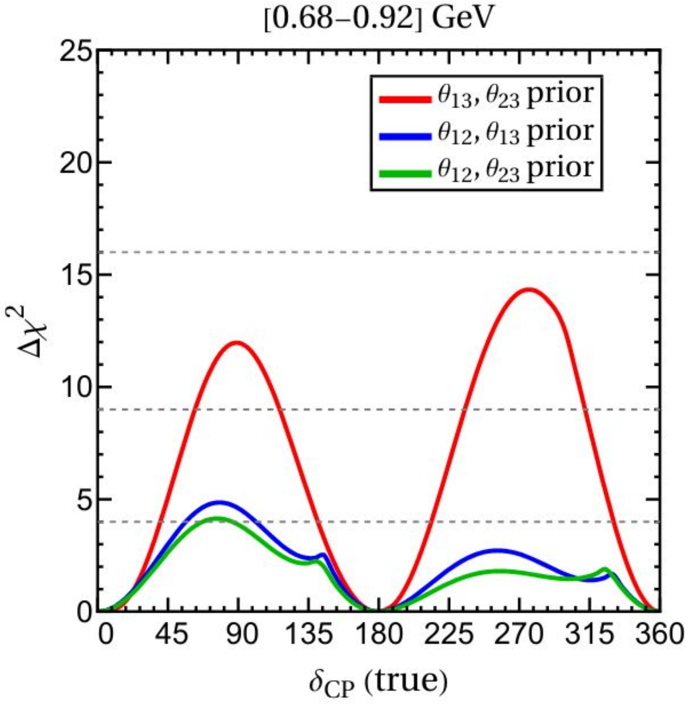
- "Near detector" prior constrains the deviation from unitarity
- Better resolution leads to a worse sensitivity,a manifestation of the larger value of $|\delta_0|$ due to the non-trivial energy averaging.
- Constraints on the zero-distance effect and on the oscillation frequency better than ≃ 1% are desirable.

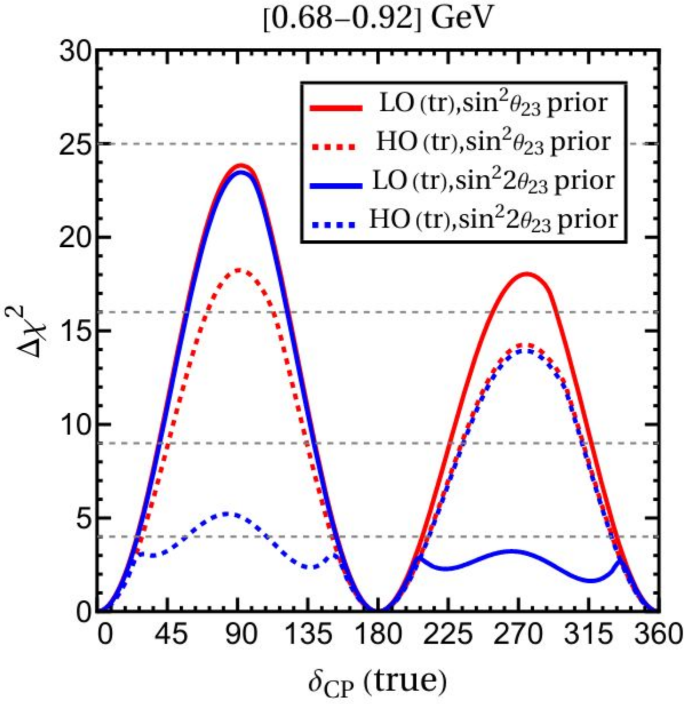


Energy dependence of T and CP sensitivities



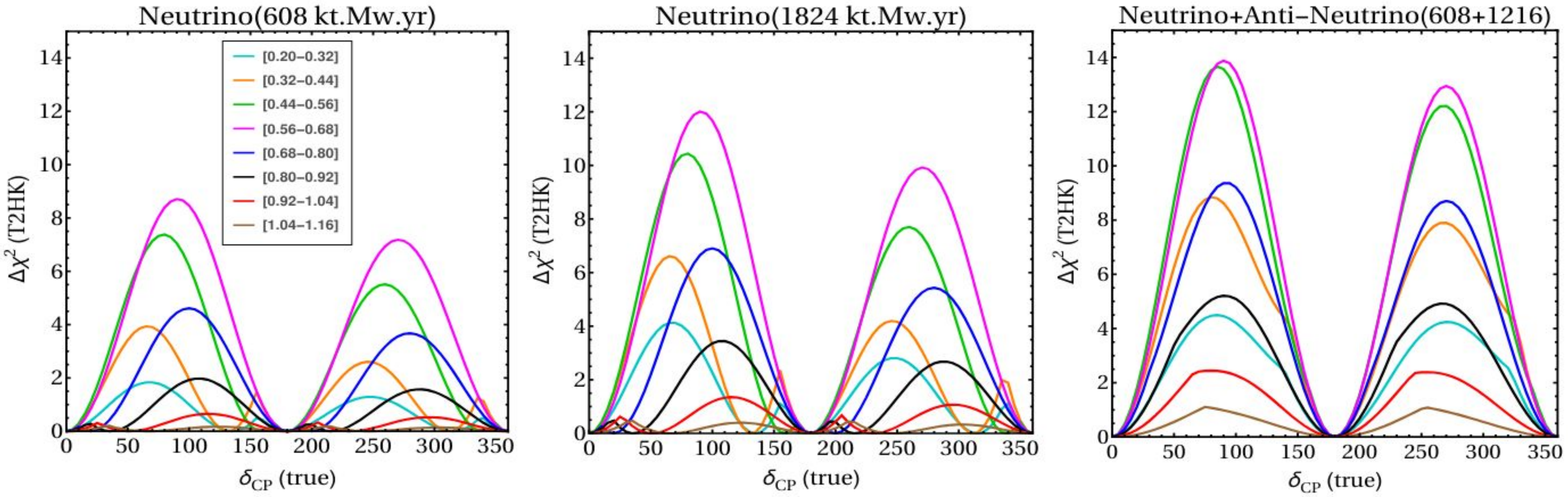
Prior knowledge on mixing angles



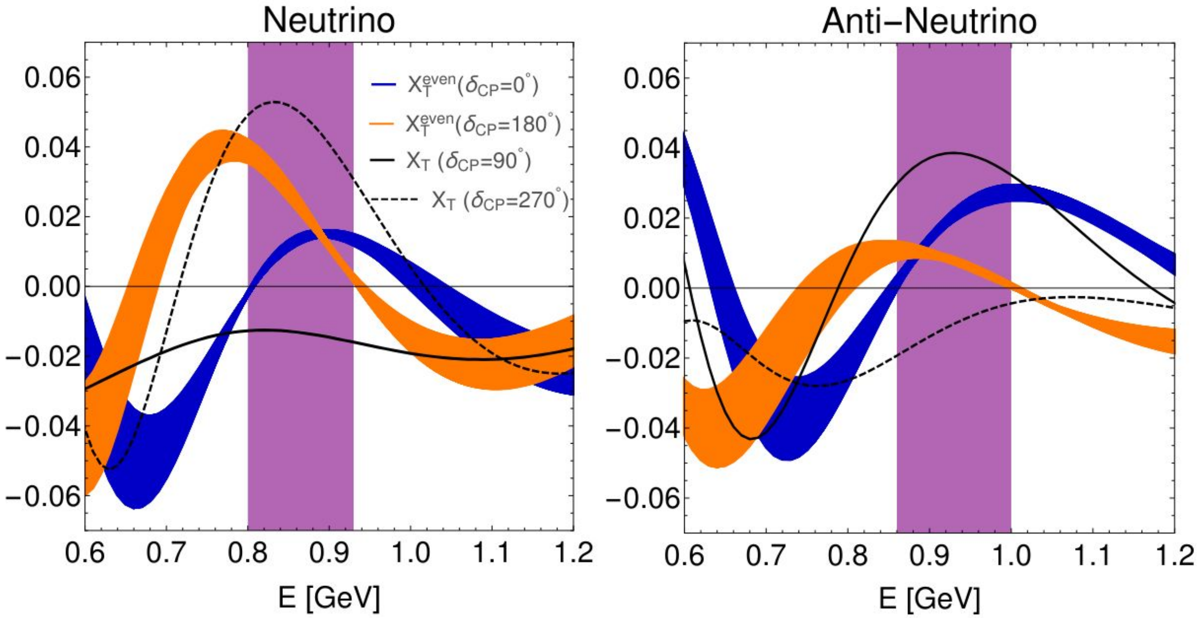


Knowledge of the θ_{23} octant is very crucial.

Energy dependence of T and CP sensitivities



X_T Test



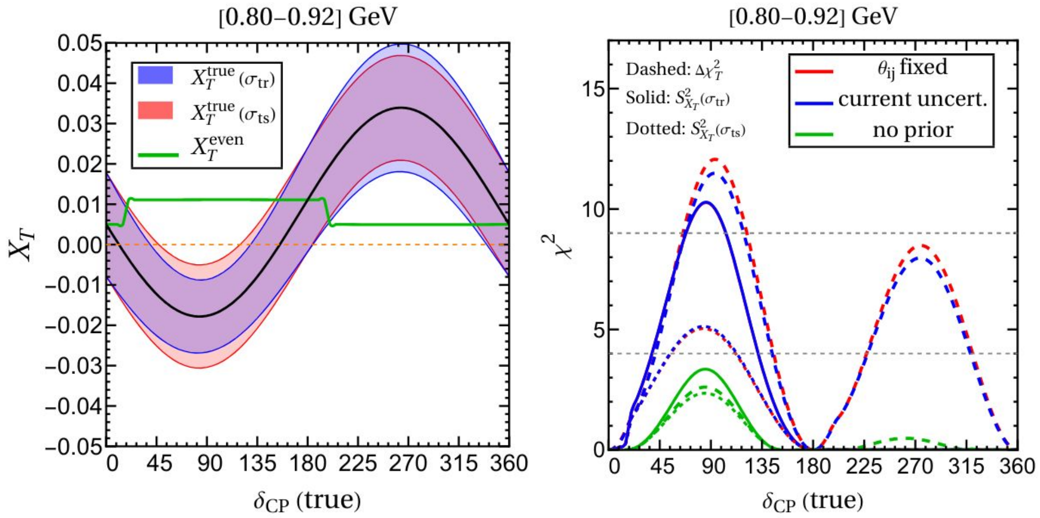
$$X_T^{\text{obs}} = P^{\text{obs}}_{\nu_\mu \to \nu_e}(L_2) - P^{\text{obs}}_{\nu_\mu \to \nu_e}(L_1)$$

X_T Test

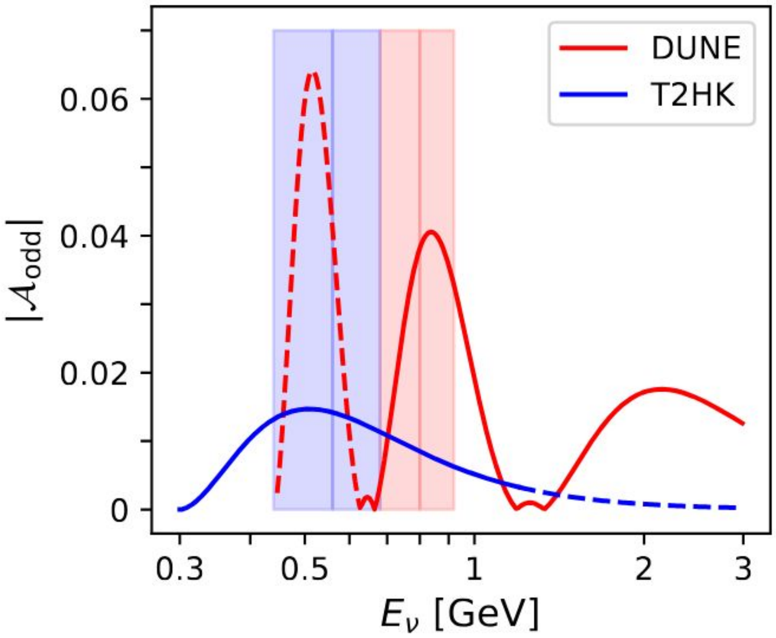
$$S_{X_T} = \frac{\Theta(X_T^{\text{even}} - X_T^{\text{obs}})}{\sigma_{X_T}}\,.$$

$$\sigma^2_{X_T} = \sum_x \frac{P_x^2}{S_x^2}\left(S_x + B_x + \sigma^2_{xS} S_x^2 + \sigma^2_{xB} B_x^2\right),$$

$$\langle P^x_{\nu_\mu \to \nu_e} \rangle \equiv P_x = \frac{S_x}{S_x(P_{\nu_\mu \to \nu_e} = 1)}$$



- P_x is the corresponding oscillation probability,
- S_x and B_x are the number of signal and background events in experiment,
- σ_{xS} (σ_{xB}) is the relative systematic uncertainty in S_x (B_x).


DUNE
T2HK
0.06
0.04
0.02
0
$|\mathcal{A}_{\rm odd}|$
0.3
0.5
1
2
3
E_ν [GeV]