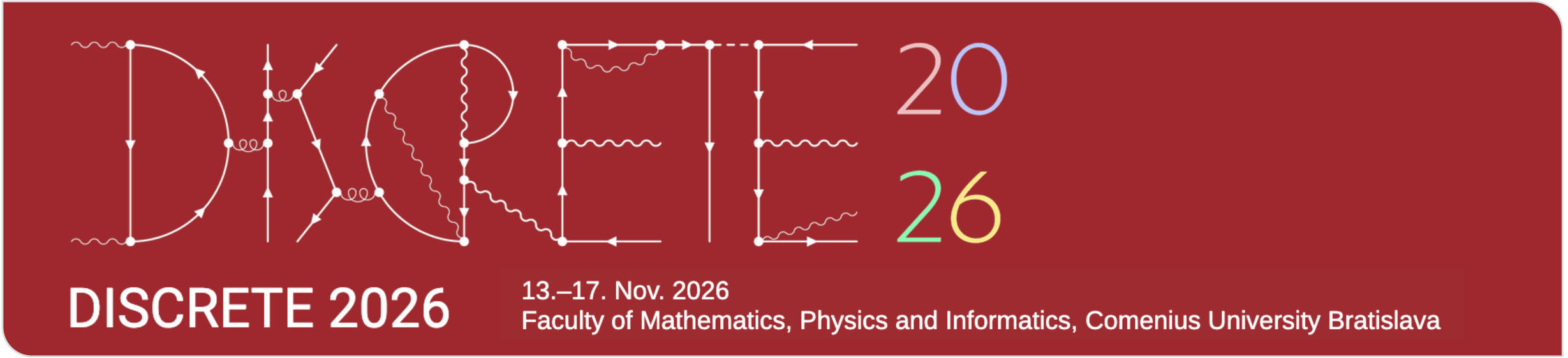
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T and CP violation searches in neutrino oscillations

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CP and T violation in neutrino oscillations

- T violation: $P_{\nu_\alpha \to \nu_\beta} \neq P_{\nu_\beta \to \nu_\alpha}$
- CP violation: $P_{\nu_\alpha \to \nu_\beta} \neq P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}$

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$=$

CPT:

$$P_{\nu_\beta \to \nu_\alpha} = P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}$$

CP and T violation in neutrino oscillations

for neutrino oscillations **in vacuum:**

Cabibbo, 1977; Bilenky, Hosek, Petcov, 1980, Barger, Whisnant, Phillips, 1980

$$P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} = -16\, J_{\alpha\beta} \sin \frac{\Delta m^2_{21} L}{4E_\nu} \sin \frac{\Delta m^2_{32} L}{4E_\nu} \sin \frac{\Delta m^2_{31} L}{4E_\nu} \,,$$

where

$$J_{\alpha\beta} = \mathrm{Im}(U_{\alpha 1} U^*_{\alpha 2} U^*_{\beta 1} U_{\beta 2}) = \pm J \,,$$

with $+(-)$ for (anti-)cyclic permutation of the indices e, μ, τ.

J: leptonic analogue to the Jarlskog-invariant in the quark sector Jarlskog, 1985

$$J = |\mathrm{Im}(U_{\alpha 1} U^*_{\alpha 2} U^*_{\beta 1} U_{\beta 2})| = s_{12} c_{12} s_{23} c_{23} s_{13} c^2_{13} \sin\delta \equiv J^{\max} \sin\delta$$

CP and T violation in neutrino oscillations

how can we observe it?

- T violation: $P_{\nu_\mu \to \nu_e} \neq P_{\nu_e \to \nu_\mu}$

- CP violation: $P_{\nu_\mu \to \nu_e} \neq P_{\bar{\nu}_\mu \to \bar{\nu}_e}$

- not practical to „flip“ neutrino source and detector
- difficult to produce a ν_e beam with suitable energy

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- earth matter effect induces **environmental CP violation**

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An observed difference in neutrino and anti-neutrino probabilities does not imply **fundamental CP violation**!

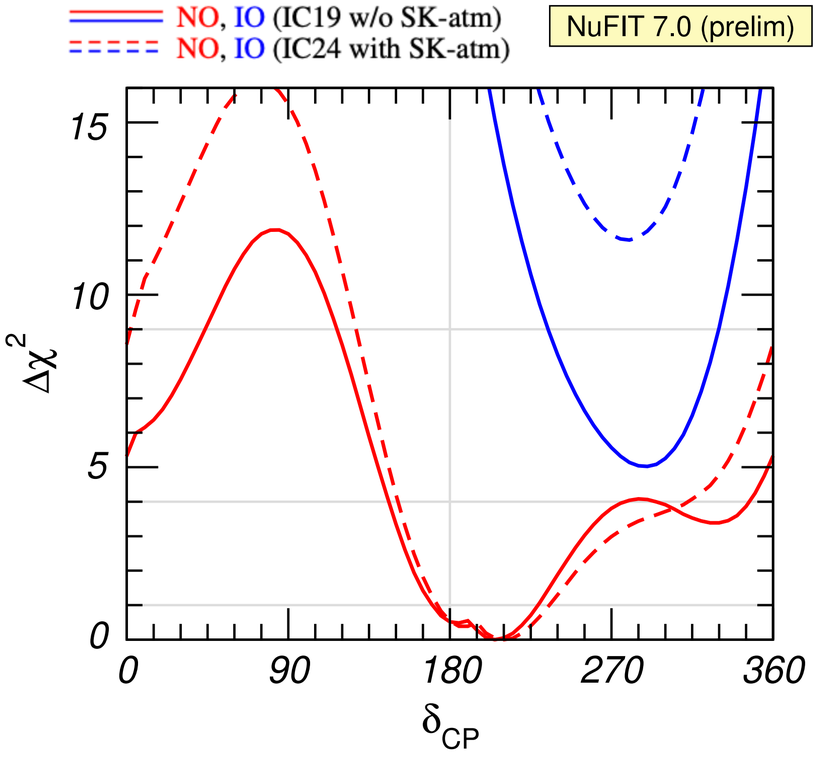
Adopt a model dependent approach

assume:

- minimal three-flavour scenario
- standard neutrino production and detection
- standard matter effect

perform combined accelerator/reactor fit
+ energy spectrum

- determine allowed range for δ_{CP}
- CPV $\Leftrightarrow$ excluding values of 0 and π for δ_{CP}

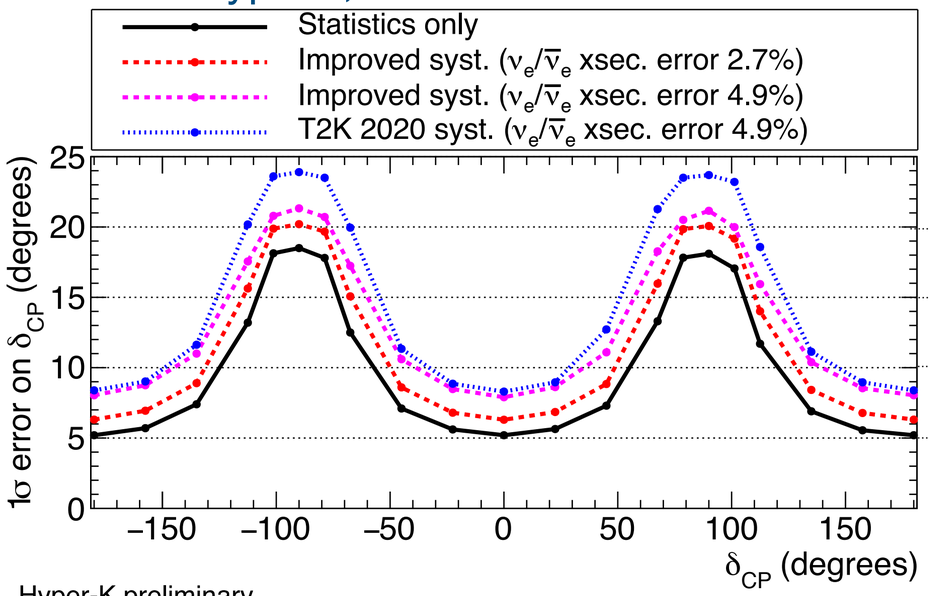


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δ_{CP}: main goal for next generation accelerator neutrino exp.

- **T2HK in Japan ($L \approx 295\,\mathrm{km}$)**

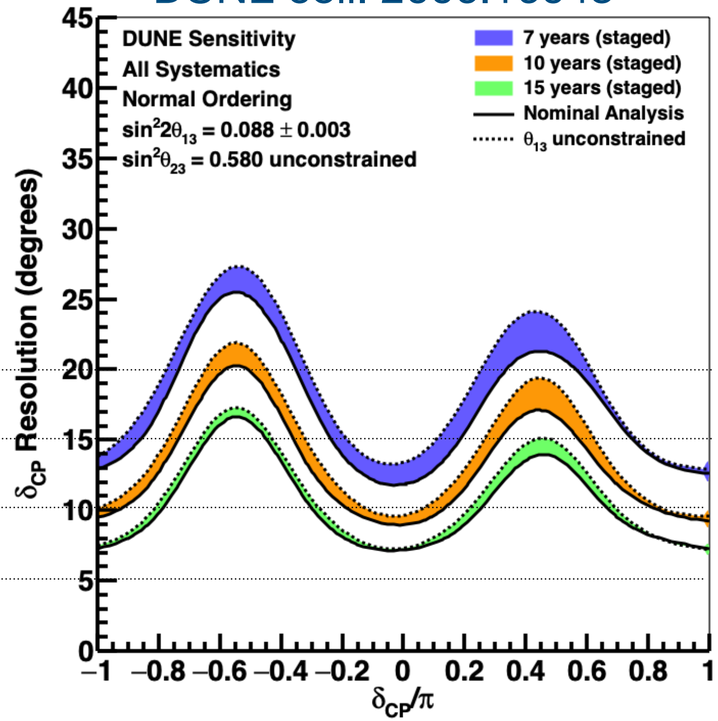
HyperK, J. Wilson @ NOW24



Hyper-K preliminary
True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
$\sin^2\theta_{13}$=0.0218±0.0007, $\sin^2\theta_{23}$=0.528, Δm^2_{32}=2.509×10^{-3}eV^2/c^4

- **DUNE in USA ($L \approx 1300\,\mathrm{km}$)**

DUNE coll. 2006.16043



10° — 20° precision on δ_{CP} in ~10 yr

Can we search for fundamental CP or T violation in a more model-independent way?

A. Segarra, TS, Phys. Rev. Lett. **128** (2022) 091801 [arXiv:2106.16099]
A. Segarra, TS, Phys. Rev. D **105** (2022) 055001 [arXiv:2112.08801]
S. Chatterjee, S. Patra, TS, **K. Sharma**, JHEP 12 (2024) 200 [arXiv:2408.06419]
S. Chatterjee, S. Patra, TS, **K. Sharma**, JHEP 11 (2025) 112 [arXiv:2508.04766]

T violation vs CP violation in presence of matter

- matter effect breaks CPT and CP and therefore directly induce environmental CP violation,

- but the matter effect does NOT induce environmental T asymmetry for a matter profile symmetric between source and detector
  e.g., Akhmedov, Huber, Lindner, Ohlsson, 01; TS, Segarra, PRD

$\Rightarrow$ T violation potentially „cleaner“ observable

T violation in neutrino oscillations — highly incomplete list of references

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- J. Bernab´eu and A. Segarra, Do T asymmetries for neutrino oscillations in uniform matter have a CP-even component?, JHEP 03, 103, arXiv:1901.02761 [hep-ph].
- O.M. Bitter, A. deGouvea, K.J.Kelly, On T-Invariance Violation in Neutrino Oscillations and Matter Effects, Phys.Rev.D 111 (2025) 055023 [arXiv:2412.13287]

A proposal of a T-violating observable

A. Segarra, TS, Phys. Rev. Lett. 128 (2022) 091801 [arXiv:2106.16099]
A. Segarra, TS, Phys. Rev. D 105 (2022) 055001 [arXiv:2112.08801]

- assume $x \approx t$, then

impractical experimentally
(need a μ-based neutrino factory)

$$\mathrm{T}[P_{\nu_\alpha \to \nu_\beta}(L)] = P_{\nu_\beta \to \nu_\alpha}(L) = P_{\nu_\alpha \to \nu_\beta}(-L)$$

- measure oscillation probabilities at several distances but at the same energy
- search for a T-odd (L-odd) component of the oscillation probability

Model-independent test of T violation

- general parameterisation of the transition probabilities:

$$P_{\mu\alpha} = \left| \sum_{i=1}^{3} c_i^{\alpha} e^{-i\lambda_i L} \right|^2$$

$$c_i^{\alpha} \equiv (N_{\alpha i}^{\mathrm{det}})^* N_{\mu i}^{\mathrm{prod}}$$

c_i^{α}, λ_i are unknown functions of energy, different for neutrinos and anti-neutrinos

holds for a broad class of BSM scenarios (non-unitarity mixing, sterile neutrinos with $|\Delta m_{s1}^2| \ll \Delta m_{21}^2$ or $\gg |\Delta m_{31}^2|$, non-standard interactions in matter, source and detector, general EFT (at leading order), light and heavy mediators) → **precise assumptions in backup**

Model-independent test of T violation

- general parameterisation of the transition probabilities:

$$P_{\mu\alpha} = \left| \sum_{i=1}^{3} c_i^\alpha e^{-i\lambda_i L} \right|^2$$

$$= \sum_i |c_i^\alpha|^2 + 2\sum_{j<i} \mathrm{Re}(c_i^\alpha c_j^{\alpha *}) \cos(\omega_{ij} L) - 2\sum_{j<i} \mathrm{Im}(c_i^\alpha c_j^{\alpha *}) \sin(\omega_{ij} L)$$

T-even

T-odd

$$c_i^\alpha \equiv (N_{\alpha i}^{\mathrm{det}})^* N_{\mu i}^{\mathrm{prod}}$$

complex phases in c_i^α lead to T violation
more sources for TV due to new physics

Model-independent test of T violation

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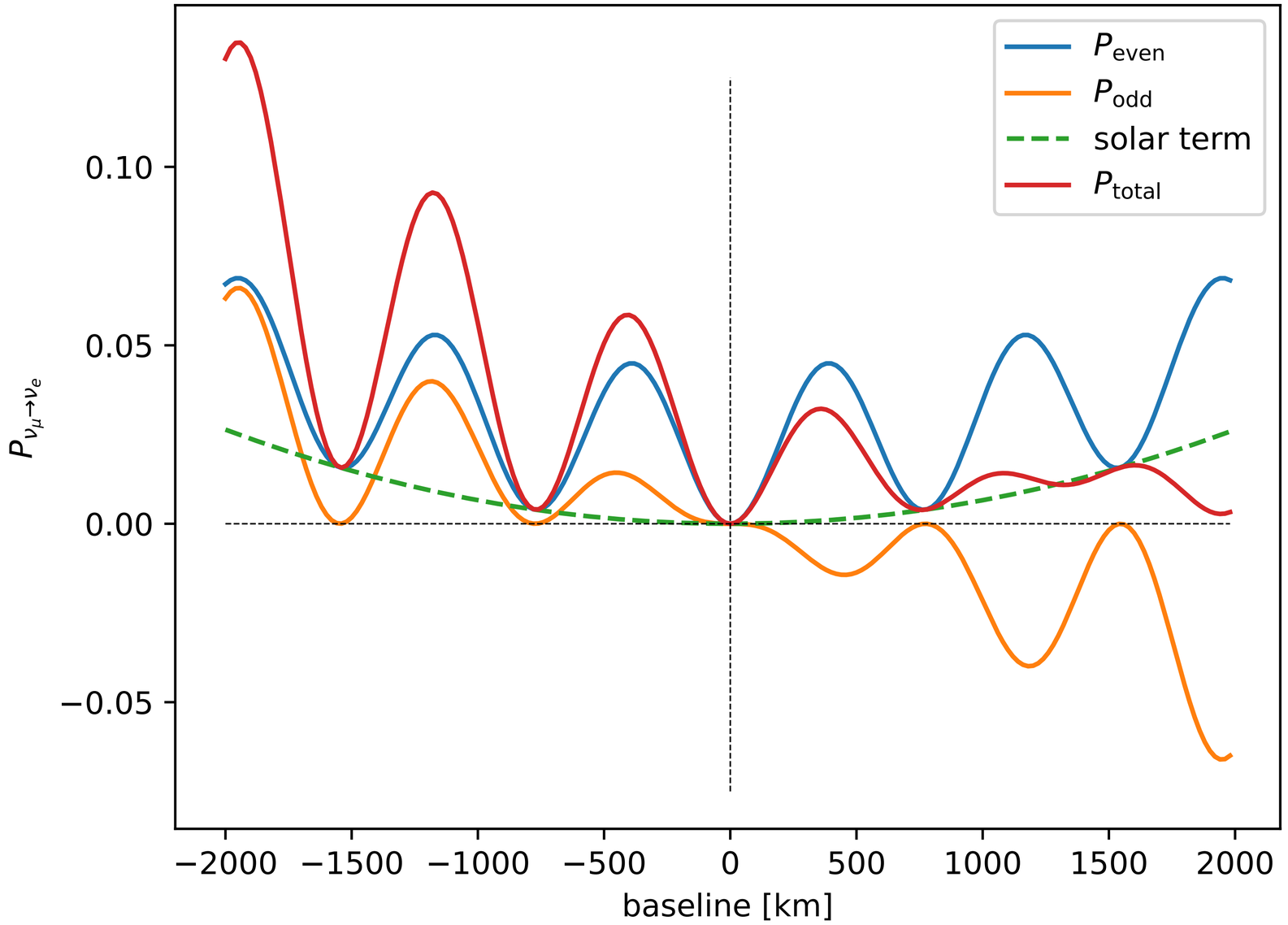
T-even → L even

T-odd → L-odd

$$= \sum_i |c_i^{\alpha}|^2 + 2\sum_{j<i} \mathrm{Re}(c_i^{\alpha} c_j^{\alpha *}) \cos(\omega_{ij} L) - 2\sum_{j<i} \mathrm{Im}(c_i^{\alpha} c_j^{\alpha *}) \sin(\omega_{ij} L)$$

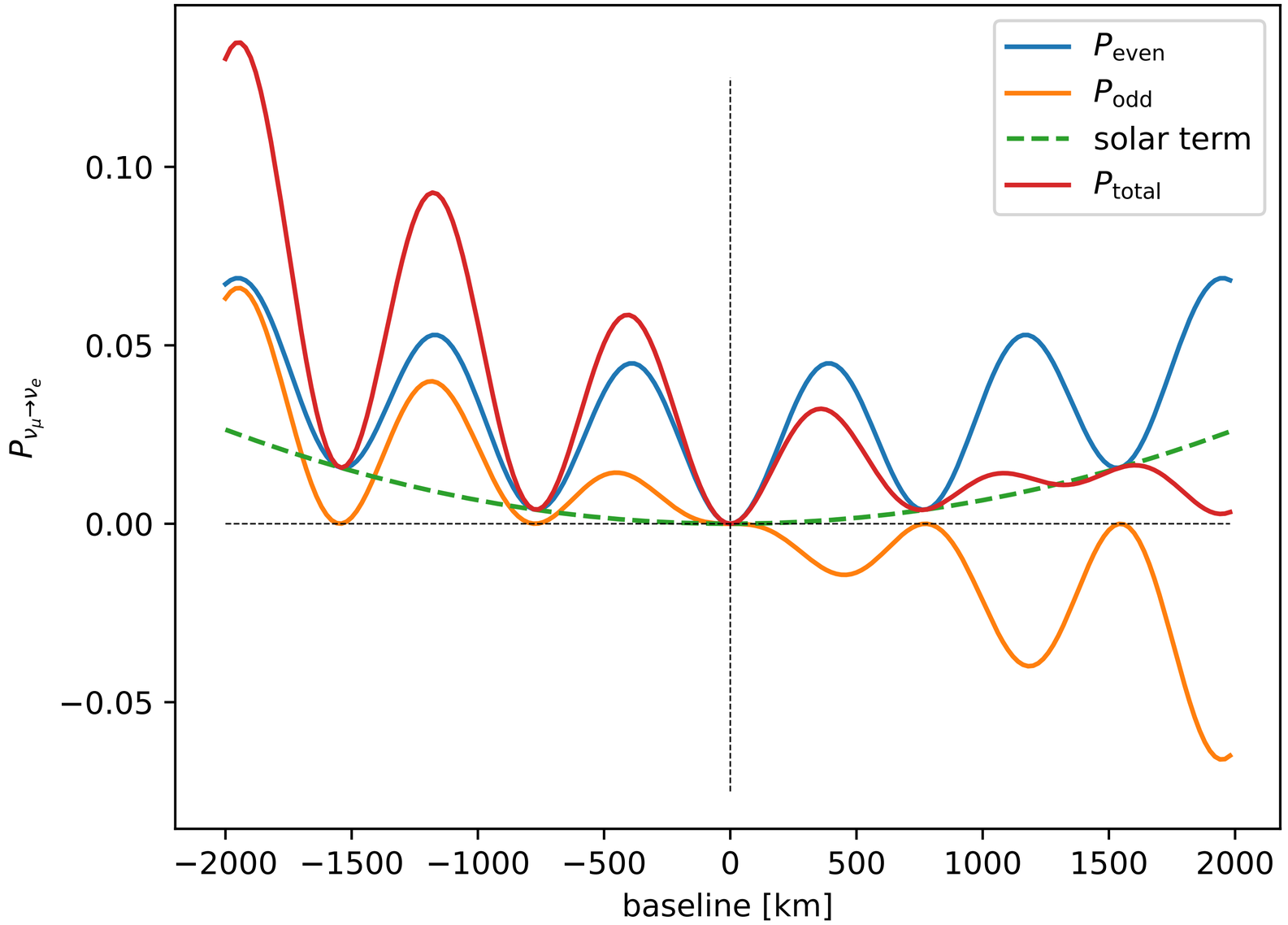
if data cannot be fitted only with the L-even part,
fundamental T violation is established model-independently

- Example:
  3-flavour vacuum probability for
  $\delta_{\mathrm{CP}} = \pi/2$
  $E_\nu = 0.75\,\mathrm{GeV}$



- Example:
  3-flavour vacuum probability for
  $\delta_{\mathrm{CP}} = \pi/2$
  $E_\nu = 0.75\,\mathrm{GeV}$

- How many data points do we need to establish that a T-odd component is present?



Need just two experiments!

Chatterjee, Patra, TS, Sharma, 2408.06419

- consider

$$X_T \equiv P_{\text{even}}(L_2) - P_{\text{even}}(L_1) - \delta_0 P_{\text{even}}^{L=0}$$

$$= c_2^2 \delta_2 + c_3^2 \delta_3 + c_2 c_3 \delta_{23}$$

where δ_i are known functions of $(\Delta m^2_{ij})_{\text{eff}} L_{1,2}/E_\nu$ → **definitions in backup**

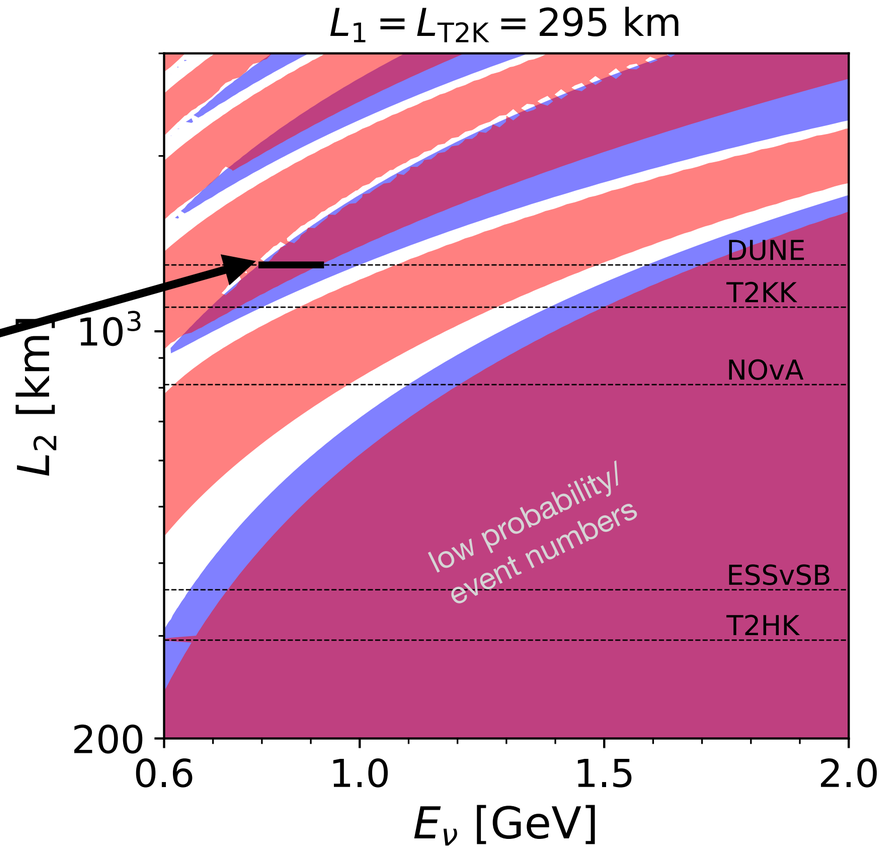
$$\Rightarrow \quad X_T \geq 0 \quad \text{if} \quad \delta_2, \delta_3 > 0 \quad \text{and} \quad \delta_{23}^2 < 4\delta_2\delta_3$$

- T has to be violated if $X_T^{\text{observed}} < 0$ and the δ_i-conditions are satisfied.

Chatterjee, Patra, TS, Sharma, 2408.06419

- where are the conditions $\delta_2, \delta_3 > 0$ and $\delta_{23}^2 < 4\delta_2\delta_3$ satisfied? (both)

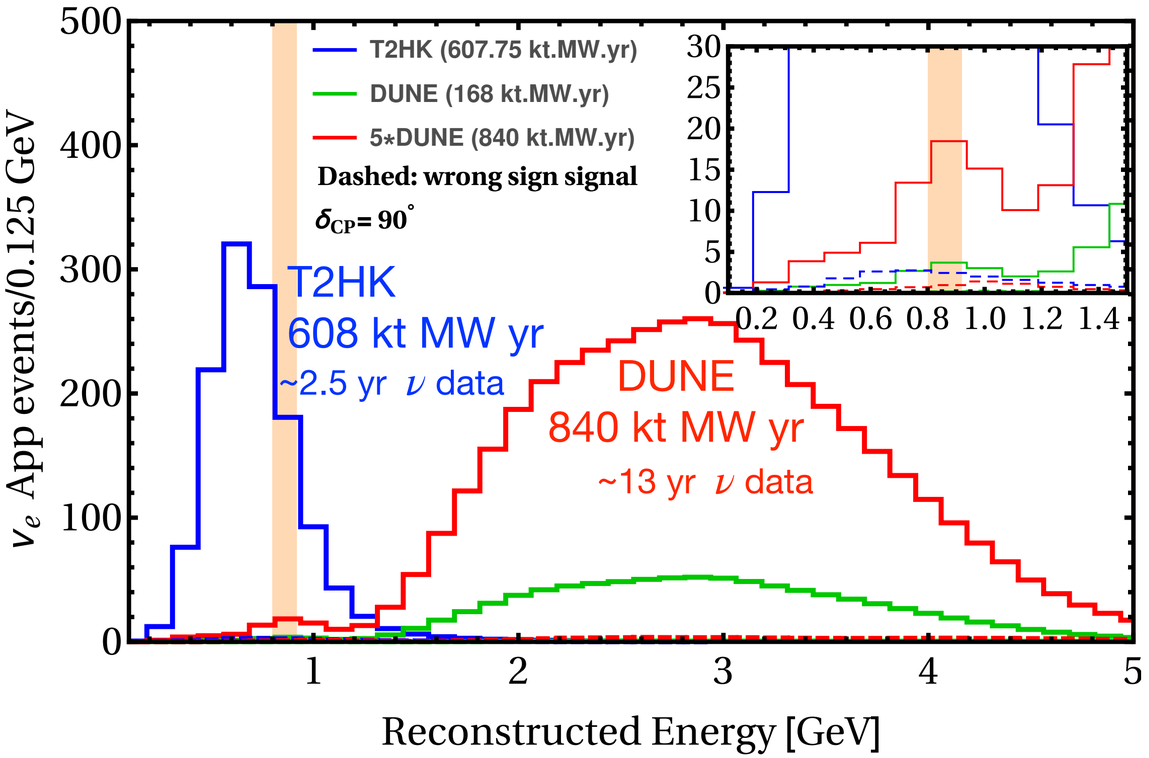
- sweet spot for T2HK and DUNE for $E_\nu \approx 0.86$ GeV



⇒ If we can establish experimentally that $P_{\mu e}(\text{DUNE}) < P_{\mu e}(\text{T2HK})$ at $E_\nu \approx 0.86$ and $P_{\mu e}(L = 0)$ is sufficiently small then T has to be violated.

Can it work in real life?

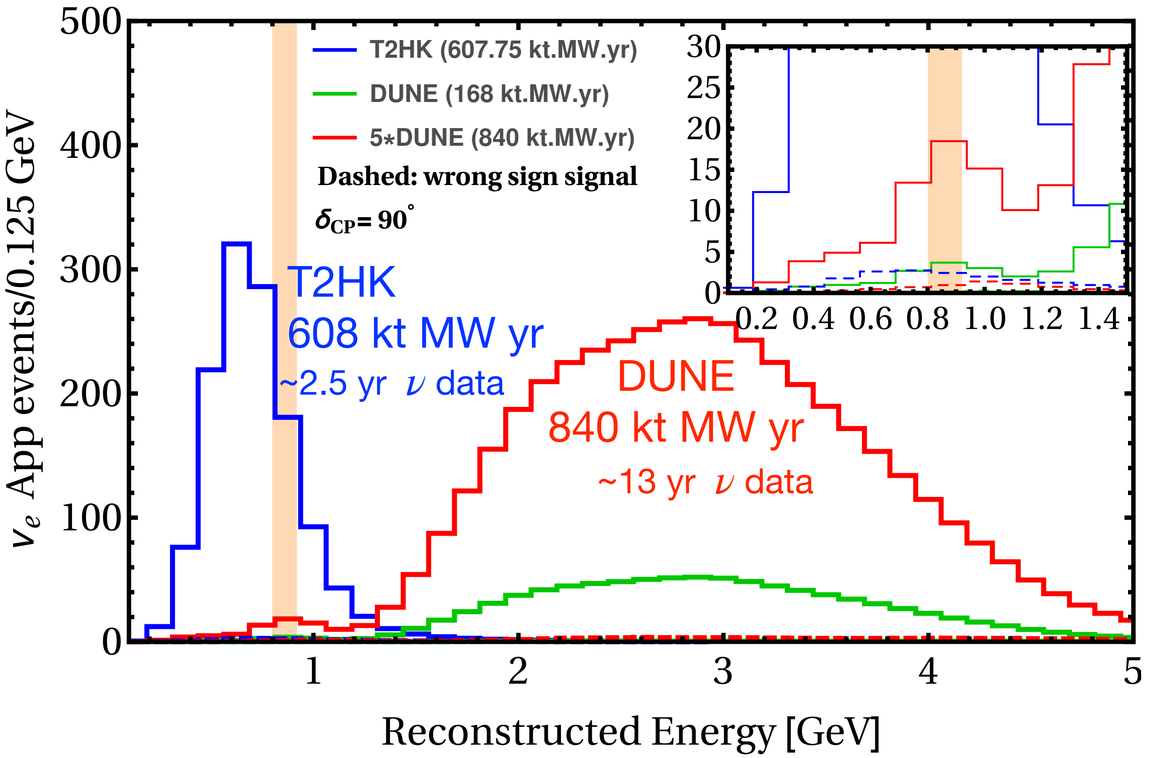
Chatterjee, Patra, TS, Sharma, 2408.06419

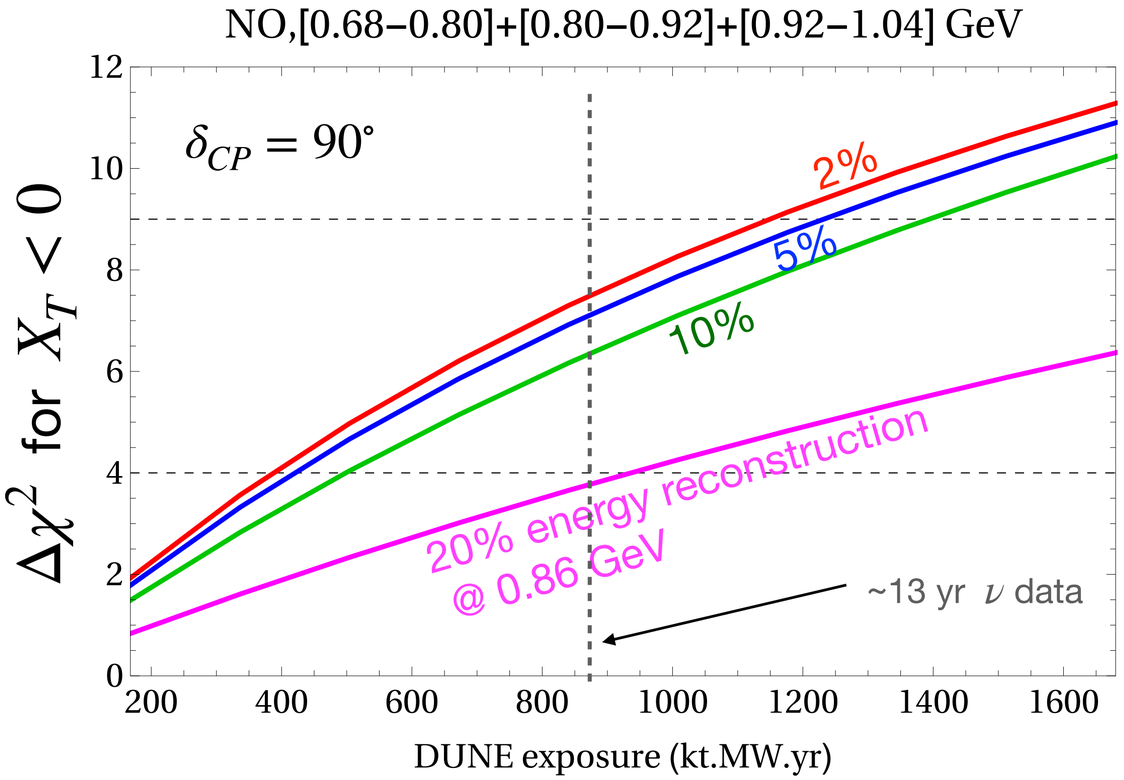


„sweet spot“ $E_\nu \approx 0.86$ GeV
is located close to
1st osc. max. at T2HK
2nd osc. max at DUNE

Can it work in real life?

Chatterjee, Patra, TS, Sharma, 2408.06419





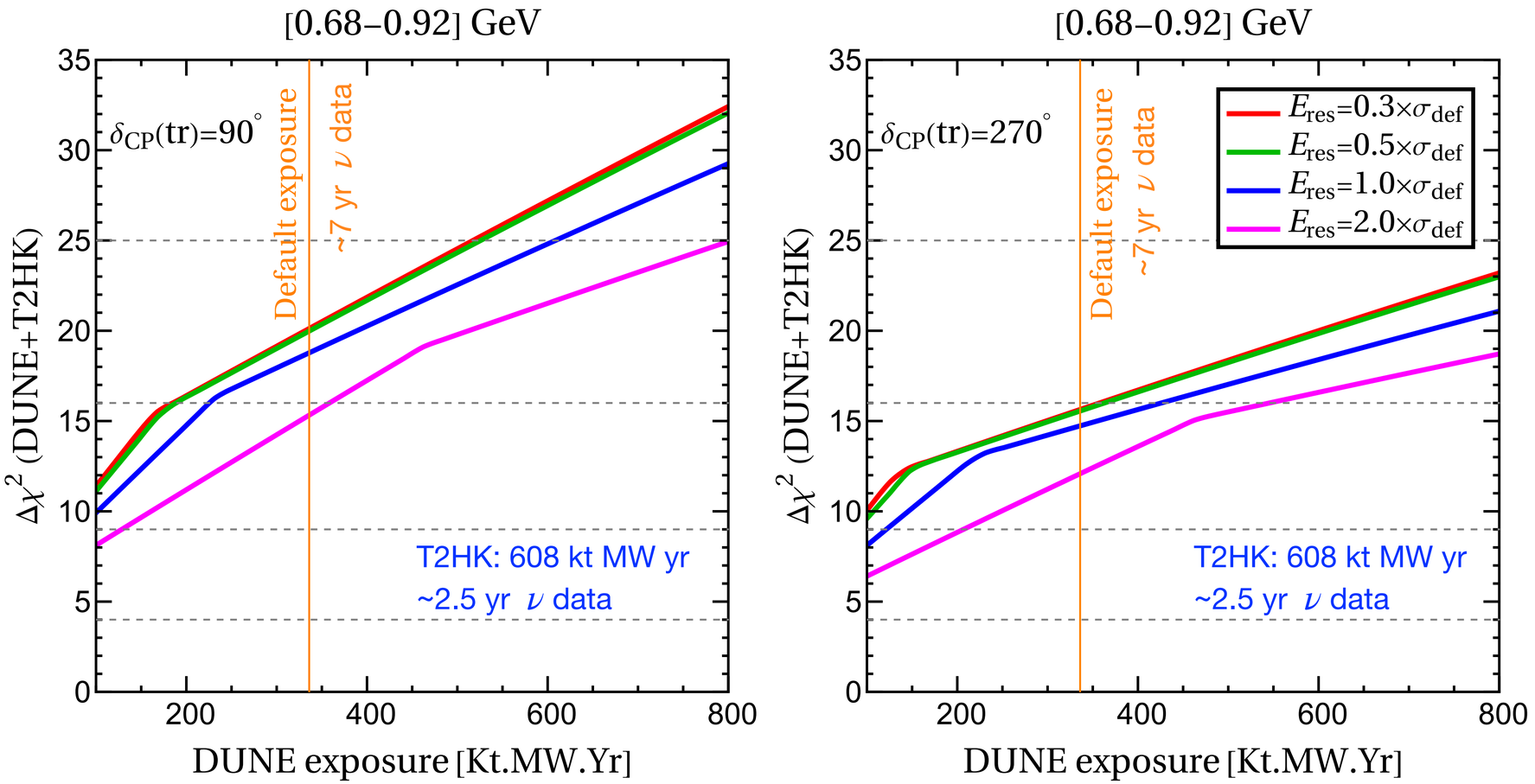
need to collect enough statistics in DUNE at $E_\nu \approx 0.86$ GeV,
and achieve good energy resolution

relaxing model-independence: assume standard 3-flavour scenario

c_i coefficients are not arbitrary, but constrained by mixing angles θ_{ij}

comparison of $P_{\nu_\mu \to \nu_e}$ at T2HK and DUNE (at same energy)

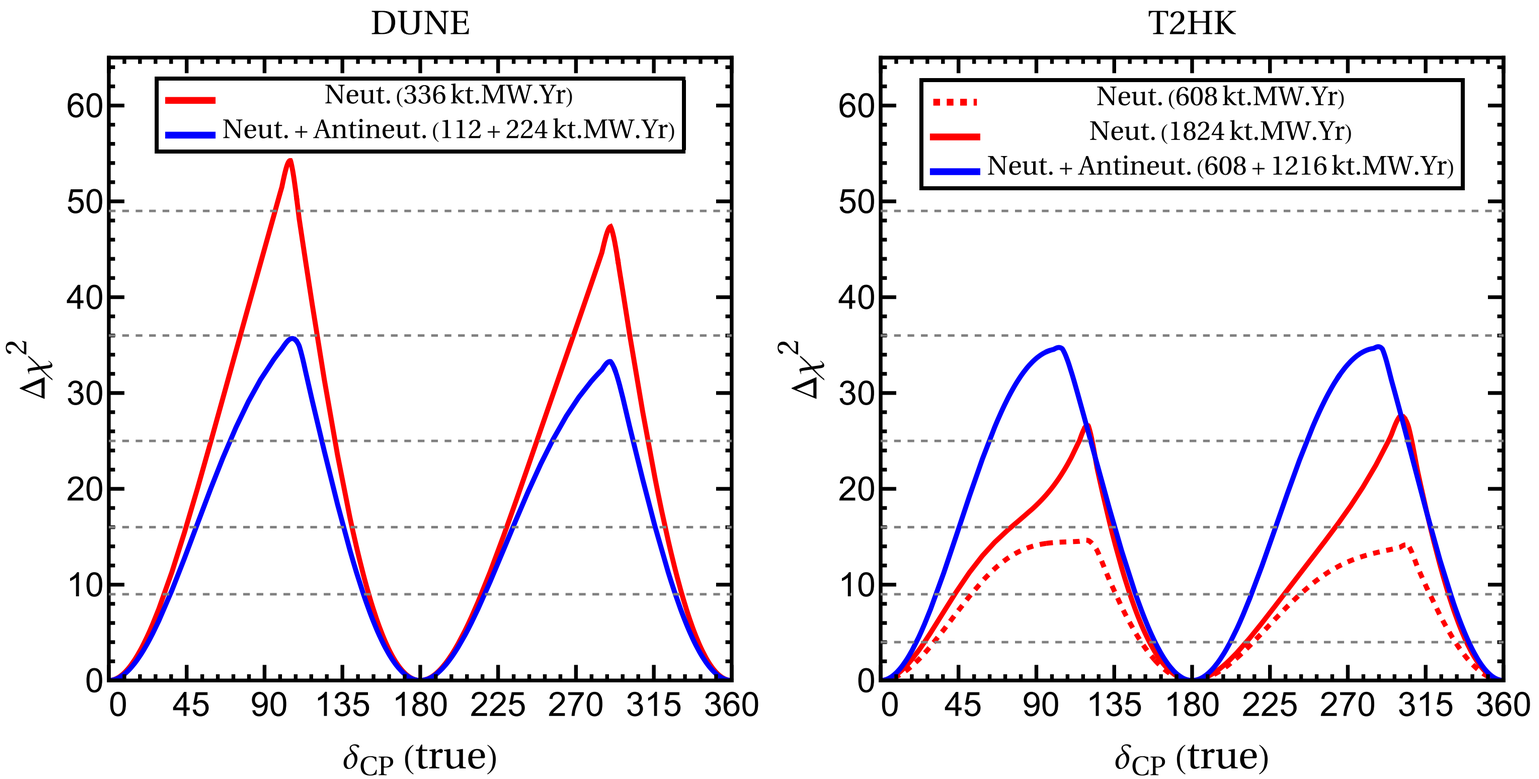
Chatterjee et al., [2508.04766]



relaxing model-independence: assume standard 3-flavour scenario

DUNE: better sensitivity for neutrino-only („**T-violation**“)

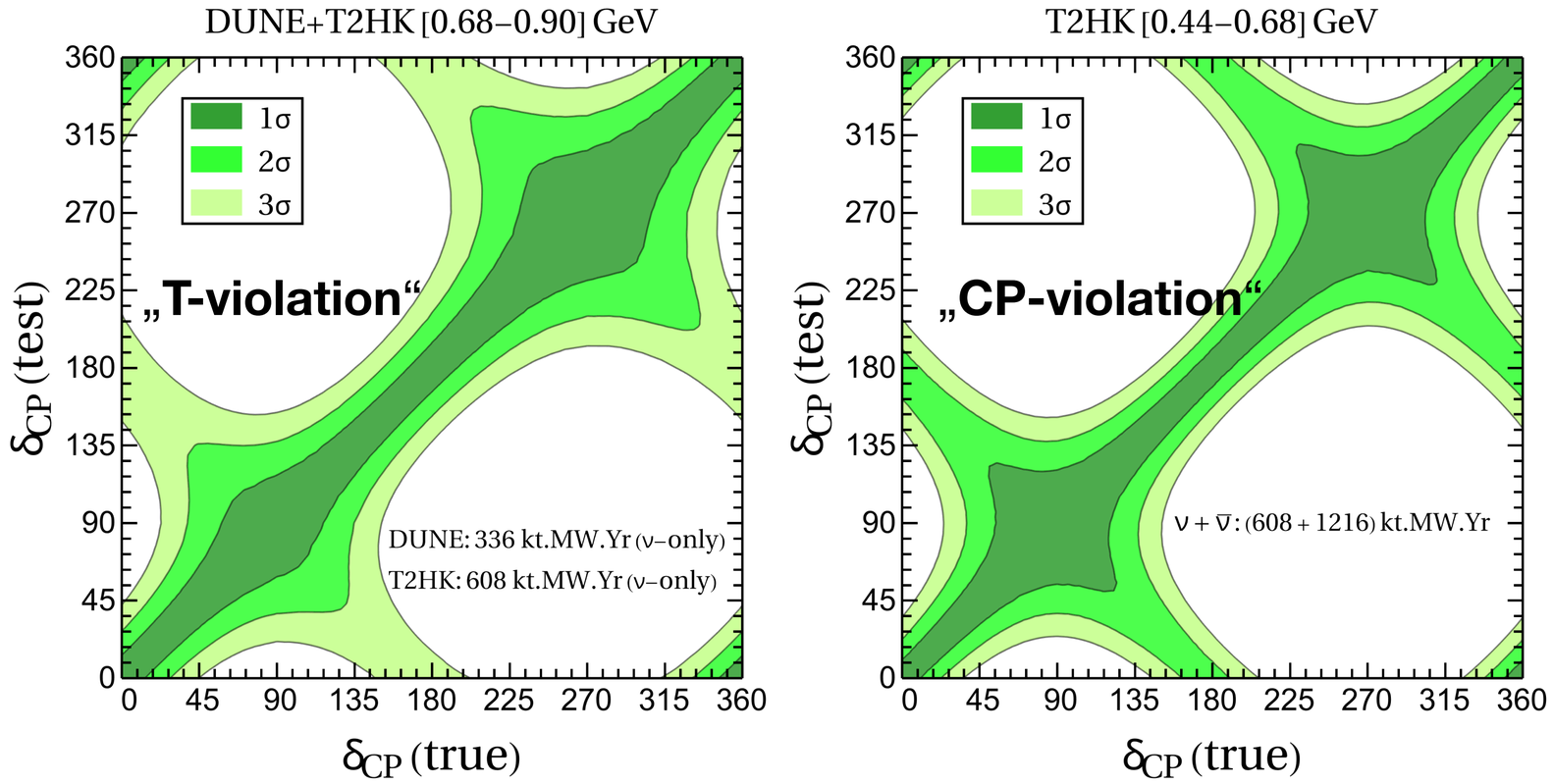
T2HK: better sensitivity from neutrino/anti-neutrino comparison („**CP-violation**“)



Chatterjee et al., [2508.04766]

relaxing model-independence: assume standard 3-flavour scenario

T and CP observables allow a similar accuracy to extract $\delta_{\rm CP}$ and therefore provide a test of the CPT symmetry



Chatterjee et al., [2508.04766]

Summary

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    measure $P(\nu_\mu \to \nu_e)$ at different L but at the same energy

Summary

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- propose a (largely) model-independent test for T violation:
  - search for L-odd terms in the oscillation probability
    measure $P(\nu_\mu \to \nu_e)$ at different L but at the same energy
  - potentially works with baselines available at T2HK and DUNE
  - covering 1st and 2nd oscillation max at the same energy
  - relies on low-energy tail of DUNE, good energy resolution essential

Final remark

- (largely) model-independent test for T violation:
  A. Segarra, TS [2106.16099], S. Chatterjee, S. Patra, TS, K. Sharma [2408.06419]
  - search for L-odd terms in the oscillation probability
    measure $P(\nu_\mu \to \nu_e)$ at different L but at the same energy
    (allows for „arbitrary“ energy dependence of new physics)

- (slightly less) model-independent test for CP violation:
  Cheng, Kelly, Knobbe, Machado [2610.37744]
  - assume specific energy dependence

$$P(L,E) = P_{\text{vac}}(L/E) + \rho L\, g_{\text{mat}}(L/E)$$

to extract „instrinsic“ $P_{\text{vac}}(\nu_\mu \to \nu_e) - P_{\text{vac}}(\bar{\nu}_\mu \to \bar{\nu}_e)$ from DUNE vs T2HK

backup

Assumptions:

- assume evolution equation $i\partial_t |\psi\rangle = H(E_\nu)|\psi\rangle$ ($H = H^\dagger$, unitary evolution)
- position independent Hamiltonian (approx. constant matter density)
  → matter effect does not introduce environmental T violation
  → can diagonalize H and go to energy-eigenbasis
- allow for arbitrary (non-standard) matter effect
- allow for arbitrary (non-unitary) mixing between flavour and energy eigenstates (possibly different for production and detection): $|\nu_\alpha\rangle = \sum_i N_{\alpha i}^{\text{prod,det}} |\nu_i\rangle$
- allow for arbitrary (sufficiently smooth) energy dependence of new physics
- only 2 independent frequencies are present (sterile neutrinos need to be heavy enough to be averaged out or light enough of not introducing oscillations)
- deviation from standard 3-flavour is „small“, in particular $(\Delta m^2_{21})_{\text{eff}}$ is close to the SM

Definitions:

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

$$\phi_{ij} \equiv \frac{\lambda_i - \lambda_j}{2}L \approx \frac{\Delta m^2_{ij,\mathrm{eff}}(E_\nu)L}{4E_\nu}$$

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

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