HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Model-independent test of T violation in neutrino oscillations

NuTs (Neutrino Theory) 2022, IFT Madrid

Thomas Schwetz
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based on work with Alejandro Segarra:

- Phys. Rev. Lett. 128 (2022) 091801 [arXiv:2106.16099]
- Phys. Rev. D 105 (2022) 055001 [arXiv:2112.08801]

CP and T violation in neutrino oscillations

Leptonic CP violation will manifest itself in a difference of the vacuum oscillation probabilities for neutrinos and anti-neutrinos

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

CP and T violation in neutrino oscillations

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

$$\boxed{J_{\rm CP}^{\max} = 0.0333 \pm 0.0006\,(\pm 0.0019) \text{ at } 1\sigma\ (3\sigma)}$$

$$J_{\rm CP}^{\rm quarks} = (3.18 \pm 0.15) \times 10^{-5}$$

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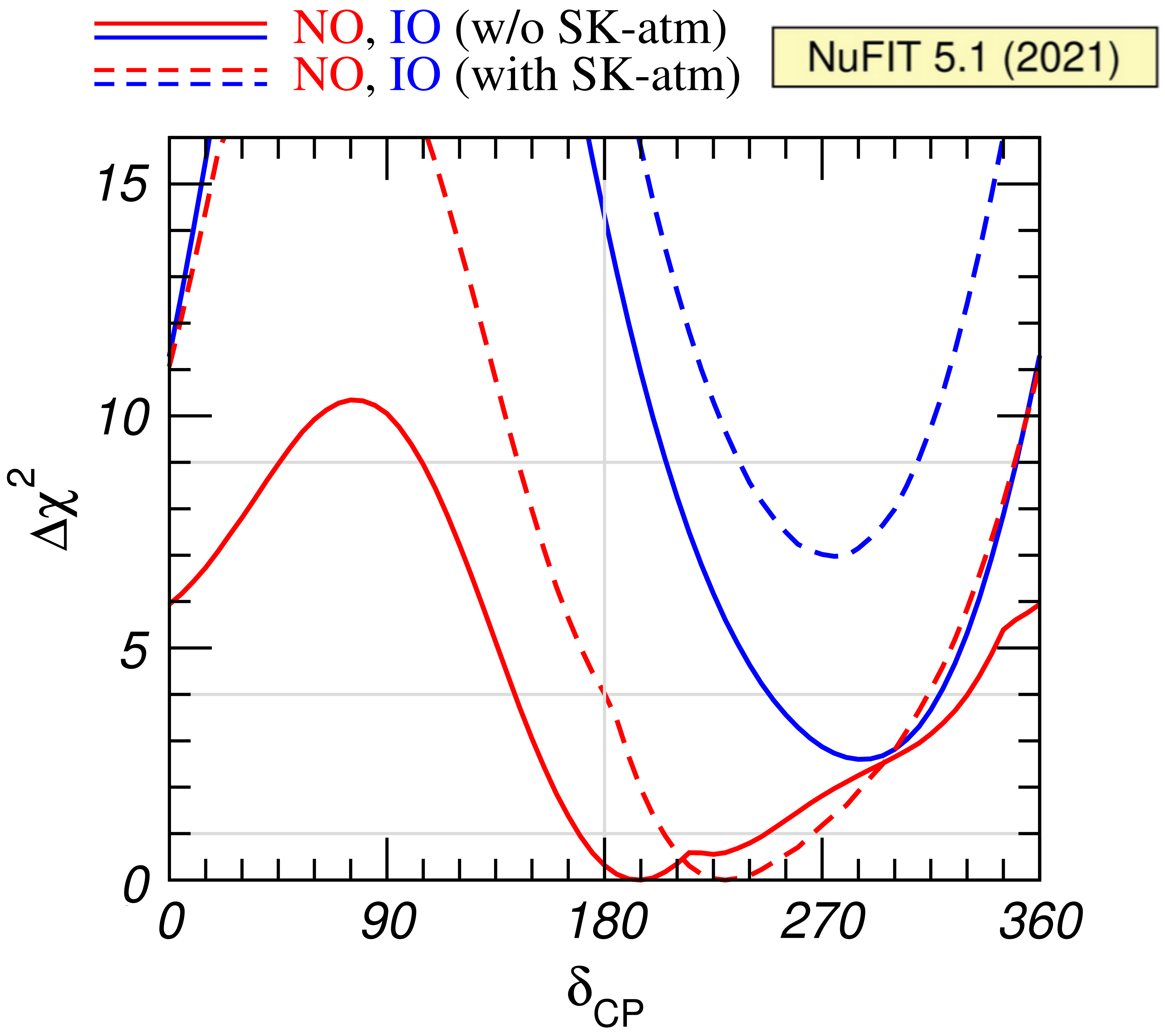
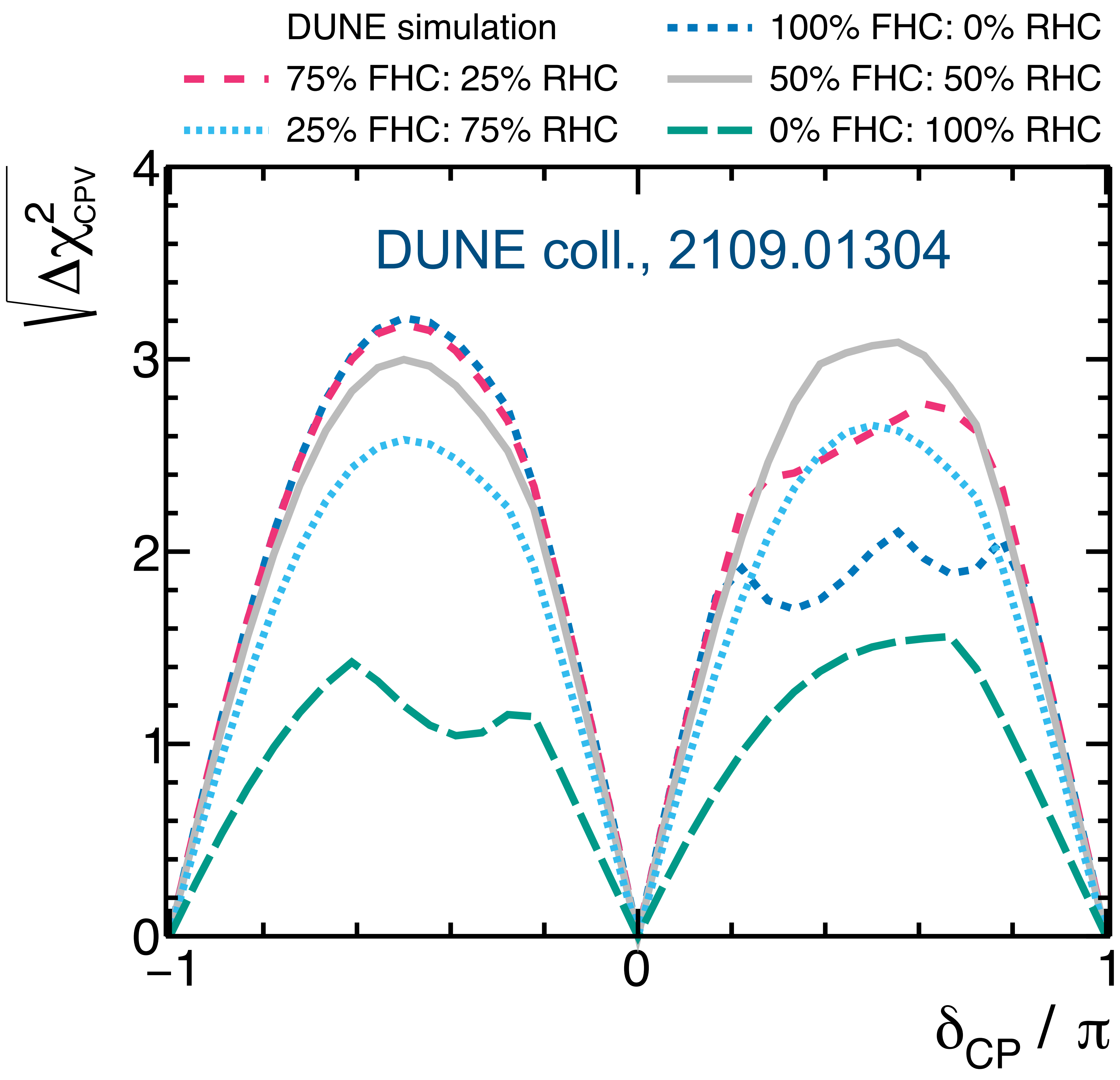


„Search for CP violation“: main goal of future experiments

- Fermilab — Homestake (1300 km):
  DUNE (USA)
- J-PARC — HyperKamiokande (295 km):
  T2HK (Japan)
- J-PARC — KNO @ Korea (1100 km):
  T2KK
- ESS (Sweden) (e.g., 540 km)



Can we measure CPV model-independently?

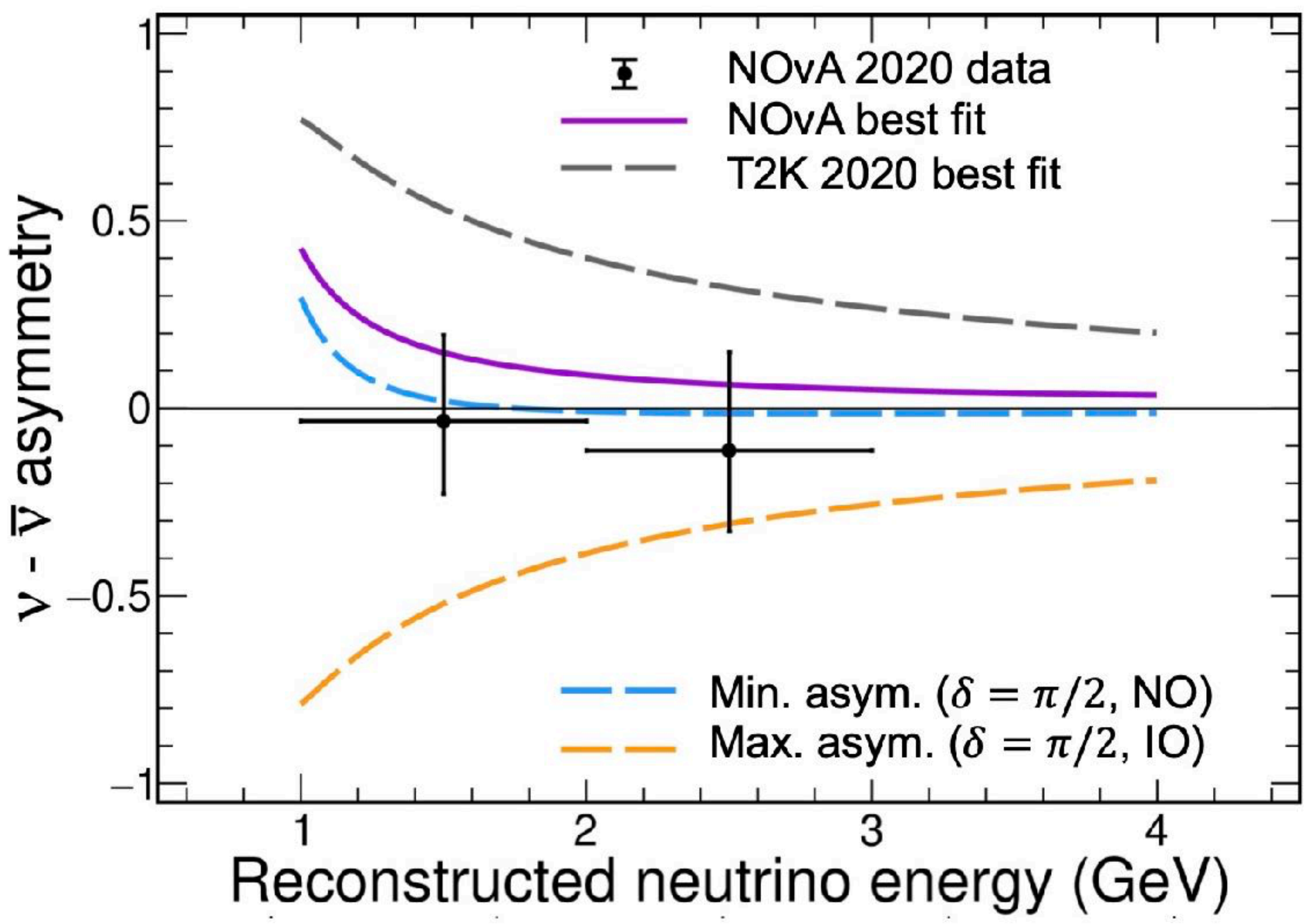
the CP asymmetry $P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

is not a (model-independent) measure for genuine CPV:

- matter effect induces environmental CP asymmetry (can only be taken into account within a model)
- fluxes & cross sections are different for neutrinos and antineutrinos (uncertainties due not cancel)

J. Hartnell @ Neutrino'22

$P(\nu_e) - P(\bar{\nu}_e) \,/\, P(\nu_e) + P(\bar{\nu}_e)$



Comments on search for CP violation

The „standard approach“ is highly model dependent:

assumes:

- 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 ⇔ excluding values of 0 and π for δ_{CP}

Comments on search for CP violation

The „standard approach“ is highly model dependent:

- In the presence of new physics, there are additional sources of CPV
  e.g.: sterile neutrinos, non-unitarity, non-standard neutrino interactions,…
- adopt model-dependent parameterization
- perform combined accelerator/reactor fit + energy spectrum
- determine allowed range for relevant CP phases
  CPV ⇔ excluding values of 0 and π

many papers, several authors in this room

T violation

In vacuum CPT holds:

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = P(\nu_\mu \to \nu_e) - P(\nu_e \to \nu_\mu)$$

T corresponds to exchange of initial and final flavour

- matter effect breaks CPT (and CP) but 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
- BUT exchanging initial and final flavour not feasible in practice

T violation — highly incomplete list of references

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

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with Alejandro Segarra:
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- assume $x \approx t$

- T: $t - t_s \rightarrow t_d - t$ or $x - x_s \rightarrow x_d - x$ or $L \rightarrow -L$ with $L = x_d - x_s$

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- assume $x \approx t$
- T: $t - t_s \to t_d - t$ or $x - x_s \to x_d - x$ or $L \to -L$ with $L = x_d - x_s$
- measure oscillation probabilities at several distances but at the same energy
- search for a T-odd (L-odd) component of the oscillation probability

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  → matter effect does not introduce environmental T violation
  → can diagonalize H and go to energy-eigenbasis

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- allow for arbitrary (non-unitary) mixing between flavour and energy eigenstates (even different for production and detection): $|\nu_\alpha\rangle = \sum_i N_{\alpha i}^{\mathrm{prod,det}}|\nu_i\rangle$
- allow for arbitrary (sufficiently smooth) energy dependence of new physics

Model-independent test of T violation

- general parameterisation of the transition probabilities:

$$
\begin{aligned}
P_{\mu\alpha} &= \left| \sum_{i=1}^{3} c_i^\alpha e^{-i\lambda_i L} \right|^2 \\
&= \sum_i |c_i^\alpha|^2 + 2\sum_{j<i} \mathrm{Re}(c_i^\alpha c_j^{\alpha *}) \cos(\omega_{ij} L) \quad - 2\sum_{j<i} \mathrm{Im}(c_i^\alpha c_j^{\alpha *}) \sin(\omega_{ij} L)
\end{aligned}
$$

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

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

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\end{aligned}
$$

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

complex phases in c_i^α lead to T violation

more sources for TV due to new physics

Model-independent test of T-violation

- general parameterisation of the transition probabilities:

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

T-even

T-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

T violation in the disappearance channel

- general parameterisation of the transition probabilities:

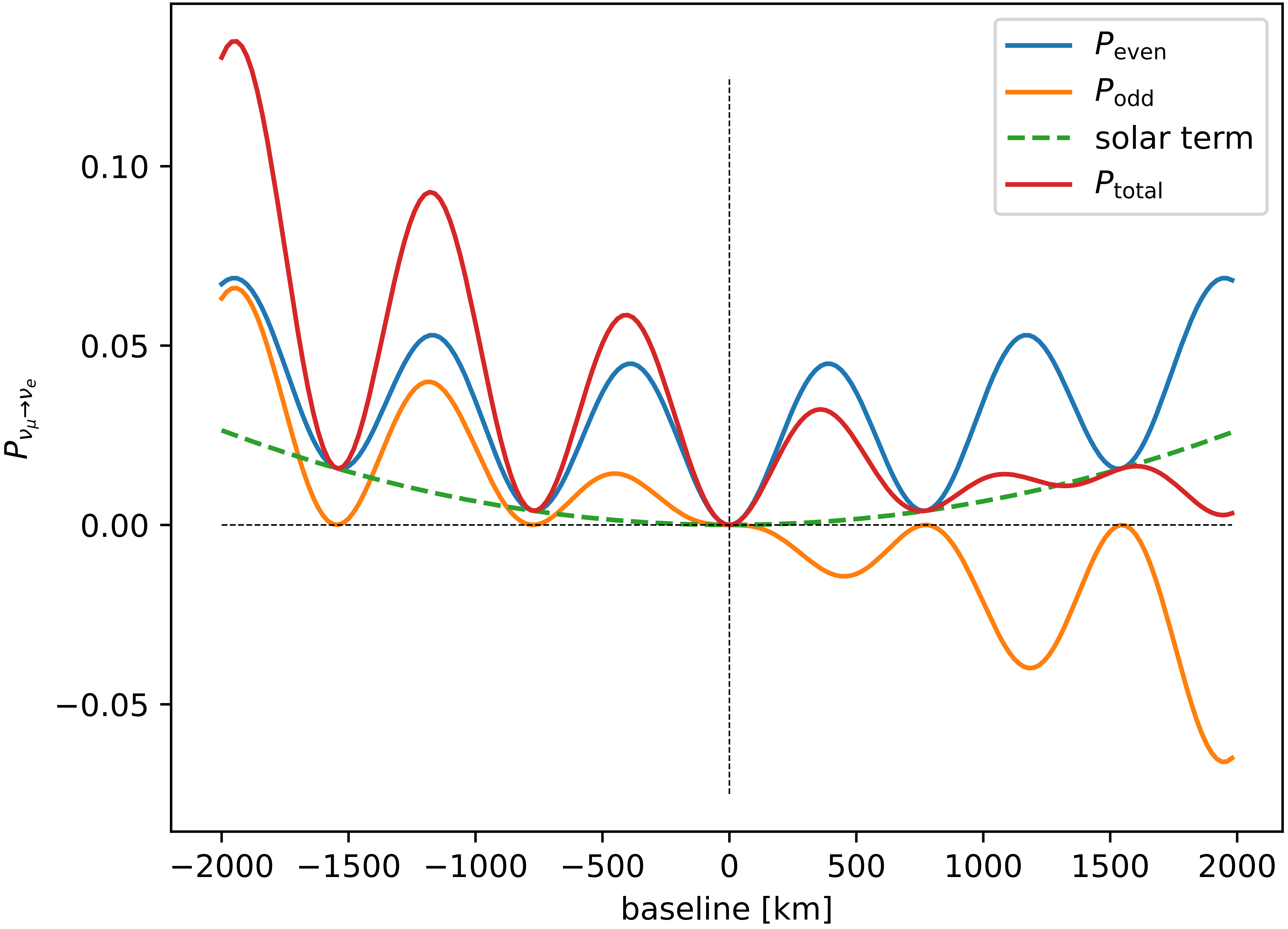
$$P_{\mu\alpha} = \left|\sum_{i=1}^{3} c_i^\alpha e^{-i\lambda_i L}\right|^2$$

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

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

for $N_{\alpha i}^{\mathrm{det}} \neq N_{\alpha i}^{\mathrm{prod}}$ also T violation in the disappearance channel! [TS Segarra, PRD]

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



Two more assumptions:

- 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 $(\Delta m^2_{21})_{\mathrm{eff}}$ is close to the SM

Model-independent test of T violation

- if data cannot be fitted with an even function of L, fundamental T violation can be established

$$P_{\mu\alpha}^{\text{even}}(L, E; \theta) = \sum_i (c_i^\alpha)^2 + 2\sum_{j<i} c_i^\alpha c_j^\alpha \cos(\omega_{ij} L) \qquad (c_i^\alpha \text{ real})$$

- measure $P_{\mu e}$ and $P_{\mu\mu}$ as a function of L (at the same E_ν)
- try to fit 8 parameters: $c^e_{1,2,3}, c^\mu_{1,2,3}, \omega_{21}, \omega_{31}$
- works already for 3 LBL experiments + near detectors (+ Δm^2_{21} prior)!

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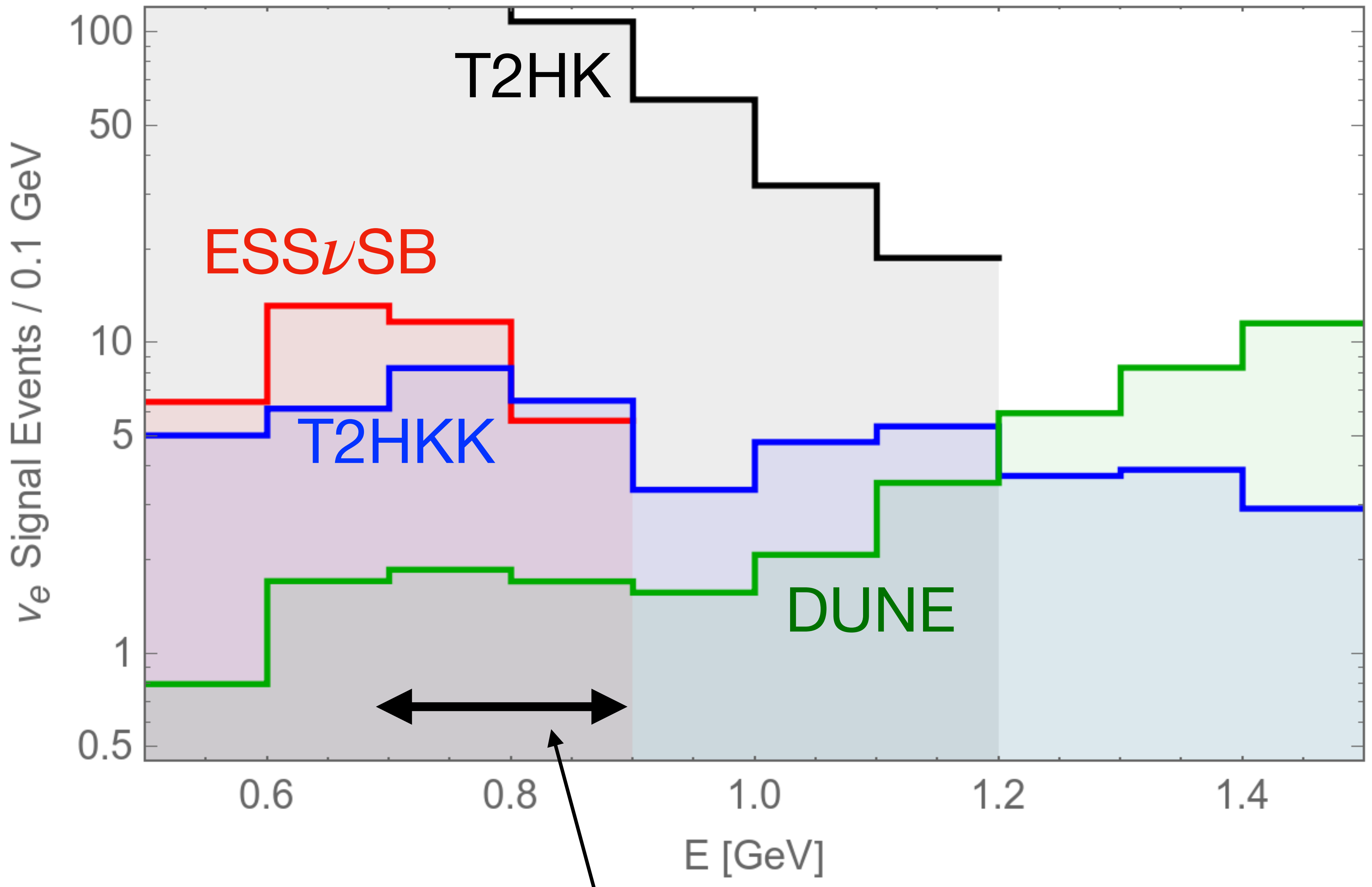
$$P^{\mathrm{even}}_{\mu\alpha}(L,E;\theta) = \sum_i (c_i^\alpha)^2 + 2\sum_{j<i} c_i^\alpha c_j^\alpha \cos(\omega_{ij} L) \qquad (c_i^\alpha \text{ real})$$

- measure $P_{\mu e}$ and $P_{\mu\mu}$ as a function of L (at the same E_ν) ←
- try to fit 8 parameters: $c^e_{1,2,3}, c^\mu_{1,2,3}, \omega_{21}, \omega_{31}$ (unknown functions of E_ν)
- works already for 3 LBL experiments + near detectors (+ Δm^2_{21} prior)!

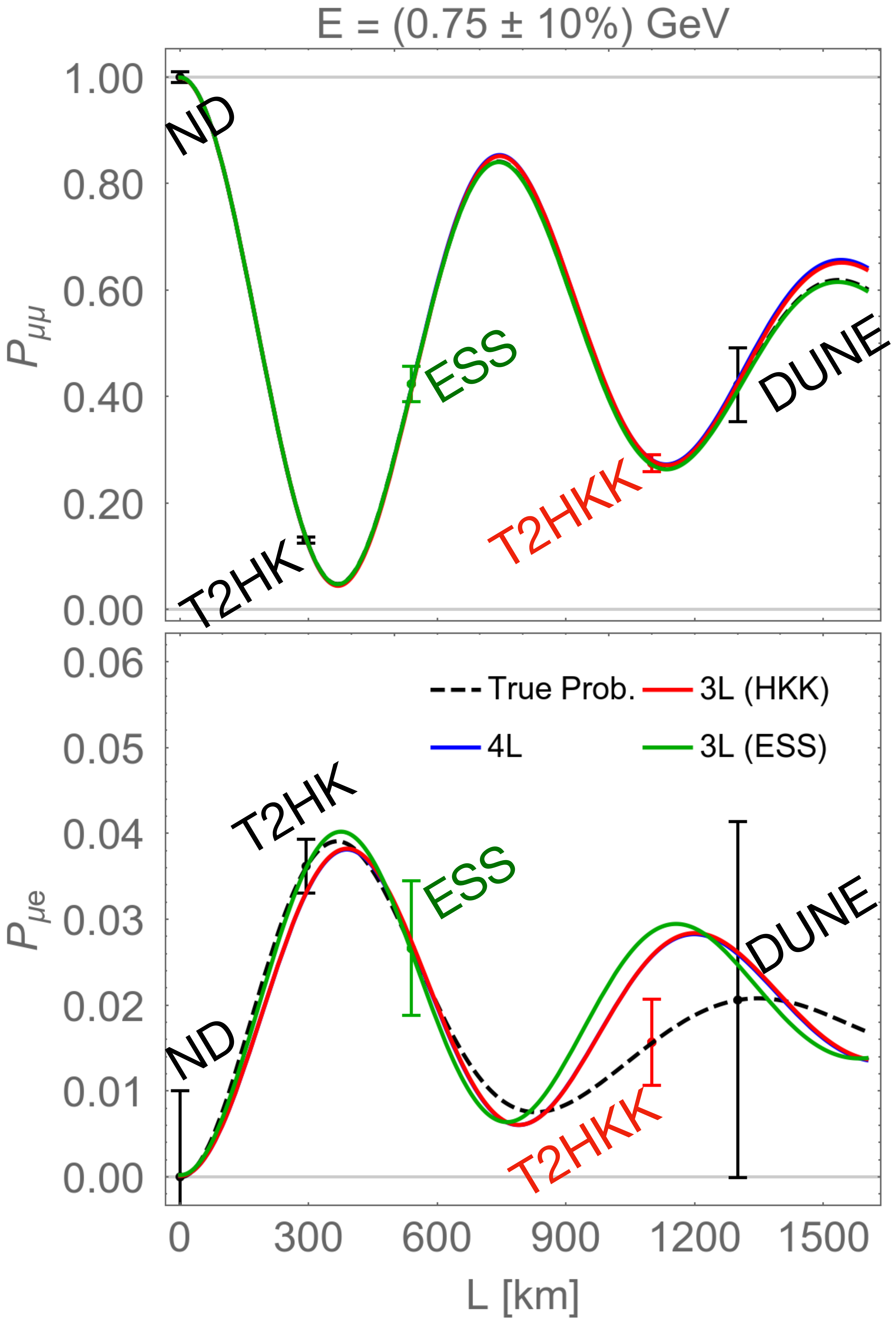
Does it work in real life?

- preliminary sensitivity studies [TS Segarra, PRL]
- assume „data“ is generated by standard 3-flavour oscillations with maximum CPV
- perform a 8-parameter fit searching for the best-fit c_i^α, ω_{ij} for each energy bin
- take $\sum_{\text{energy bins}} \chi^2_{\text{min}}$ as rough measure for sensitivity

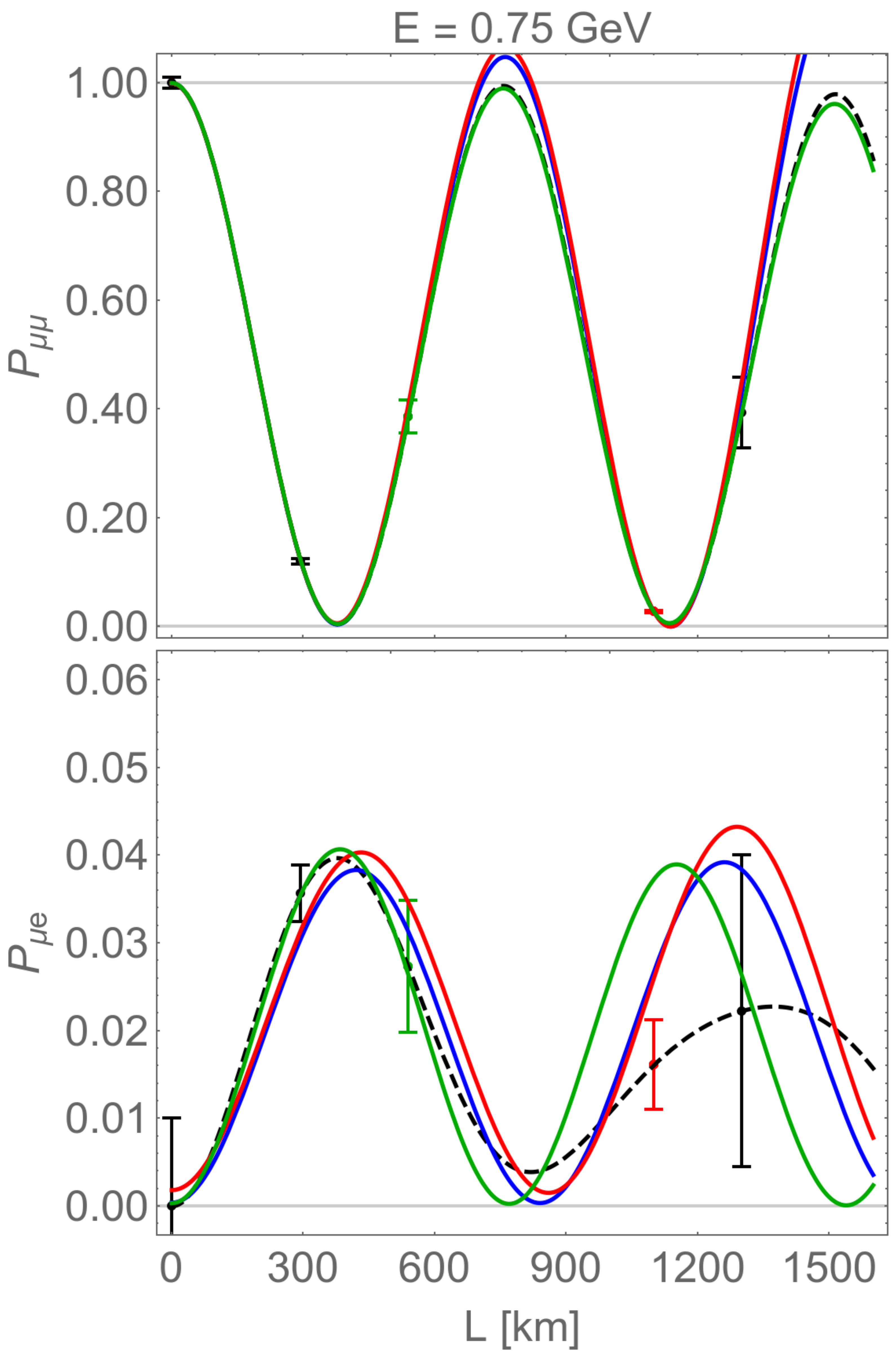
Does it work in real life?

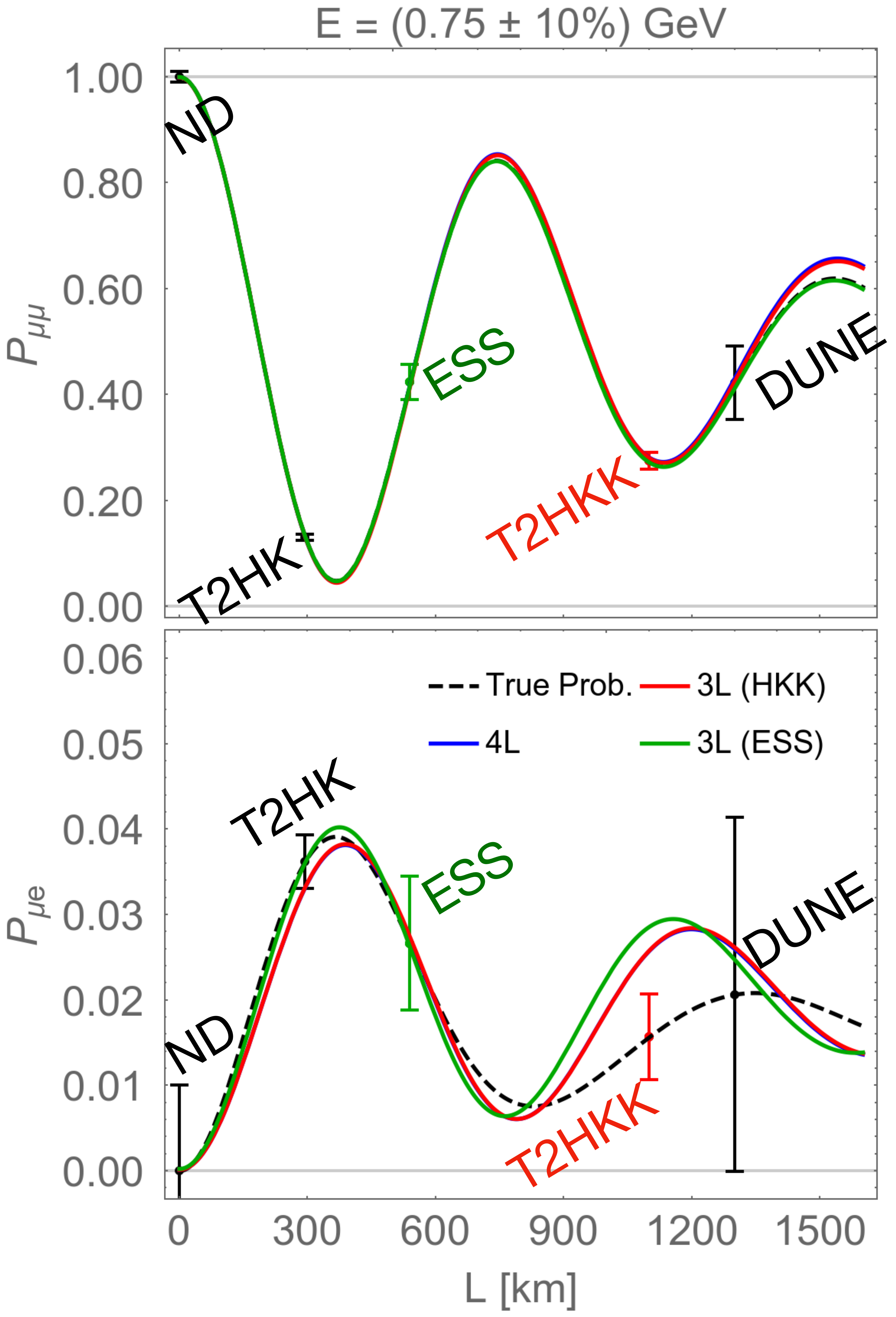


most sensitive energy interval



energy resolution is crucial!





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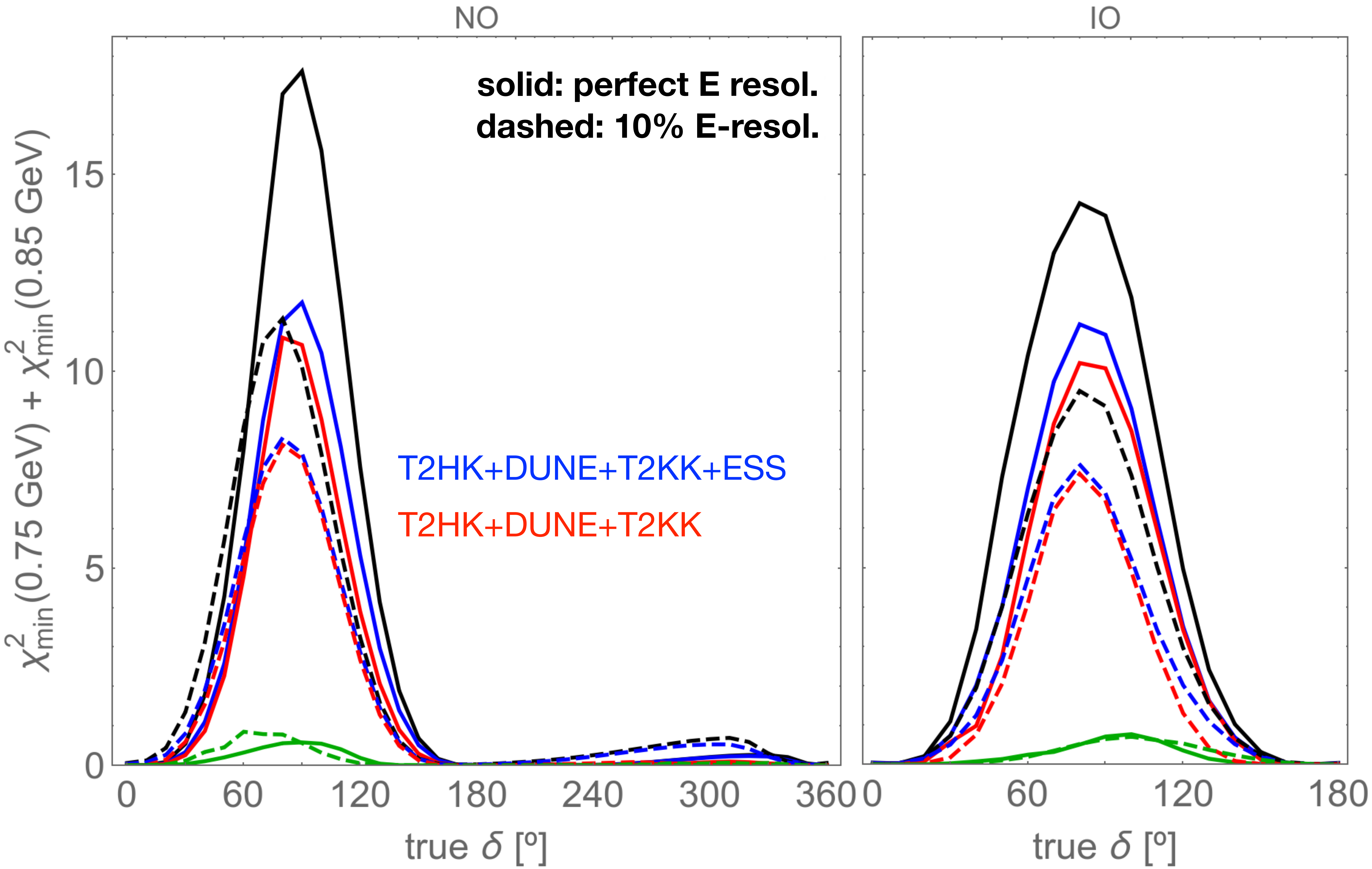

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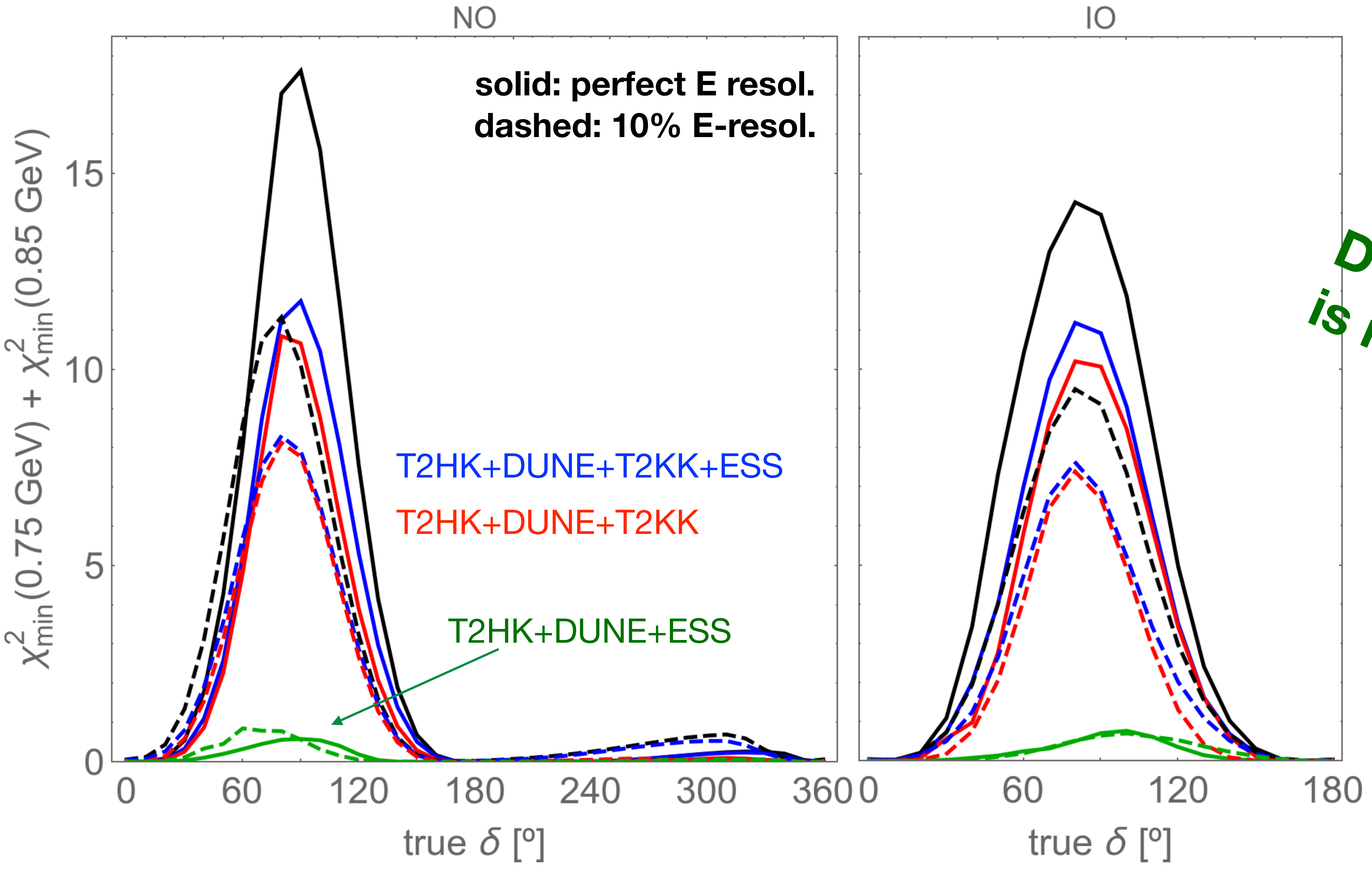
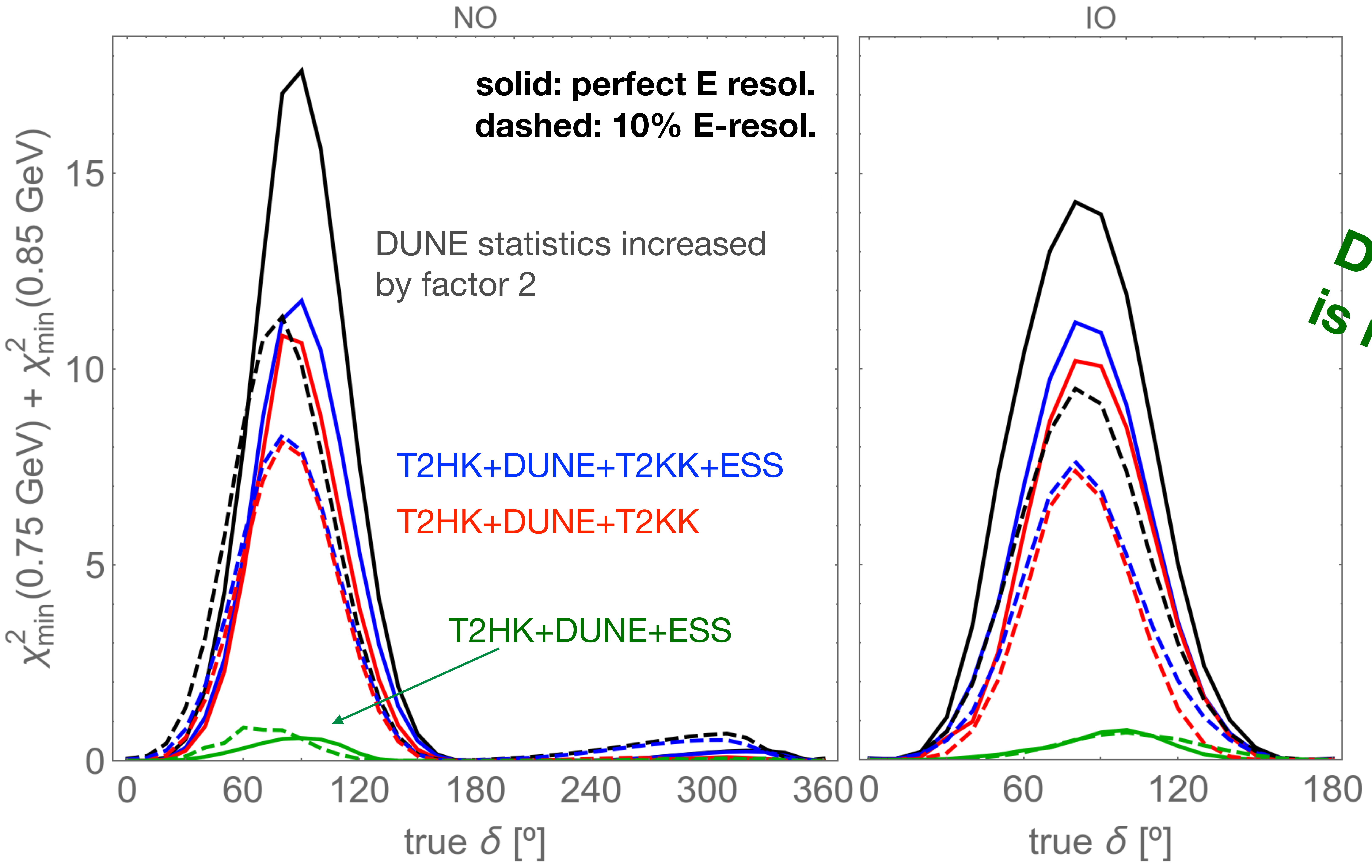


Detector in Korea is needed!

Does it work in real life?



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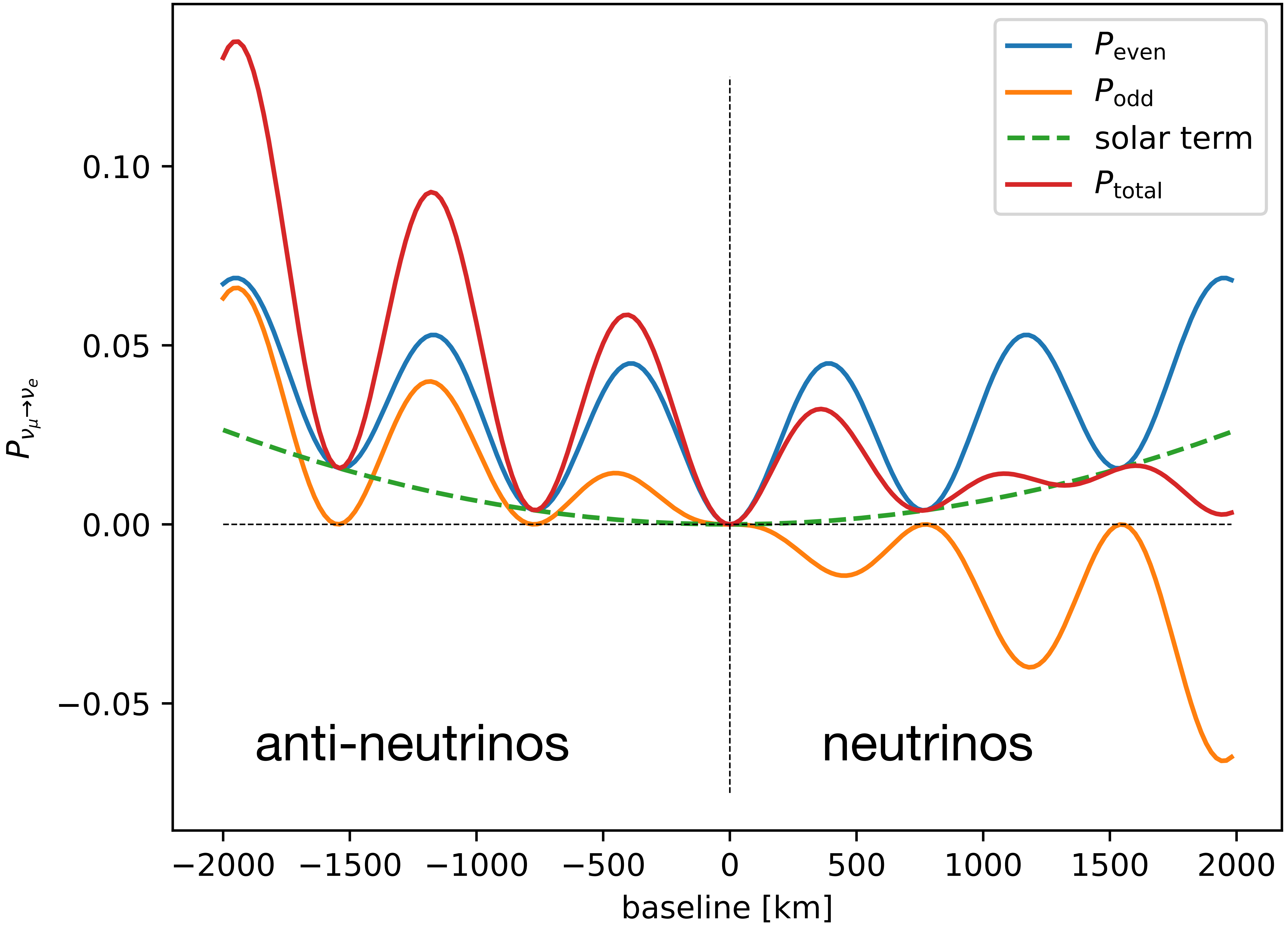
Sensitivity at $\delta_{\mathrm{CP}} \sim 270^\circ$ provided by anti-neutrinos

- in general
  $P_{\mu e}^{\mathrm{even}}(2\mathrm{nd\,max}) \geq P_{\mu e}^{\mathrm{even}}(1\mathrm{st\,max})$
- test works only if
  $P_{\mu e}^{\mathrm{total}}(2\mathrm{nd\,max}) < P_{\mu e}^{\mathrm{total}}(1\mathrm{st\,max})$
- this happens
  for neutrinos at $\delta_{\mathrm{CP}} \sim 90^\circ$
  for anti-neutrinos at $\delta_{\mathrm{CP}} \sim 270^\circ$



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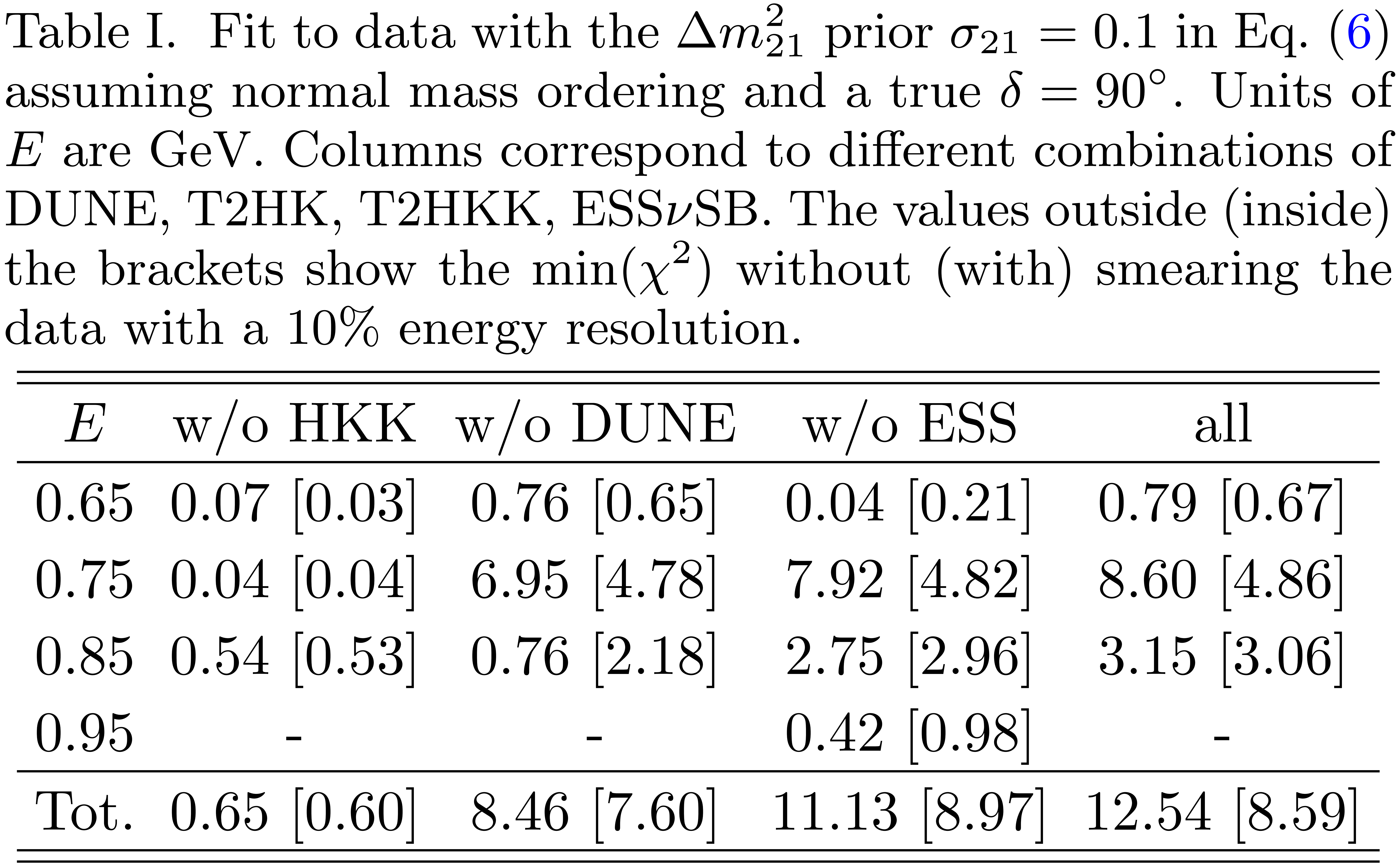


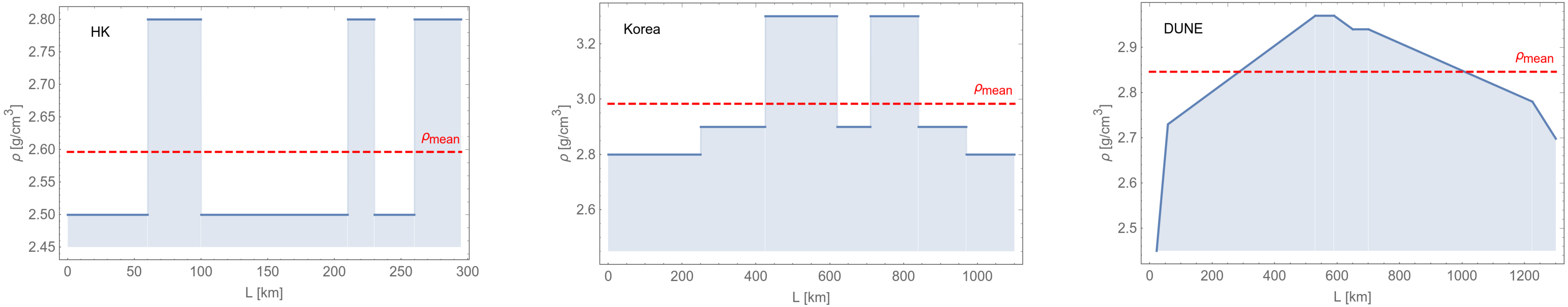
Table I. Fit to data with the Δm^2_{21} prior $\sigma_{21} = 0.1$ in Eq. (6) assuming normal mass ordering and a true $\delta = 90^\circ$. Units of E are GeV. Columns correspond to different combinations of DUNE, T2HK, T2HKK, ESSνSB. The values outside (inside) the brackets show the min(χ^2) without (with) smearing the data with a 10% energy resolution.

E	w/o HKK	w/o DUNE	w/o ESS	all
0.65	0.07 [0.03]	0.76 [0.65]	0.04 [0.21]	0.79 [0.67]
0.75	0.04 [0.04]	6.95 [4.78]	7.92 [4.82]	8.60 [4.86]
0.85	0.54 [0.53]	0.76 [2.18]	2.75 [2.96]	3.15 [3.06]
0.95	-	-	0.42 [0.98]	-
Tot.	0.65 [0.60]	8.46 [7.60]	11.13 [8.97]	12.54 [8.59]

Correction due to non-constant matter density

[TS Segarra, PRD]

- have to assume: constant matter density, same for all experiments
- assuming new-physics is small correction, effect of non-constant density can be taken into account perturbatively

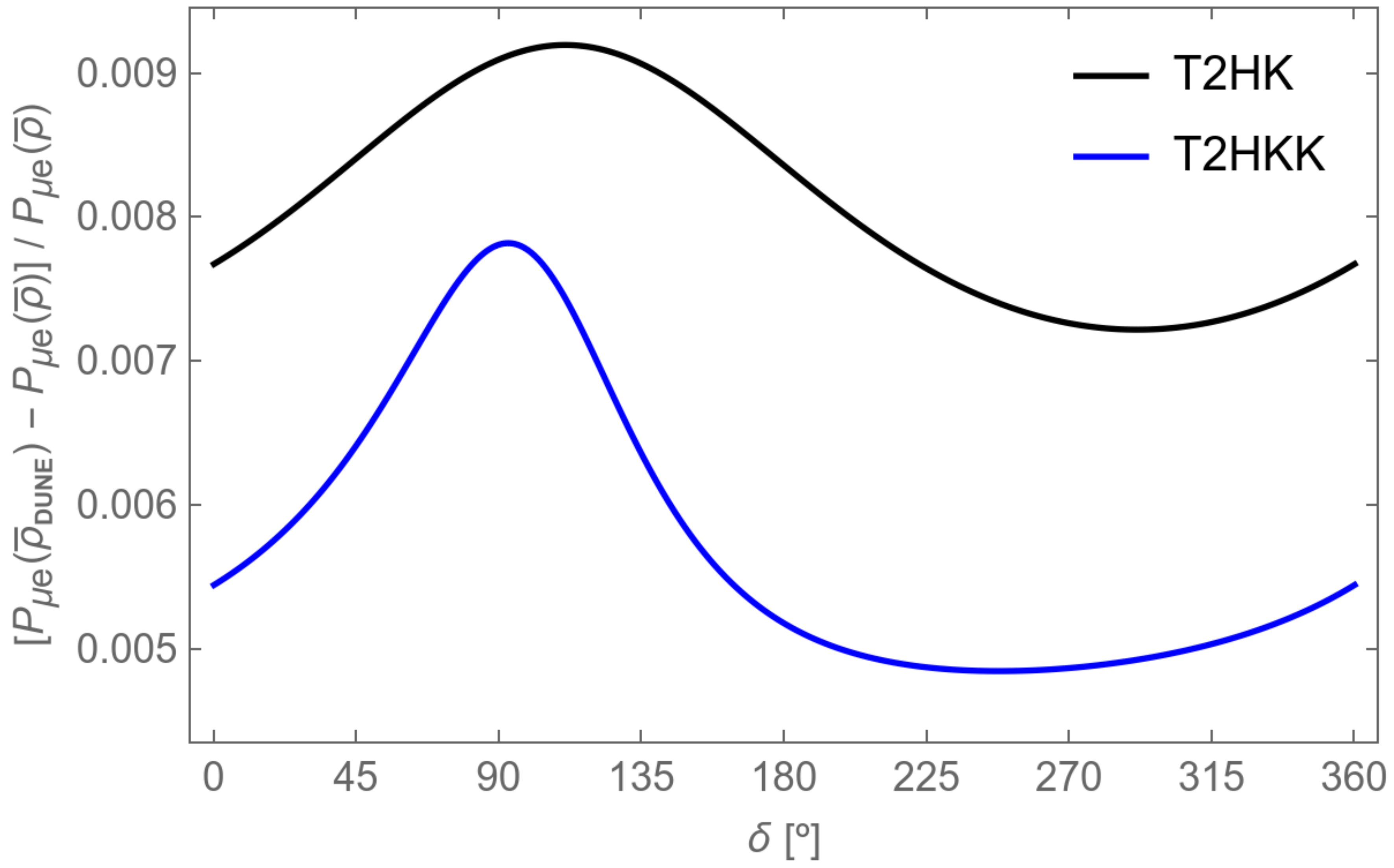


Hagiwara, Okamura, Senda, JHEP 09, 082, arXiv:1107.5857; B. Roe, PRD 95, 113004 (2017), arXiv:1707.02322

Correction due to non-constant matter density

[TS Segarra, PRD]

rel. error due to „wrong“ average density



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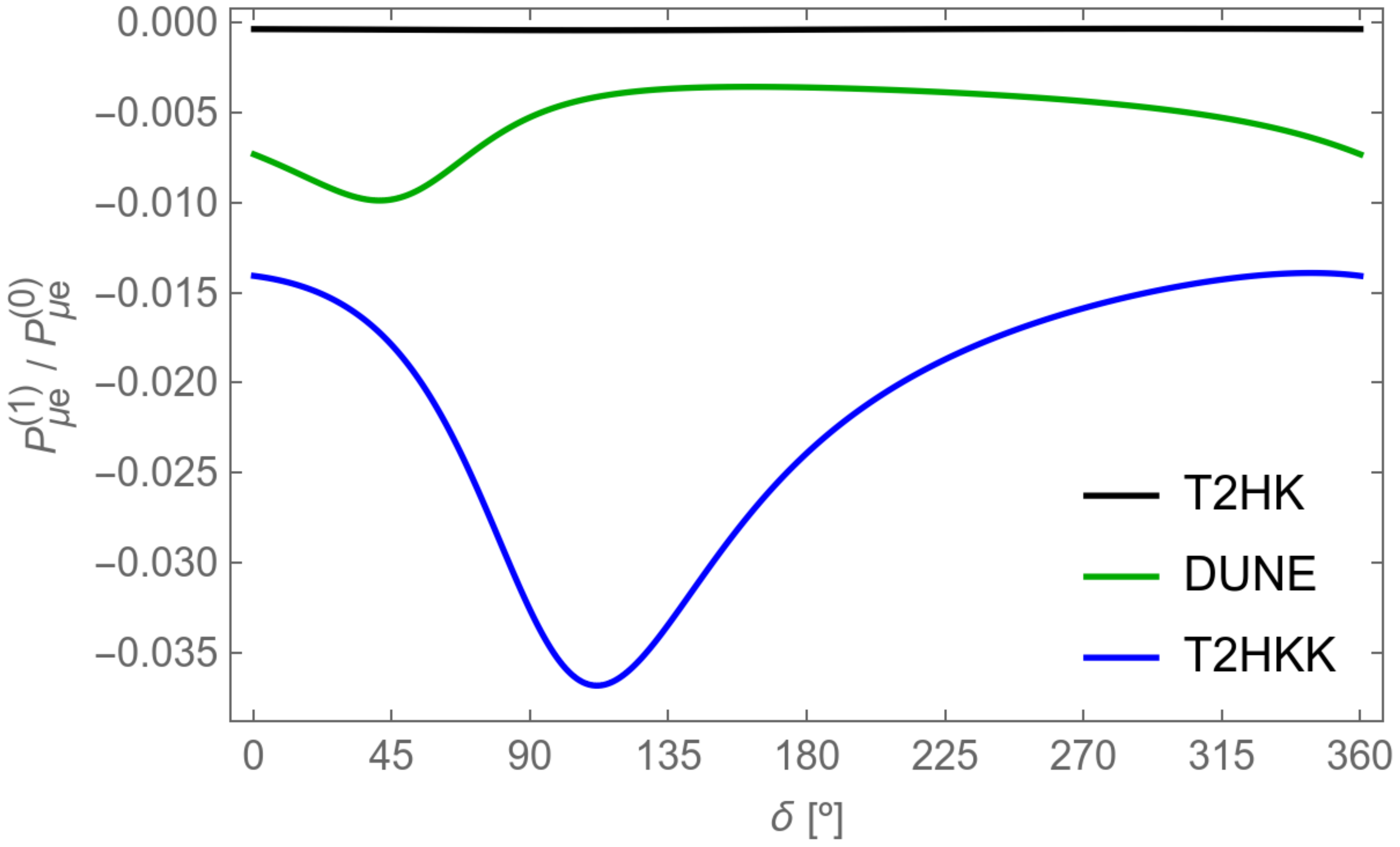

environmentally induced T asymmetry

$$
\begin{aligned}
\text{T2HKK:}\quad & A^{(1)}_{\mu e} \approx 3.5\,(5.3) \times 10^{-4}\,, \\
\text{DUNE:}\quad & A^{(1)}_{\mu e} \approx -2.9\,(-2.0) \times 10^{-4}
\end{aligned}
$$

correction to T asymmetry for $\delta_{\rm CP} = \pi/2$

$$
\begin{aligned}
\text{T2HKK:}\quad & A^{(0)}_{\mu e} \approx 7.1\, \times 10^{-2}\,, \quad A^{(1)}_{\mu e} \approx -9.1\, \times 10^{-4}\,, \\
\text{DUNE:}\quad & A^{(0)}_{\mu e} \approx 6.5\, \times 10^{-2}\,, \quad A^{(1)}_{\mu e} \approx 3.8\, \times 10^{-4}\,.
\end{aligned}
$$

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  - potentially works with 3 baselines covering 1st and 2nd oscillation max at the same energy
  - good energy resolution essential detector in Korea is needed relies on low-energy tail of DUNE

Outlook

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- applies to
  - sterile neutrinos ($|\Delta m^2_{s1}| \ll \Delta m^2_{21}$ or $\gg |\Delta m^2_{31}|$)
  - non-unitarity
  - NSI in matter, source and detector, general EFT (at leading order), light and heavy mediators

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Thank you for your attention!

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