CP and T violation in neutrino oscillations

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based on:

- arXiv:2007.14792: NuFit Coll., Esteban, Gonzalez-Garcia, Maltoni, TS, Zhou
- arXiv:2106.16099: Alejandro Segarra, TS

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

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

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

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

CP and T violation in neutrino oscillations

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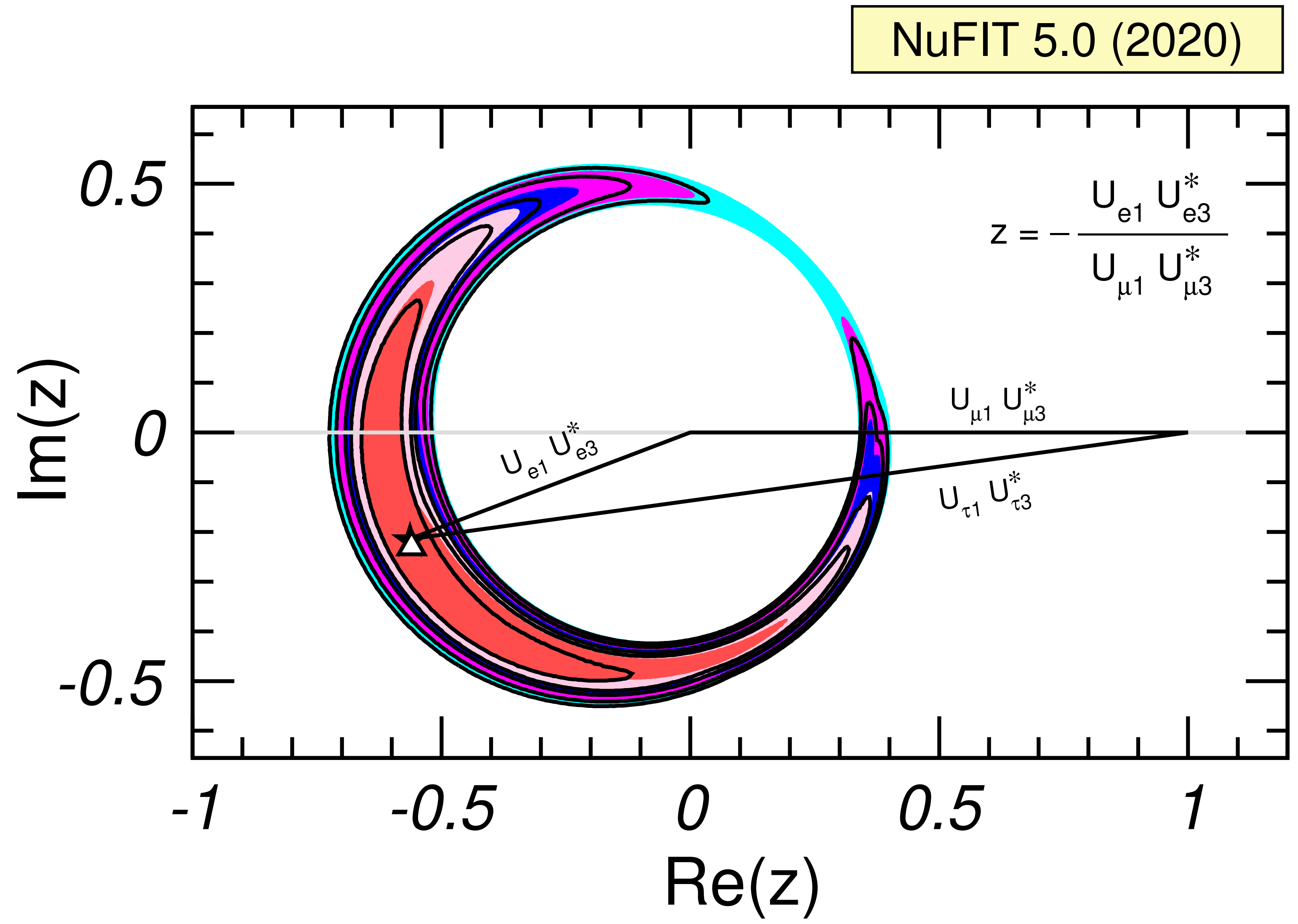
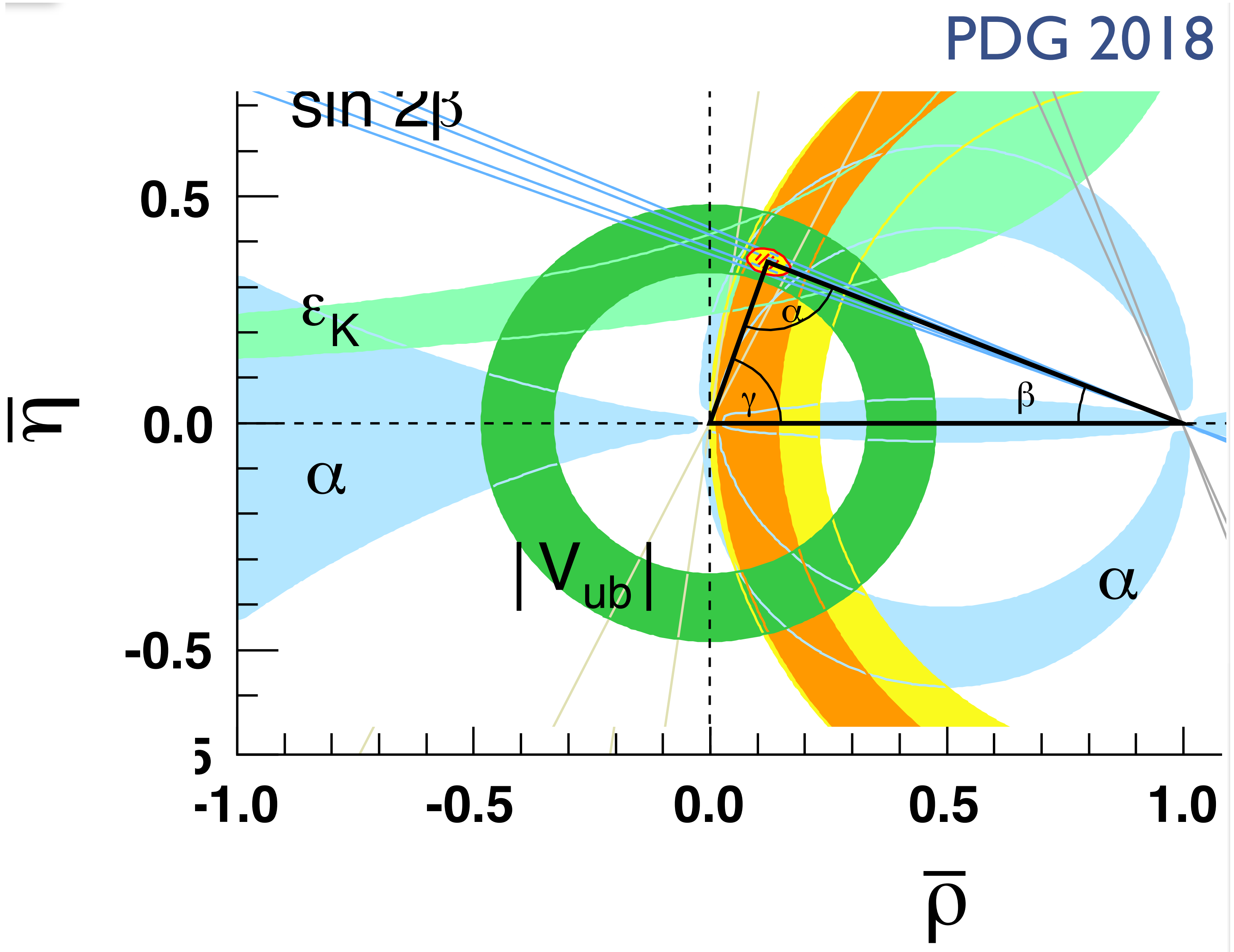


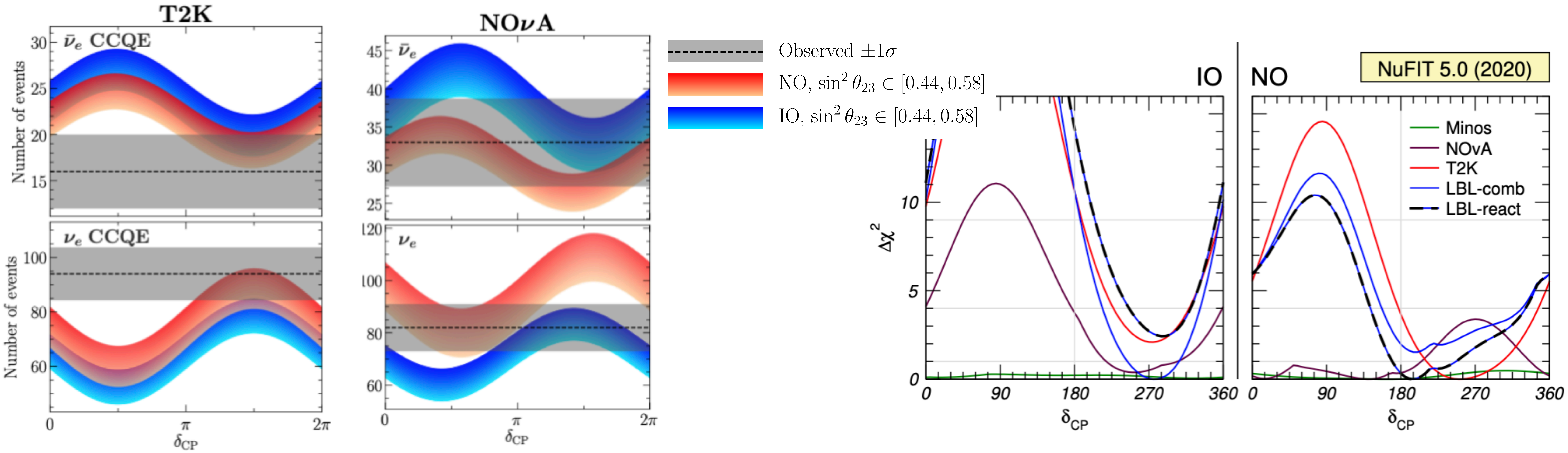


Determination of δ_{CP} from the global 3-flavour fit

NuFit 5.0 (2020) www.nu-fit.org Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, 2007.14792

- some indications from the interplay of long-baseline accelerator, reactor, and atmospheric neutrino experiments
- entangled with the unknown neutrino mass ordering and θ_{23}

Mass ordering and CP phase: LBL accelerator & reactor data



- T2K and NOvA better compatible for IO → LBL combination best fit for IO
- LBL/reactor complementarity in $|\Delta m^2_{31}|$ determination → combination prefers NO
- CP phase best fit at δ=195° (shifted towards 180°) → CP conservation allowed at 0.6σ
- for IO: best fit close to δ=270°, CP conservation disfavoured at 3σ

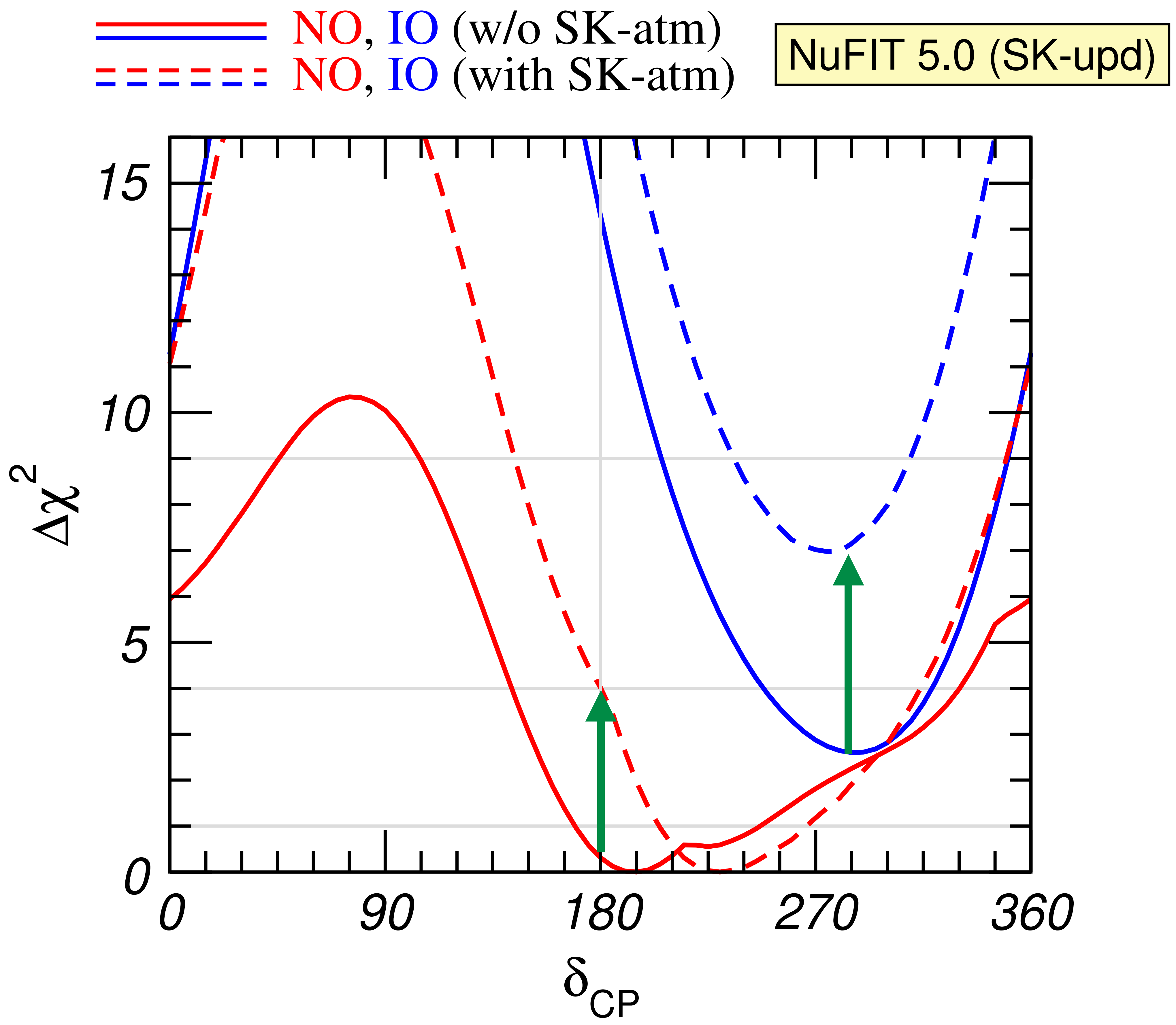
Including atmospheric neutrinos: global fit results

- NuFit 5.0 updated with SK I-IV analysis presented @ Neutrino'20

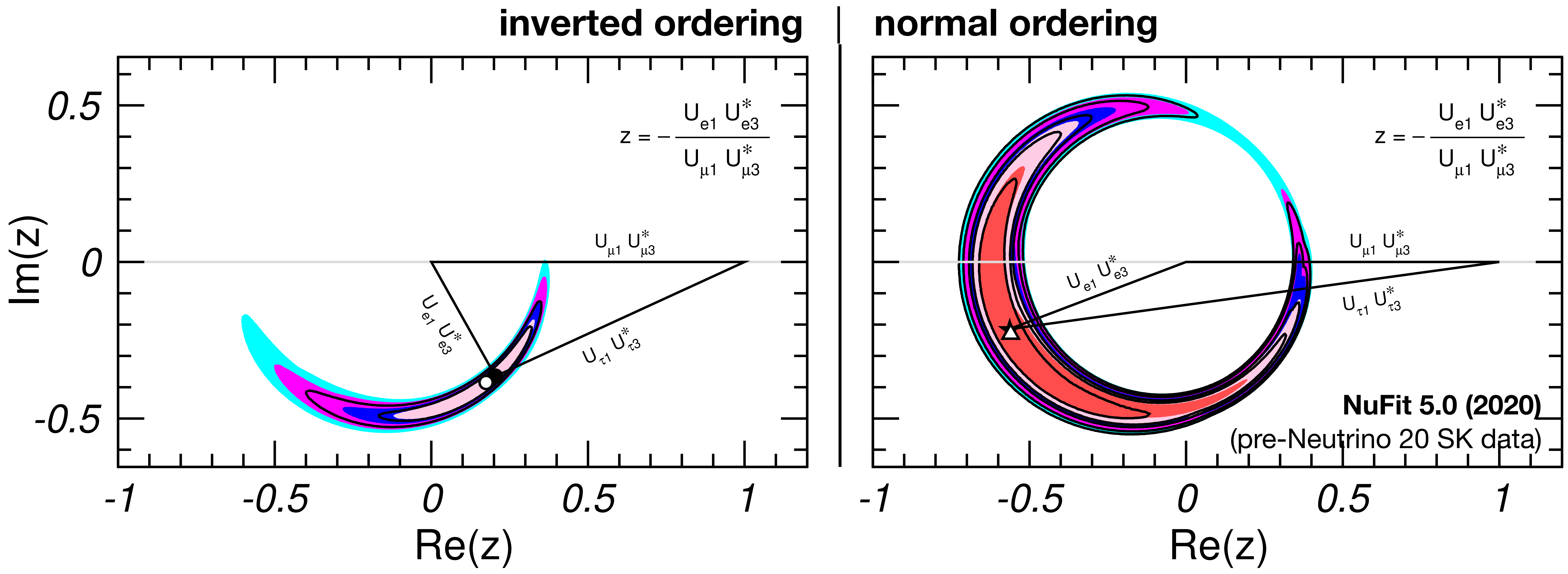
- CP conservation @ 0.6σ (no SK)
  → 2σ (w SK) best fit: $\delta_{CP} \approx 230°$

- χ^2(IO) - χ^2(NO) = 2.7 (no SK)
  → 7.1 (w SK) 2.7σ

- restricting to inverted ordering:
  CP cons. @ $> 3\sigma$, best fit: $\delta_{CP} \approx 290°$

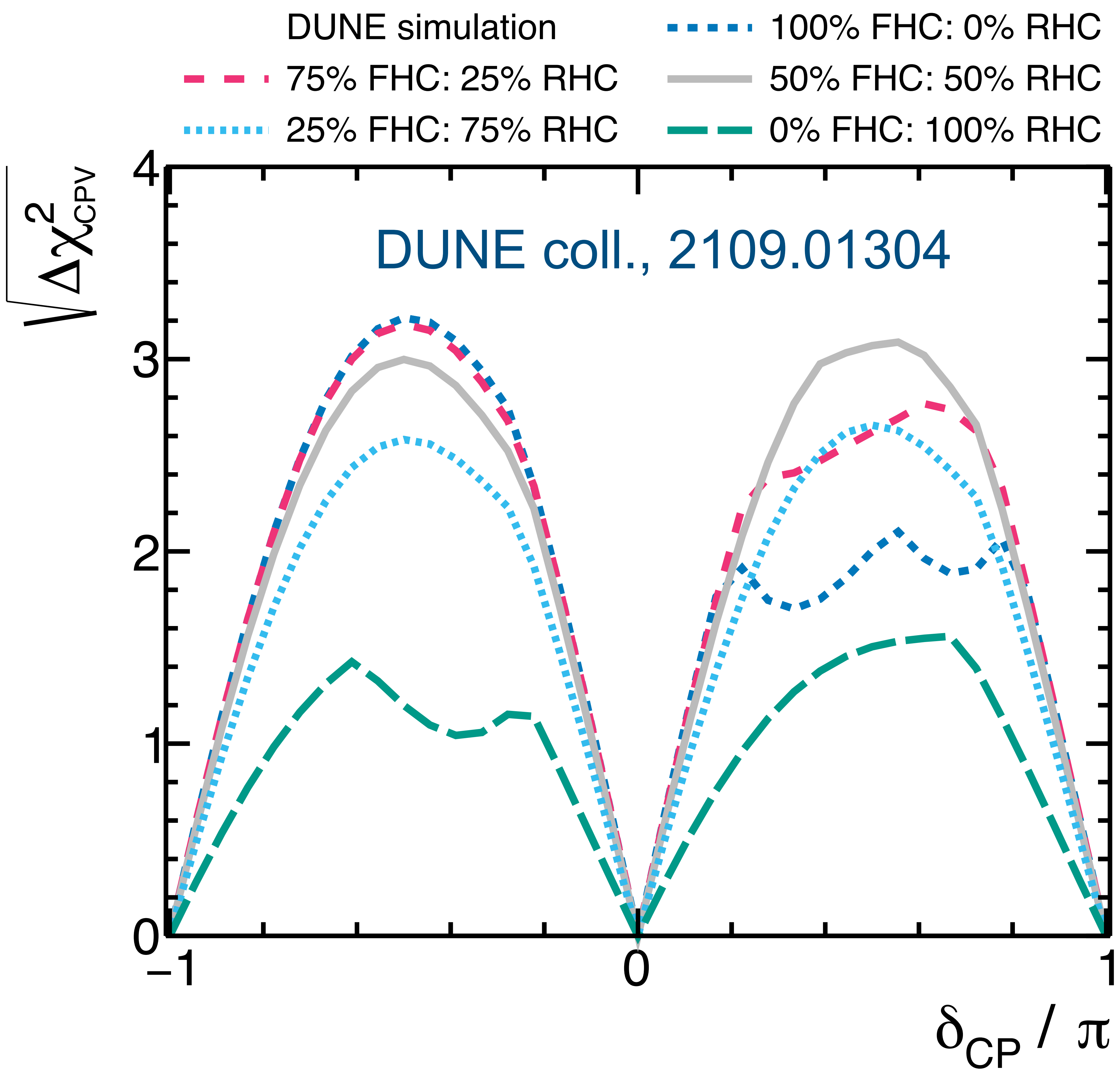


The leptonic unitarity triangle



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

- Fermilab — Homestake (1300 km):
  DUNE (USA)
- J-PARC — HyperKamiokande (295 km):
  T2HK (Japan)
- possible extension: 2nd detector @ Korea:
  T2KK (1100 km)
- ESS (Sweden) (540 km)



Comments on search for CP violation

the CP asymmetry

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

is not directly observable:

- fluxes & cross sections are different for neutrinos and antineutrinos
- matter effect induces environmental CP asymmetry

Comments on search for 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 but does NOT induce environmental T asymmetry for a matter profile symmetric between source and detector
  [e.g., Akhmedov, Huber, Lindner, Ohlsson, 01]
- BUT exchanging initial and final flavour not feasible in practice

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:

- no „direct test“ of CP violation possible
- In the presence of new physics, there are additional sources of CPV e.g.: sterile neutrinos, non-unitarity, non-standard neutrino interactions,…

Comments on search for CP violation

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

Model-independent test of T violation

A. Segarra, TS, 2106.16099

- fundamental T-viol equivalent to CP-viol. assuming CPT conservation
- assume evolution equation

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

- position independent Hamiltonian (approx. constant matter density) → matter effect does not introduce environmental T violation
- allow for arbitrary (non-standard) matter effect
- allow for arbitrary (non-unitary) mixing between flavour and energy eigenstates (even different for production and detection):

$$|\nu_\alpha\rangle = \sum_i N_{\alpha i}^{\text{prod,det}} |\nu_i\rangle$$

Model-independent test of T violation

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- general parameterisation of the transition probabilities:

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

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

Model-independent test of T violation

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- 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

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

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

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

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

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

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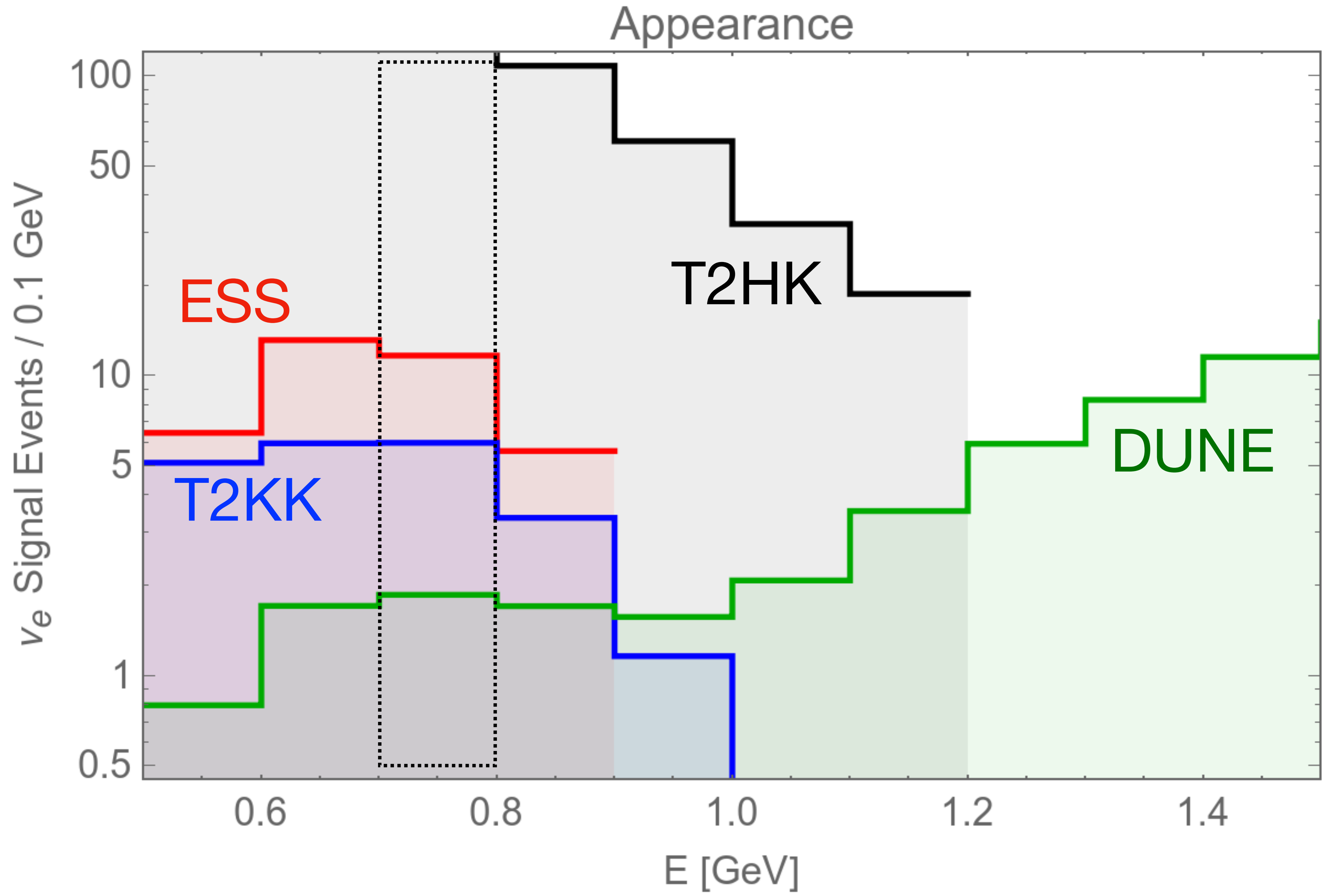
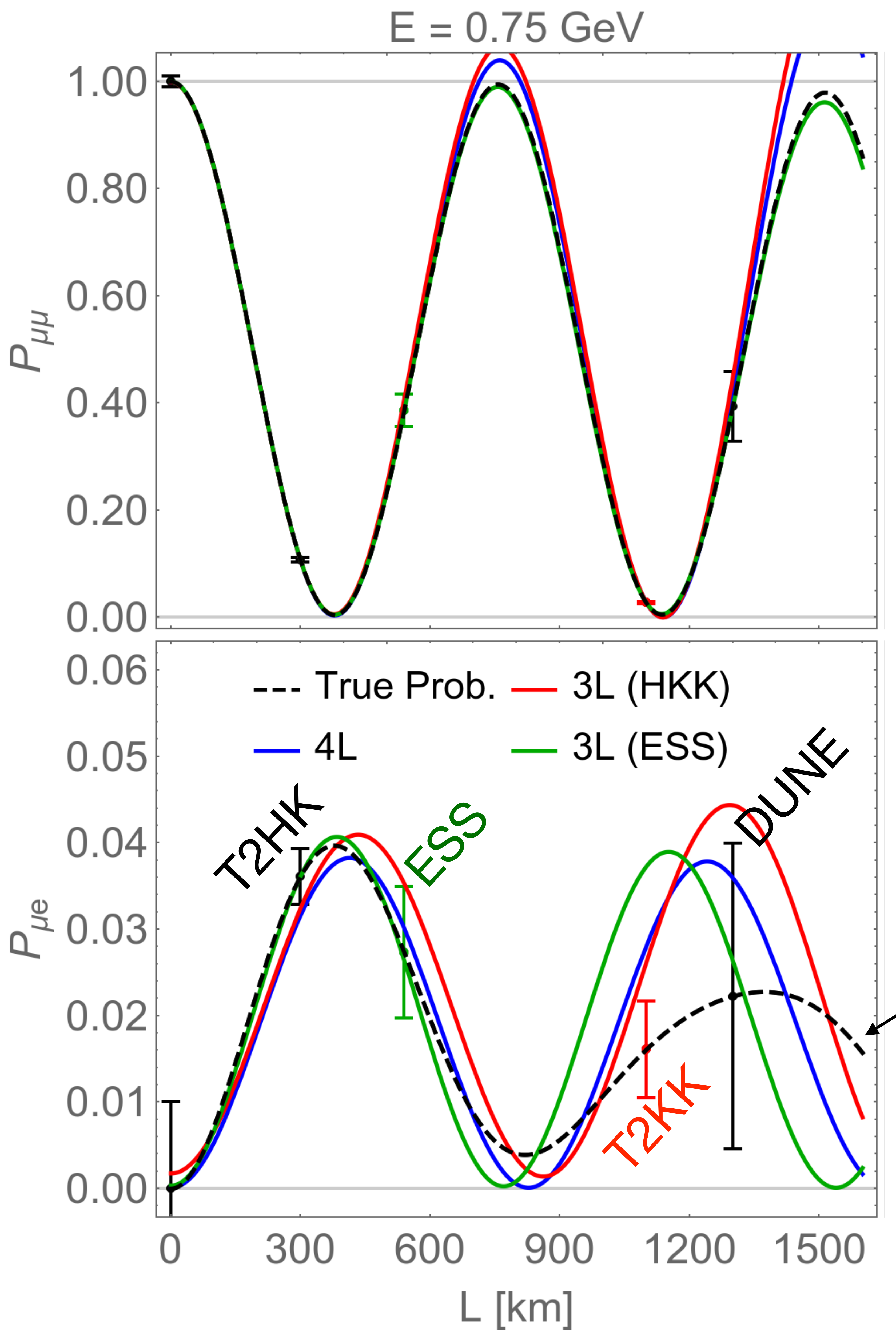
- measure $P_{\mu e}$ and $P_{\mu\mu}$ as a function of L (at the same E_ν) ←
- try to fit 8 parameters: $c^e_{1,2,3}, c^\mu_{1,2,3}, \omega_{21}, \omega_{31}$ (unknown functions of E_ν)
- works already for 3 LBL experiments + near detectors!

Does it work in real life?

- DUNE, T2HK, T2KK, ESSνSB
  (no overlap bin with NOvA)





best fit with L-even prob.

3nu probability with $\delta_{\rm CP} = 90°$

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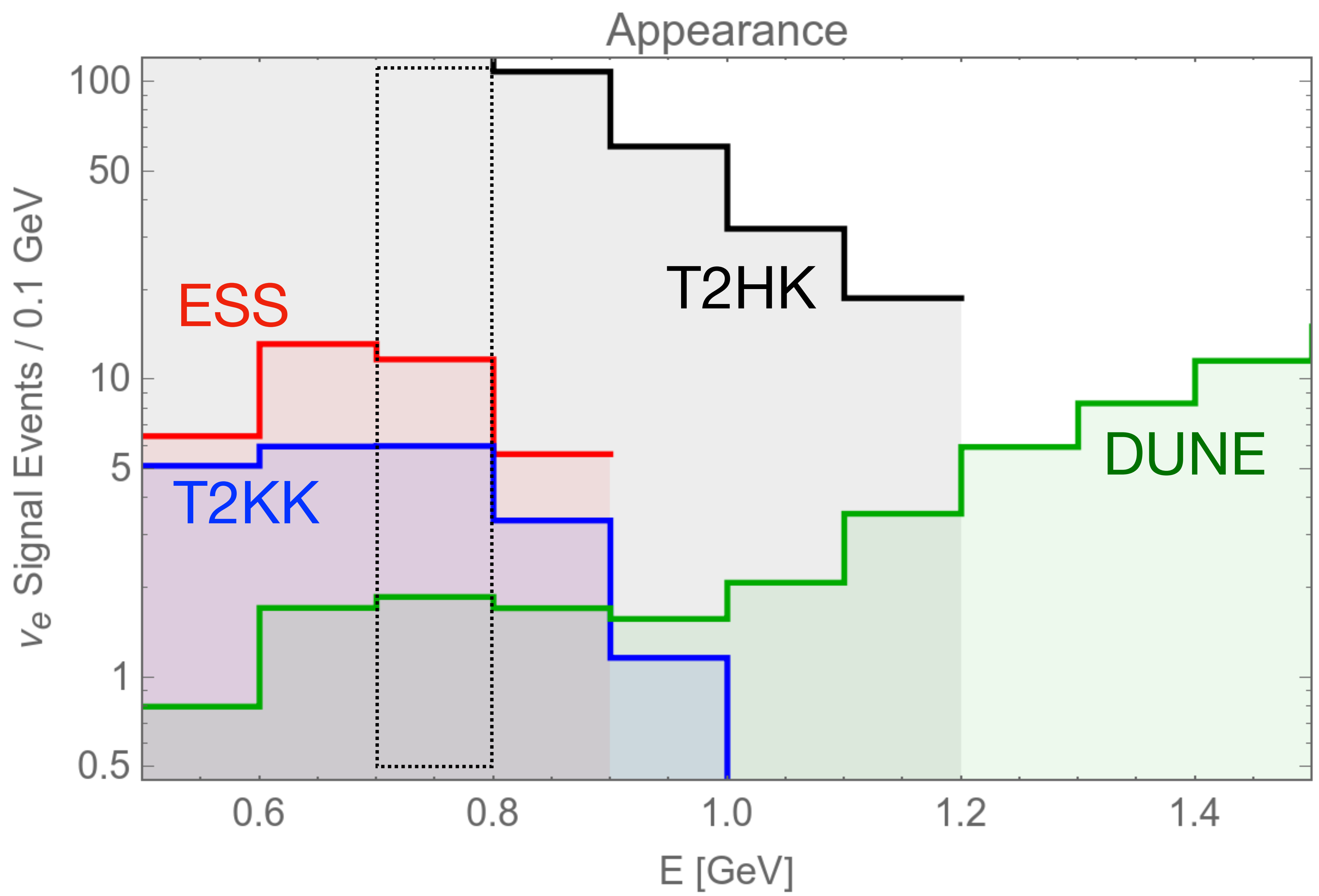
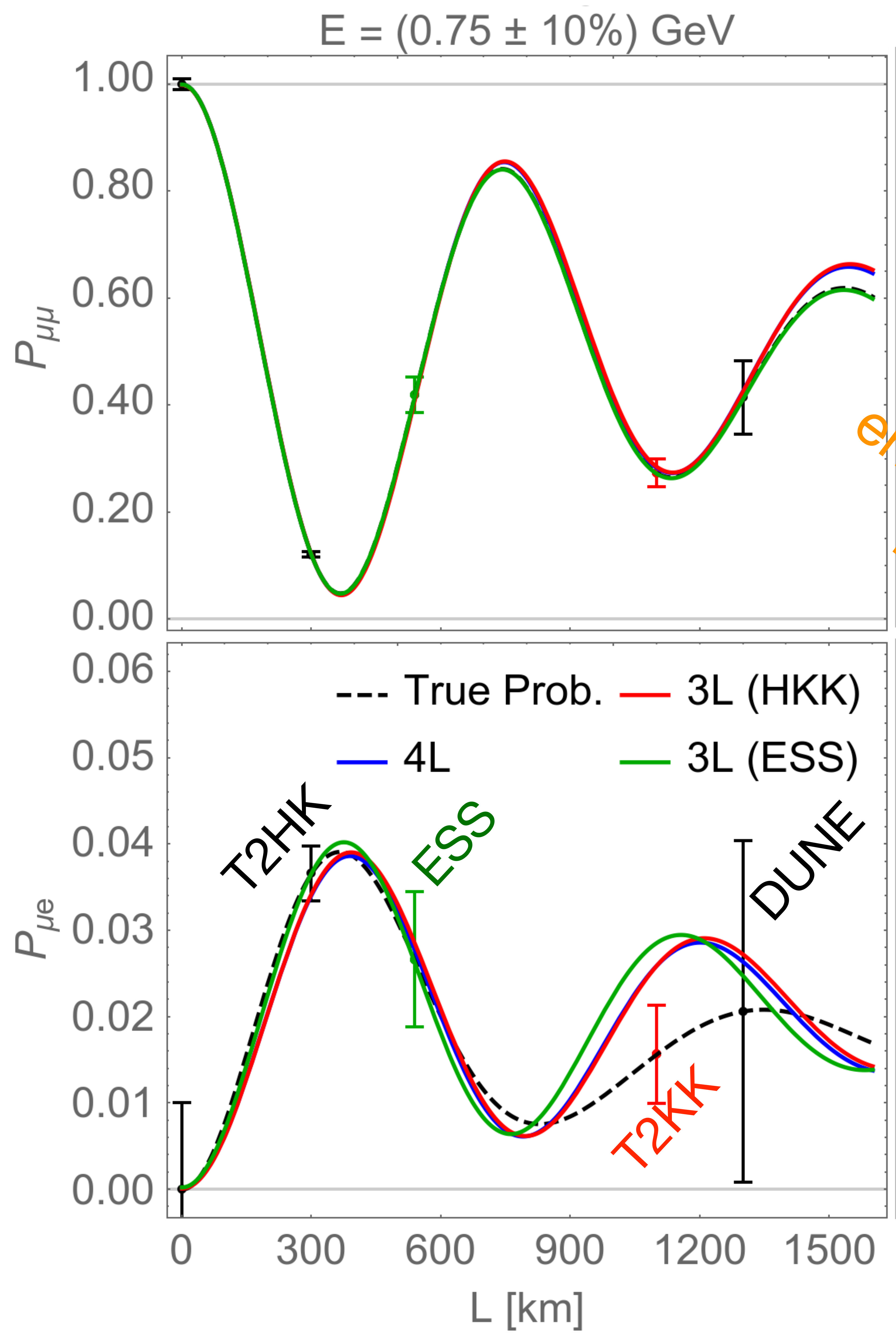
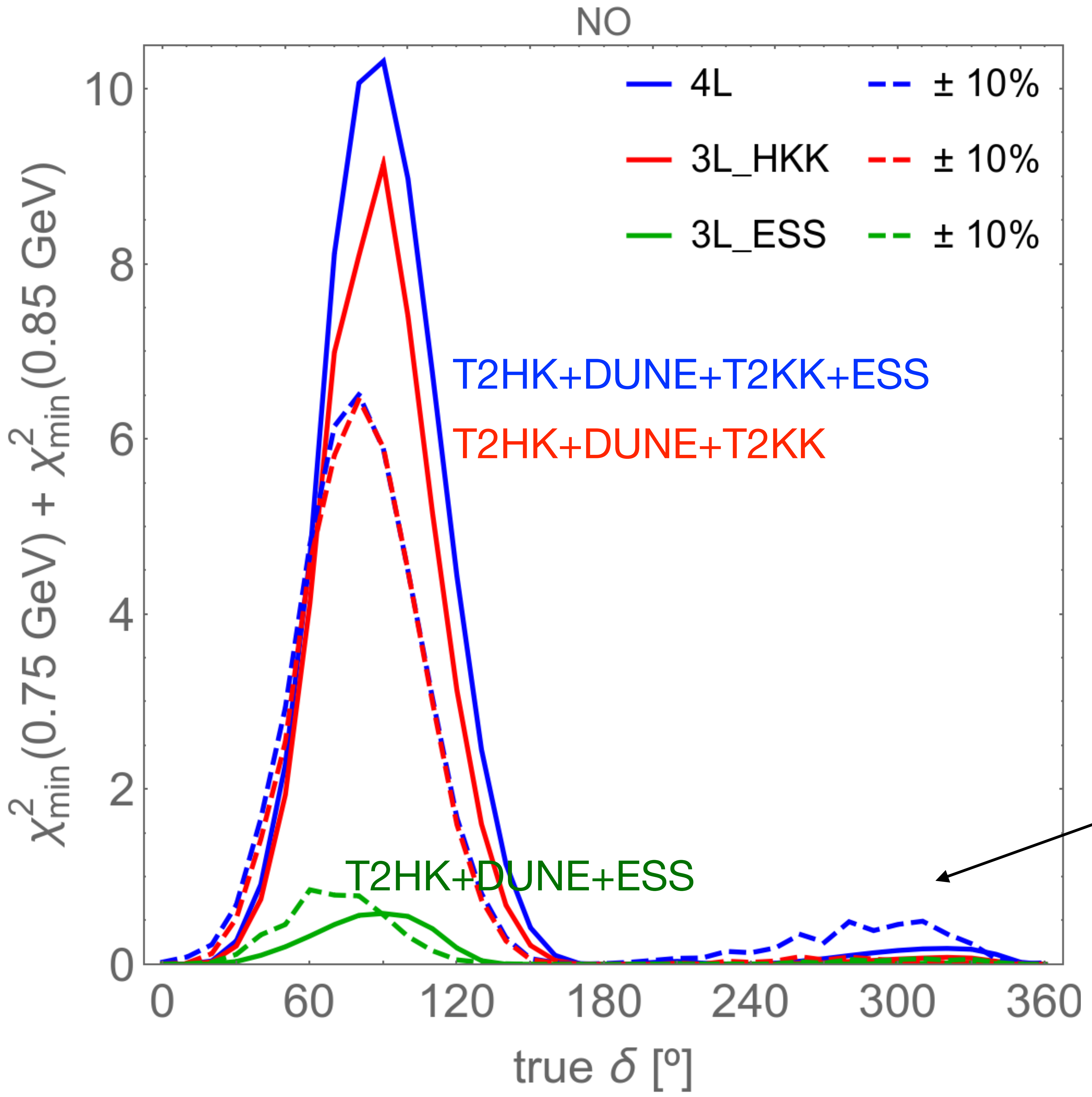




energy resolution is crucial!

Does it work in real life?



- T2HK + T2KK + ESS works also
- DUNE + NOvA + Potvino-ORCA under investigation
- inverted ordering very similar
- $\delta_{\rm CP} \sim 270°$ can be tested with antineutrino data

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Summary

- standard „search for CP violation“ is highly model-dependent: parametric fit for $\delta_{\rm CP}$ within the Standard Model
- propose a model-independent test for T violation
  - search for L-odd terms in the oscillation probability
  - need to measure $P(\nu_\mu \to \nu_\alpha)$ at different L but at the same energy
  - potentially works with 3 long-baseline experiments need overlap in energy and good energy resolution
  - motivation for more than one experiment: DUNE & T2HK & in particular for the T2KK detector in Korea

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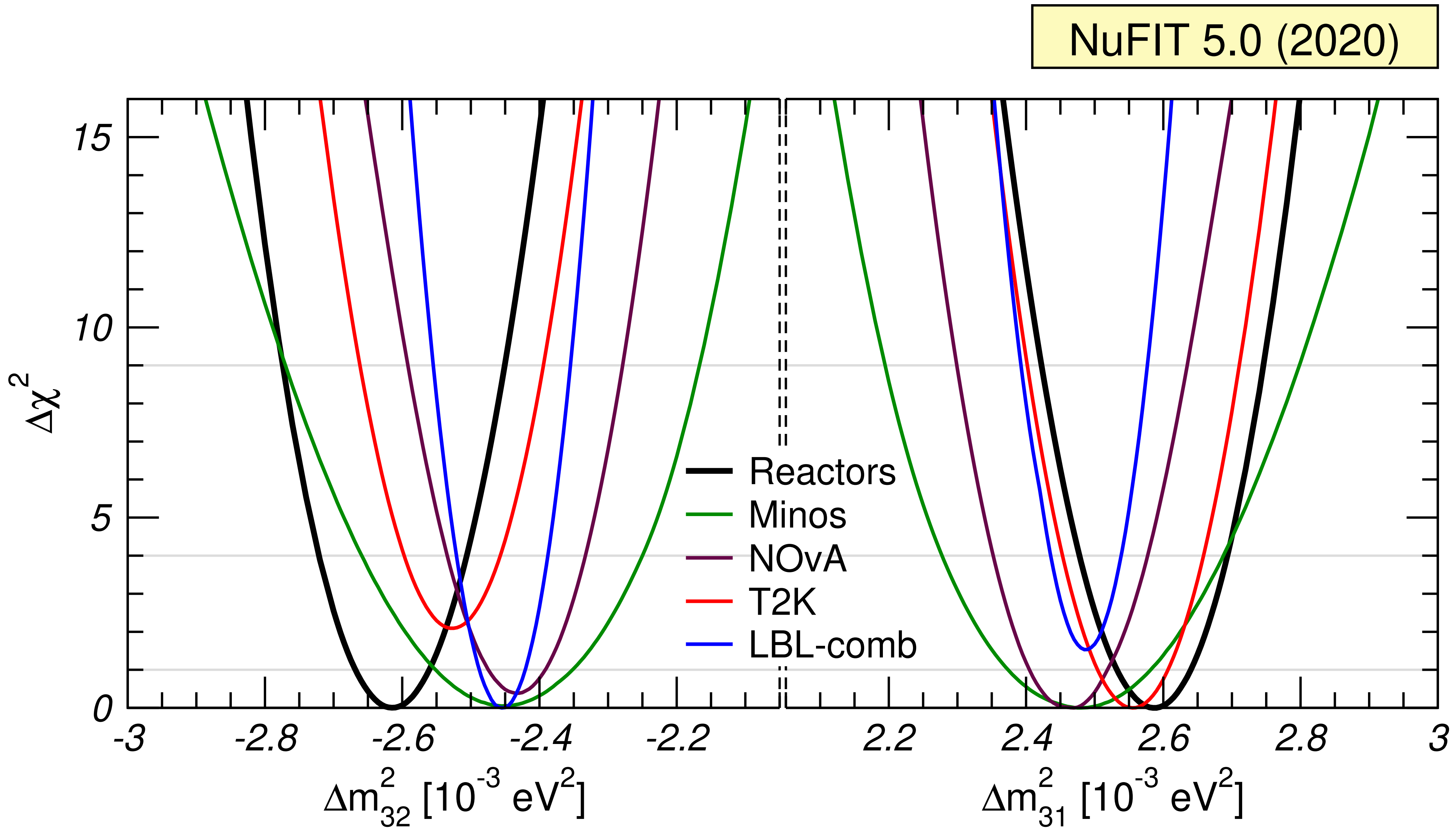
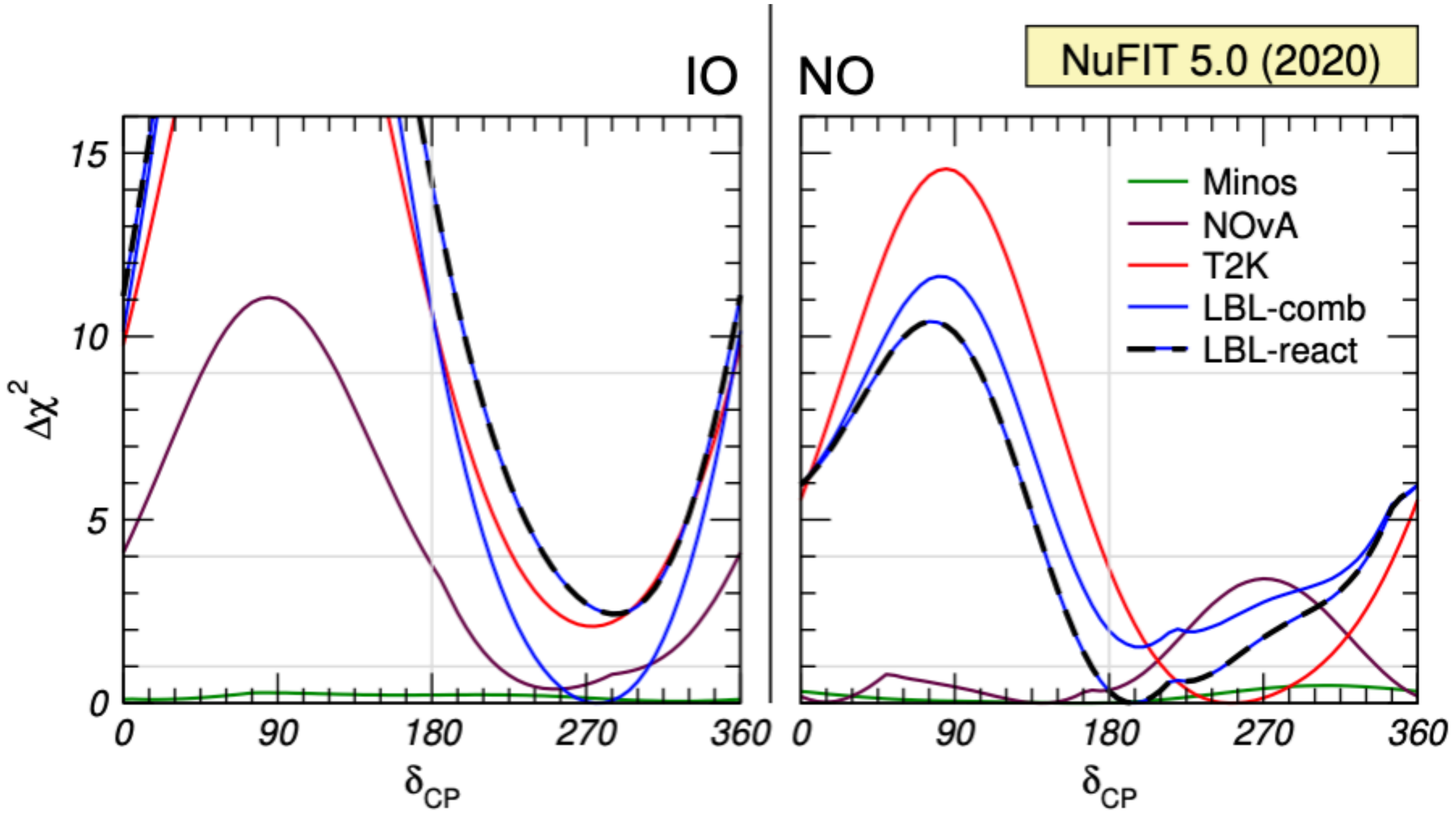
Thank you for your attention!

back up slides

Mass ordering and CP phase: LBL accelerator & reactor data





- T2K and NOvA better compatible for IO → LBL combination best fit for IO
- LBL/reactor complementarity in $|\Delta m^2_{31}|$ determination → combination prefers NO
- this effect will be very power full in the future [Blennow, TS, 2013], by combining reactor data from JUNO with atmospheric data from IceCube [1911.06745] or KM3NET/ORCA [2108.06293]

Model-independent test of T violation

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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 $\delta = 90^\circ$. Results with 3 baselines use either DUNE + T2HK + ESSνSB data (3L ESS), or DUNE + T2HK + T2HKK data (3L HKK); the column 4L shows the results with all four baselines. The values outside (inside) the brackets show the min(χ^2) without (with) smearing the data with a 10% energy resolution.

E (GeV)	3L (ESS)	3L (HKK)	4L
0.65	0.07 [0.03]	0.04 [0.27]	0.83 [0.47]
0.75	0.04 [0.04]	7.04 [3.82]	7.40 [3.84]
0.85	0.54 [0.53]	2.10 [1.97]	2.92 [2.05]
0.95	-	0.21 [0.77]	-
Total	0.65 [0.60]	9.39 [6.83]	11.15 [6.36]