Global analyses of neutrino oscillation data

Thomas Schwetz
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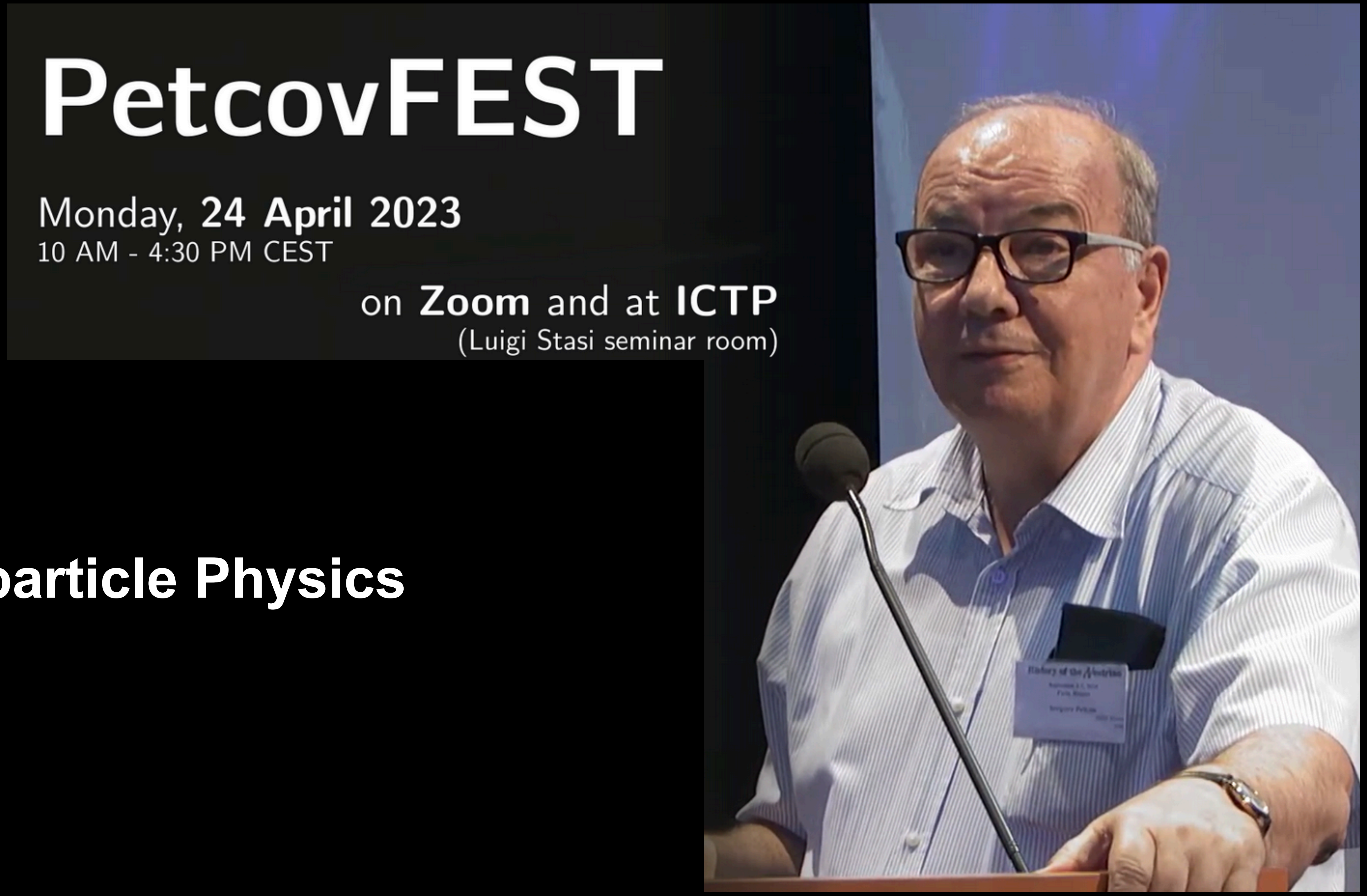


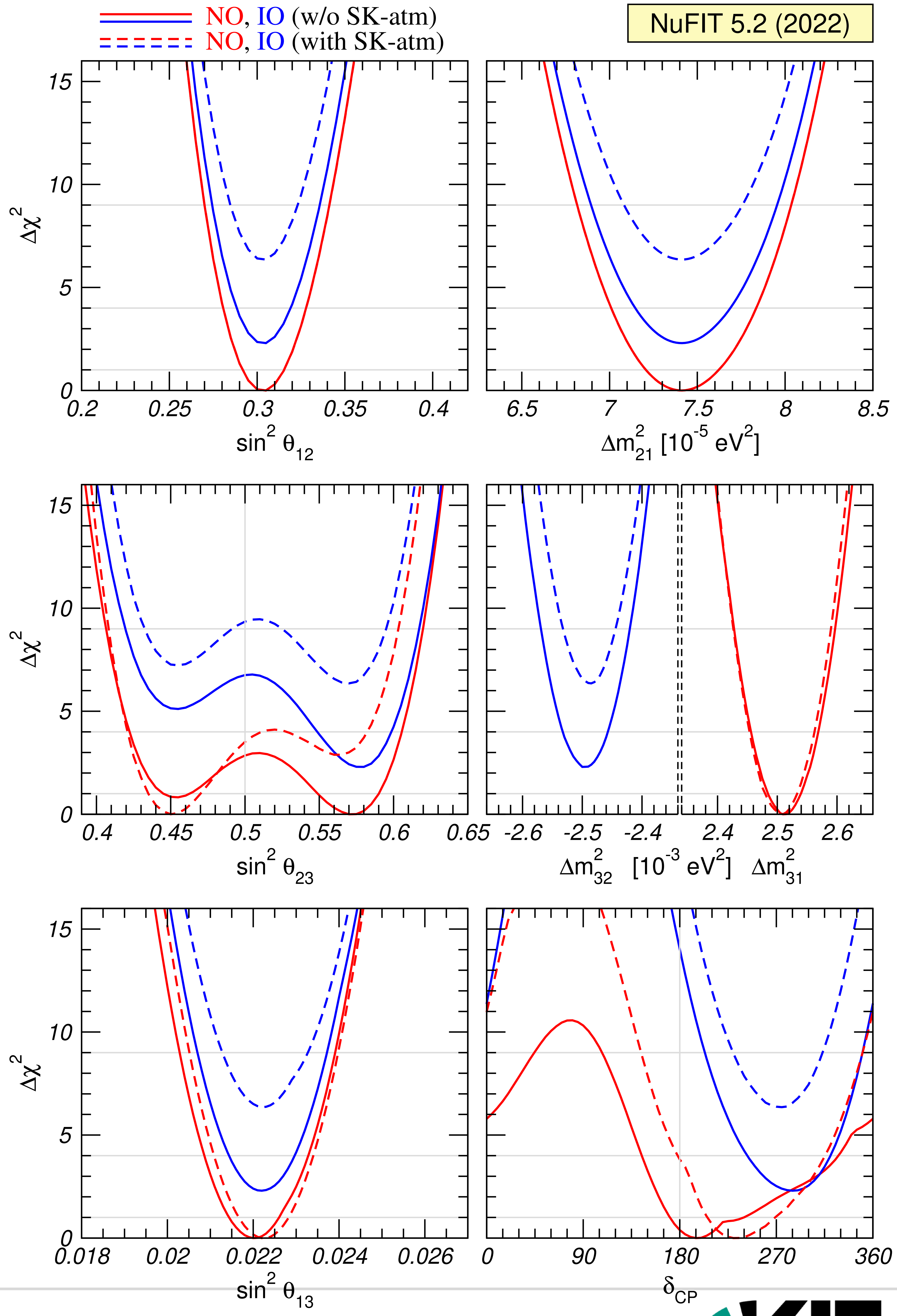
Sales, Trieste, 2006

Three flavour oscillation parameters

global analysis **NuFIT 5.2 (Nov. 2022) results** www.nu-fit.org

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

with SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
	$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
	$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
	$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$



comparable results:
Bari: e.g. Capozzi et al., 2107.00532, talk by E. Lisi
Valencia: e.g. deSalas et al., 2006.11237

Four well-known parameters

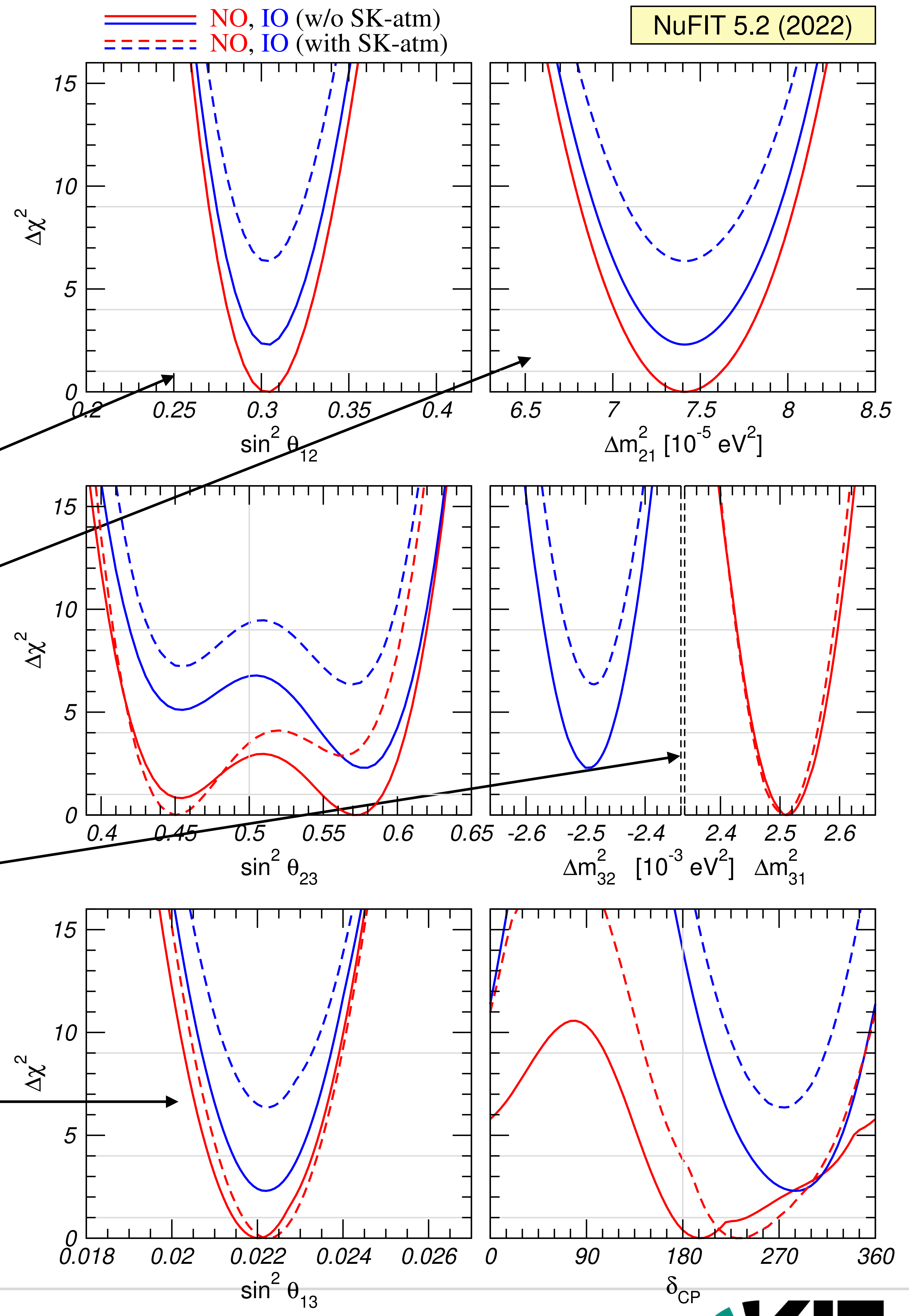
- robust determination (relat. precision at 3σ)

θ_{12} : 13%

Δm^2_{12} : 16%

$|\Delta m^2_{31}|$: 6.5%

θ_{13} : 7.9%



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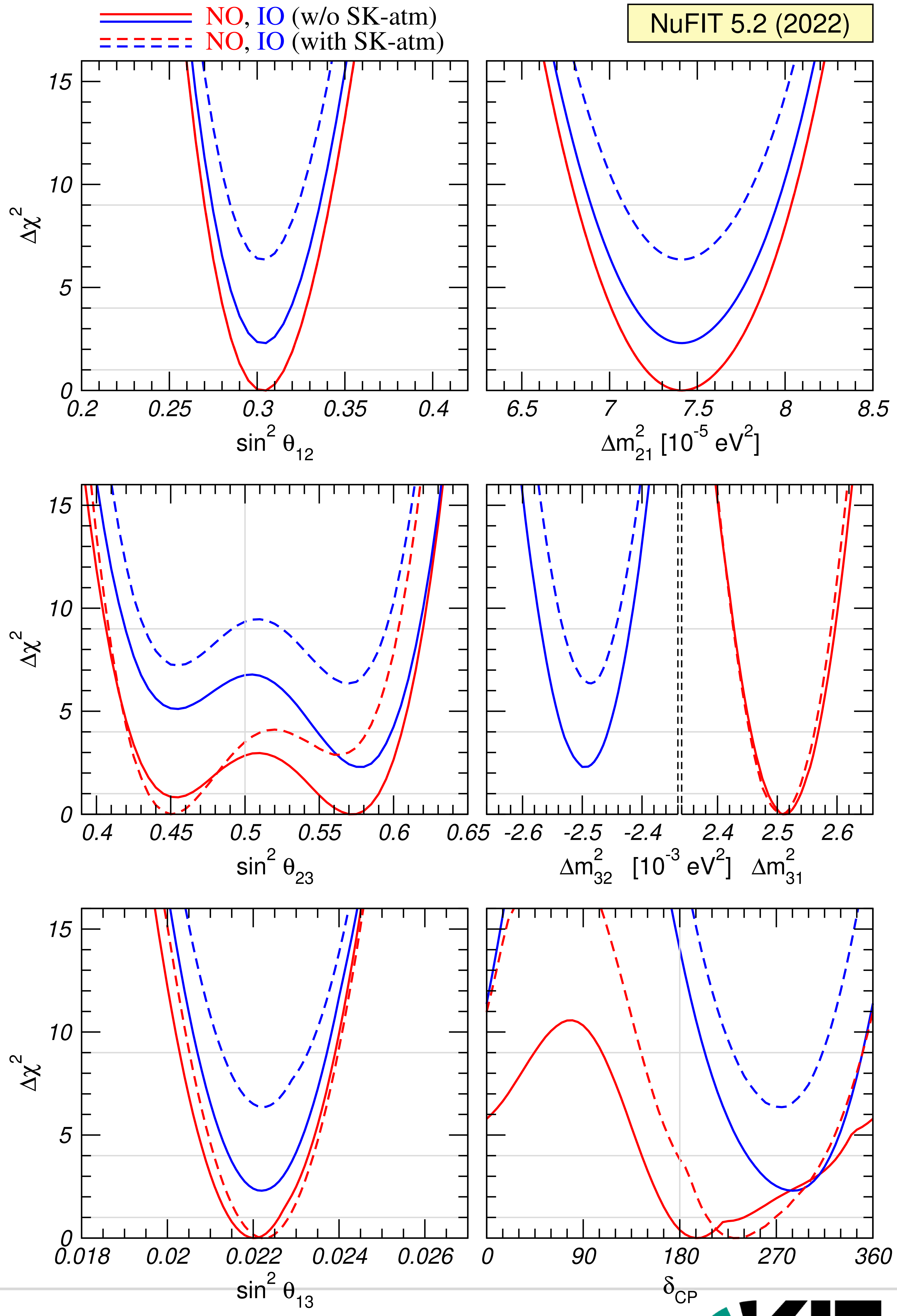
Four well-known parameters

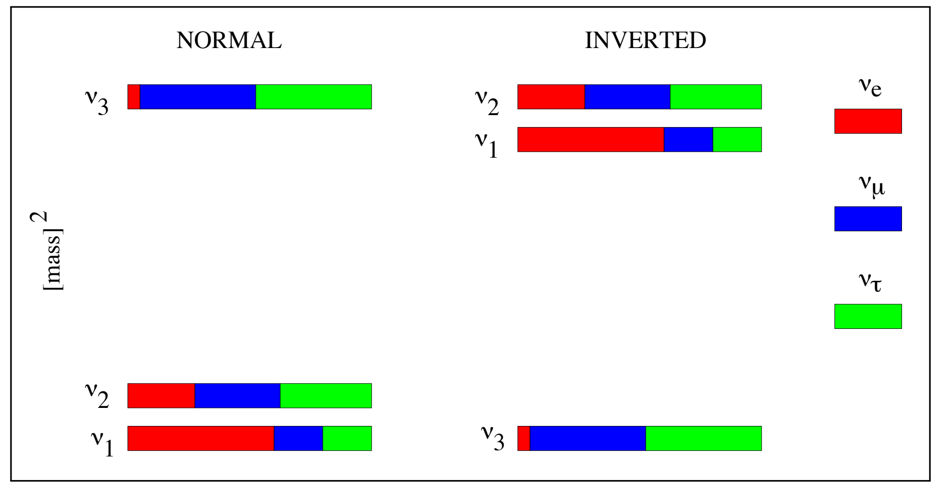
- robust determination (relat. precision at 3σ)

θ_{12} :	13%	0.6 %
Δm^2_{12} :	16%	
$\|\Delta m^2_{31}\|$:	6.5%	**for quarks**
θ_{13} :	7.9%	8.3 %

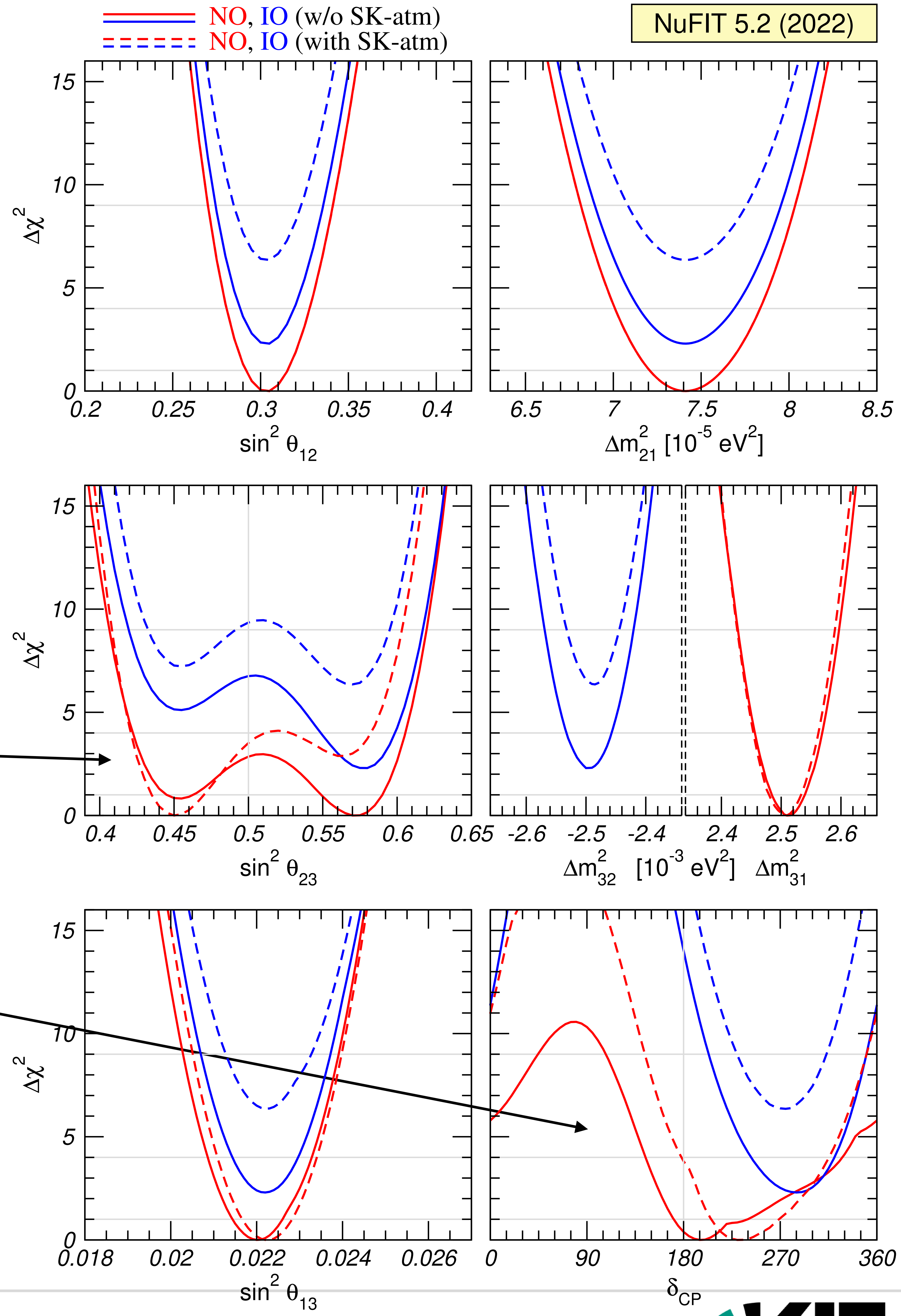


The unknowns:

- neutrino mass ordering (red vs blue curves)



- octant of θ_{23}
- status of leptonic CP violation



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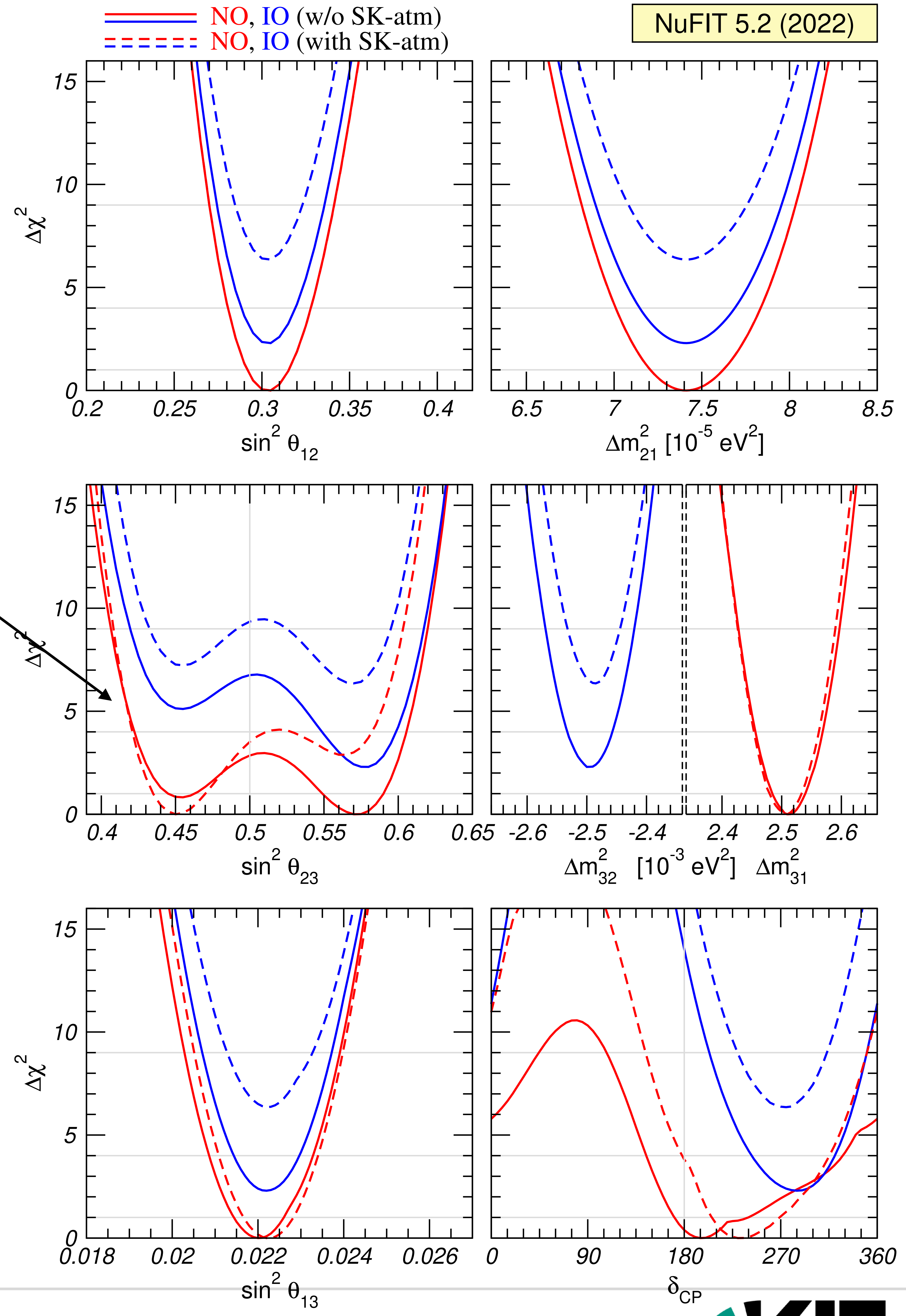
The least known mixing angle

- broad allowed range for θ_{23} (25%)

  for quarks: 5.2%

- ambiguity in the octant
  - fragile with respect to atmospheric neutrino analysis and mass ordering



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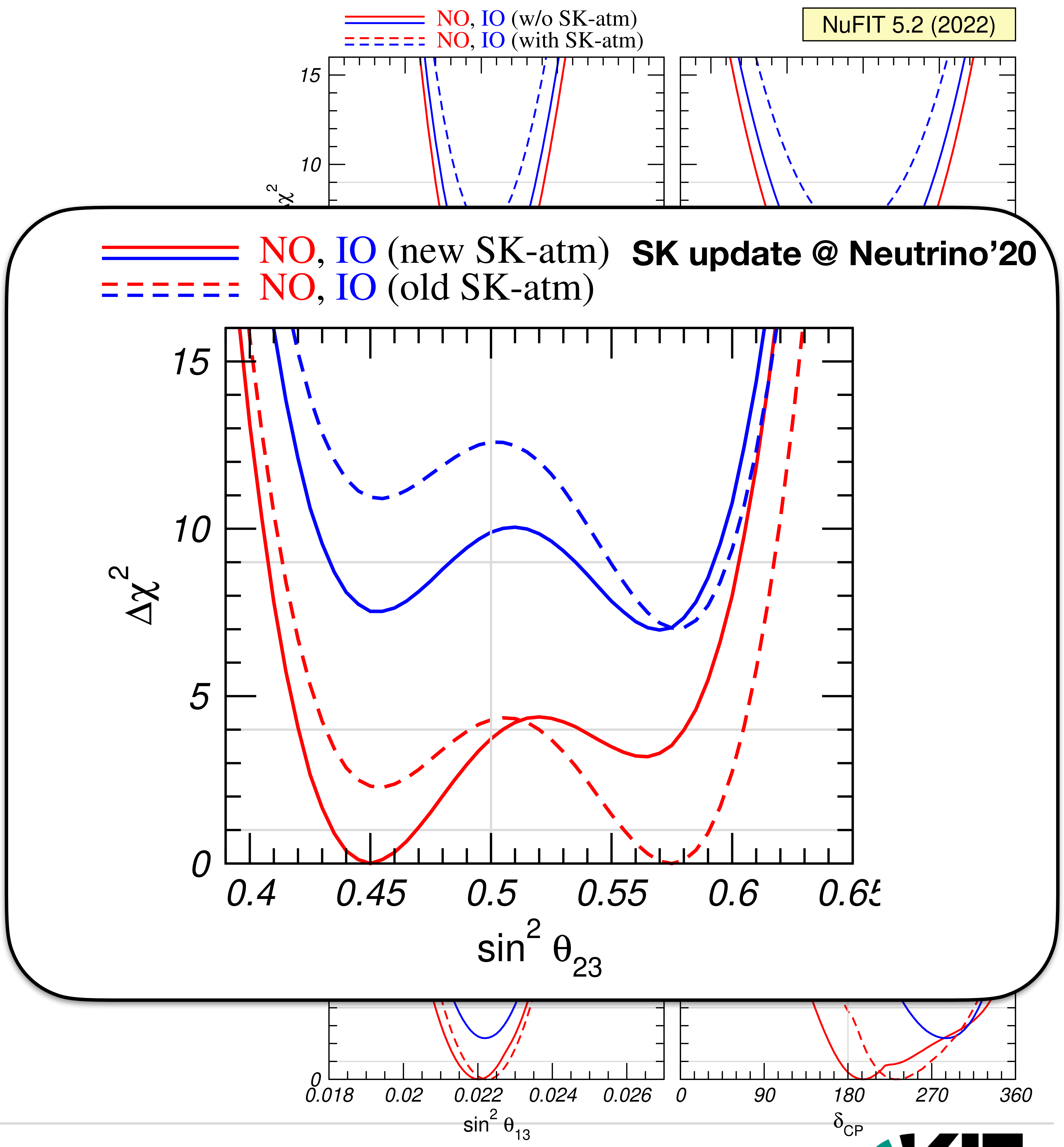

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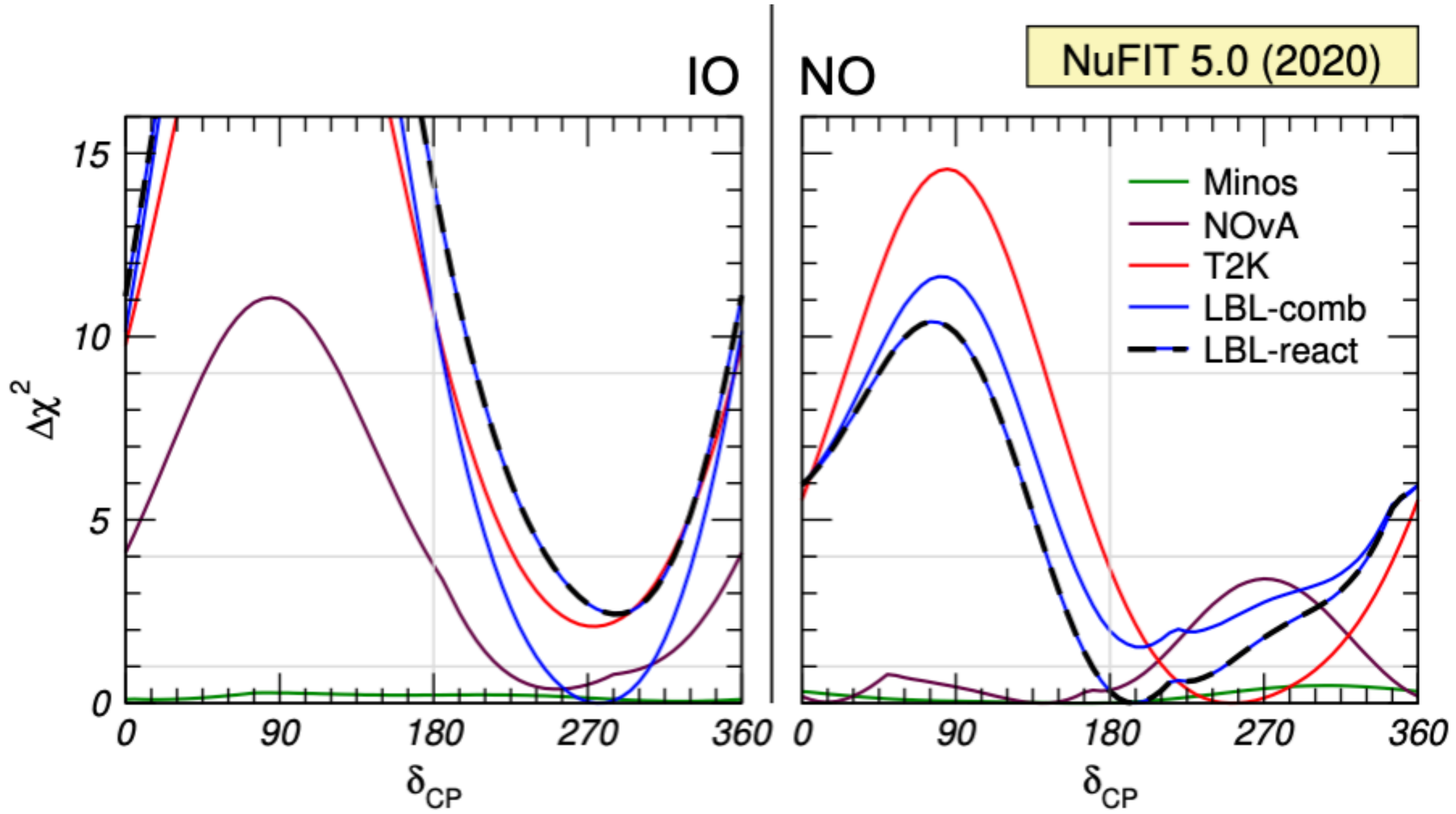
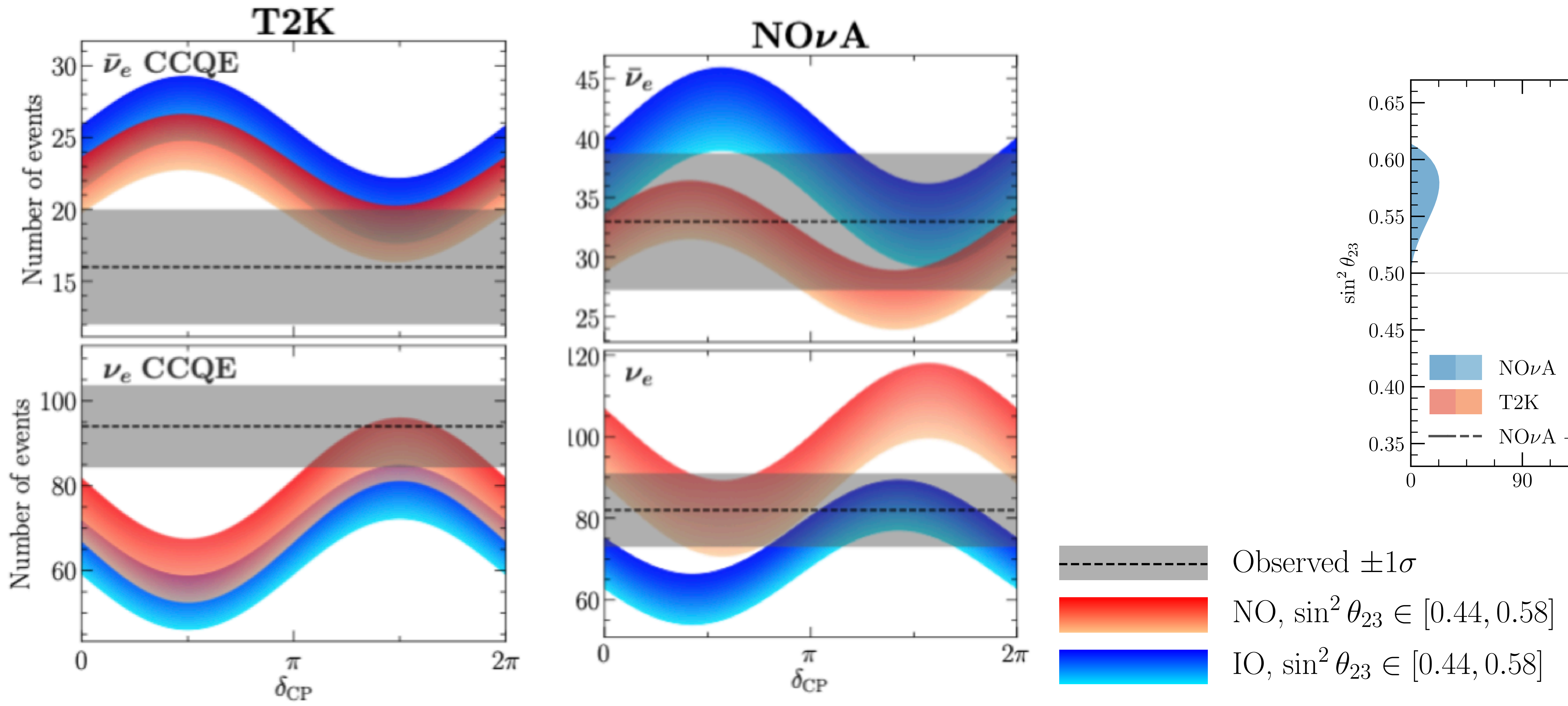
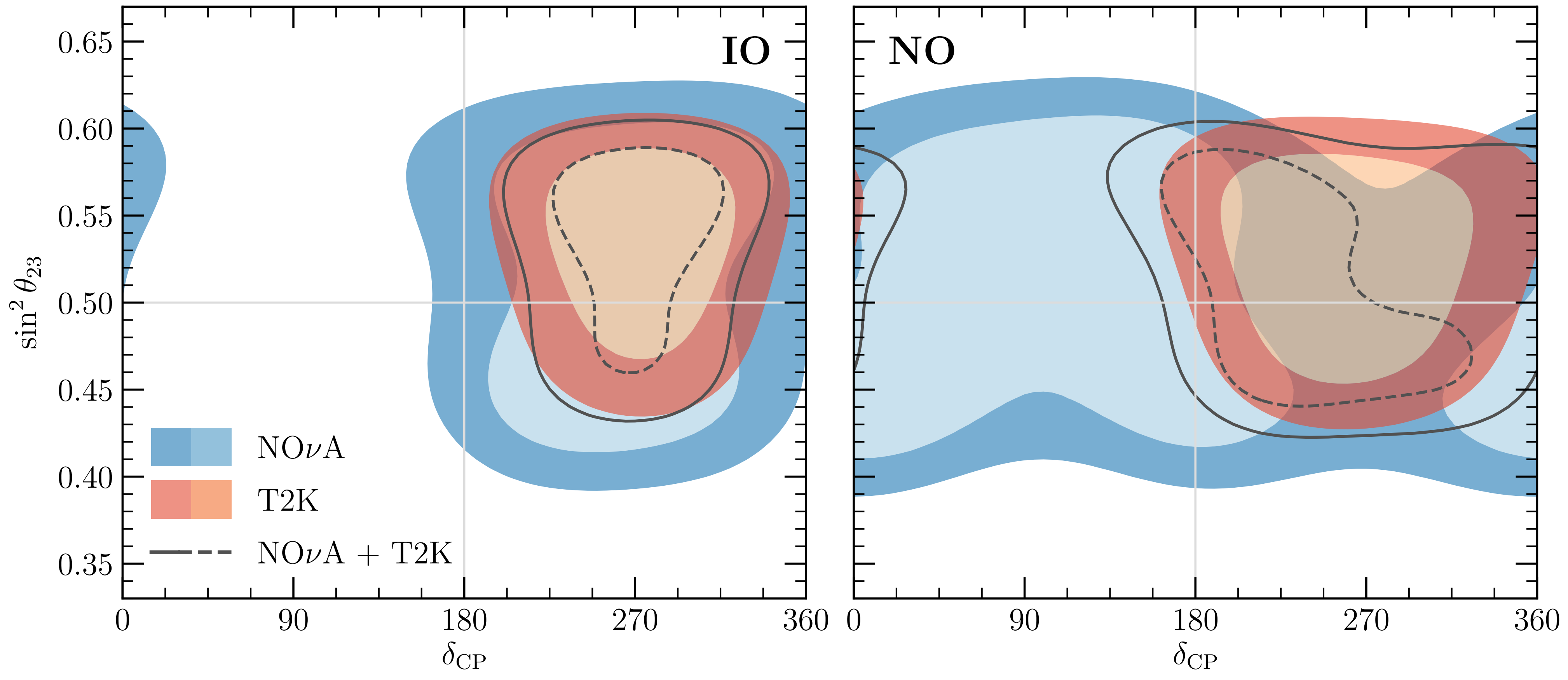
Mass ordering and CP phase

- different tendencies in
  - LBL accelerator data:
    T2K & NOvA better compatible for IO







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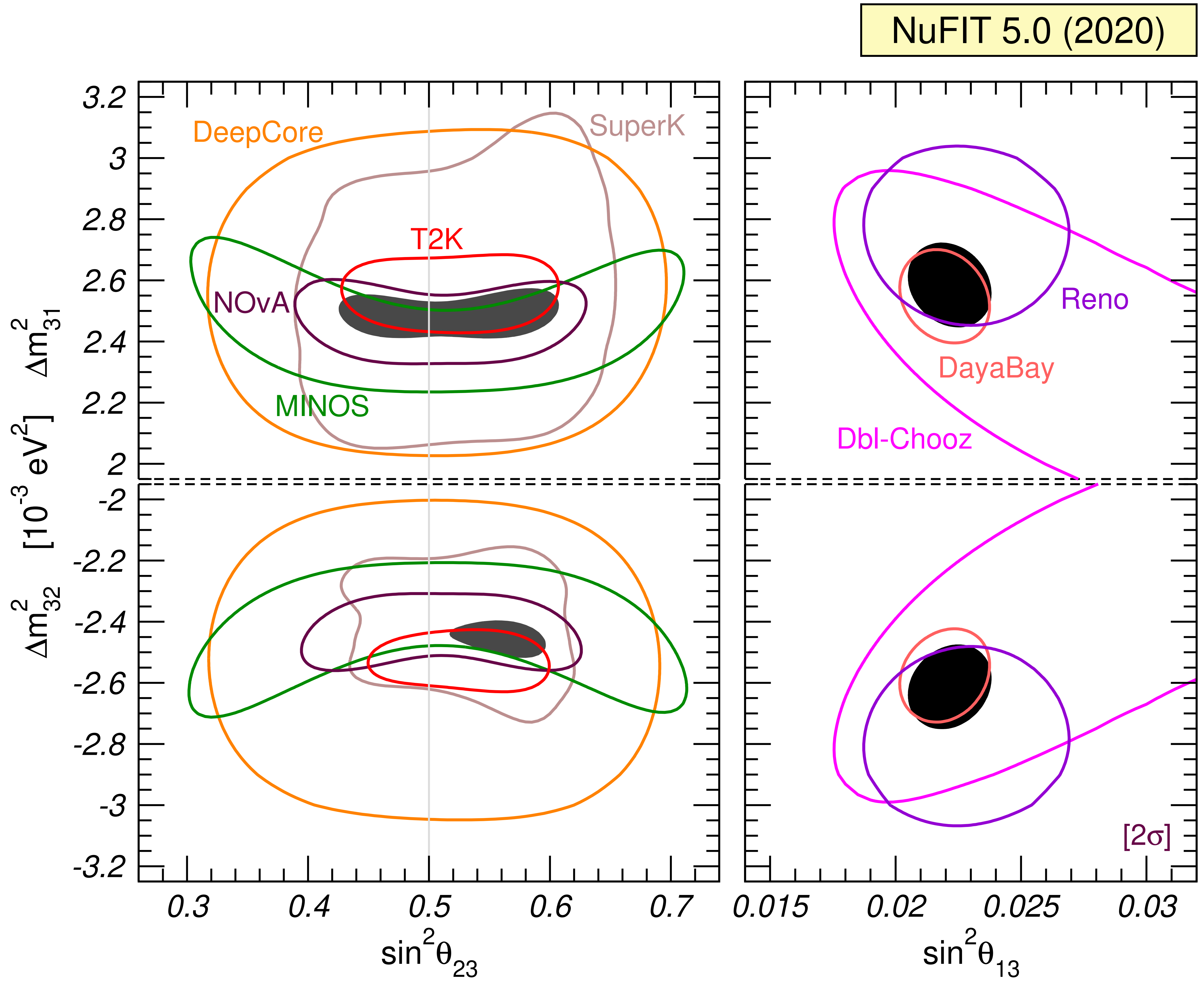
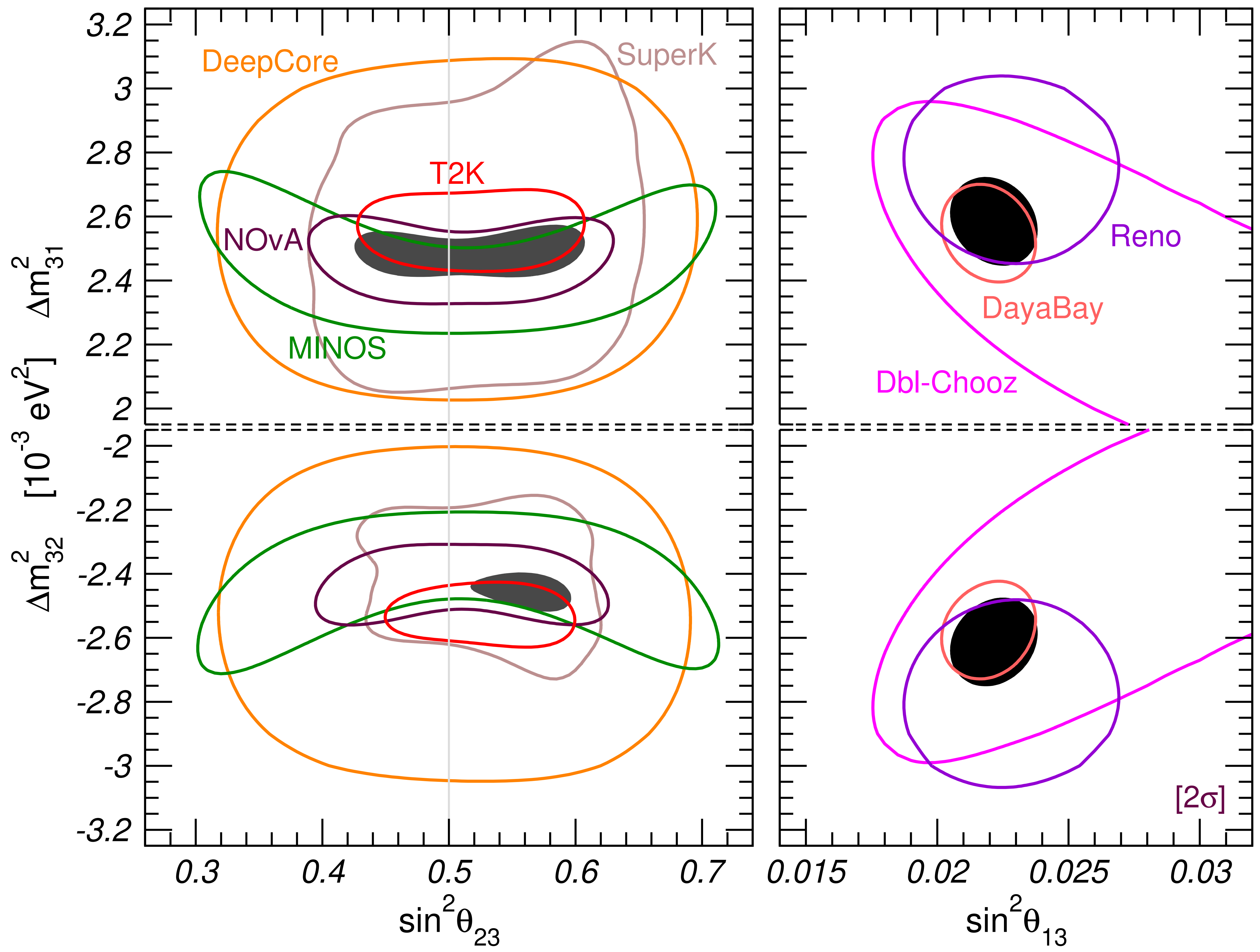
Consistency of μ and e disappearance



Consistency of μ and e disappearance

NuFIT 5.0 (2020)

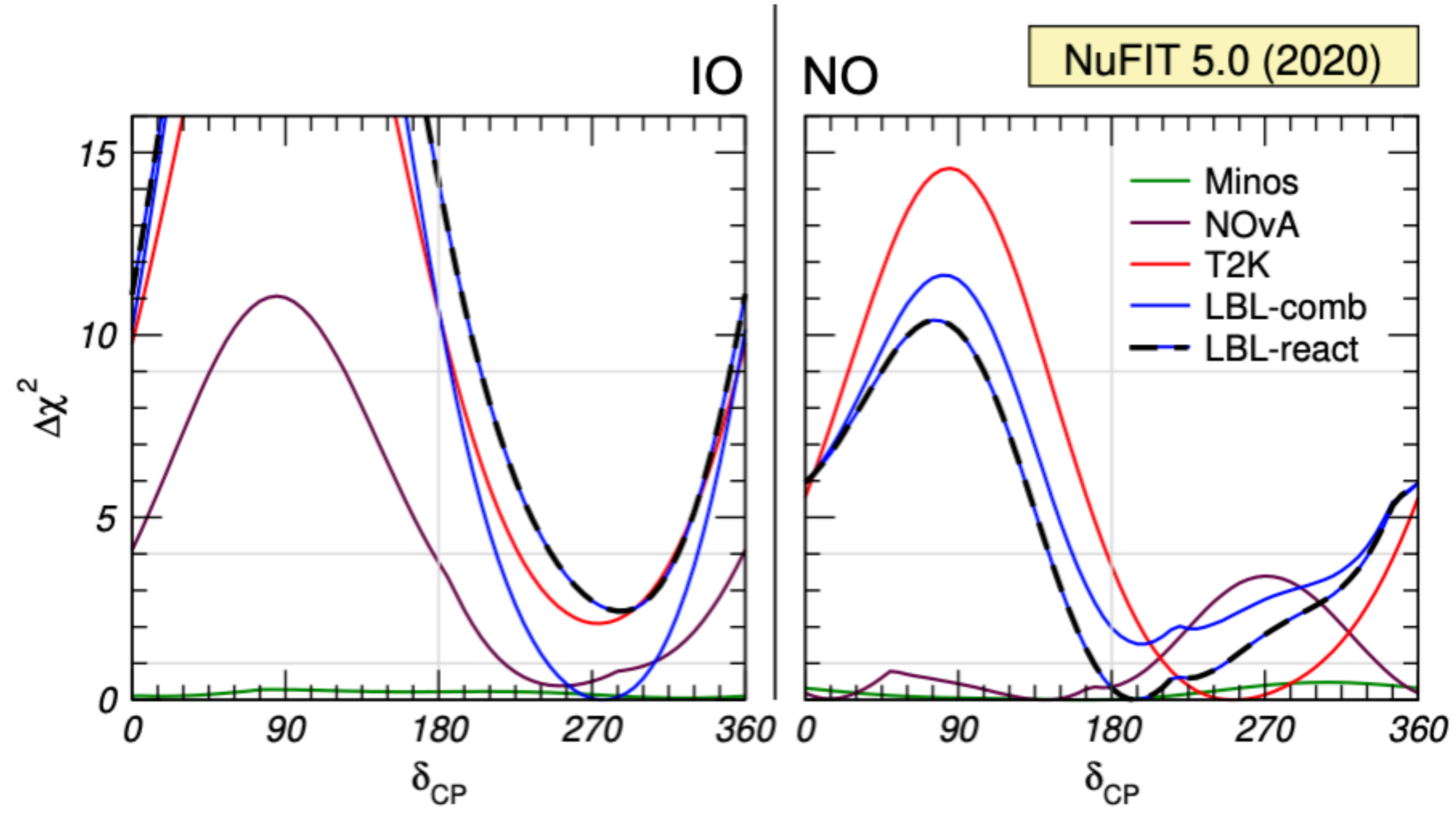


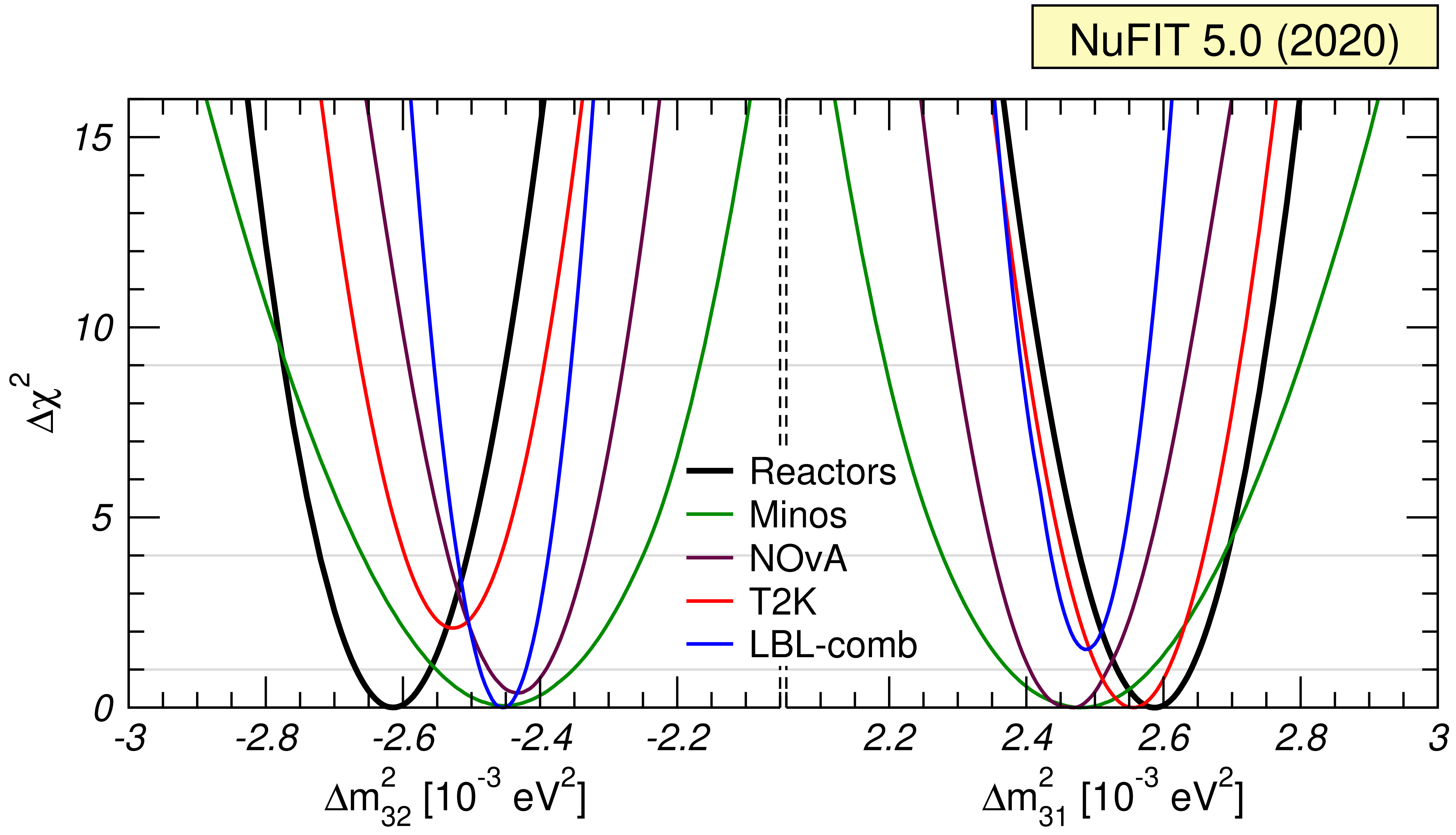
$$|\Delta m^2_{\mu\mu}| = |\Delta m^2_{ee}| \mp \Delta m^2_{21}\,[\cos 2\theta_{12} - \cos\delta \sin\theta_{13} \sin 2\theta_{12} \tan\theta_{23}]$$

slightly different *effective* mass-squared differences: -/+ for NO/IO Nunokawa, Parke, Zukanovich, 05

Mass ordering and CP phase

- different tendencies in
  - LBL accelerator data:
    T2K & NOvA better compatible for IO
  - Reactor and LBL data:
    better agreement of $|\Delta m^2_{31}|$ for NO
- overall preference for NO with
  $\Delta\chi^2 = 2.3$ (was 6.2 in 2019)





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PHYSICS LETTERS B

www.elsevier.com/locate/npe

The LMA MSW solution of the solar neutrino problem, inverted neutrino mass hierarchy and reactor neutrino experiments

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Received 11 December 2001; received in revised form 14 March 2002; accepted 18 March 2002

Editor: G.F. Giudice

Abstract

In the context of three-neutrino oscillations, we study the possibility of using antineutrinos from nuclear reactors to explore the $10^{-4}\ \mathrm{eV}^2 < \Delta m^2_\odot \lesssim 8 \times 10^{-4}\ \mathrm{eV}^2$ region of the LMA MSW solution of the solar neutrino problem and measure $\Delta m^2_\odot$ with high precision. The KamLAND experiment is not expected to determine $\Delta m^2_\odot$ if the latter happens to lie in the indicated region. By analysing both the total event rate suppression and the energy spectrum distortion caused by $\bar{\nu}_e$ oscillations in vacuum, we show that the optimal baseline of such an experiment is $L \sim (20\text{–}25)$ km. Furthermore, for $10^{-4}\ \mathrm{eV}^2 < \Delta m^2_\odot \lesssim 5 \times 10^{-4}\ \mathrm{eV}^2$, the same experiment might be used to try to distinguish between the two possible types of neutrino mass spectrum—with normal or with inverted hierarchy, by exploring the effect of interference between the atmospheric- and solar-Δm^2 driven oscillations; for larger values of $\Delta m^2_\odot$ not exceeding $8.0 \times 10^{-4}\ \mathrm{eV}^2$, a shorter baseline, $L \simeq 10$ km, would be needed for the purpose. The indicated interference effect modifies in a characteristic way the energy spectrum of detected events. Distinguishing between the two types of neutrino mass spectrum requires, however, a high precision determination of the atmospheric Δm^2, a sufficiently large $\sin^2\theta$ and a non-maximal $\sin^2 2\theta_\odot$, where θ and $\theta_\odot$ are the mixing angles, respectively, limited by the CHOOZ and Palo Verde data and characterizing the solar neutrino oscillations. It also requires a relatively high precision measurement of the positron spectrum in the reaction $\bar{\nu}_e + p \to e^+ + n$.

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Mass ordering from combining reactor and atmospheric data

- Petcov, Schwetz, Precision measurement of solar neutrino oscillation parameters by a long-baseline reactor neutrino experiment in Europe [hep-ph/0607155]

- Petcov, Schwetz, Determining the neutrino mass hierarchy with atmospheric neutrinos [hep-ph/0511277]

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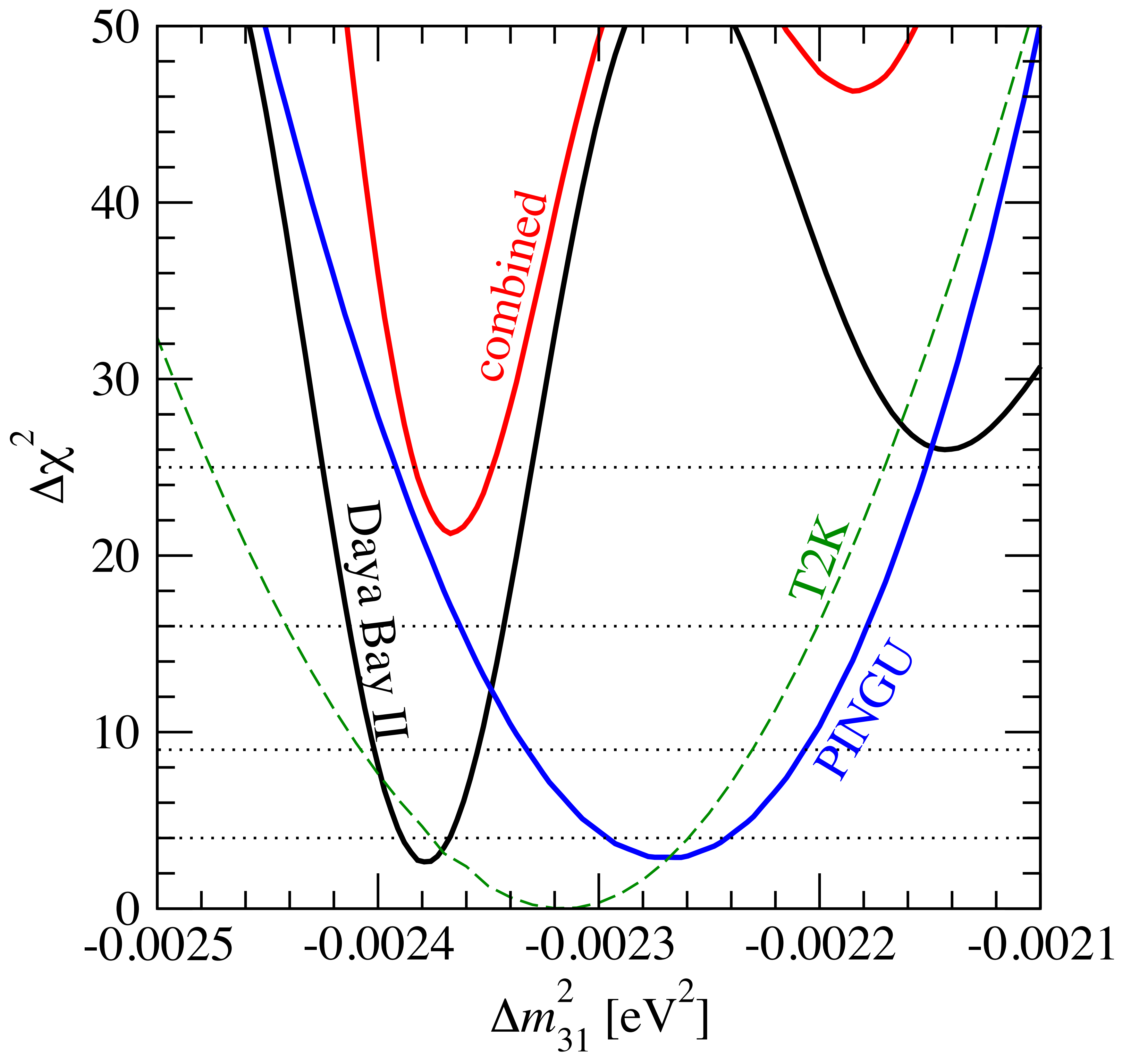
- combination of reactor and atmospheric neutrino data can be very power full in the future
  JUNO & IceCube [1911.06745] or
  JUNO & KM3NET/ORCA [2108.06293]

Blennow, Schwetz,1306.3988

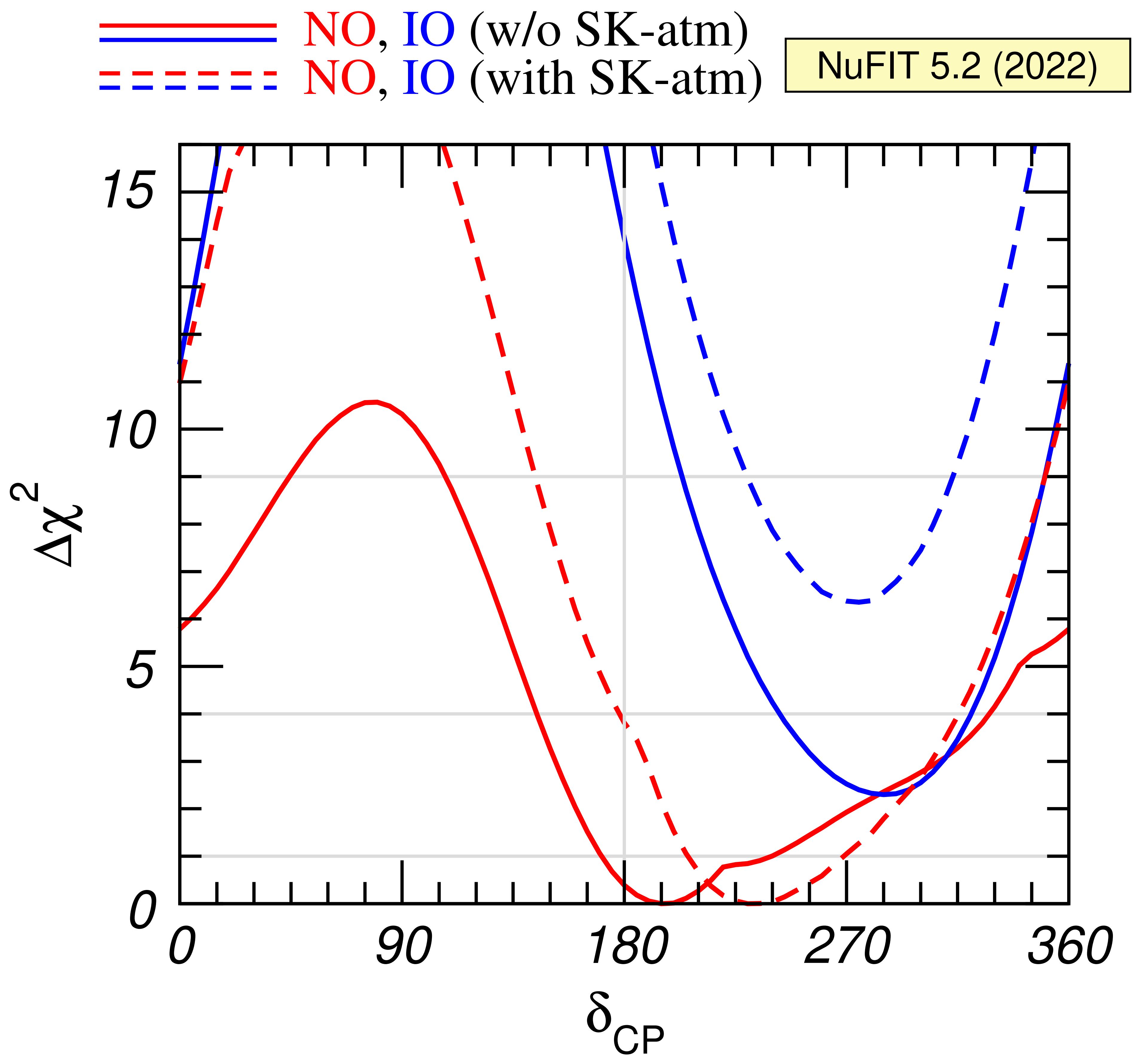


Mass ordering and CP phase: atmospheric neutrinos

- improved sensitivity to MO:
  $\chi^2(\text{IO}) - \chi^2(\text{NO}) = 3.2$ (atm only)
  pre-Neutrino'20: 4.3

- added to global fit via χ^2 table:
  $\chi^2(\text{IO}) - \chi^2(\text{NO}) = 2.3$ (no SK)
  $\rightarrow$ 6.4 (w SK) 2.5σ

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



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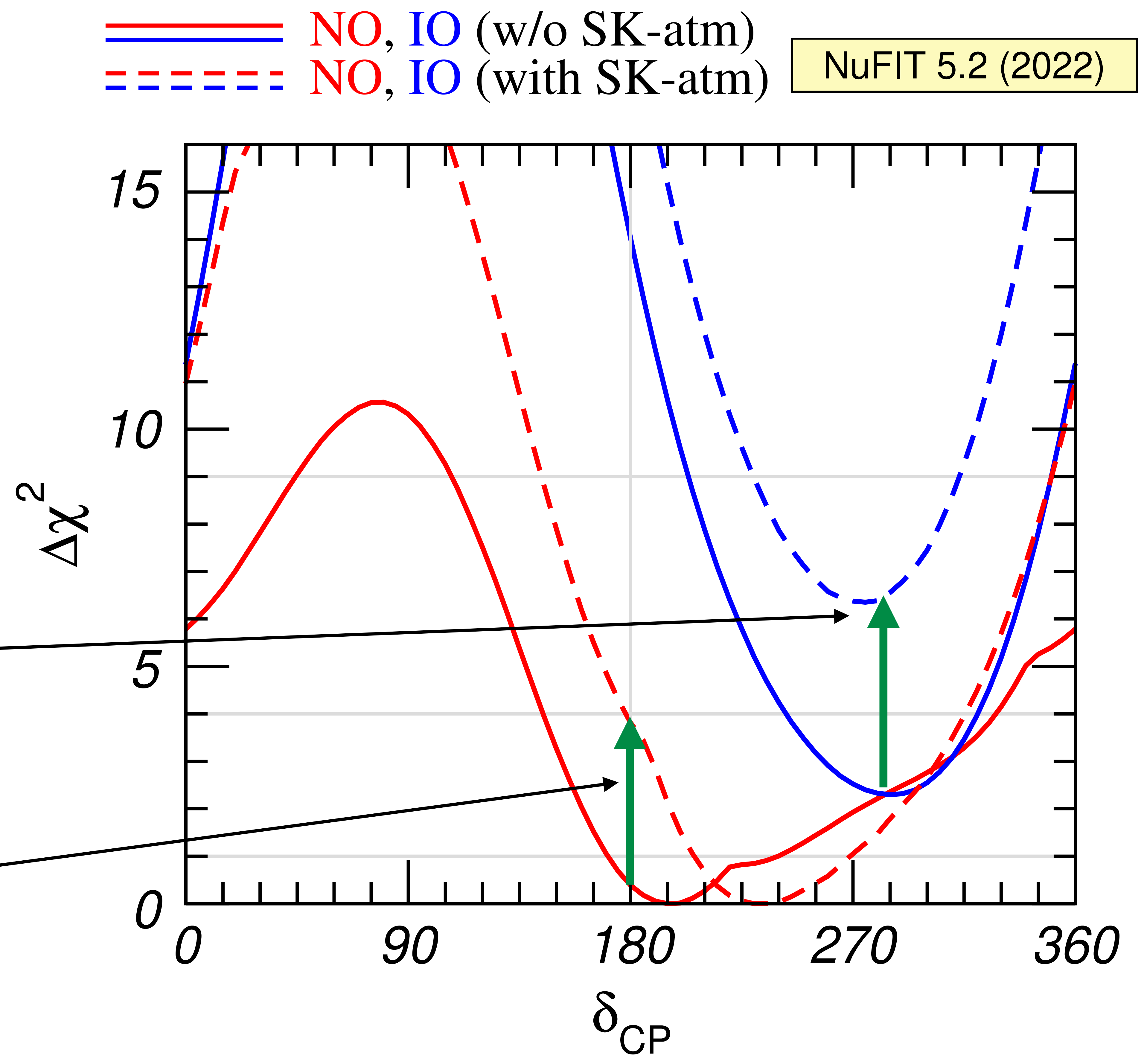
  → 6.4 (w SK) 2.5σ

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



Comment on the search for CP and T violation

ON THE OSCILLATIONS OF NEUTRINOS WITH DIRAC AND MAJORANA MASSES

S.M. BILENKY, J. HOŠEK [1] and S.T. PETCOV [2]
Joint Institute for Nuclear Research, Dubna, USSR

Received 2 June 1980

Pontecorvo neutrino oscillations are discussed in the case of Dirac as well as Majorana neutrino mass terms. We prove that none of the possible experiments on neutrino oscillations including those on *CP* nonconservation, can distinguish between these two possibilities. Oscillations of neutrinos having both Dirac and Majorana mass terms are also considered.

Comment on the search for CP and T violation

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RESONANCE AMPLIFICATION AND *T*-VIOLATION EFFECTS IN THREE-NEUTRINO OSCILLATIONS IN THE EARTH

P.I. KRASTEV and S.T. PETCOV
Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Boulevard Lenin 72, 1784 Sofia, Bulgaria

Received 25 January 1988

On neutrino mixing in matter and CP and T violation effects in neutrino oscillations

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[b] *Kavli IPMU (WPI), The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*
[c] *Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, United Kingdom*

Comment on the search for CP and T violation

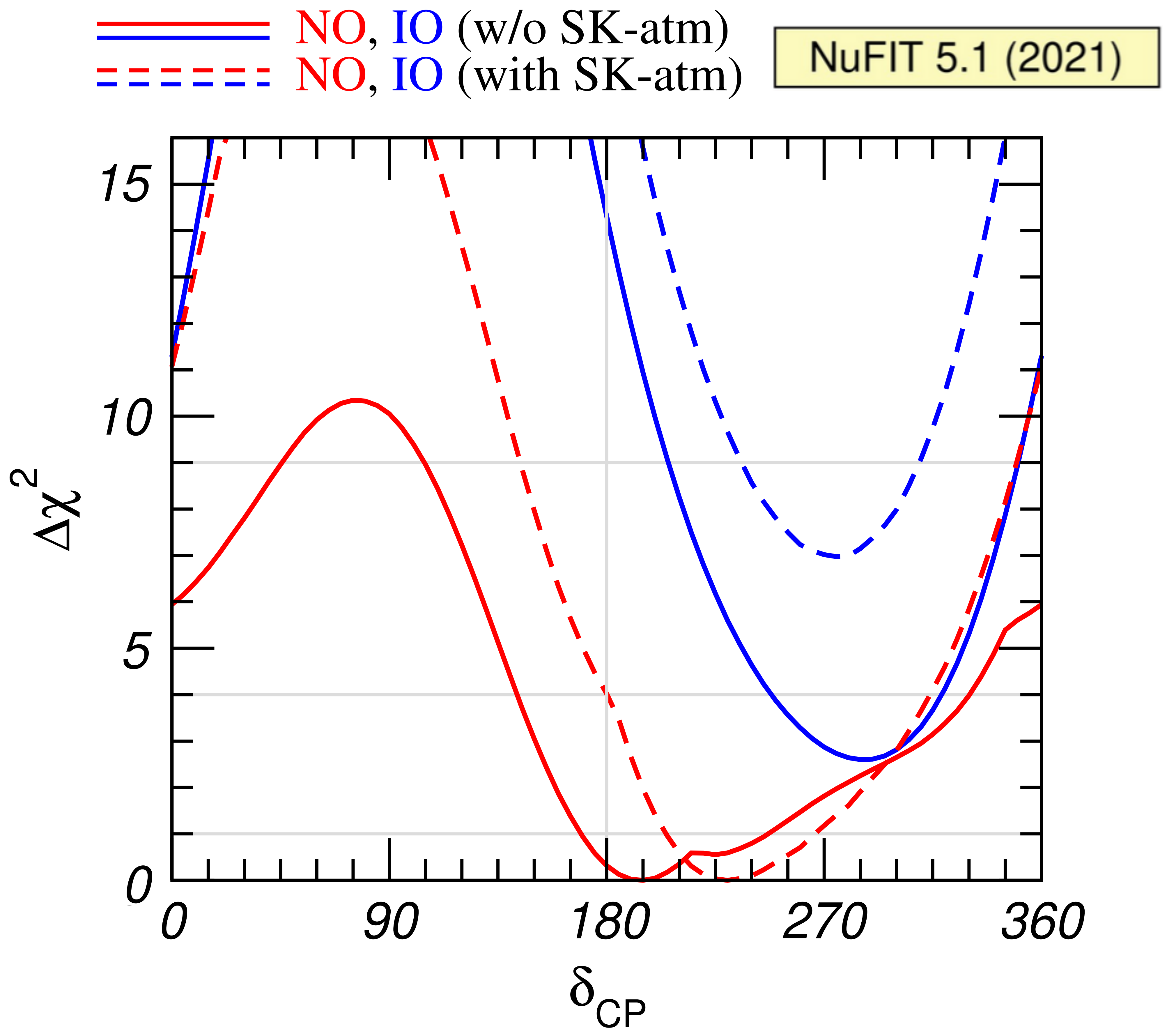
The „standard approach“ is highly model dependent:

no model-indep. CPV observable → assume:

- minimal three-flavour (unitary) scenario
- standard neutrino interactions

perform a parametric fit of combined accelerator/ reactor data

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



Looking T violation by exchanging source and detector difficult to realise

Model-independent test of T-violation

A. Segarra, TS, 2106.16099

- general parameterisation of the transition probabilities:

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

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

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

N. Cabibbo, 1977, Bilenky, Hosek, Petcov, 1980

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T-even

T-odd

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

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

N. Cabibbo, 1977, Bilenky, Hosek, Petcov, 1980

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

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

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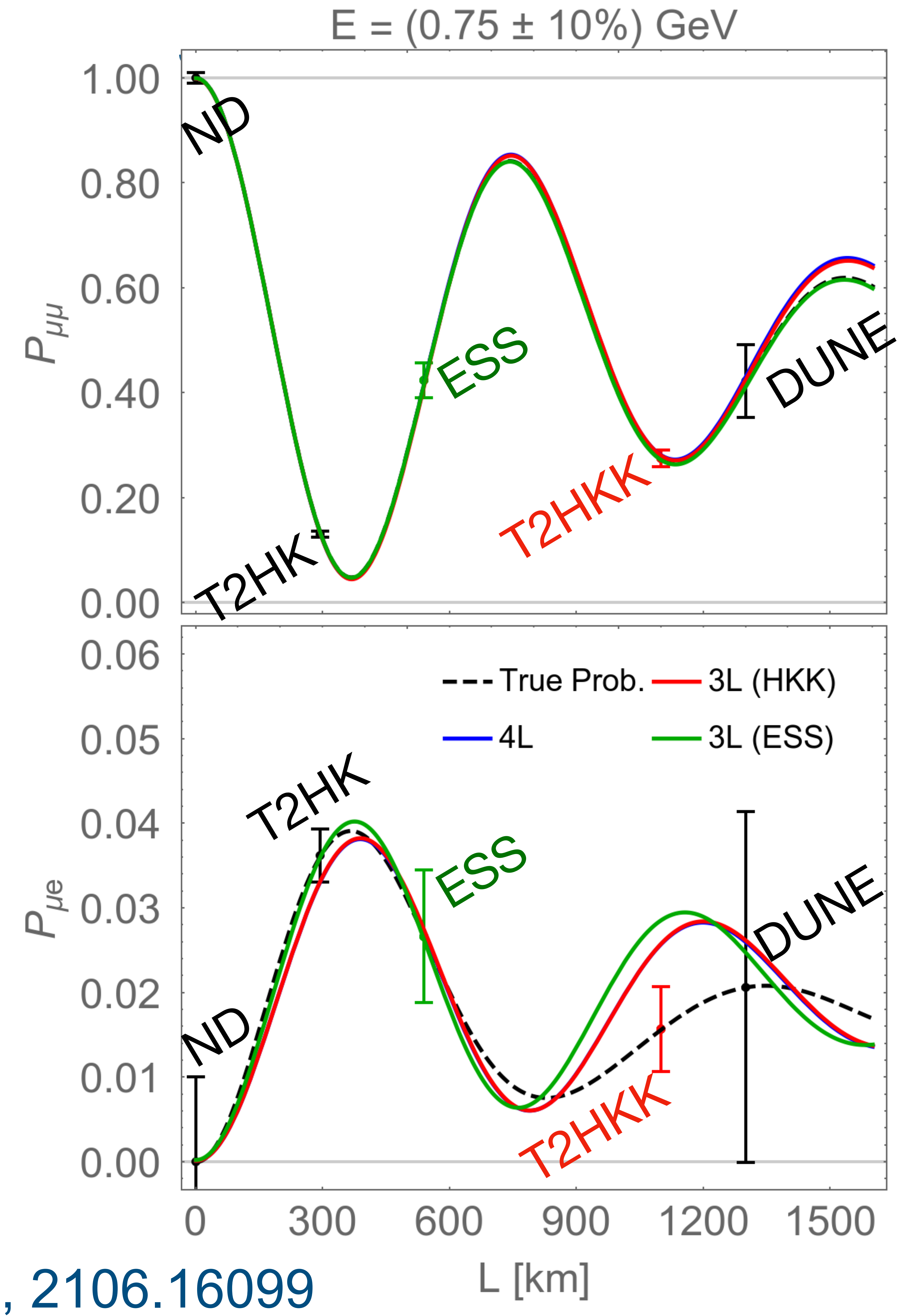
Model-independent test of T-violation

- search for a T-odd component of the oscillation probability
- measure oscillation probabilities at several distances but at the same energy
- works already with 3 experiments if they cover 1st and 2nd oscillation maxima

  ⇒ **combined analysis of T2HK & T2KK & DUNE**
- works without assuming unitarity, and allowing for non-standard physics in production, propagation, and detection
- insensitive to (std or non-std) matter effect (for symmetric density profile)



A. Segarra, TS, 2106.16099

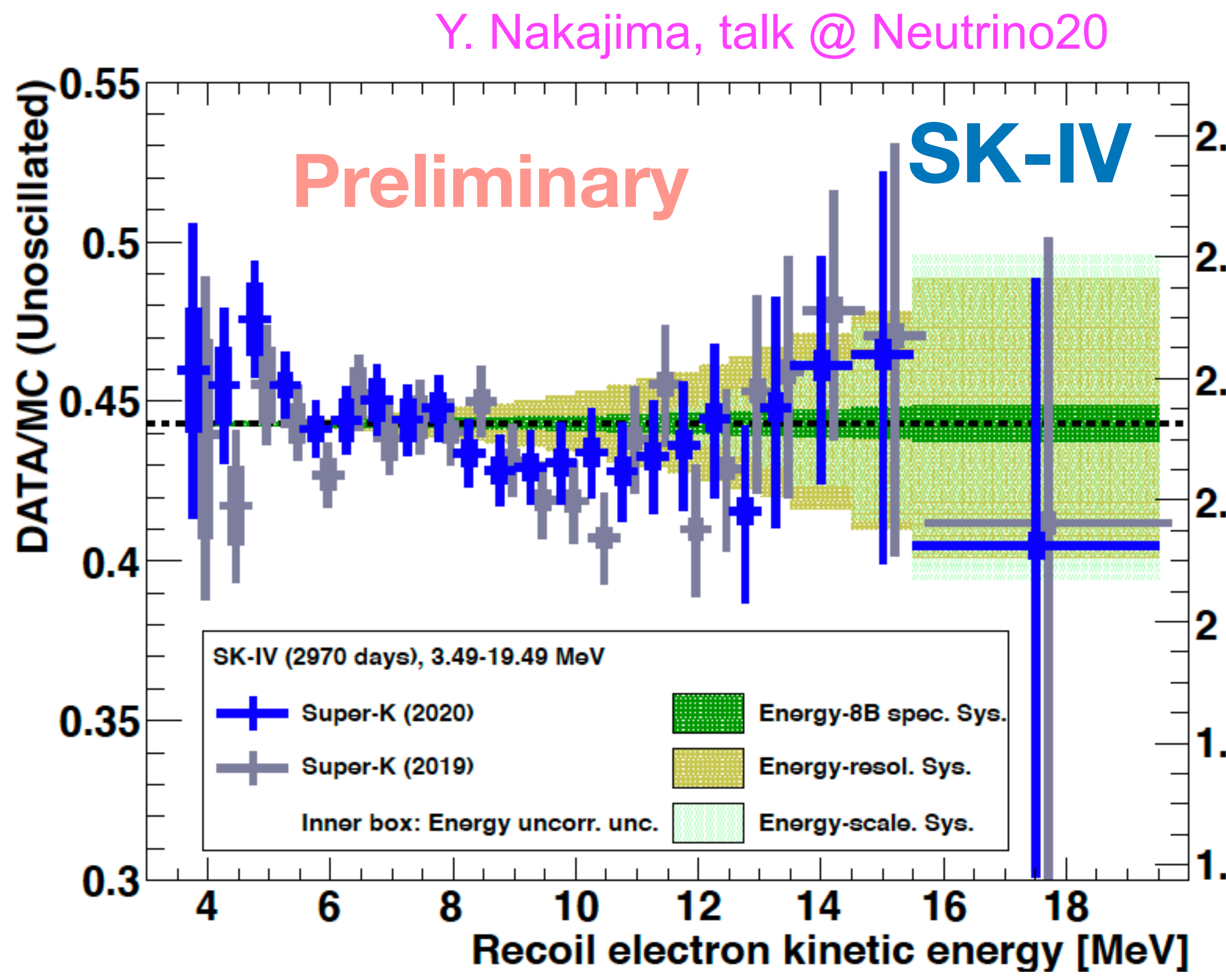
Happy Birthday — Serguey!

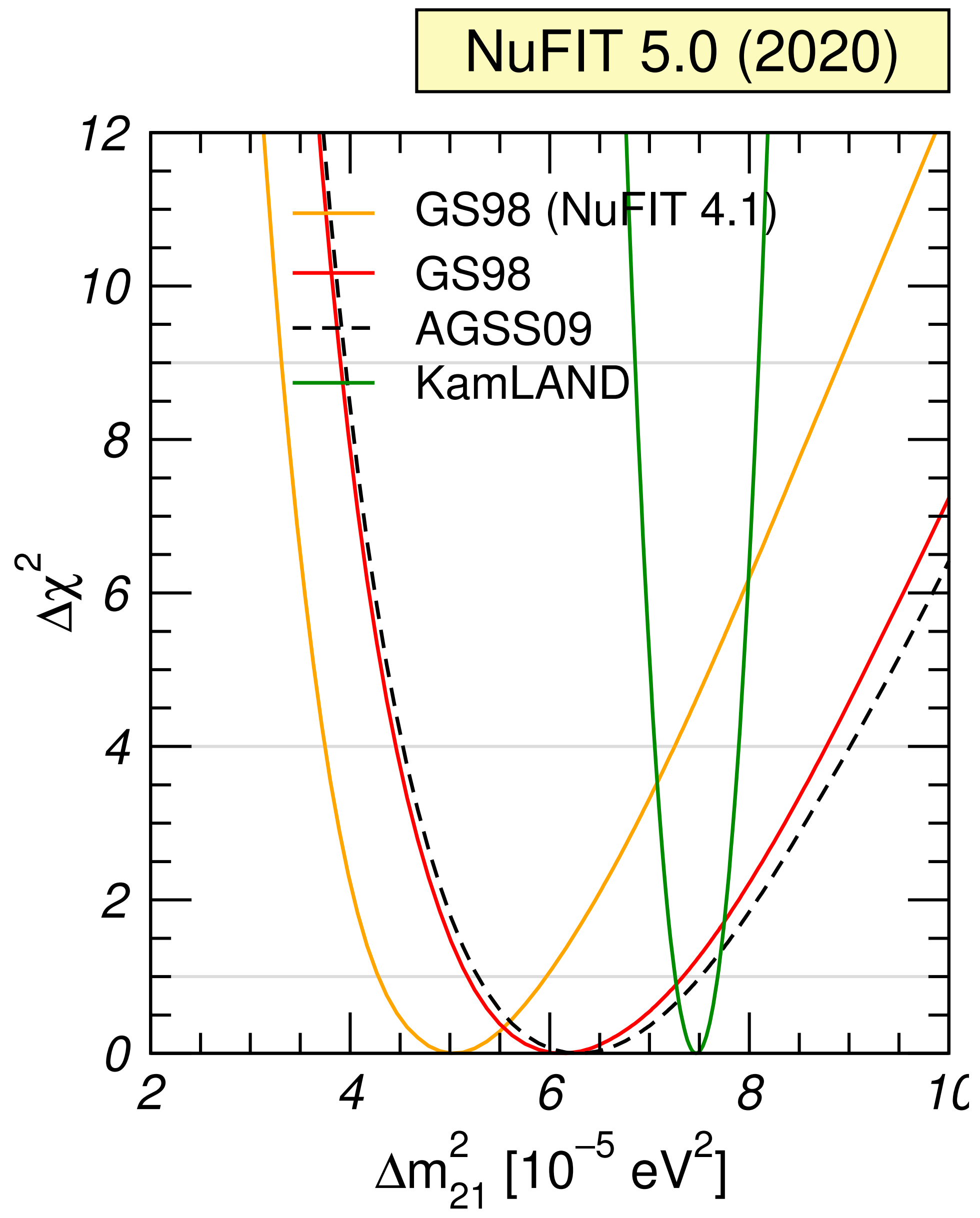
Thank you
for your inspiring work on neutrino physics,
the opportunity to work with you
and the wonderful time I could spend in Trieste!

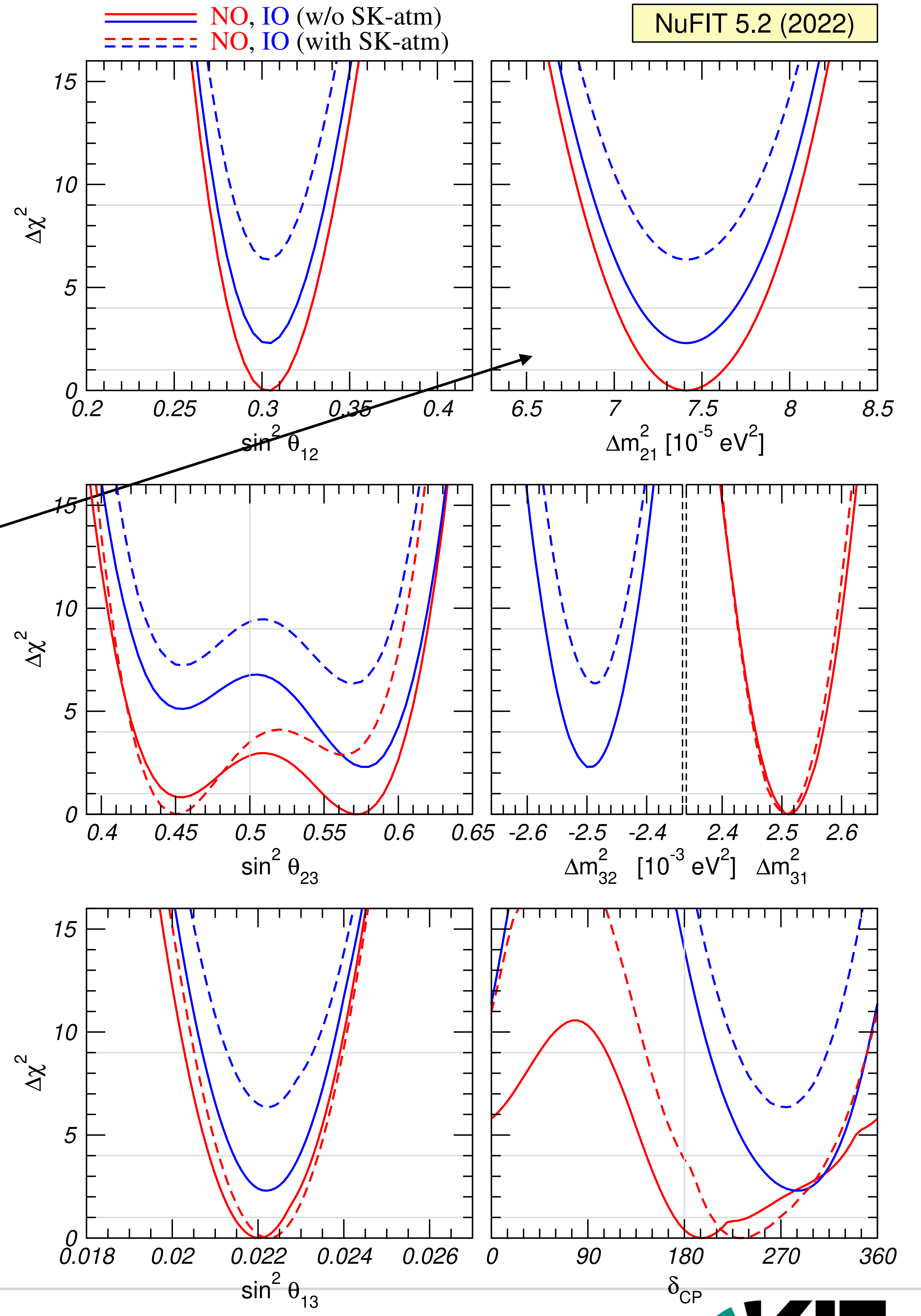
back up

Four well-known parameters

- long-standing tension (2σ) between solar and KamL data resolved by latest SK-solar data





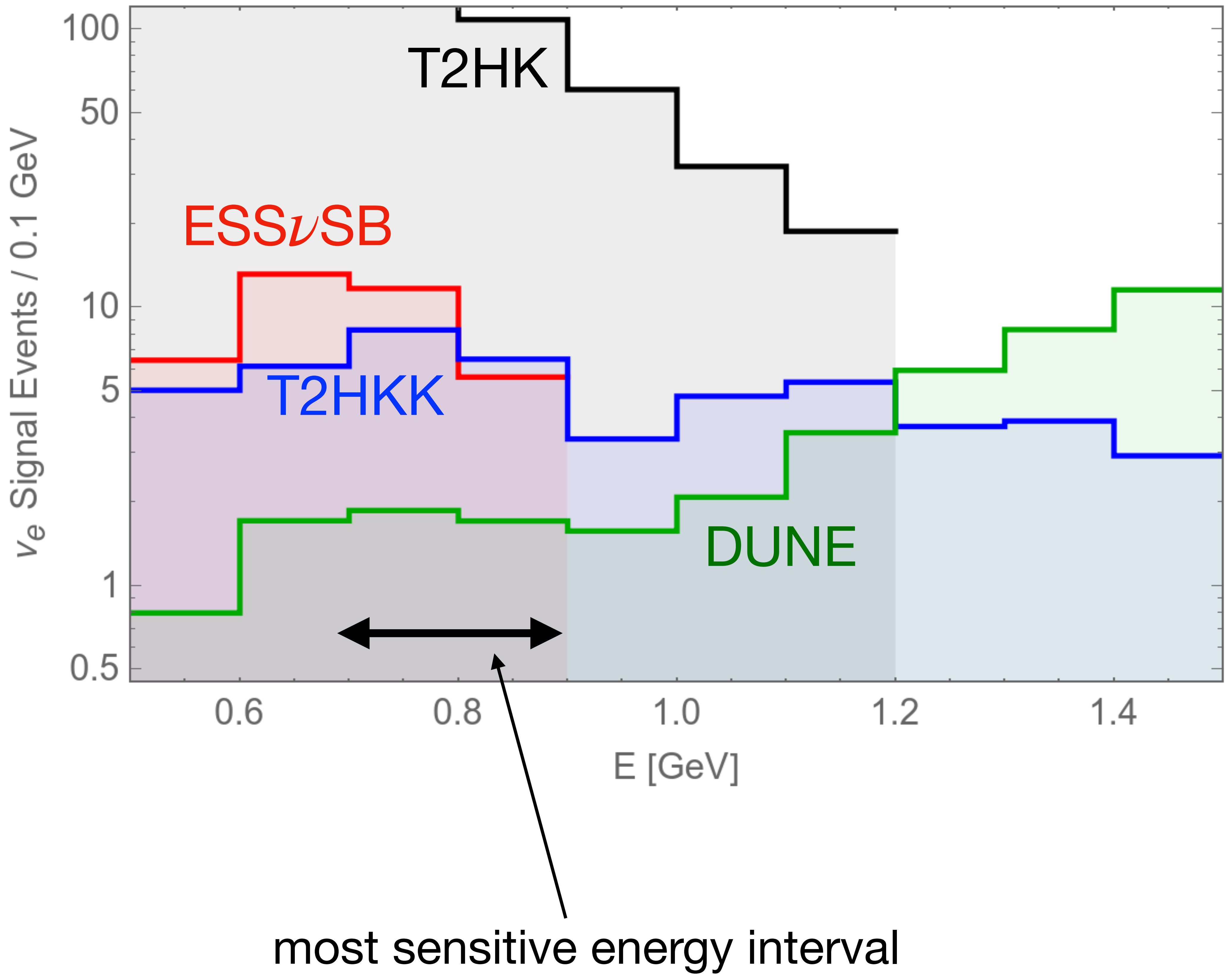


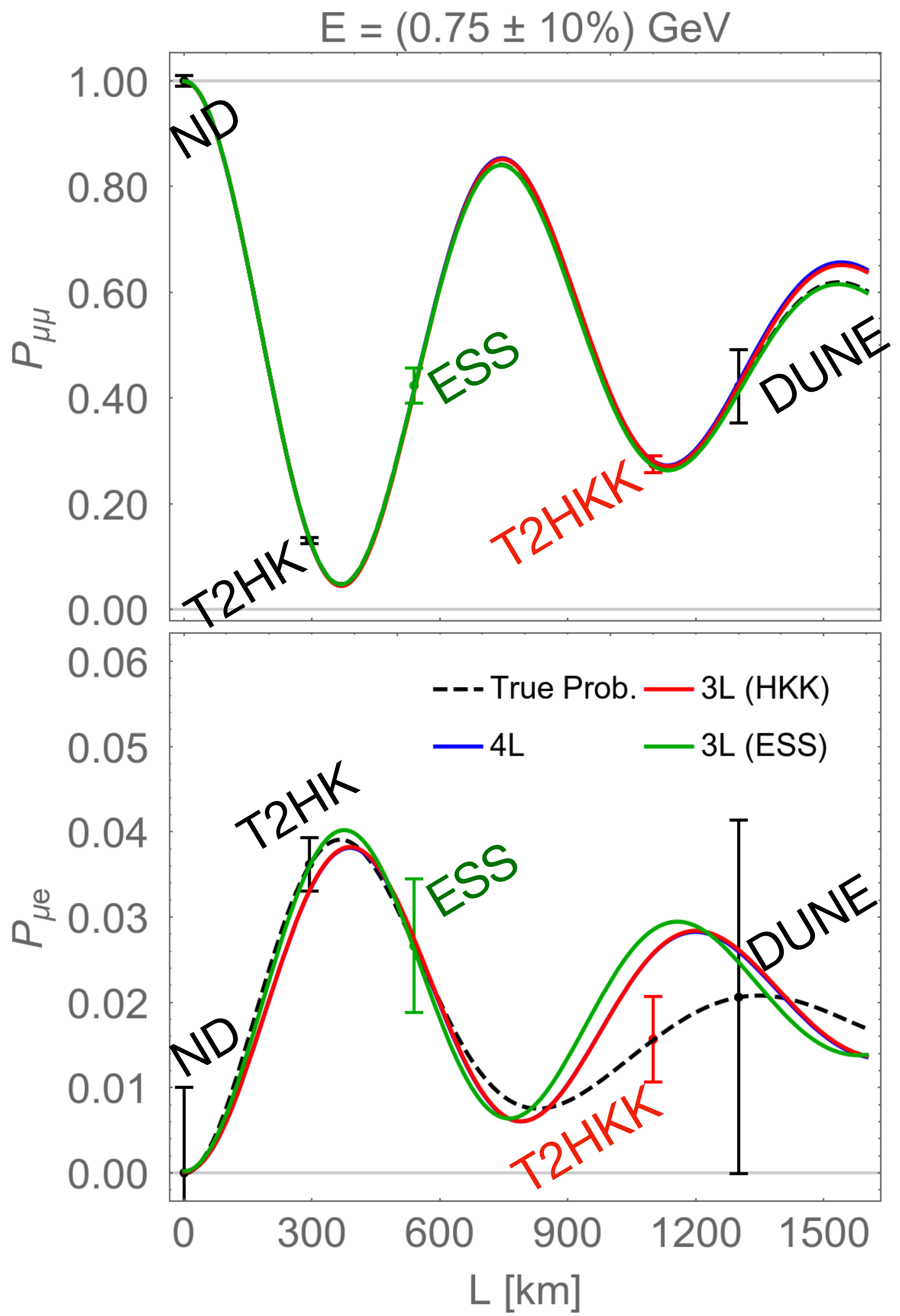
$A_{DN}^{Fit} = (-3.6 \pm 1.6(stat) \pm 0.6(syst))\,\% \rightarrow A_{DN}^{Fit} = (-2.1 \pm 1.1)\,\%$

- solar neutrino and KamLAND data compatible at 1.1σ

Model-independent test of T-violation

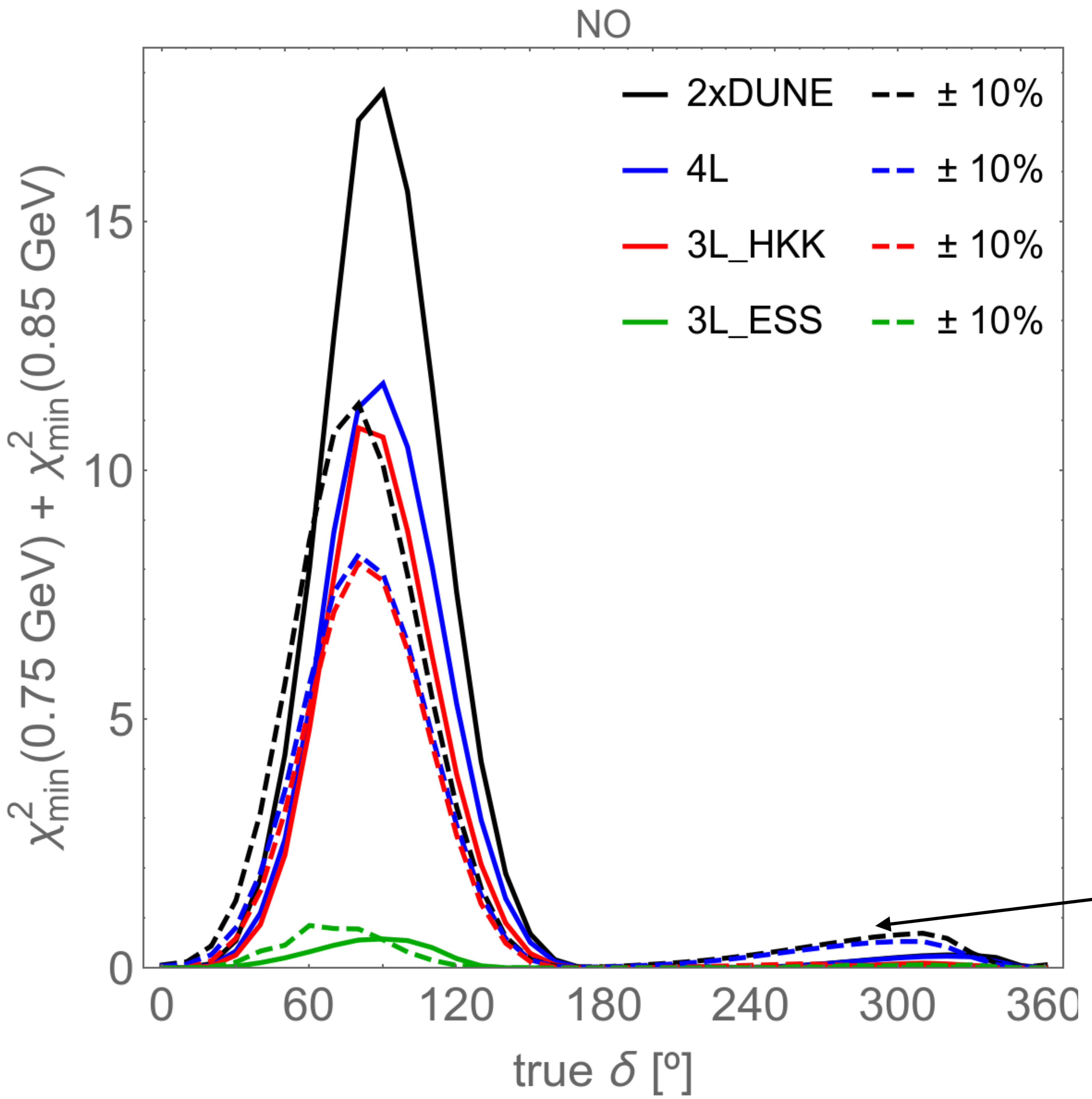
Does it work in real life?





Model-independent test of T-violation

Does it work in real life?



- $\sim 3\sigma$ sensitivity seems possible with DUNE & T2HK & T2KK
- good energy resolution crucial
- uses low-energy tail of DUNE
- detector in Korea needed to cover 2nd osc. max.
- $\delta_{CP} \sim 270°$ can be tested with antineutrino data (not shown)