Karlsruher Institut für Technologie

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Three neutrino phenomenology and global analyses

Neutrino 2022, 1 June 2022, Virtual Seoul

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Outline

- Global oscillation analysis in the three-neutrino framework
- Comment on neutrino mass ordering determination from cosmology
- Proposal for a model-independent test for T-violation

Neutrino mass implies physics beyond the SM

- effective low-energy description: $$\mathcal{L}_{M_\nu} = \frac{1}{2}\overline{\nu^c_{aL}} m_{ab} \nu_{bL}$$
- not gauge invariant, new physics origin of m_{ab}
- **low-energy phenomenology** encoded in m_{ab}
  symmetric complex matrix → 9 real physical parameters:
  - 6 neutrino oscillation params: $\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$
  - 1 absolute mass observable: lightest neutrino mass m_0

  } good prospects to determine experimentally

  - 2 Majorana phases α, β (neutrinoless double beta decay)

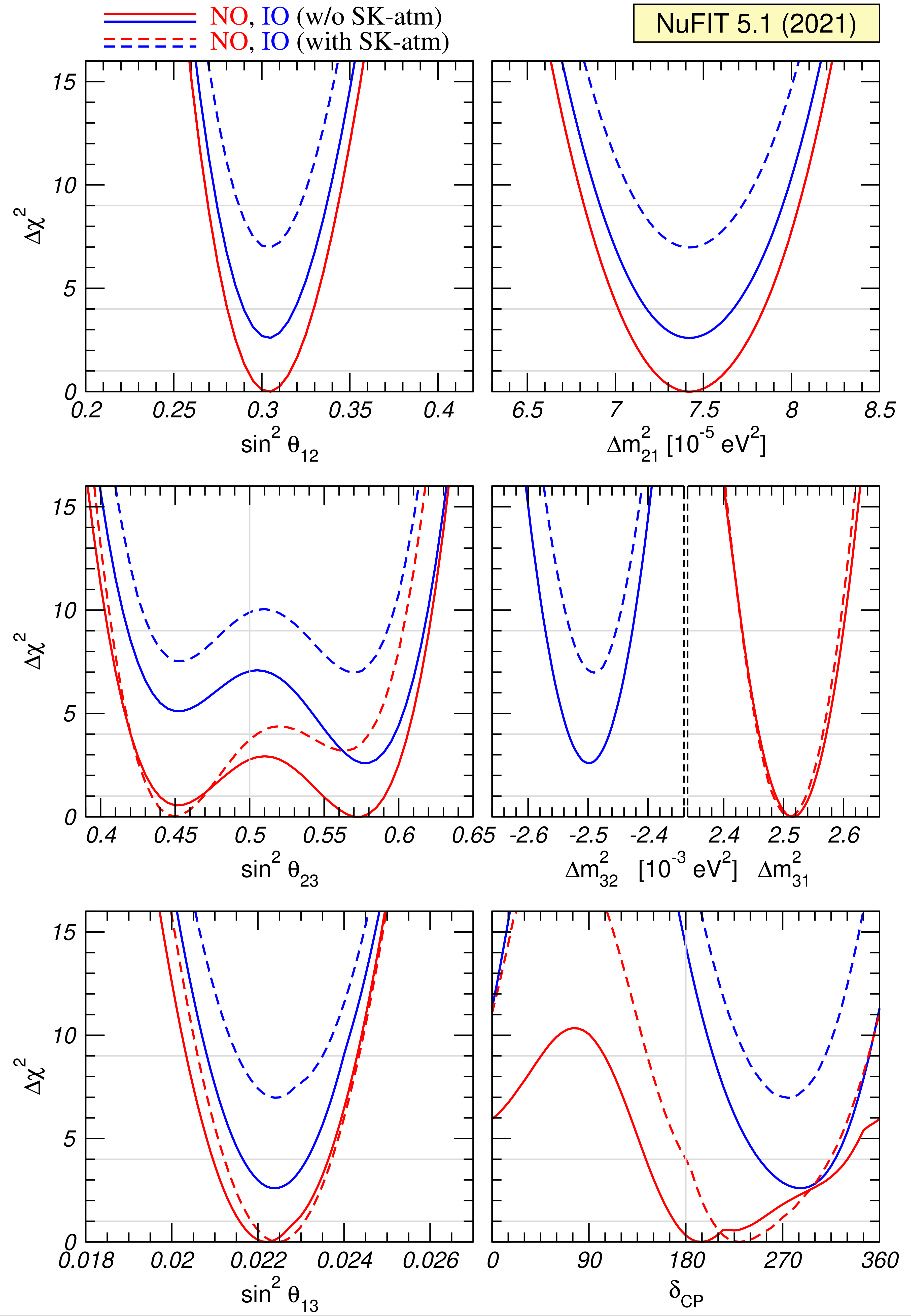
  absent for Dirac neutrinos

Three flavour oscillation parameters

global analysis **NuFIT 5.1 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 ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$



comparable results:
Bari: e.g. Capozzi et al., 2107.00532
Valencia: e.g. deSalas et al., 2006.11237

Evolution of global 3 flavour fit

Gonzalez-Garcia, Maltoni, TS [arXiv:2111.03086]

	2012 NuFIT 1.0	2014 NuFIT 2.0	2016 NuFIT 3.0	2018 NuFIT 4.0	2021 NuFIT 5.1	
θ_{12}	15%	14%	14%	14%	14%	**1.07**
θ_{13}	30%	15%	11%	8.9%	9.0%	**3.3**
θ_{23}	43%	32%	32%	27%	27%	**1.6**
Δm^2_{21}	14%	14%	14%	16%	16%	**0.88**
$\lvert\Delta m^2_{3\ell}\rvert$	17%	11%	9%	7.8%	6.7% [6.5%]	**2.5**
δ_{CP}	100%	100%	100%	100% [92%]	100% [83%]	**1 [1.2]**
$\Delta\chi^2_{\text{IO-NO}}$	± 0.5	-0.97	$+0.83$	$+4.7$ [$+9.3$]	$+2.6$ [$+7.0$]	

w/o [w] SK atm data

relat. precision at 3σ: $\frac{2(x^+ - x^-)}{(x^+ + x^-)}$

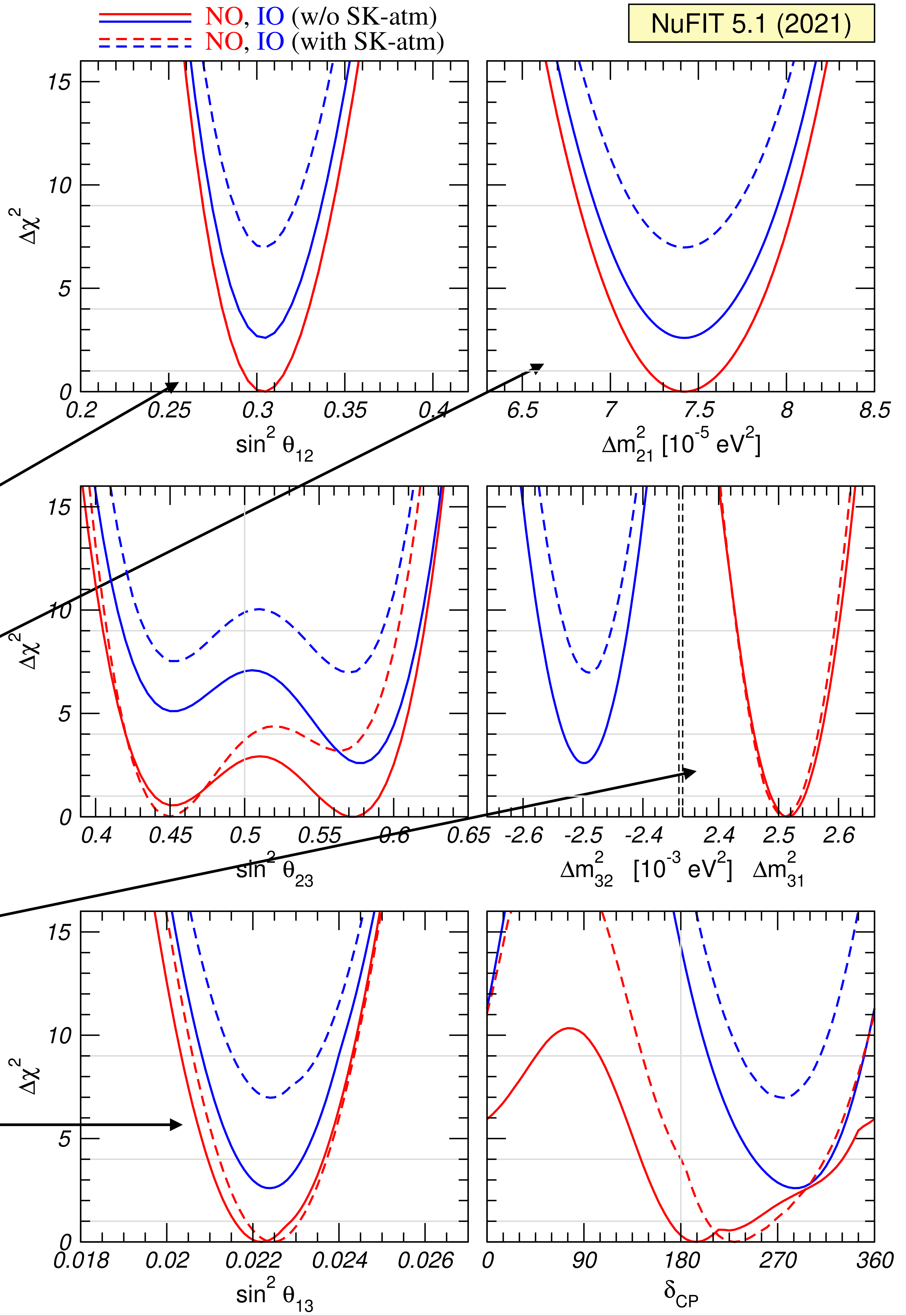
improvement factor from 2012 to 2021

Four well-known parameters

NuFIT 5.1 results www.nu-fit.org

- robust determination
  (relat. precision at 3σ)

θ_{12} (14%)
Δm^2_{21} (16%)
$|\Delta m^2_{31}|$ (7%)
θ_{13} (9%)



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NuFIT 5.1 results www.nu-fit.org

- robust determination
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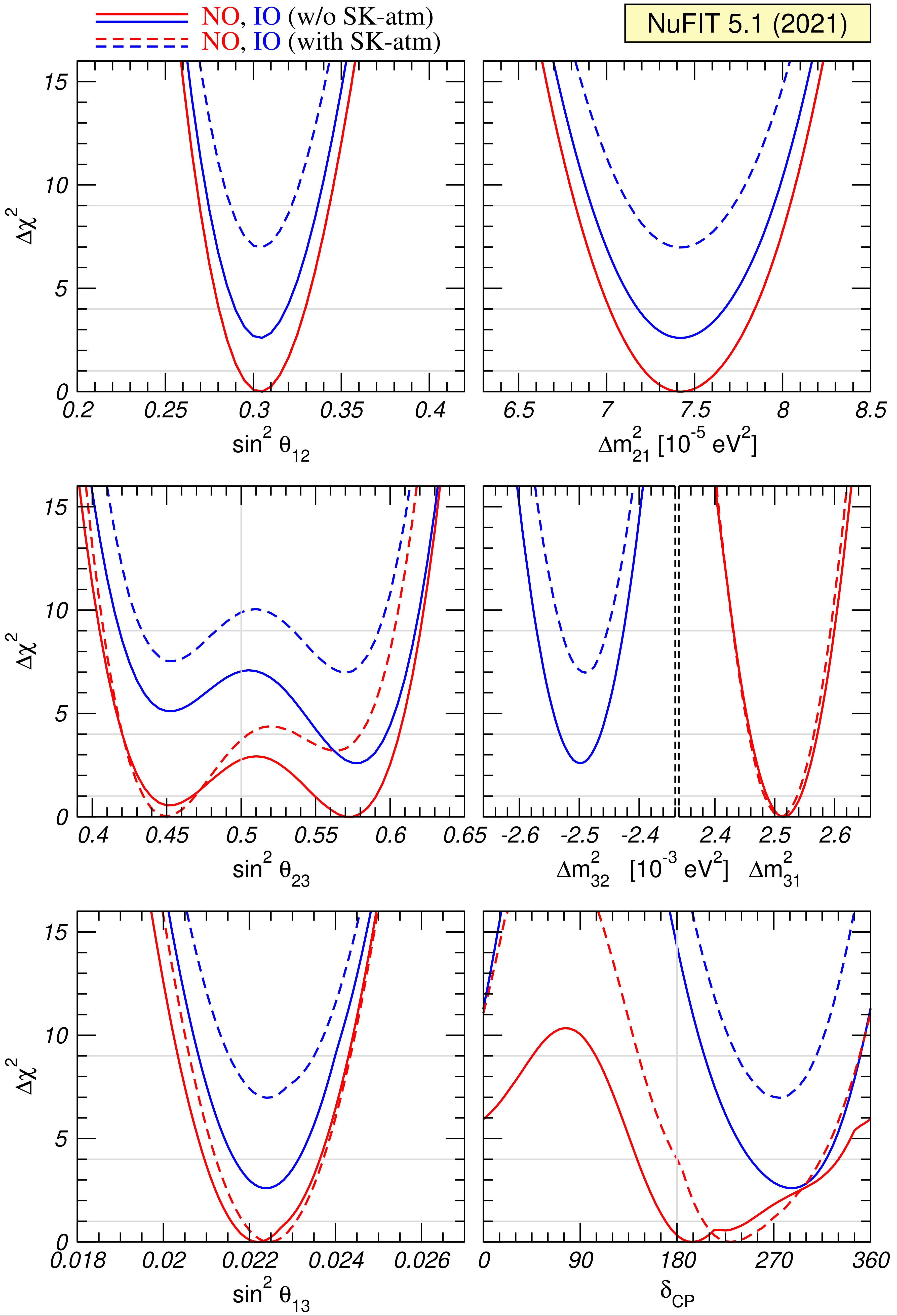
for quarks

θ_{12}	(14%)	$0.6\ \%$
Δm^2_{21}	(16%)	
$\lvert\Delta m^2_{31}\rvert$	(7%)	
θ_{13}	(9%)	$8.3\ \%$



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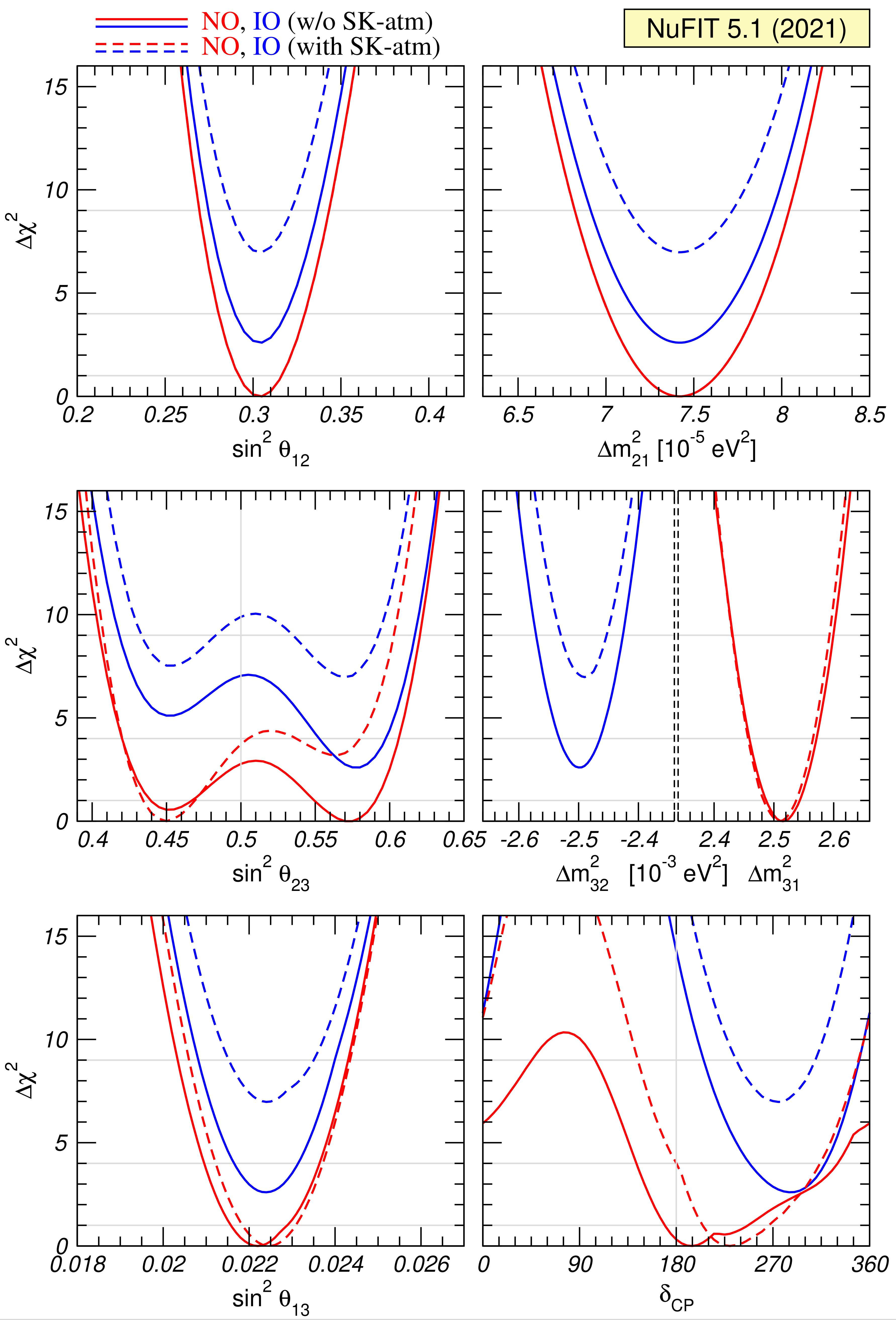
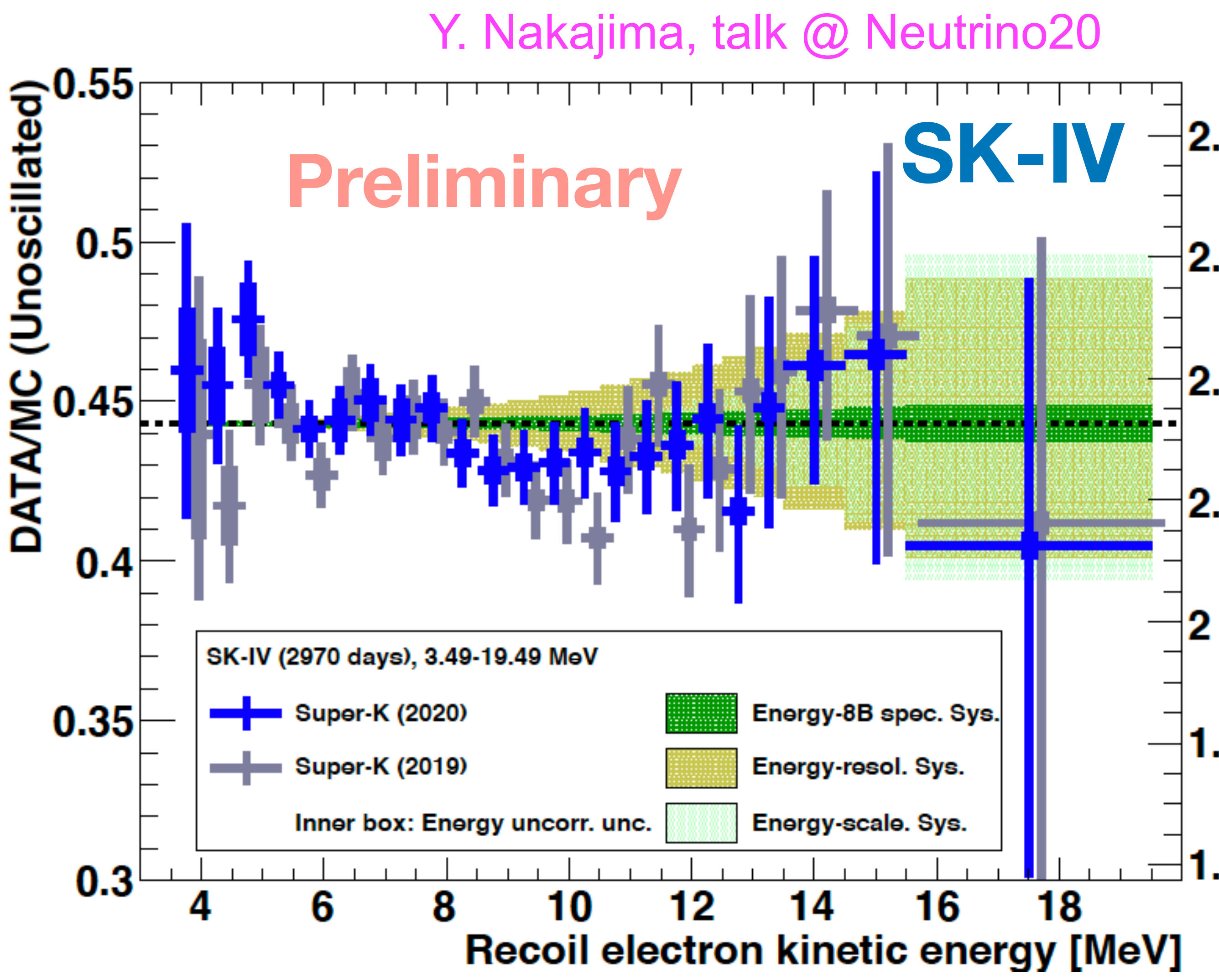
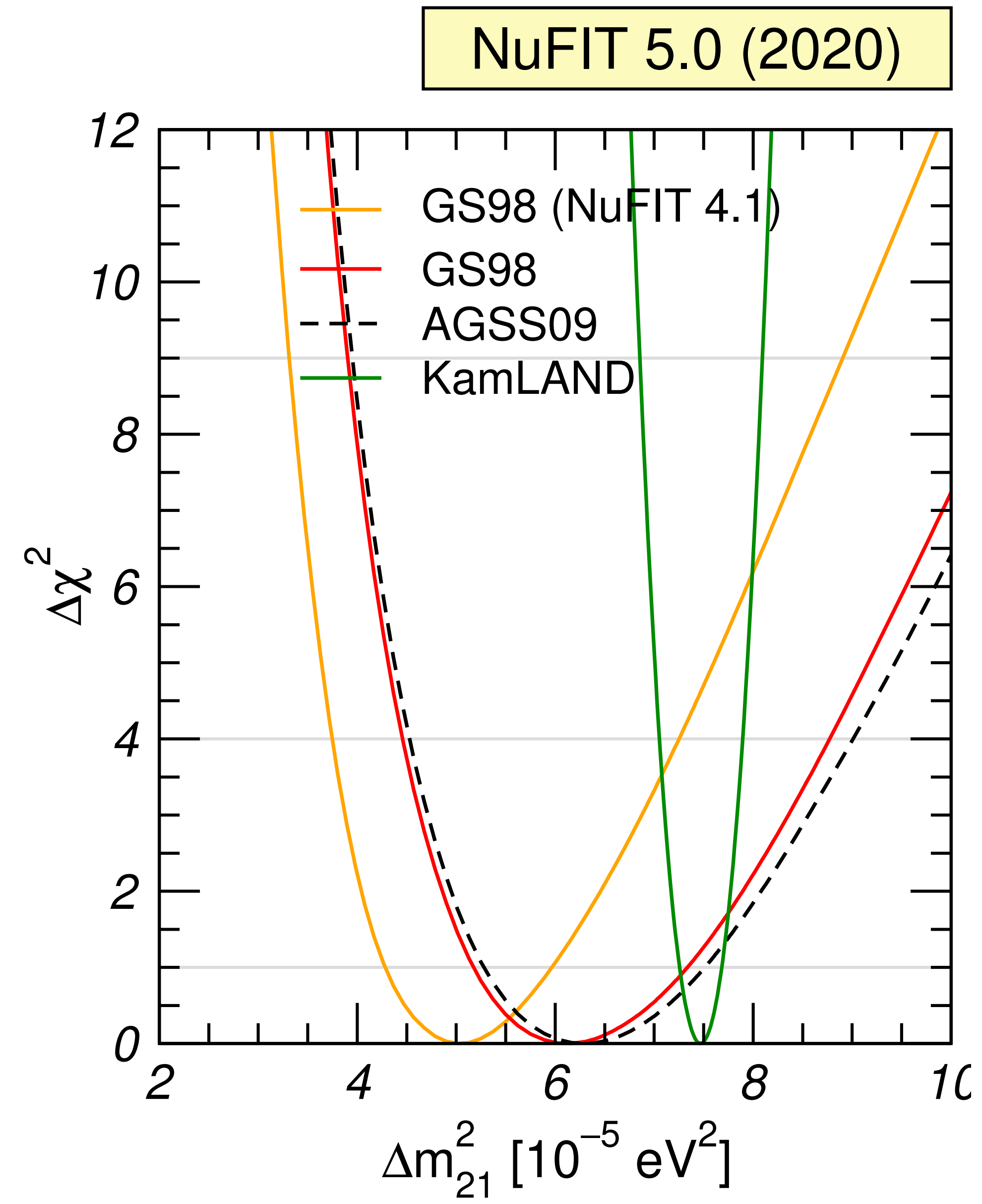
today's result from Daya Bay $\theta_{13} \rightarrow 8.7\ \%$

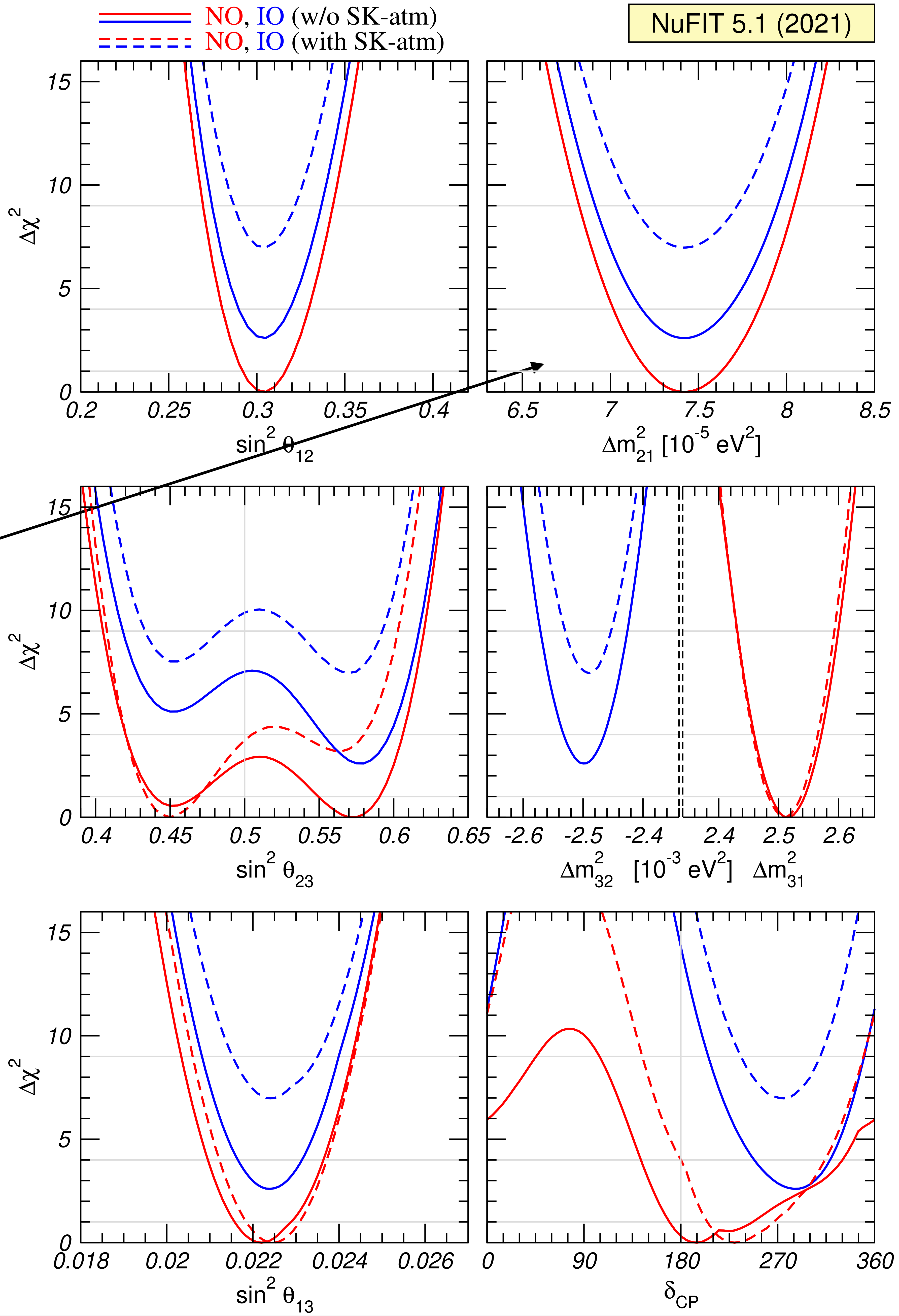


Four well-known parameters

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





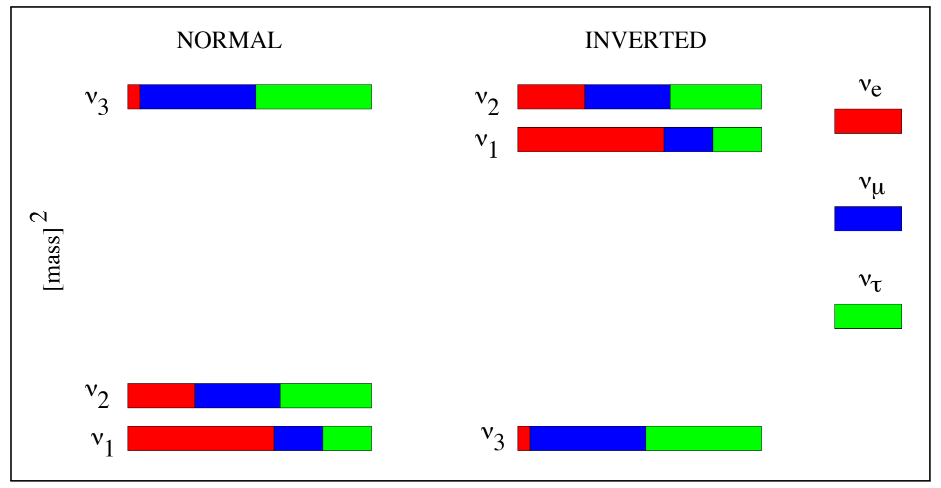


$A_{DN}^{Fit} = (-3.6 \pm 1.6(stat) \pm 0.6(syst))\,\%$ → $A_{DN}^{Fit} = (-2.1 \pm 1.1)\,\%$

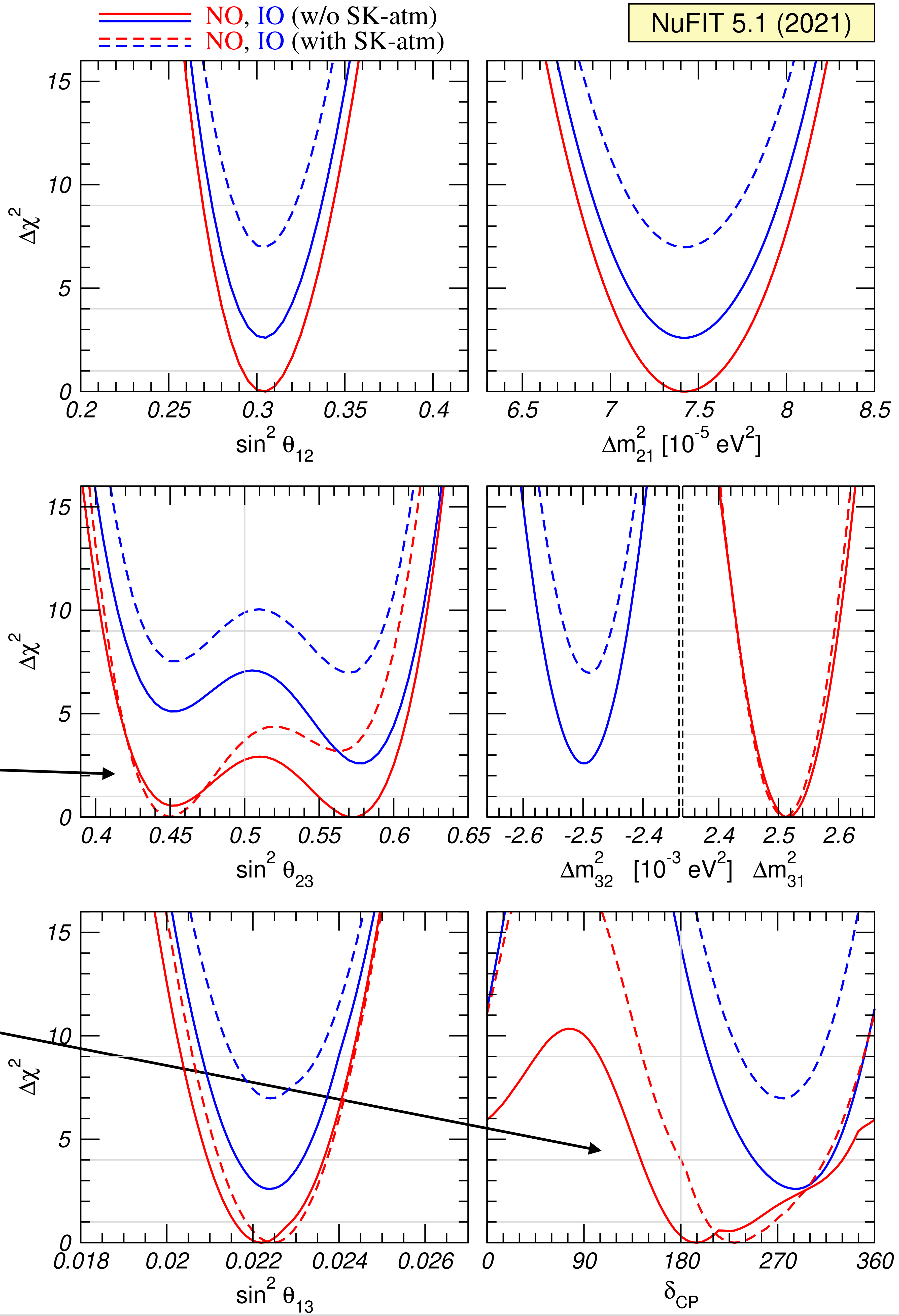
- solar neutrino and KamLAND data compatible at 1.1σ

The unknowns:

- neutrino mass ordering (red vs blue curves)



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



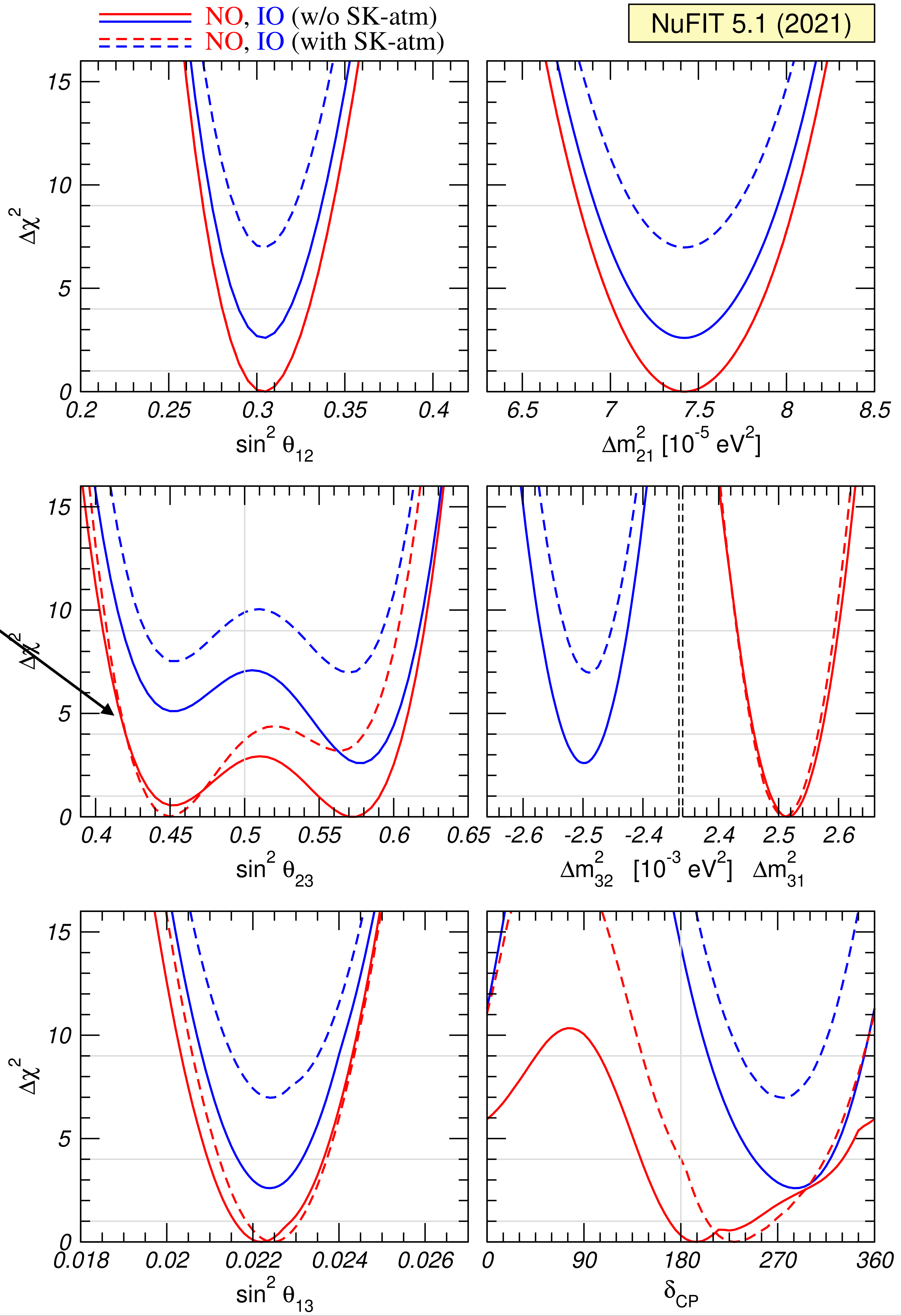
The least known mixing angle

NuFIT 5.1 results www.nu-fit.org

- broad allowed range for θ_{23} (24%)

  for quarks: 5.2%

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



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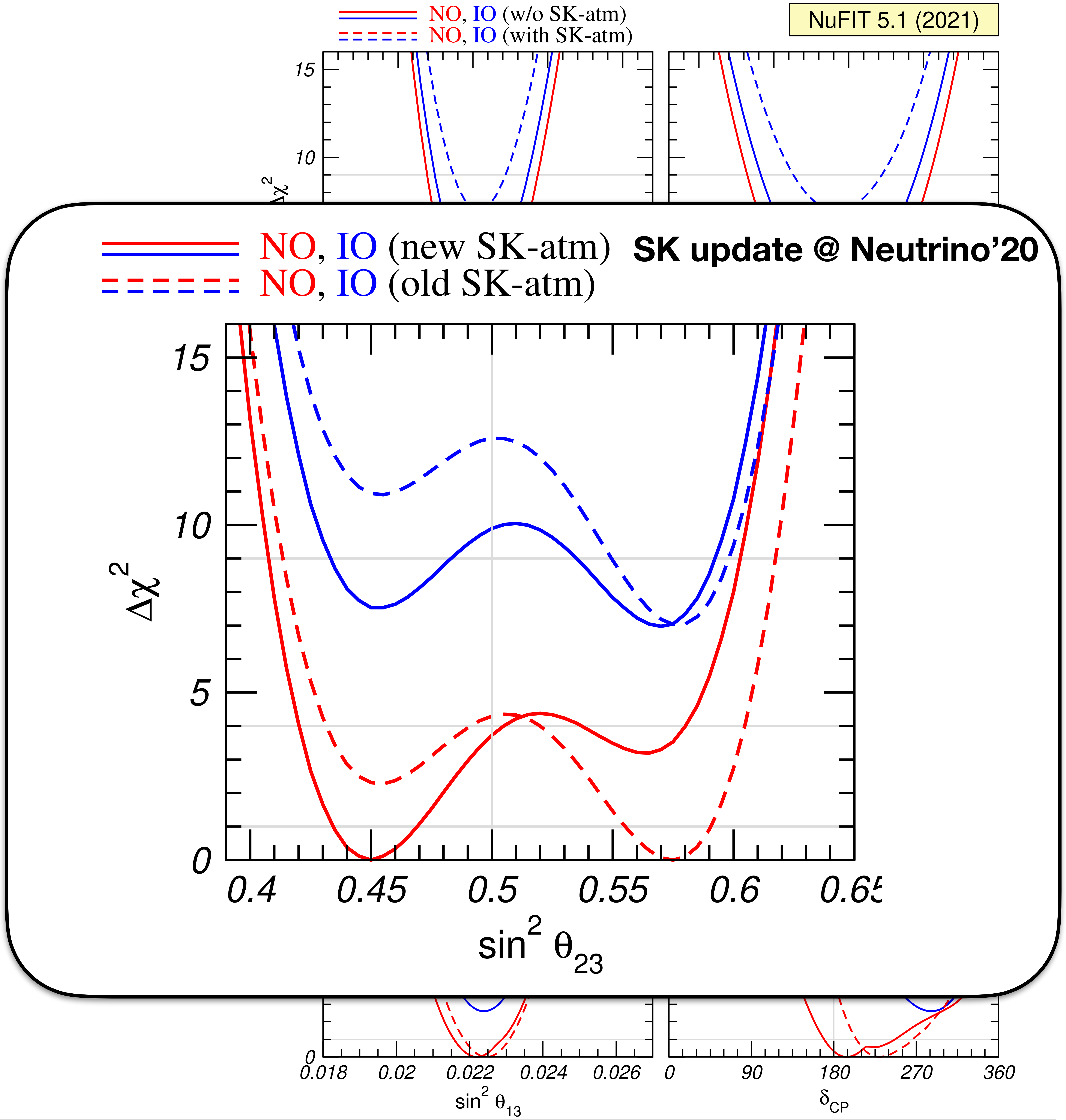

Mass ordering and CP phase

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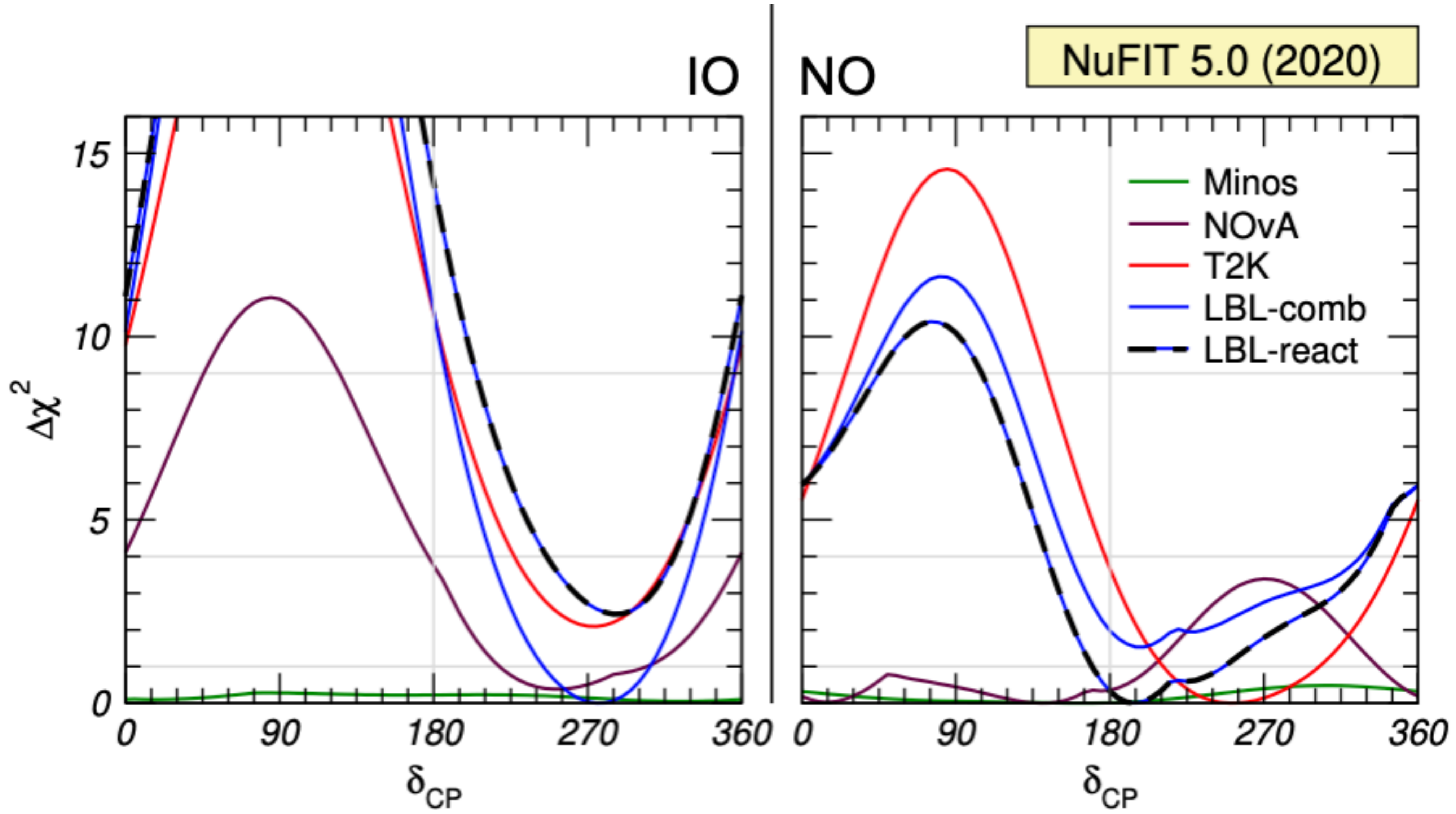
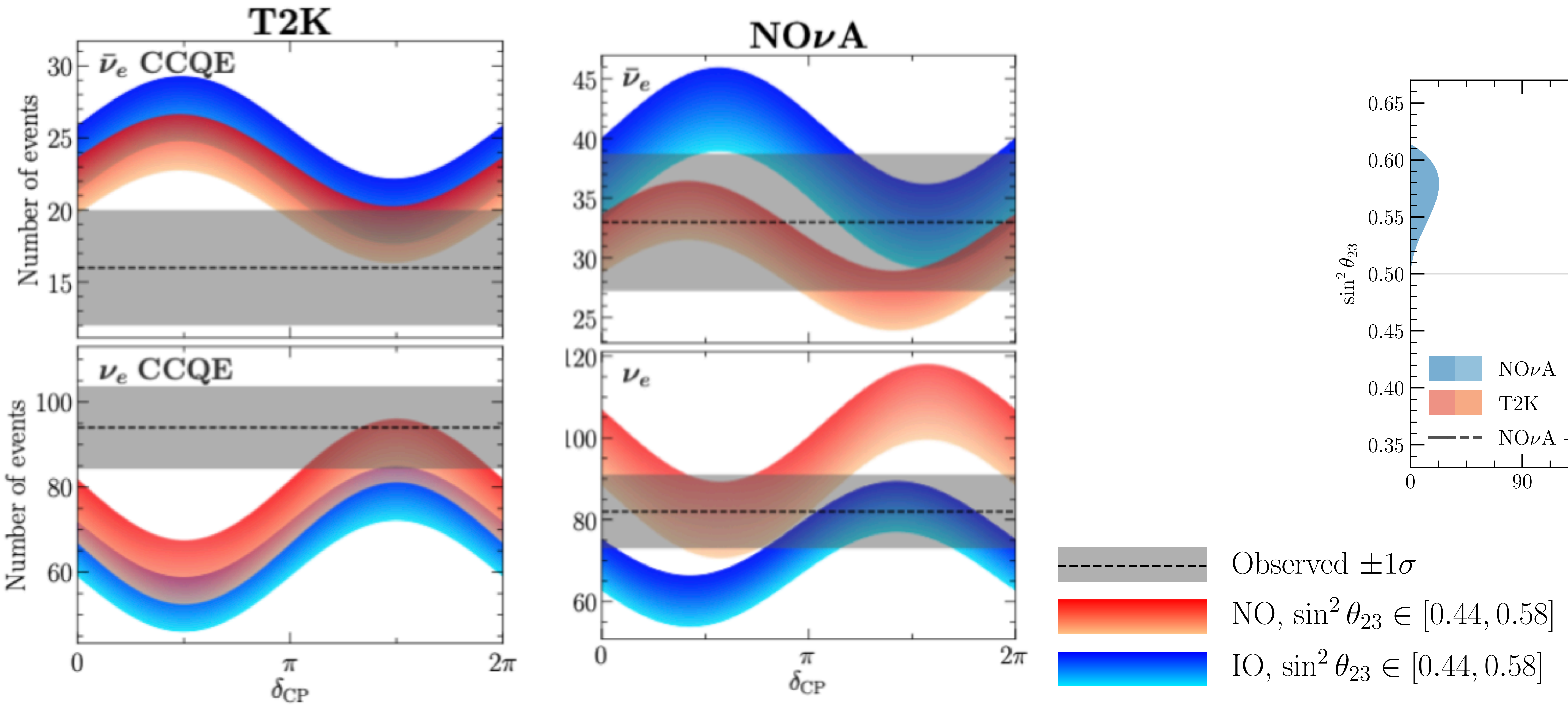
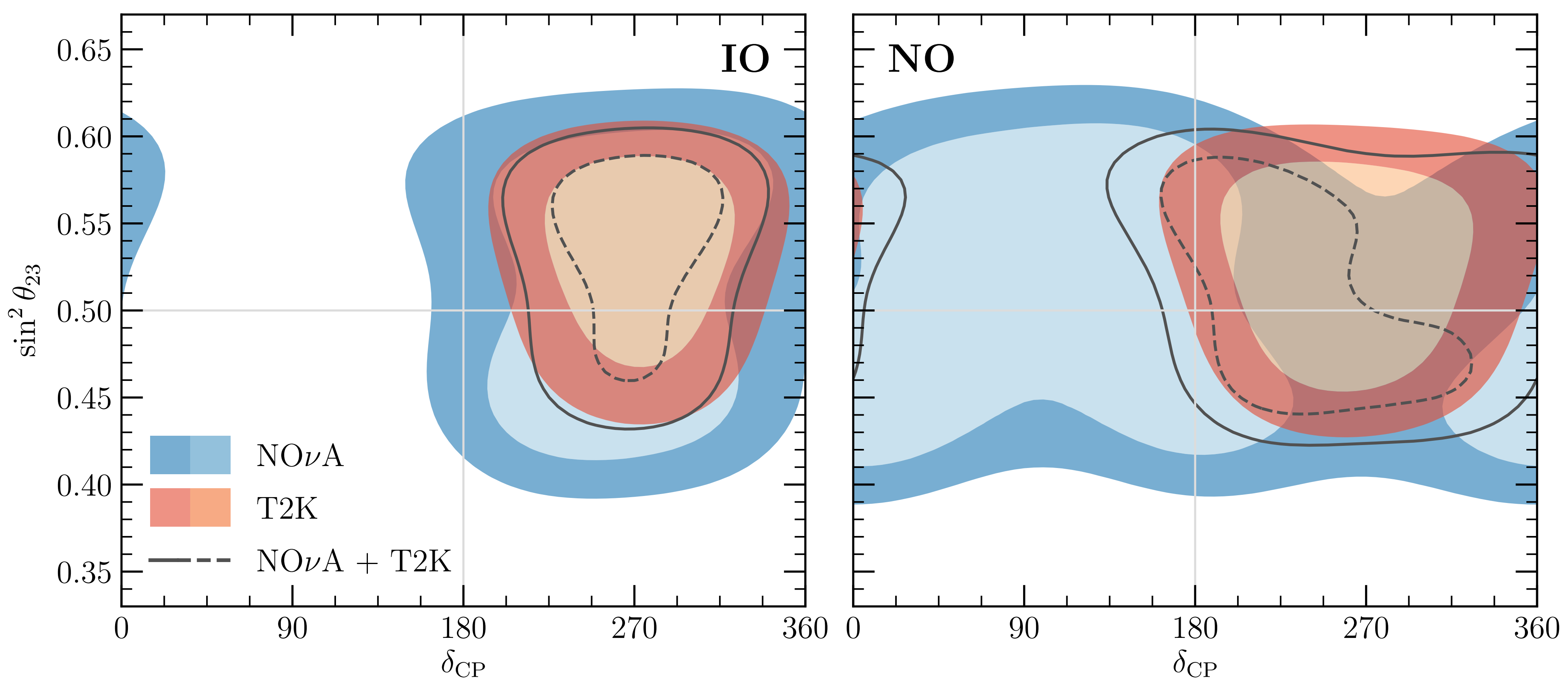
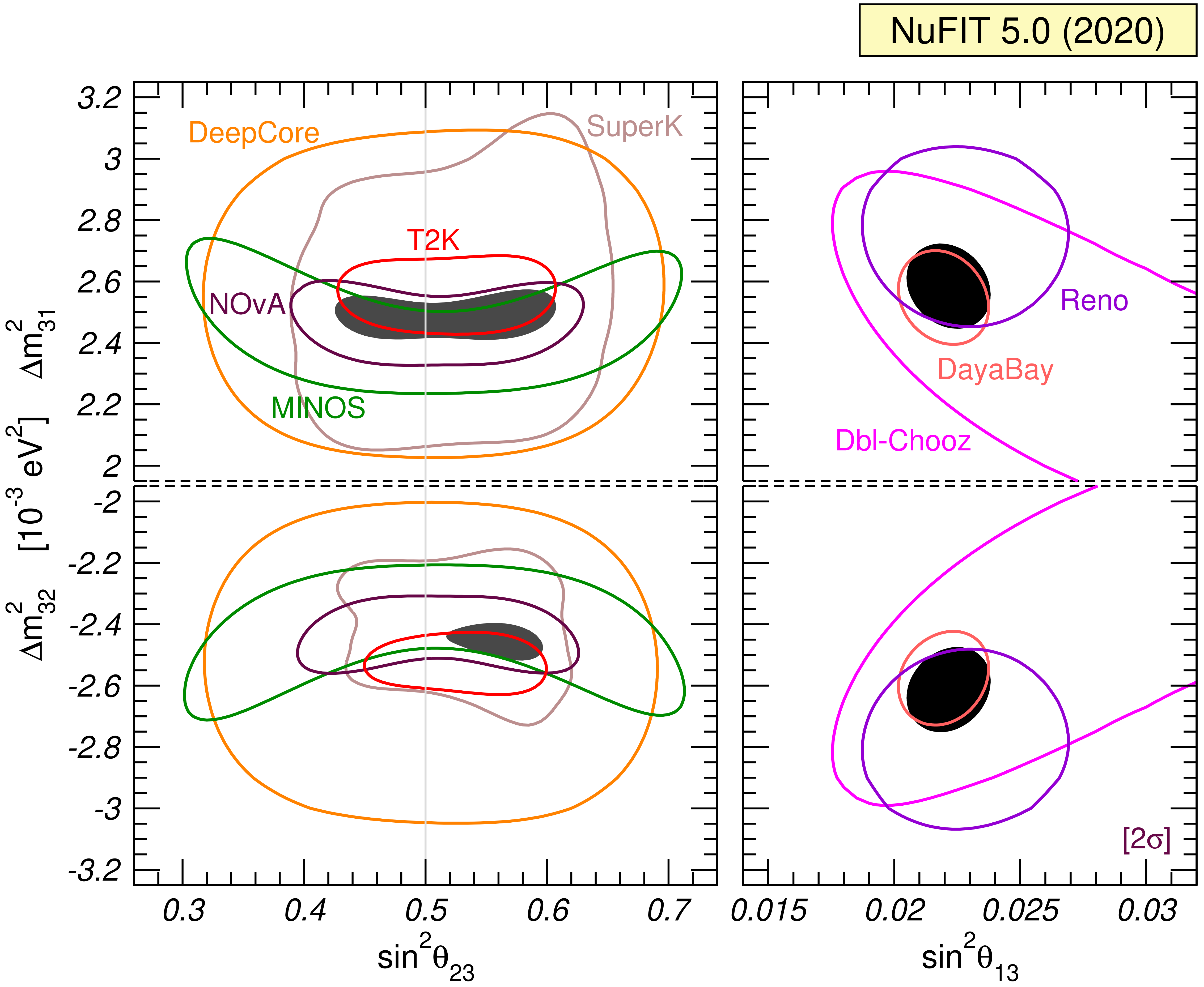
  - LBL accelerator data:
    T2K & NOvA better compatible for IO







Consistency of *μ* and *e* disappearance



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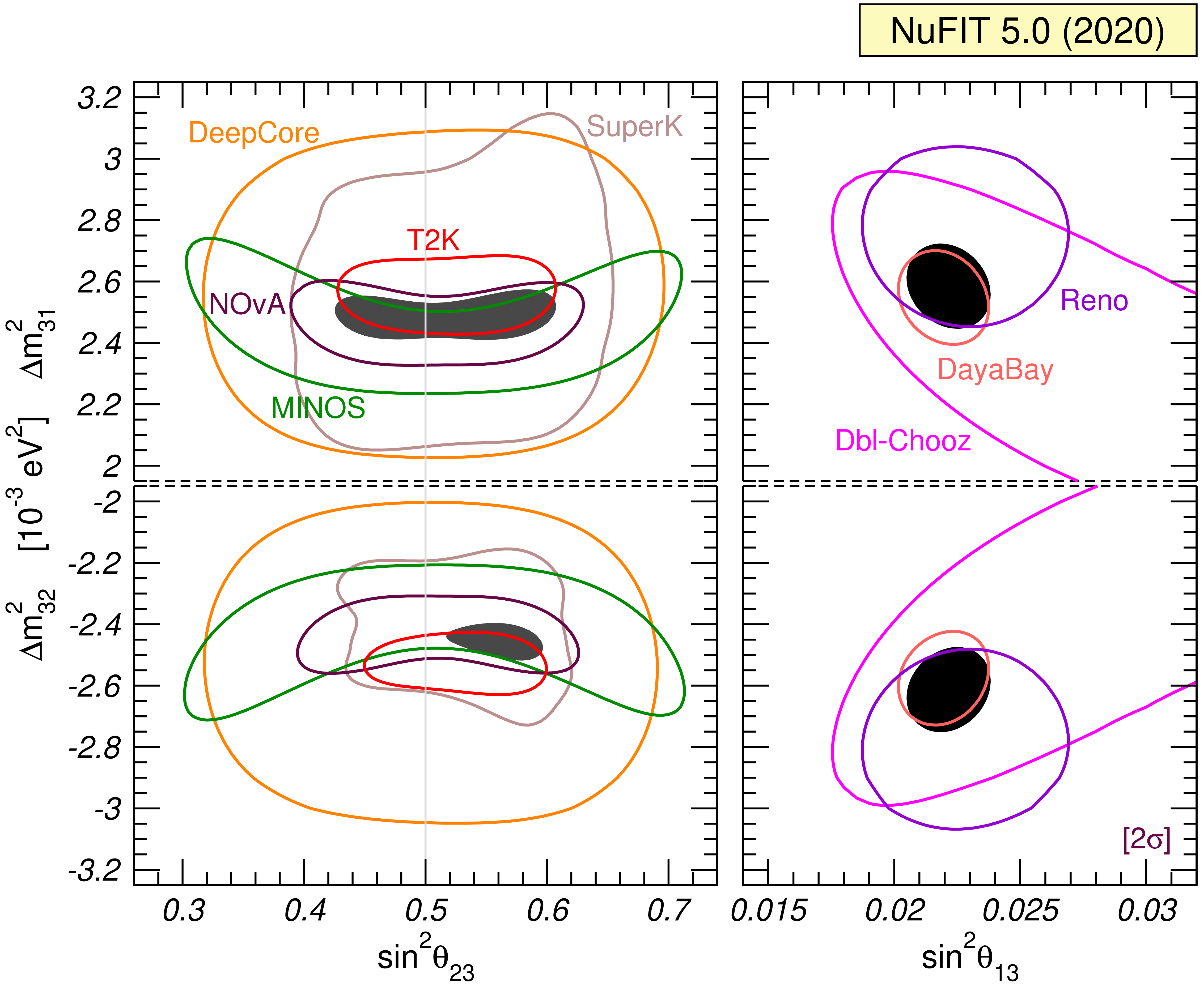
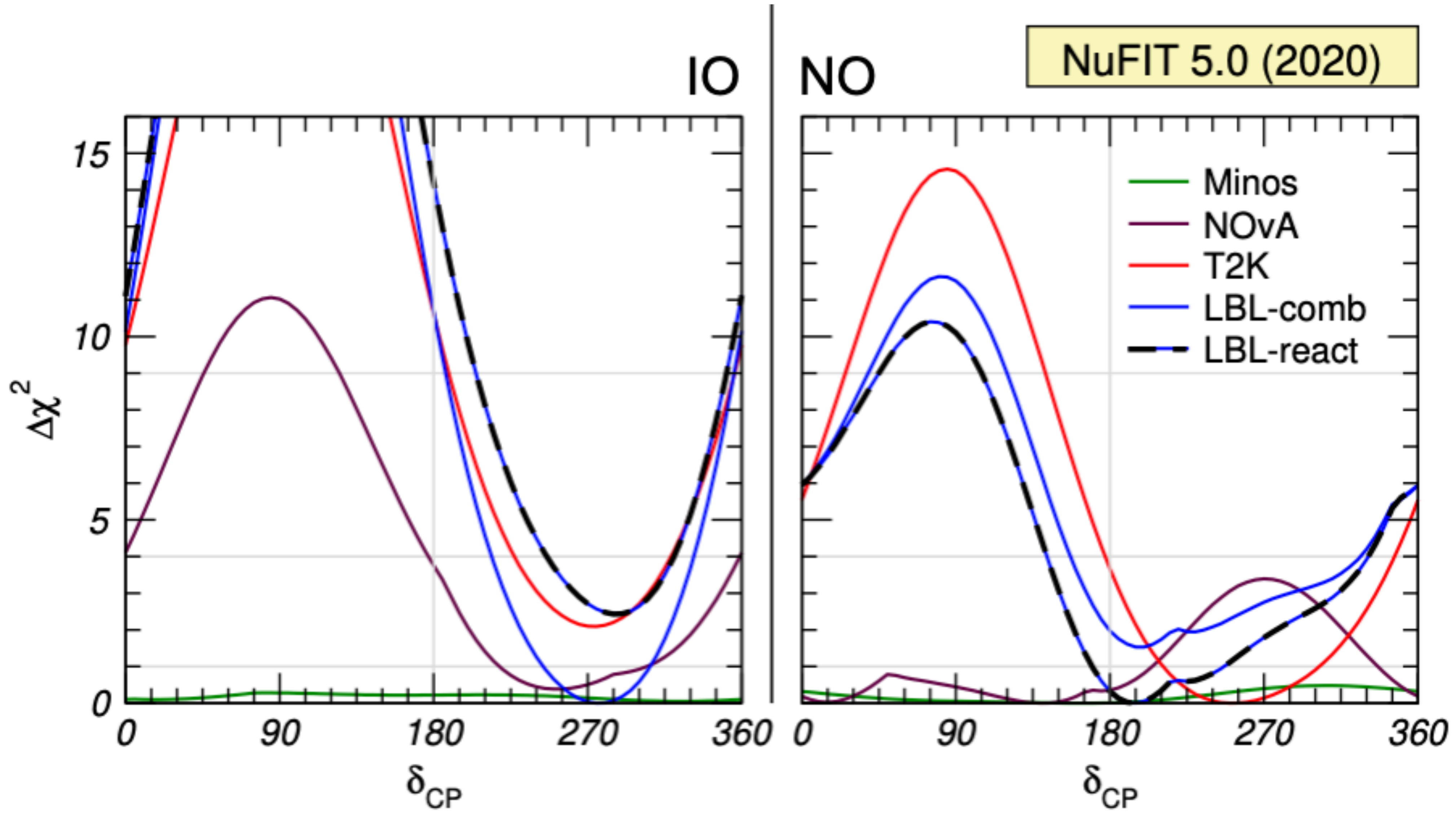


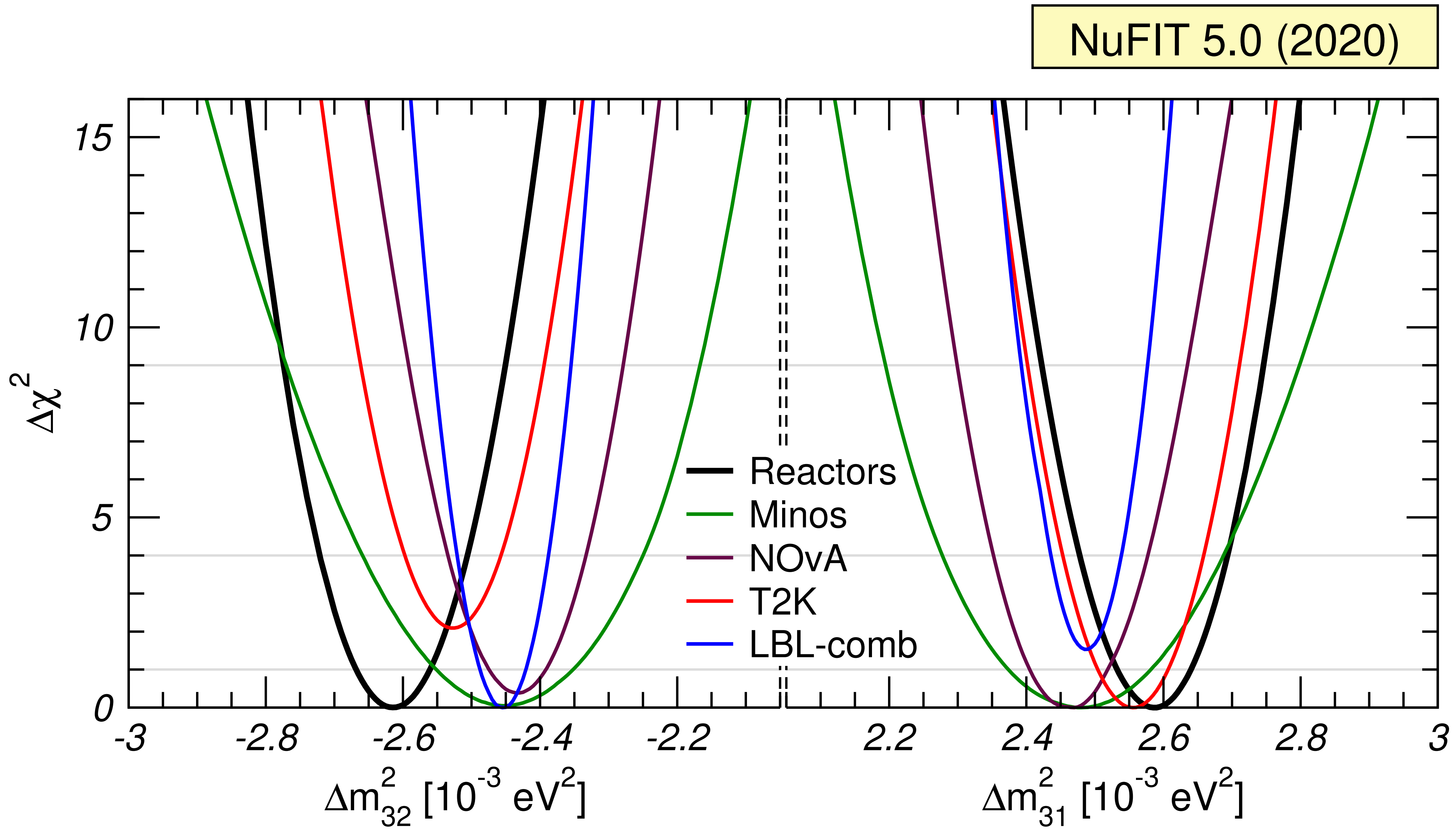
$$|\Delta m^2_{\mu\mu}| = |\Delta m^2_{ee}| \mp \Delta m^2_{21}\,[\cos 2\theta_{12} - \cos\delta \sin\theta_{13} \sin 2\theta_{12} \tan\theta_{23}]$$

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
  $\Delta\chi^2 = 2.7$ (was 6.2 in 2019)





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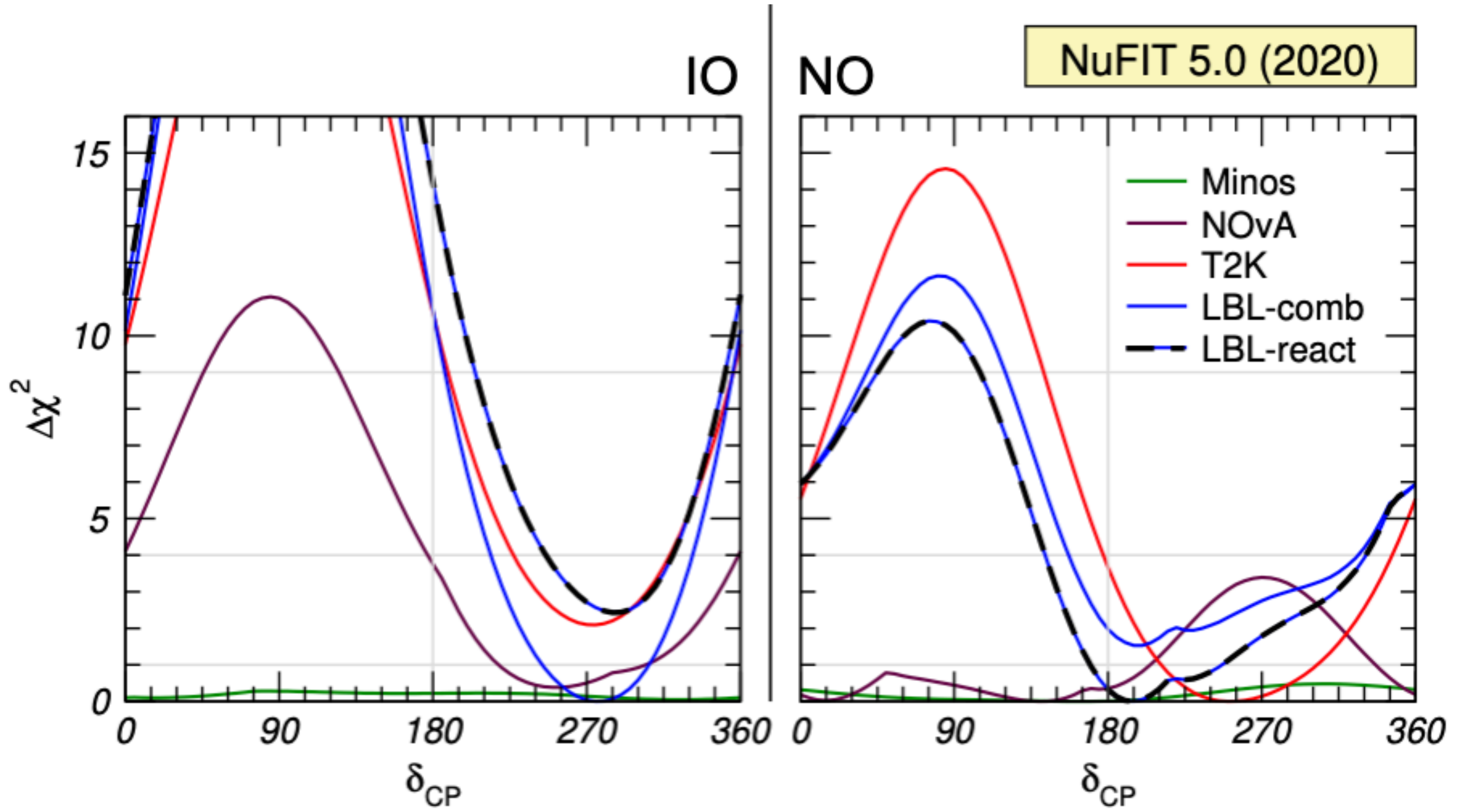
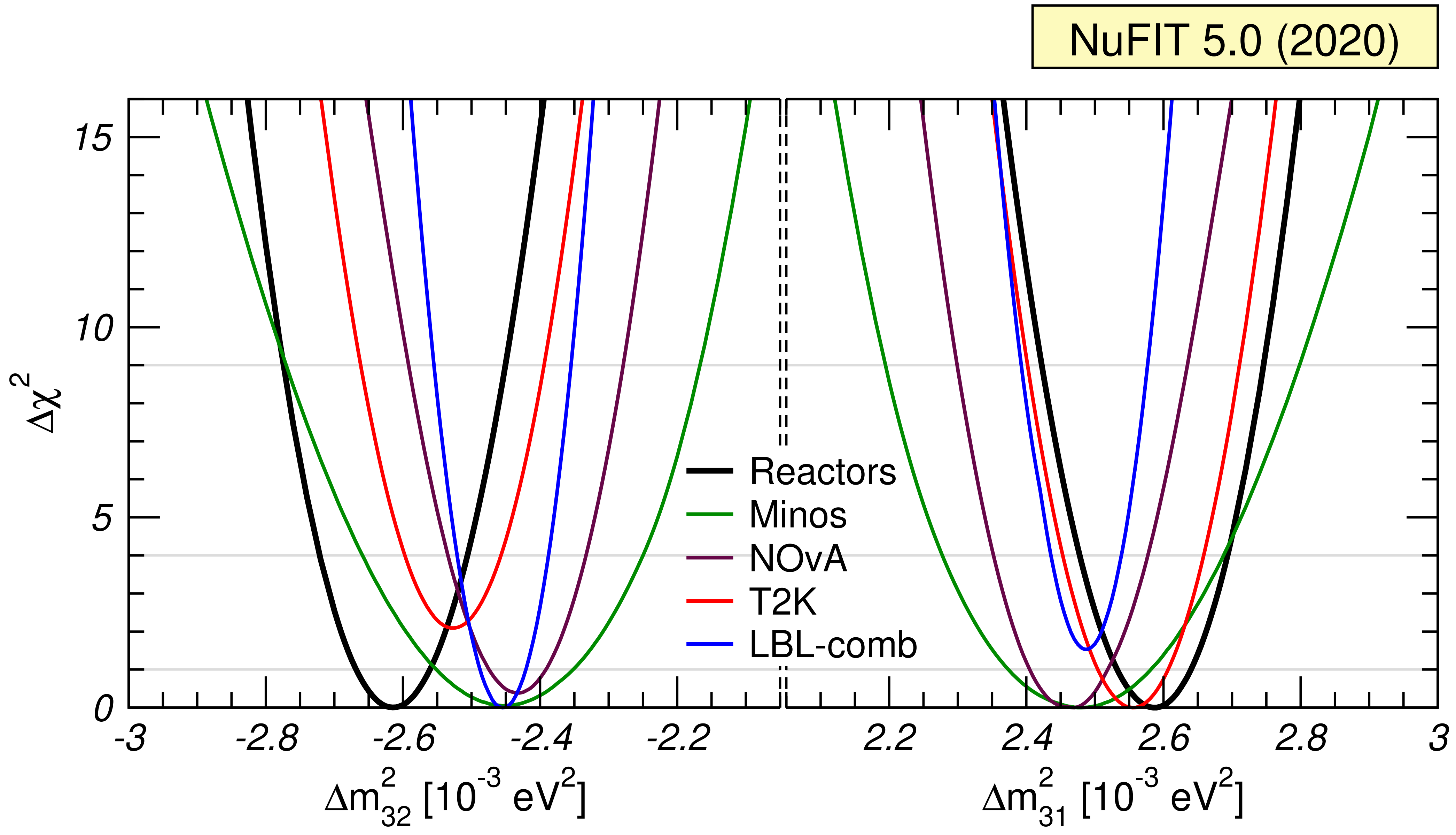
very power full in the future [Blennow, TS, 2013] combining reactor data from **JUNO** with atmospheric data from **IceCube** [1911.06745] or **KM3NET/ORCA** [2108.06293]





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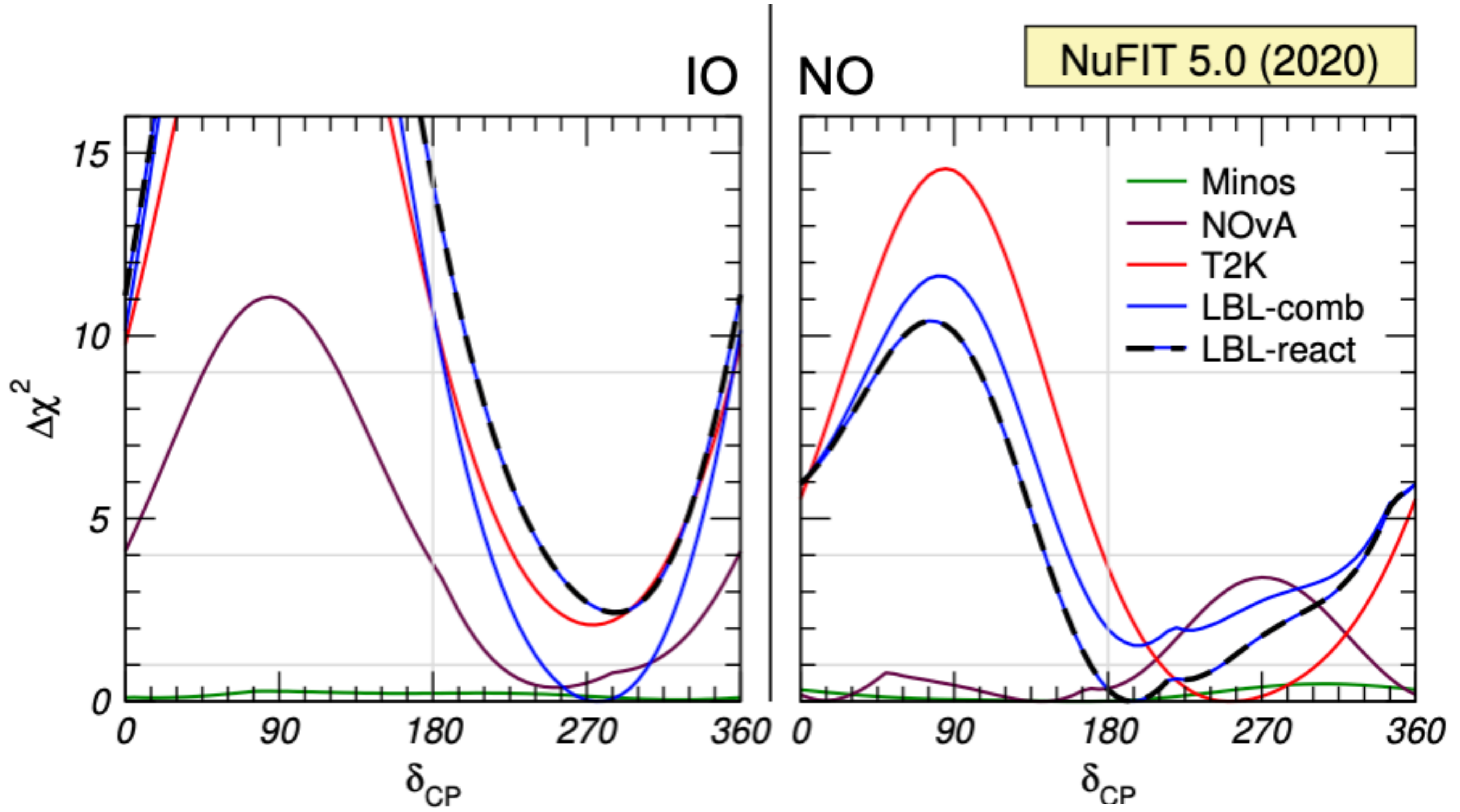
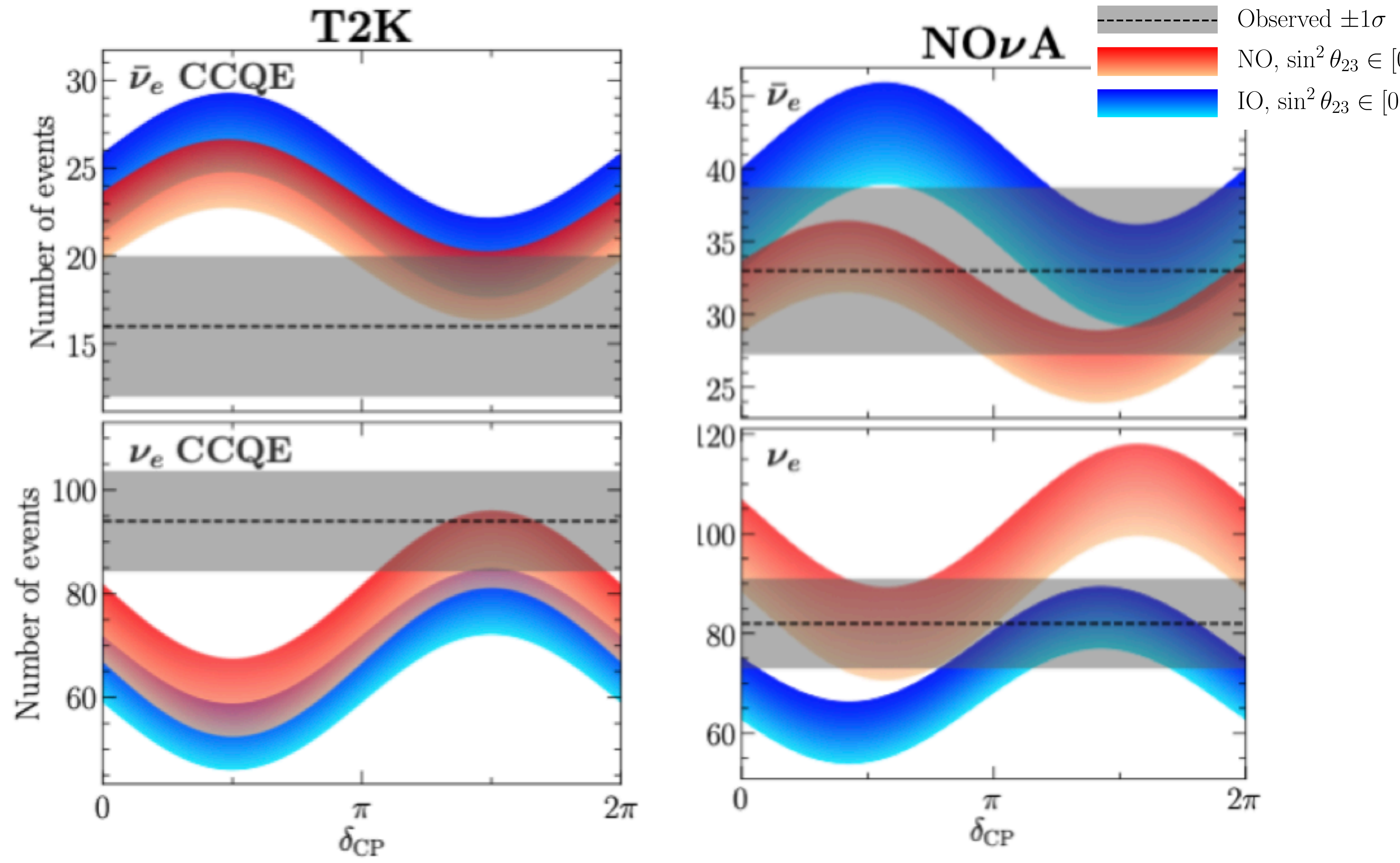
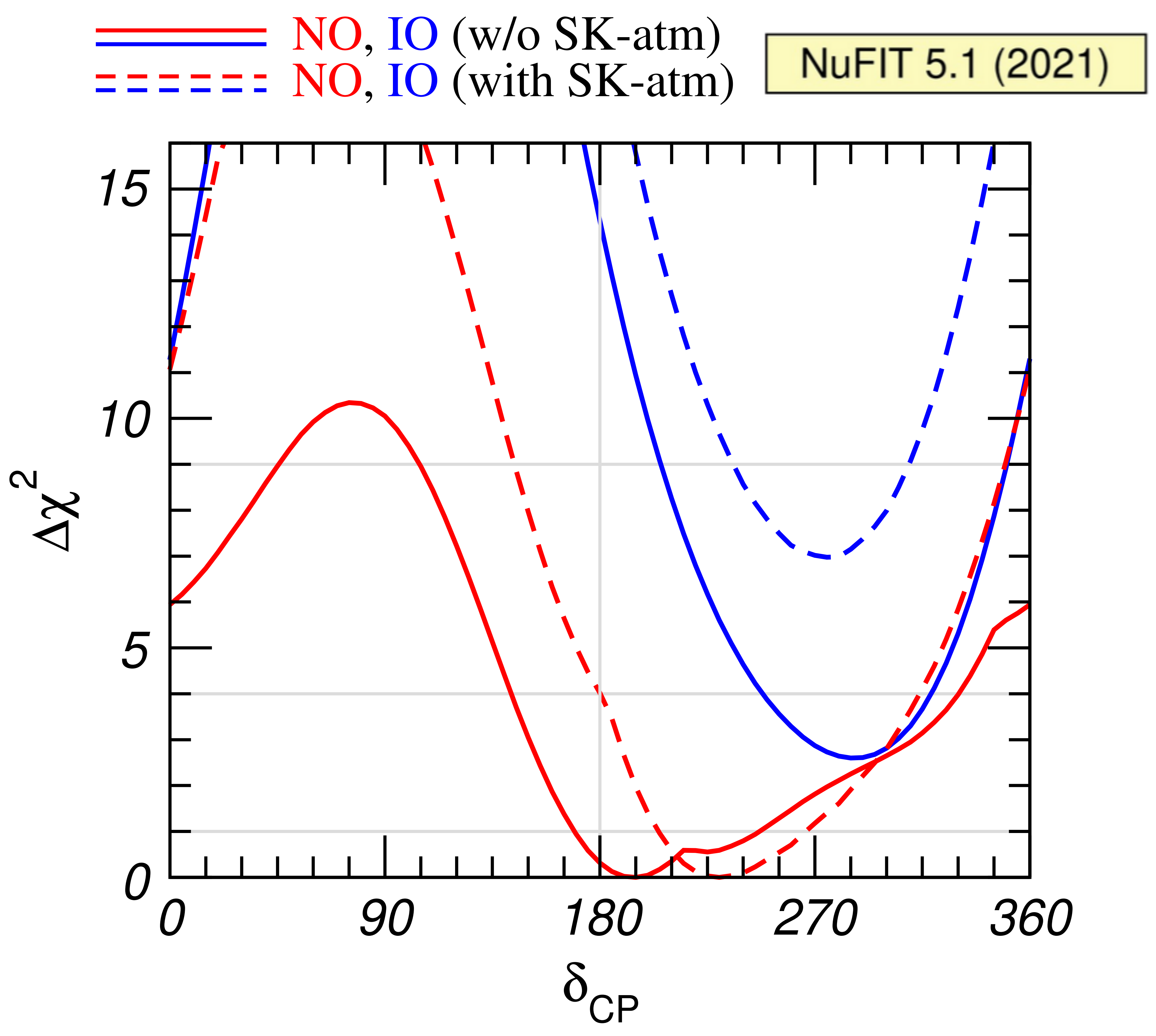
- overall preference for NO with
  $\Delta\chi^2 = 2.7$ (was 6.2 in 2019)
- CP phase best fit at δ=195° →
  CP conservation allowed at 0.6σ
- for IO: best fit close to δ=270°,
  CP conservation disfavoured at 3σ





Mass ordering and CP phase: atmospheric neutrinos

- NuFit 5.0 updated with SK I-IV analysis presented @ Neutrino'20
- improved sensitivity to MO:
  χ^2(IO) - χ^2(NO) = 3.2 (atm only)
  pre-Neutrino'20: 4.3
- added to global fit via χ^2 table:
  χ^2(IO) - χ^2(NO) = 2.7 (no SK)
  → 7.1 (w SK) 2.7σ
- CP conservation @ 0.6σ (no SK)
  → 2σ (w SK)
  best fit: $\delta_{CP} \approx 230°$



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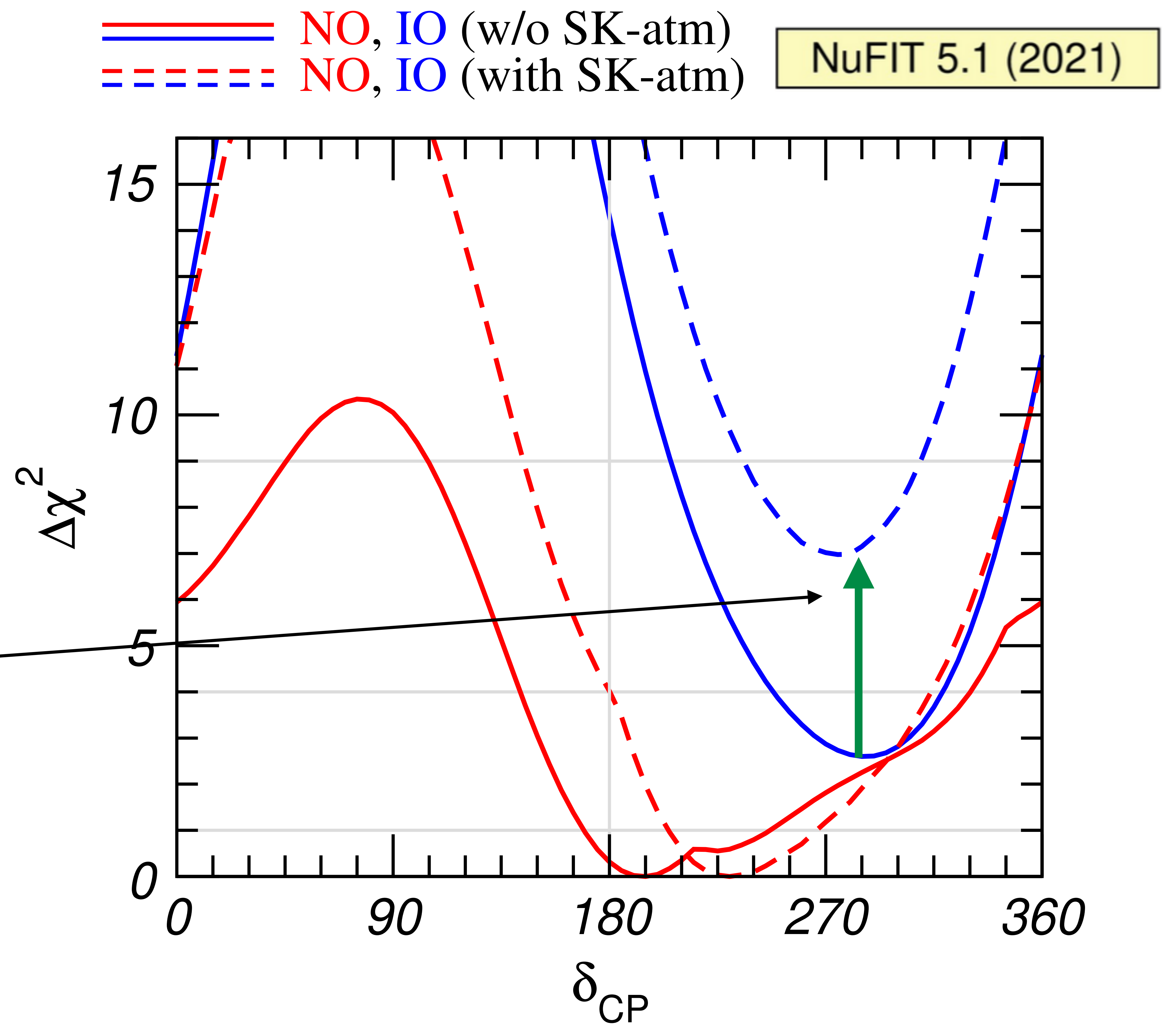

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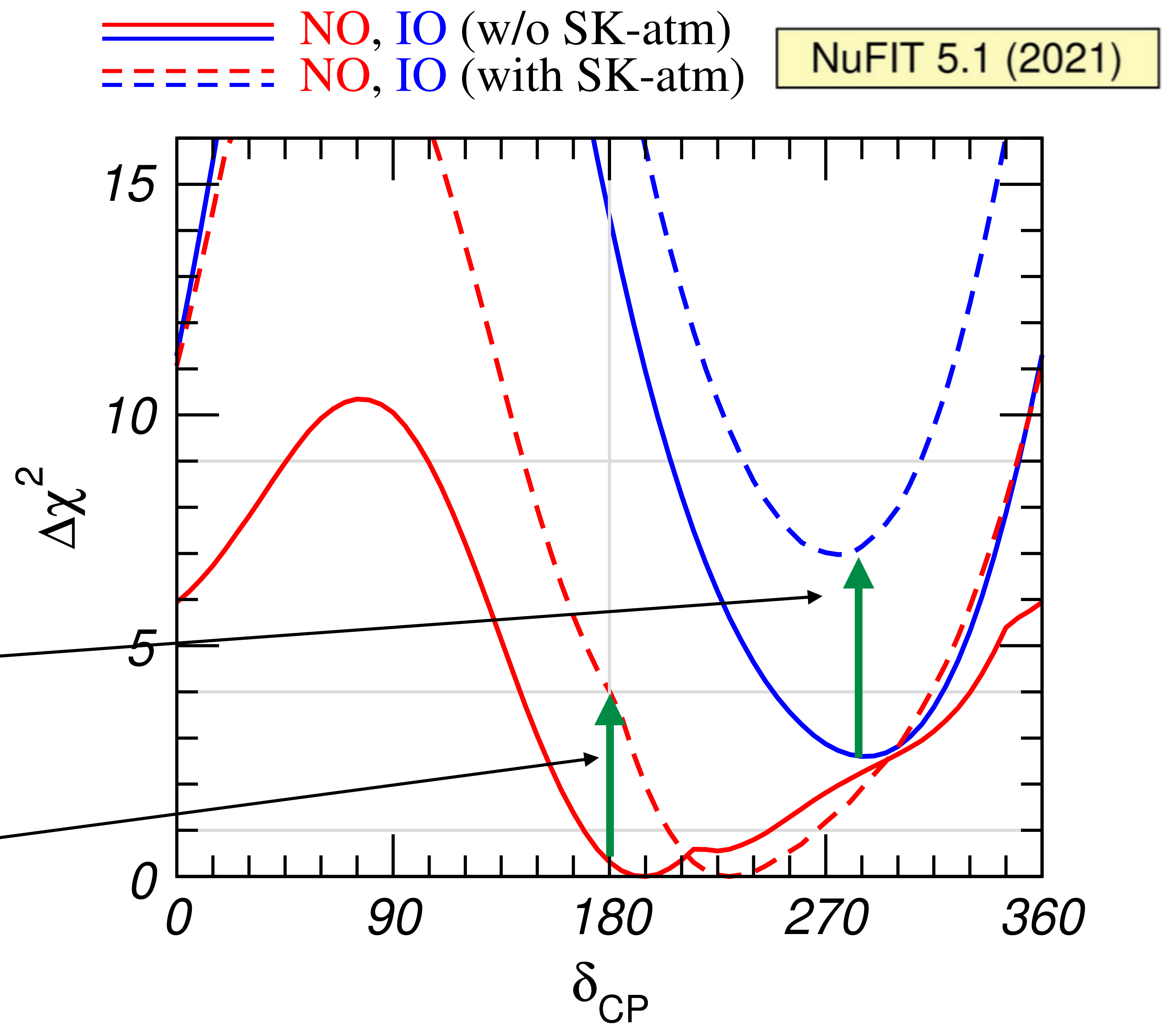


Intermediate summary:

- results from global 3-flavour oscillation fit
  - robust determination of $\Delta m^2_{21}, |\Delta m^2_{31}|, \theta_{12}, \theta_{13}$
  - determination of mass-ordering, θ_{23}-octant, CP phase depends on sub-leading three-flavour effects — not yet statistically significant
  - interplay of accelerator / reactor / atmospheric data

	best fit MO	$\Delta\chi^2(\mathrm{MO})$	best fit δ_{CP}	$\Delta\chi^2(\mathrm{CPC})$	oct. θ_{23}	$\Delta\chi^2(\mathrm{oct.})$
accelerator	IO	1.5	275°	2.0	2nd	2.2
+ reactors	NO	2.7	195°	0.4	2nd	0.5
+ atmospheric	**NO**	**7.1**	**230°**	**4.0**	**1st**	**3.2**

Neutrino mass from cosmology

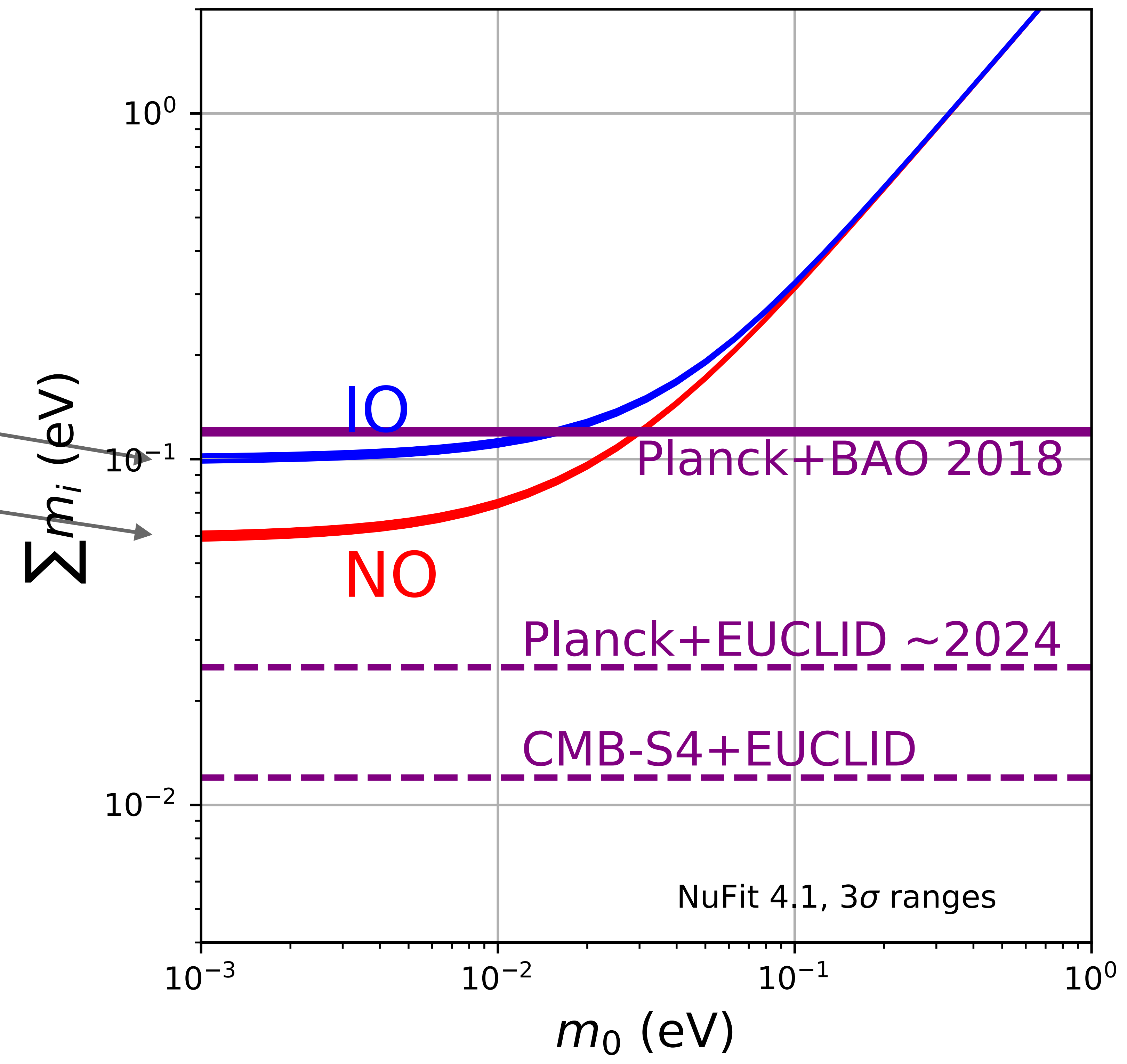
talks by J. Lesgourgues, O. Mena

$$\Sigma \equiv \sum_{i=1}^{3} m_i = \begin{cases} m_0 + \sqrt{\Delta m_{21}^2 + m_0^2} + \sqrt{\Delta m_{31}^2 + m_0^2} & \text{(NO)} \\ m_0 + \sqrt{|\Delta m_{32}^2| + m_0^2} + \sqrt{|\Delta m_{32}^2| - \Delta m_{21}^2 + m_0^2} & \text{(IO)} \end{cases}$$

- minimal values predicted from oscillation data for $m_0 = 0$:

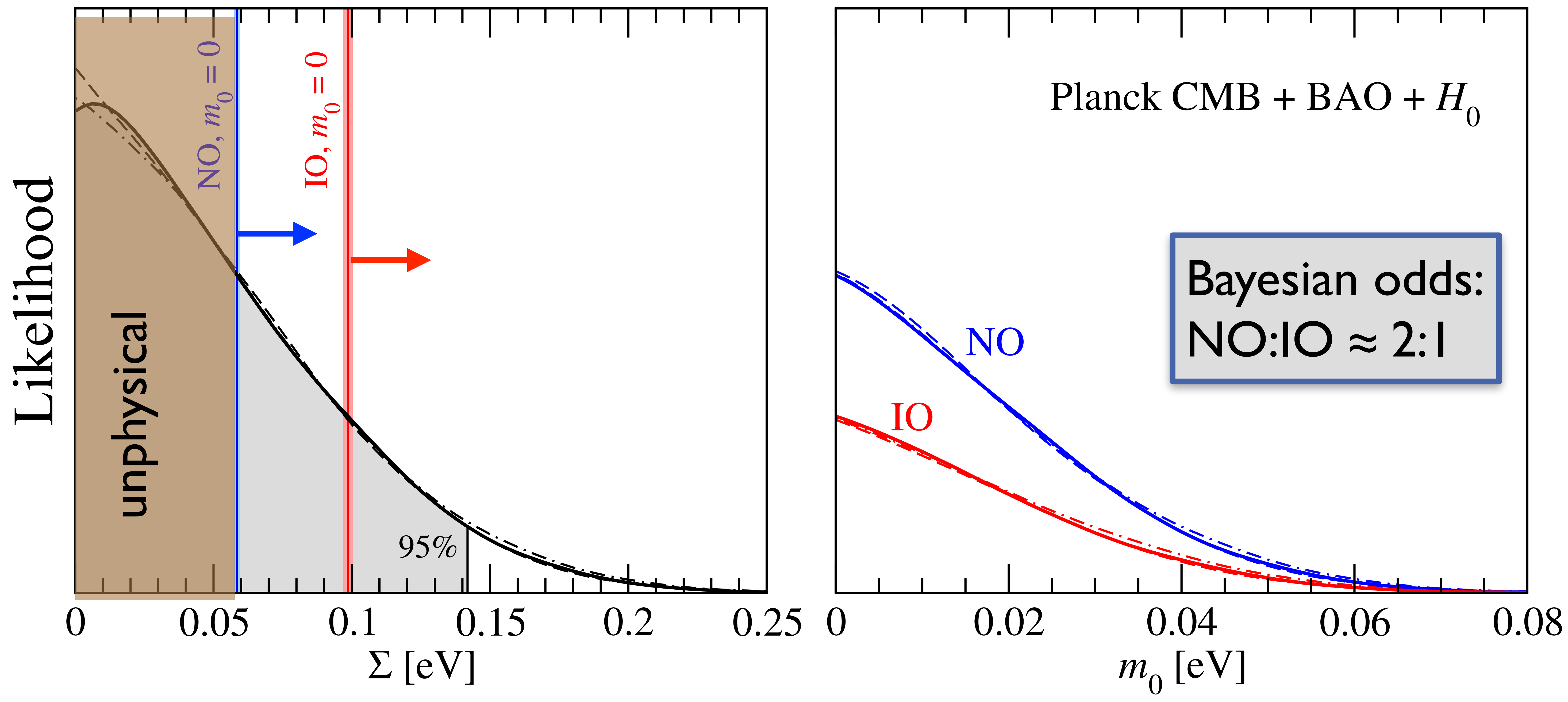
$$\Sigma_{\min} = \begin{cases} 98.6 \pm 0.85\,\mathrm{meV} & \text{(IO)} \\ 58.5 \pm 0.48\,\mathrm{meV} & \text{(NO)} \end{cases}$$

- **detection of non-zero neutrino mass expected soon!**
- **current limit close to IO minimum**



Excluding inverted ordering with cosmology?

Hannestad, Schwetz, 1606.04691



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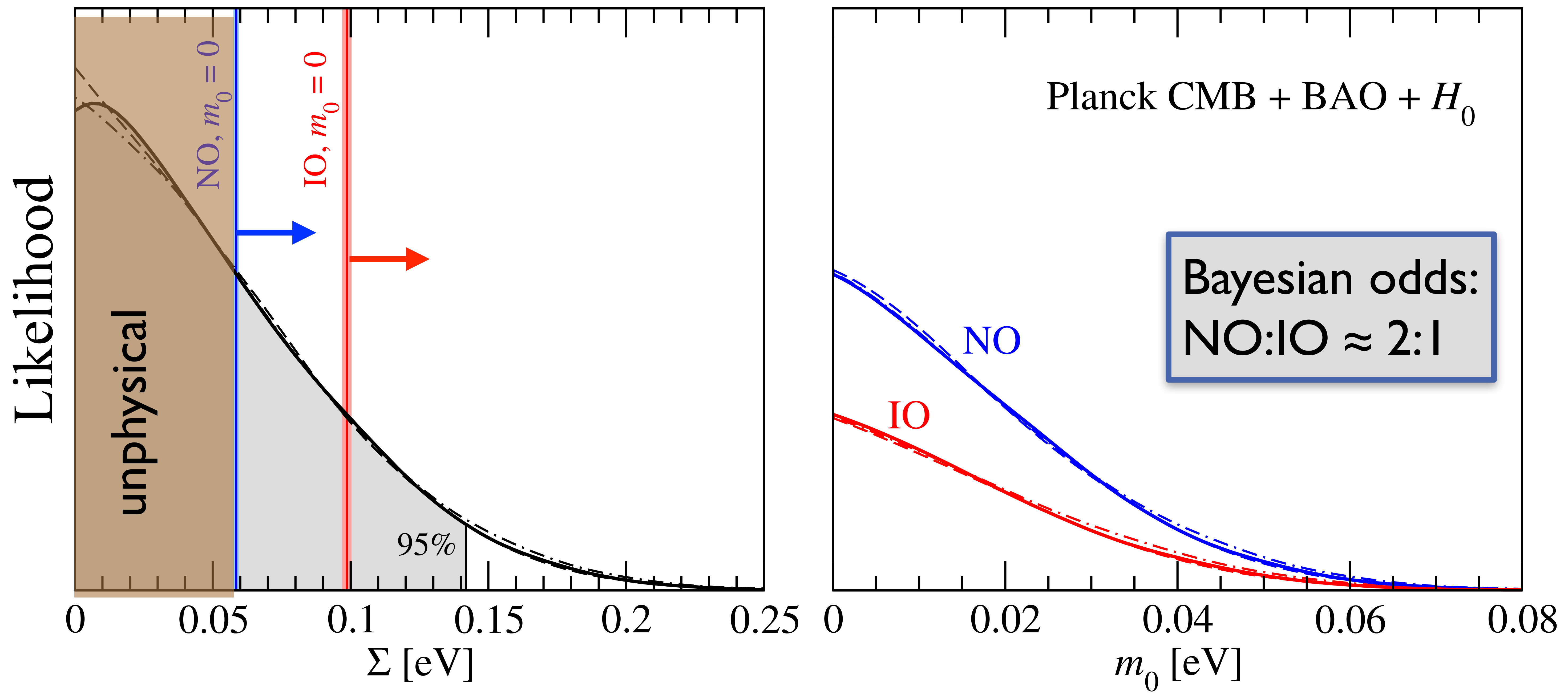
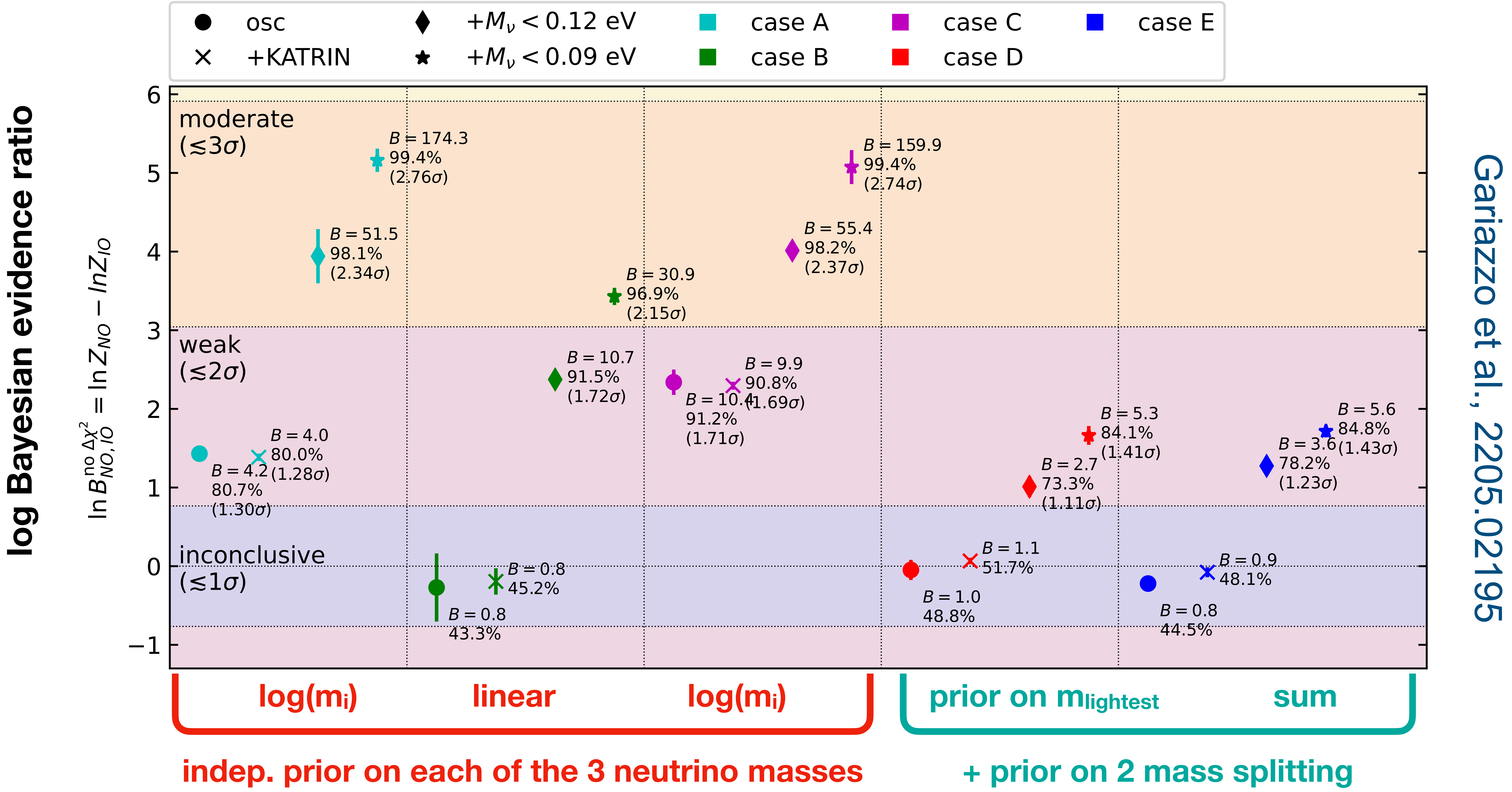
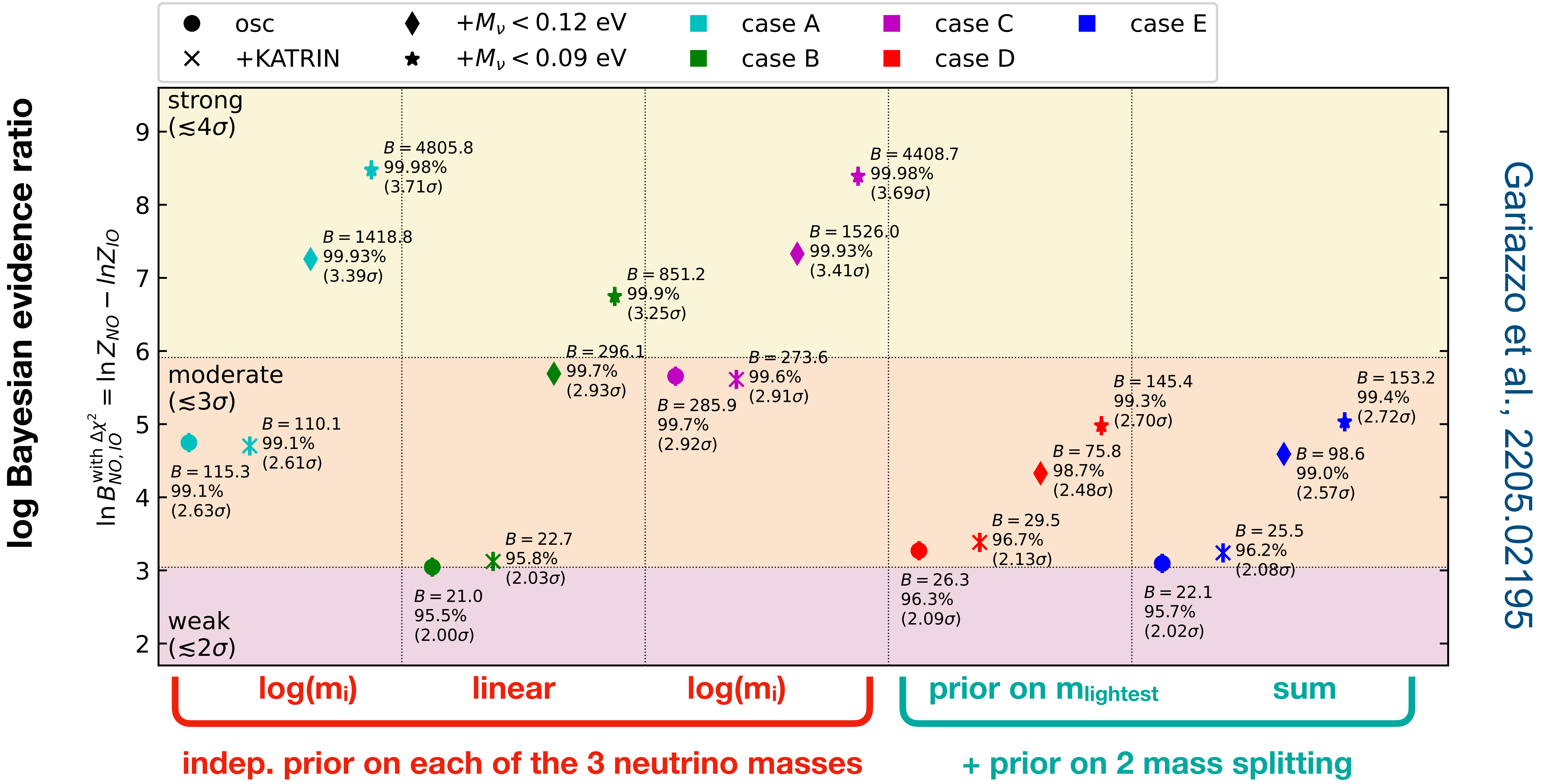


- **Strong Bayesian Evidence for the Normal Neutrino Hierarchy** Simpson et al., 1703.03425; Jimenez et al., 2203.14247
- **No conclusive evidence for normal ordering:** TS et al. 1703.04585; Vagnozzi et al., 1701.08172; Gariazzo et al., 1801.04946; Heavens, Sellentin, 1802.09450; deSalas et al., 1806.11051; Mahony et al., 1907.04331; Hannestad, Roy Choudhury, 1907.12598; Gariazzo et al., 2205.02195

Preference for normal ordering (w/o $\Delta\chi^2_{\mathrm{IO/NO}}$ from oscillation)

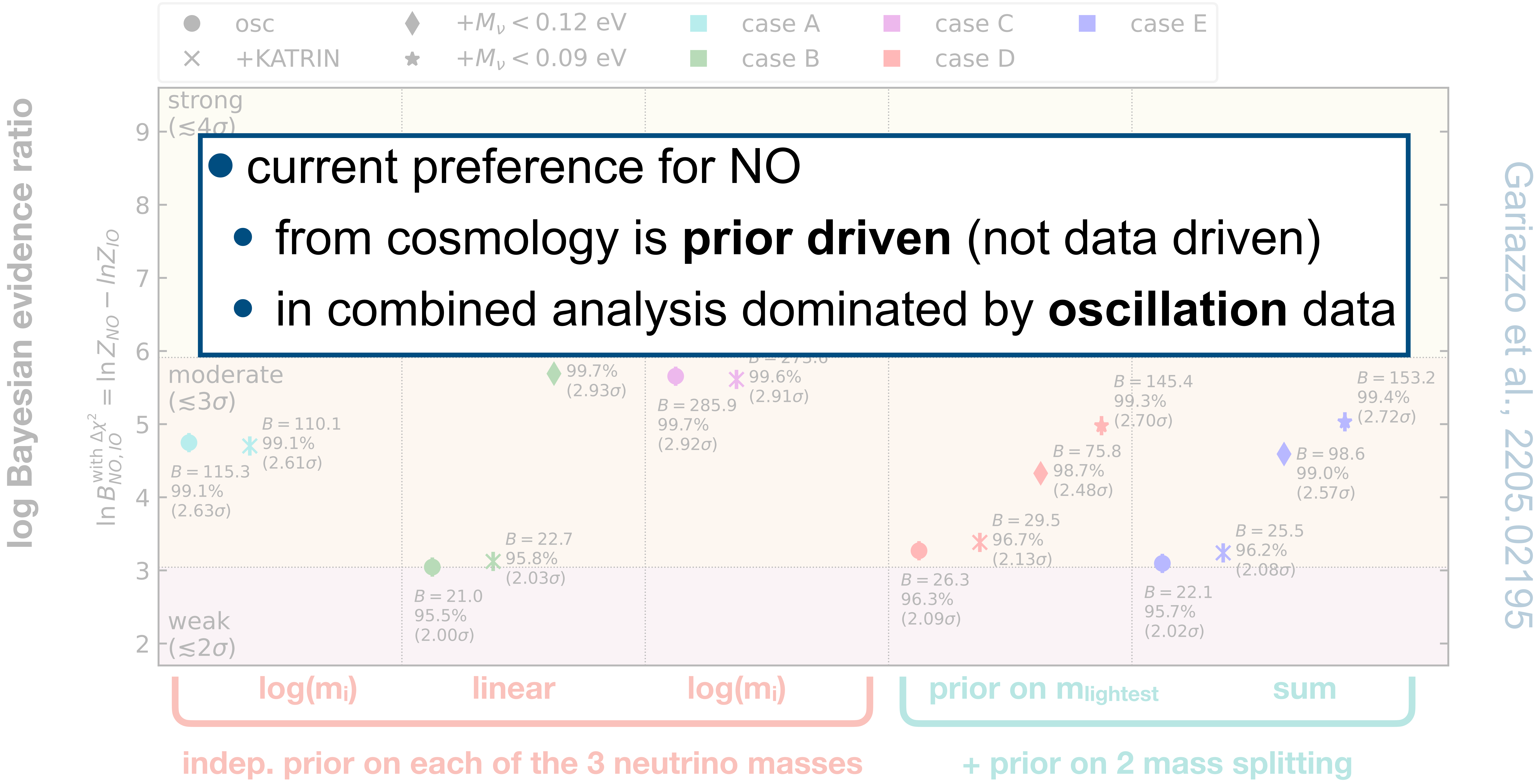


Preference for normal ordering (including $\Delta\chi^2_{IO/NO}$ from oscillation)



Preference for normal ordering (including $\Delta\chi^2_{\mathrm{IO/NO}}$ from oscillation)

- current preference for NO
  - from cosmology is **prior driven** (not data driven)
  - in combined analysis dominated by **oscillation** data



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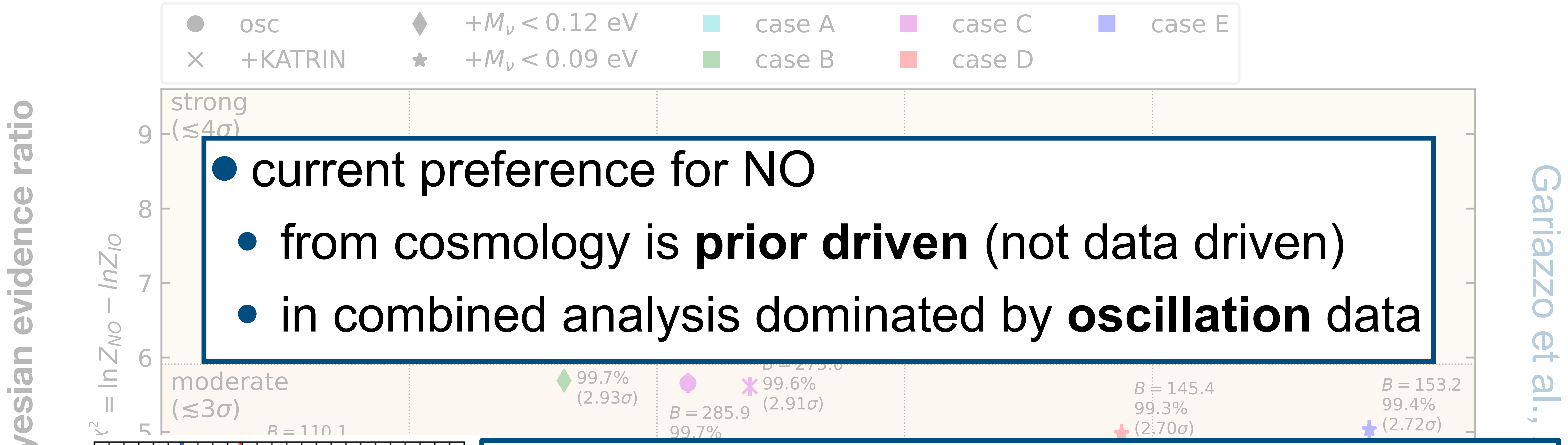

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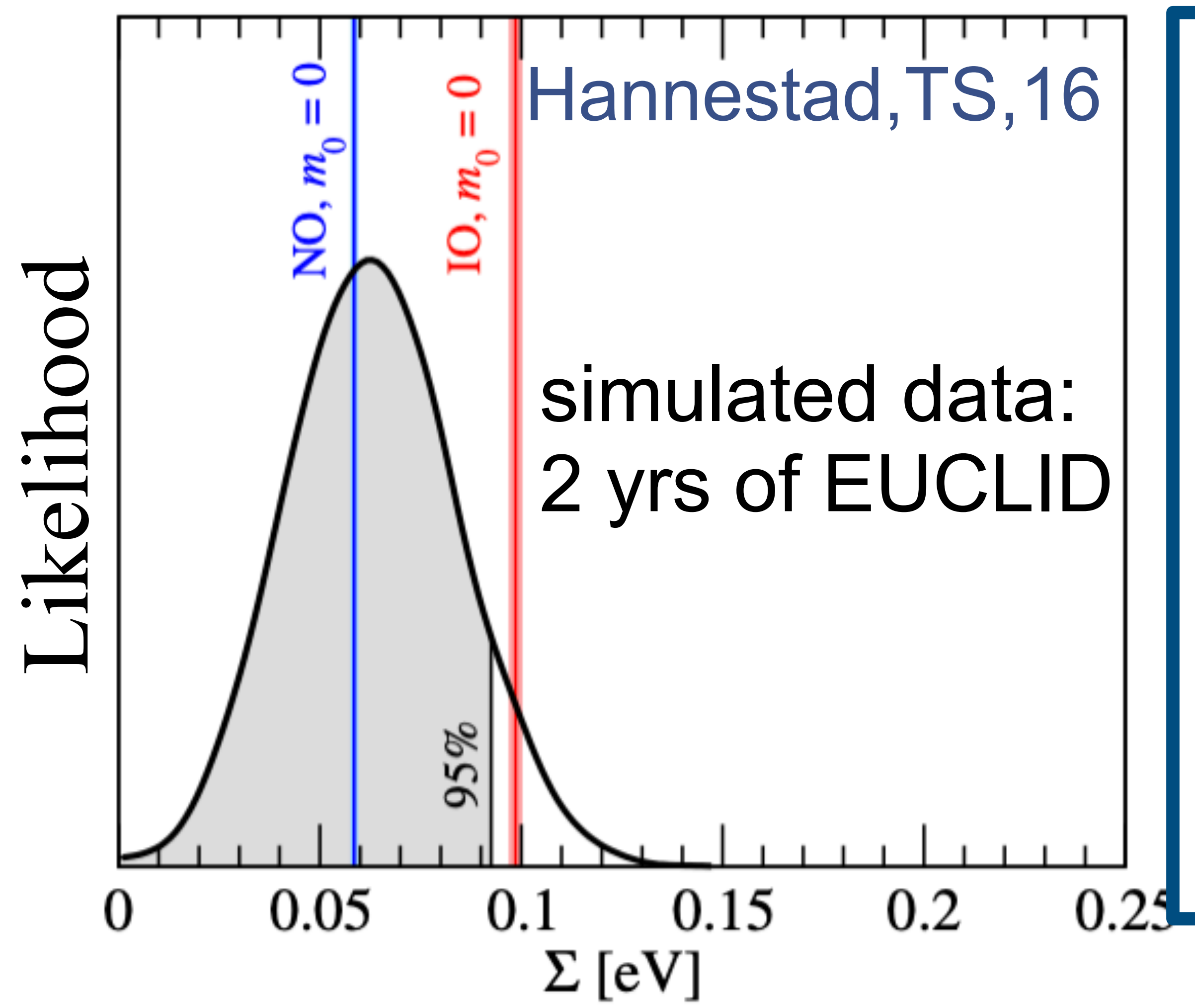


But cosmology may become powerful in the future:

- need **accuracy better than 0.02 eV** to exclude 0.1 eV against 0.06 eV at 2σ
- this would imply a **3σ evidence for non-zero neutrino mass** (for Σ = 0.06 eV)

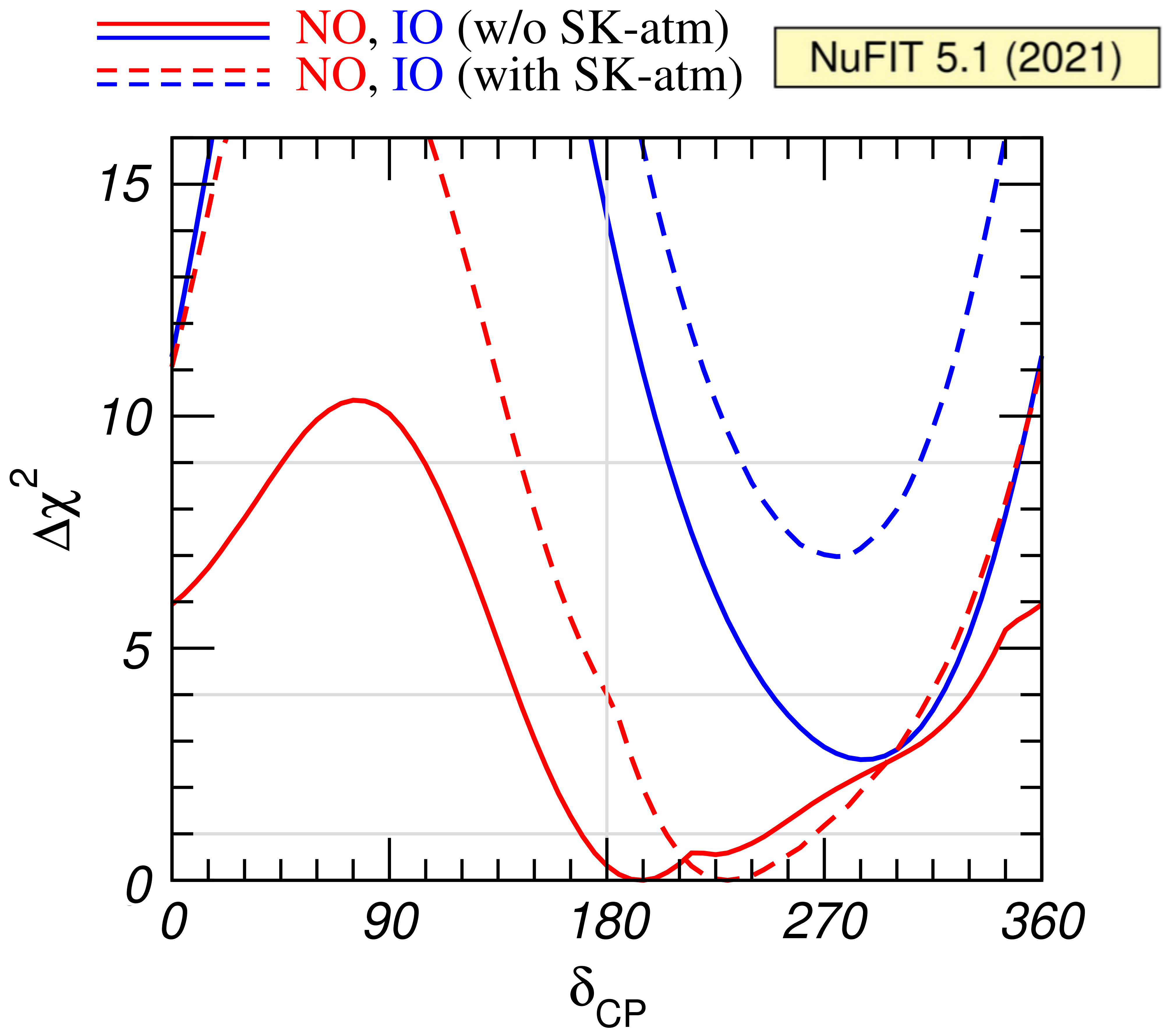
Comment on the search for CP violation

The „standard approach" is highly model dependent:

no model-indep. CPV observable → assume:

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

talk by P. Denton



perform a parametric fit of combined accelerator/reactor data

- determine allowed range for $\delta_{\rm CP}$
- CPV ⇔ excluding values of 0 and π for $\delta_{\rm CP}$

Model-independent test of T-violation

with Alejandro Segarra:
Phys. Rev. Lett. **128** (2022) 091801 [arXiv:2106.16099]
Phys. Rev. D **105** (2022) 055001 [arXiv:2112.08801]

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

Model-independent test of T-violation

A. Segarra, TS, 2106.16099

- general parameterisation of the transition probabilities:

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

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

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

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

T-even

T-odd

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

Model-independent test of T-violation

A. Segarra, TS, 2106.16099

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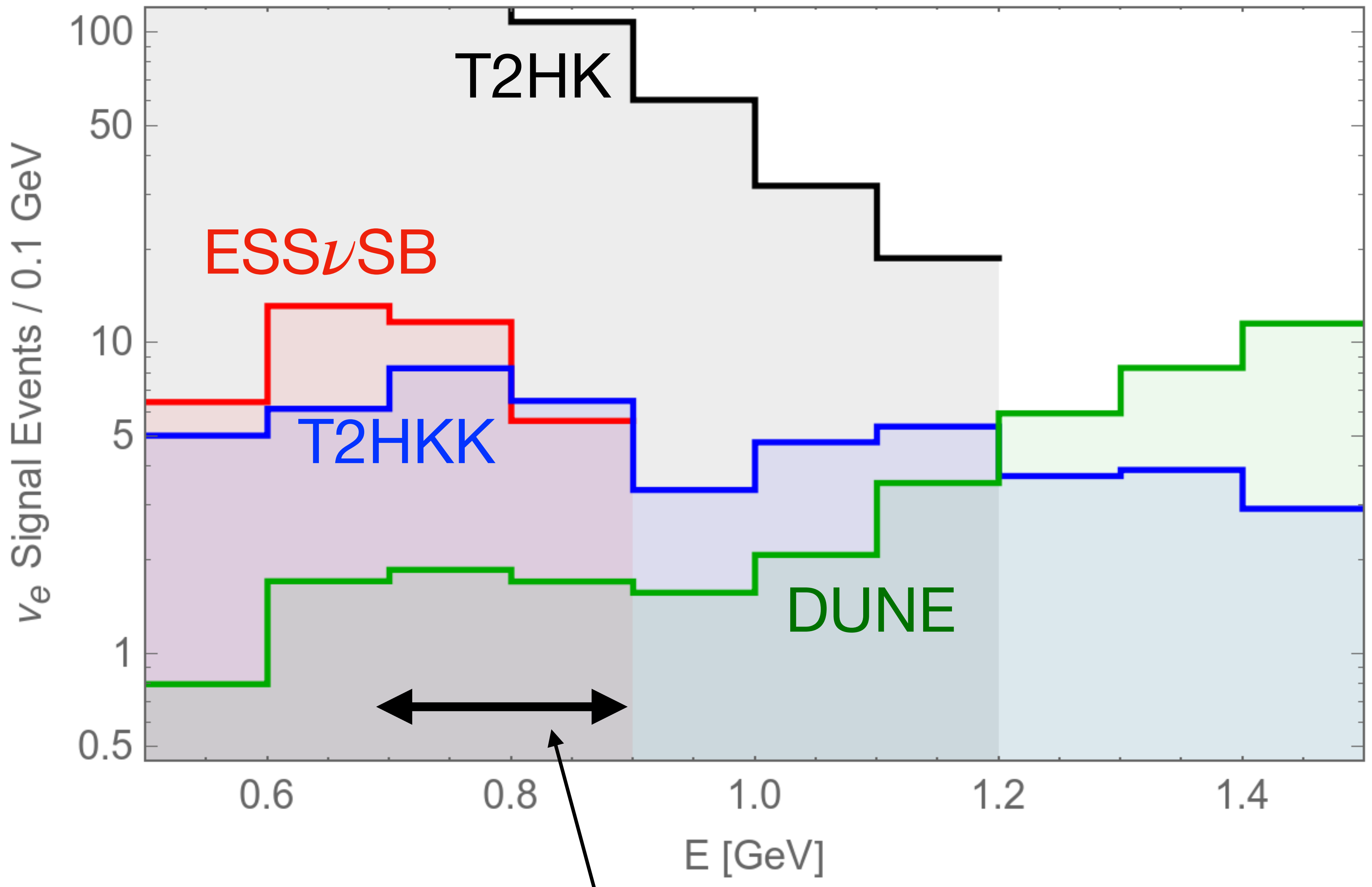
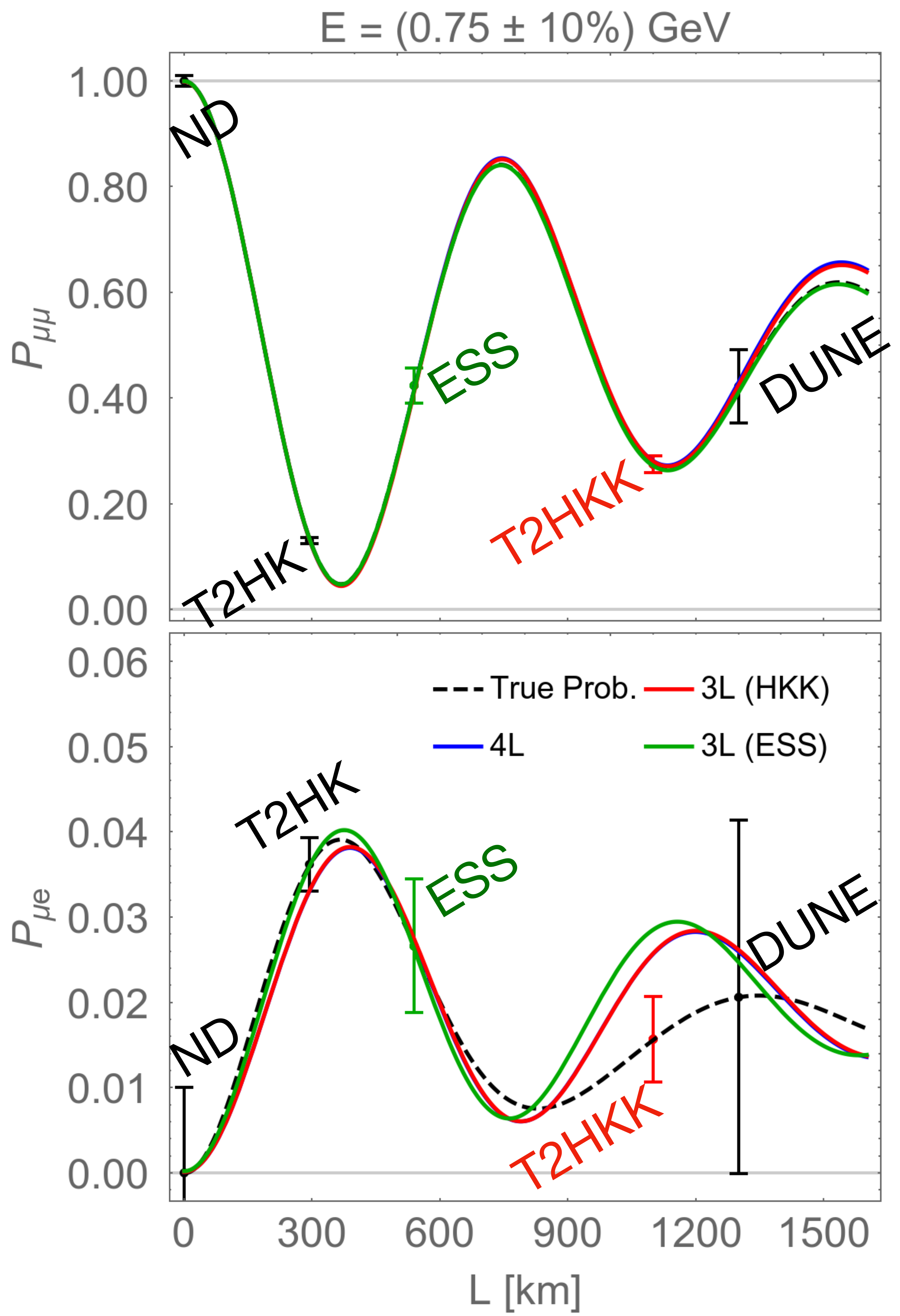
if data cannot be fitted only with the L-even part, fundamental T violation is established model-independently

Model-independent test of T-violation

Does it work in real life?



most sensitive energy interval



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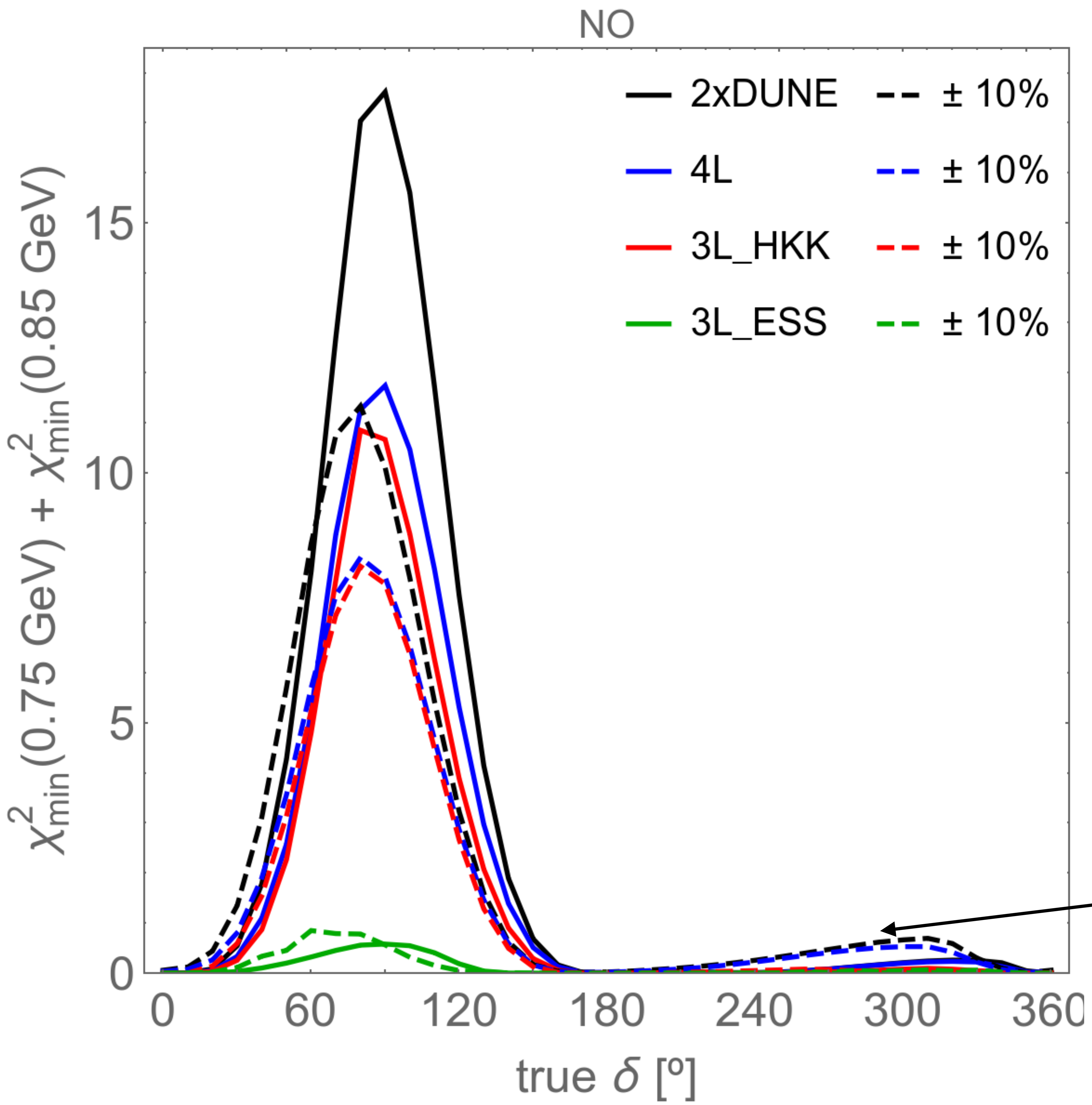

- $\sim 3\sigma$ sensitivity seems possible with DUNE & T2HK & T2KK
- good energy resolution crucial
- uses low-energy tail of DUNE
- detector in Korea needed to cover 2nd osc. max.
- $\delta_{CP} \sim 270°$ can be tested with antineutrino data (not shown)

Summary

- great progress in 3-flavour oscillation parameters
- hint for CP violation below 2σ
- slight preference for normal ordering from oscillations ($\Delta\chi^2_{\rm IO/NO} \approx 7$)

- cosmology sensitivity to neutrino mass very exciting
- current cosmo preference for normal ordering is strongly prior dependent
  (for ordering-agnostic prior the preference is dominated by oscillation data)

- propose model-independent test for T-violation
  combining data from 3 LBL experiments at the same energy
- requires detector at 2nd osc. max. (T2KK), good energy resolution,
  low-energy tail of beam in DUNE

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Thank you for your attention!