Global Fits of Neutrino Oscillation Parameters

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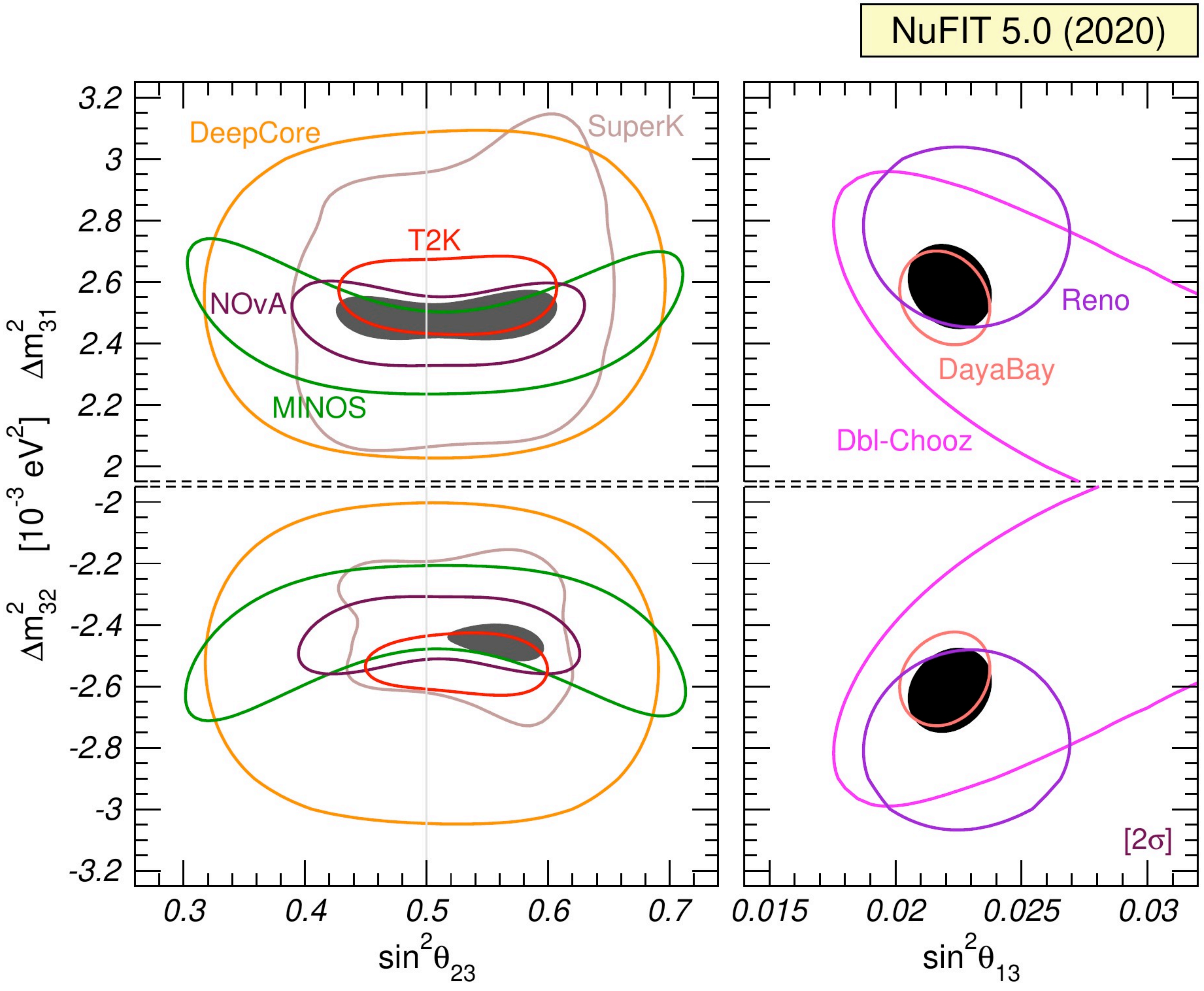
Outline

- Results from global 3-flavour oscillation fit (NuFit 5.0)
  - interplay of accelerator / reactor / atmospheric neutrinos for neutrino mass ordering and CP phase

- Search for deviations from the 3-flavour paradigm
  - light sterile neutrinos
  - nonstandard neutrino interactions

Three flavour oscillation parameters

- 6 neutrino oscillation params:
  $\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$
- complementarity between different experiments → consistency checks
- global analysis:
  NuFit collab.: www.nu-fit.org
  Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, 2007.14792



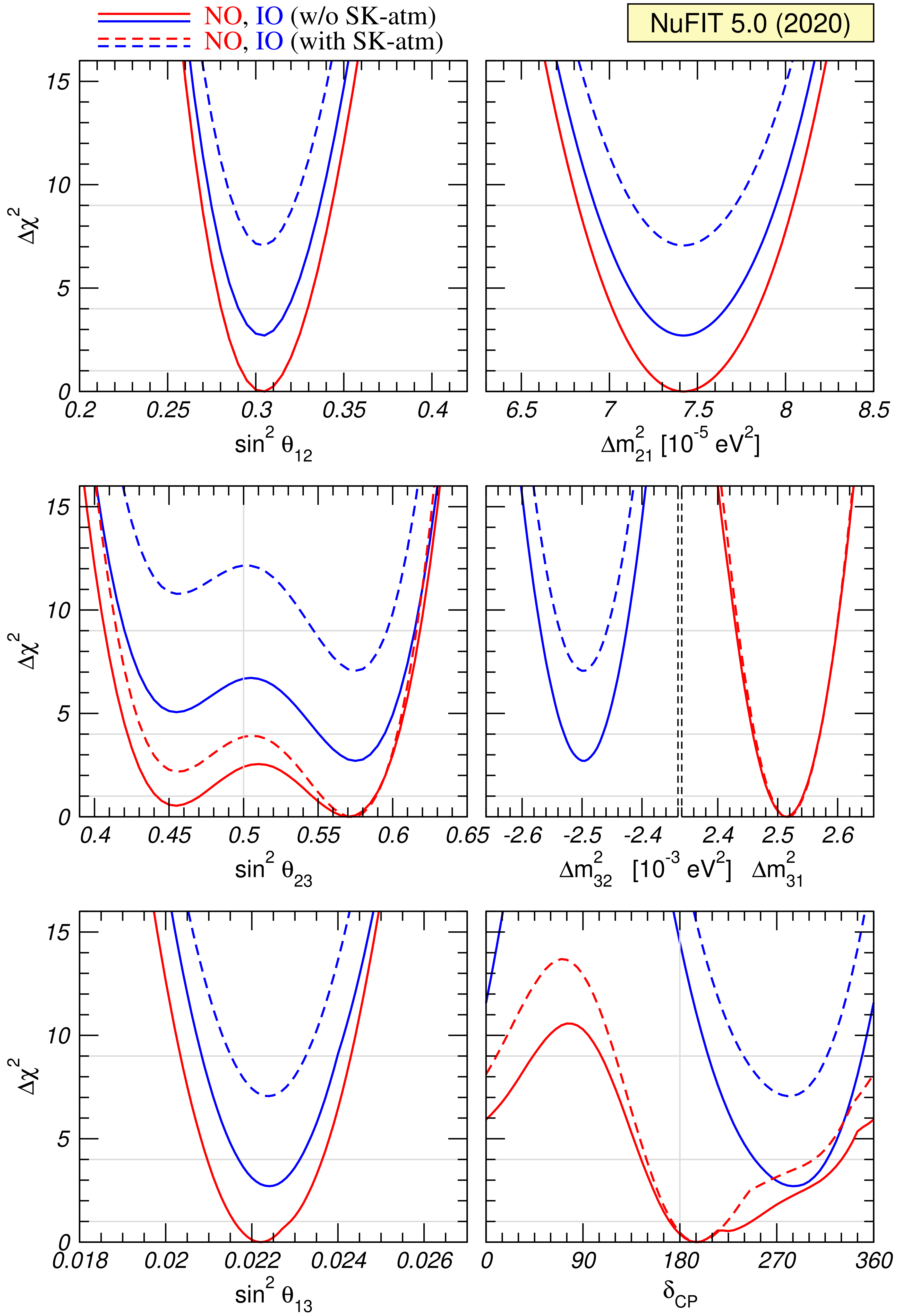
see also for comparable results:
Bari: e.g. Capozzi et al., 2107.00532
Valencia: e.g. deSalas et al., 2006.11237

Three flavour oscillation parameters

global analysis **NuFIT 5.0 results** www.nu-fit.org

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

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$



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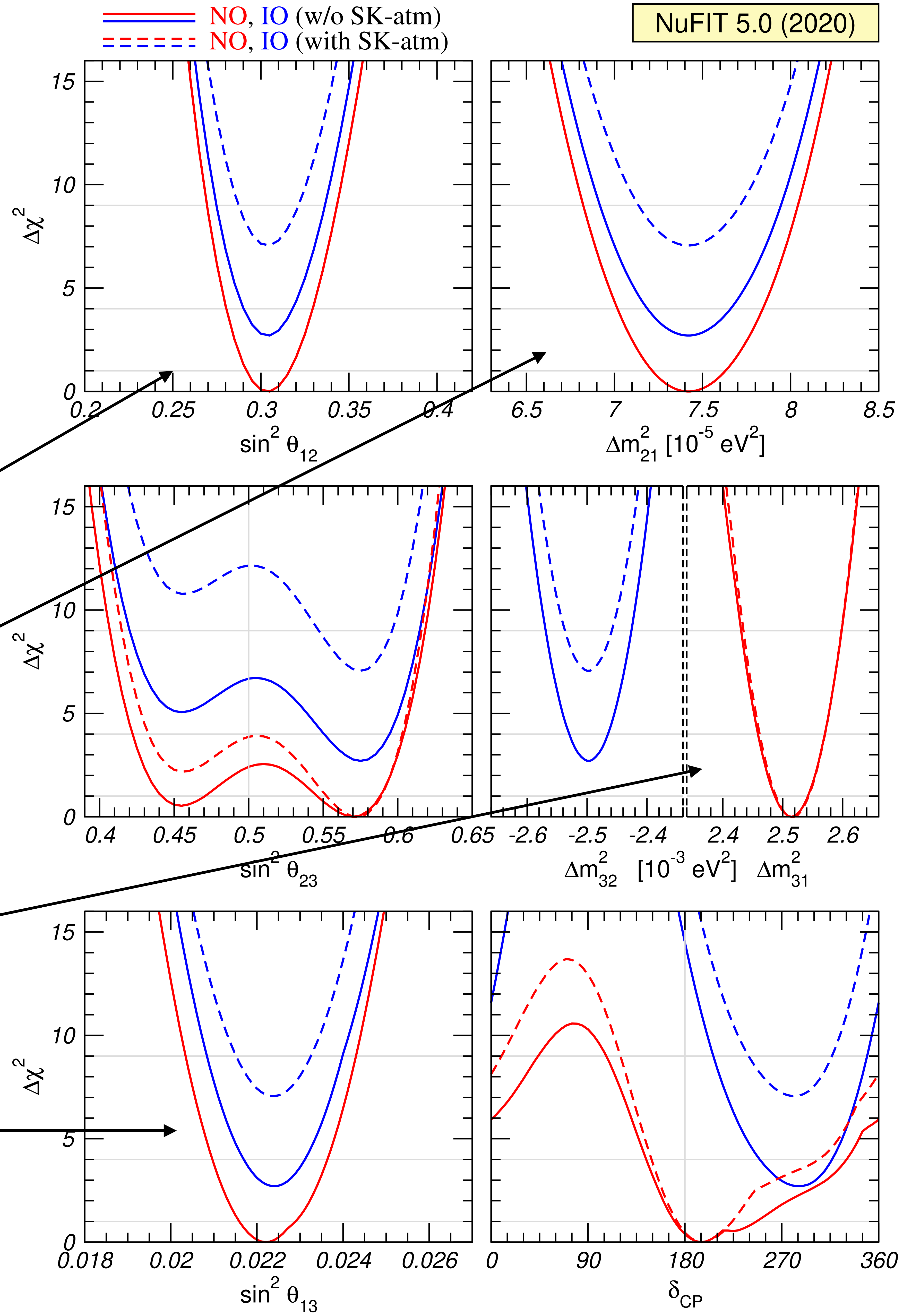
Four well-known parameters

NuFIT 5.0 results www.nu-fit.org

- robust determination
  (relat. precision at 3σ)

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



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Four well-known parameters

NuFIT 5.0 results www.nu-fit.org

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

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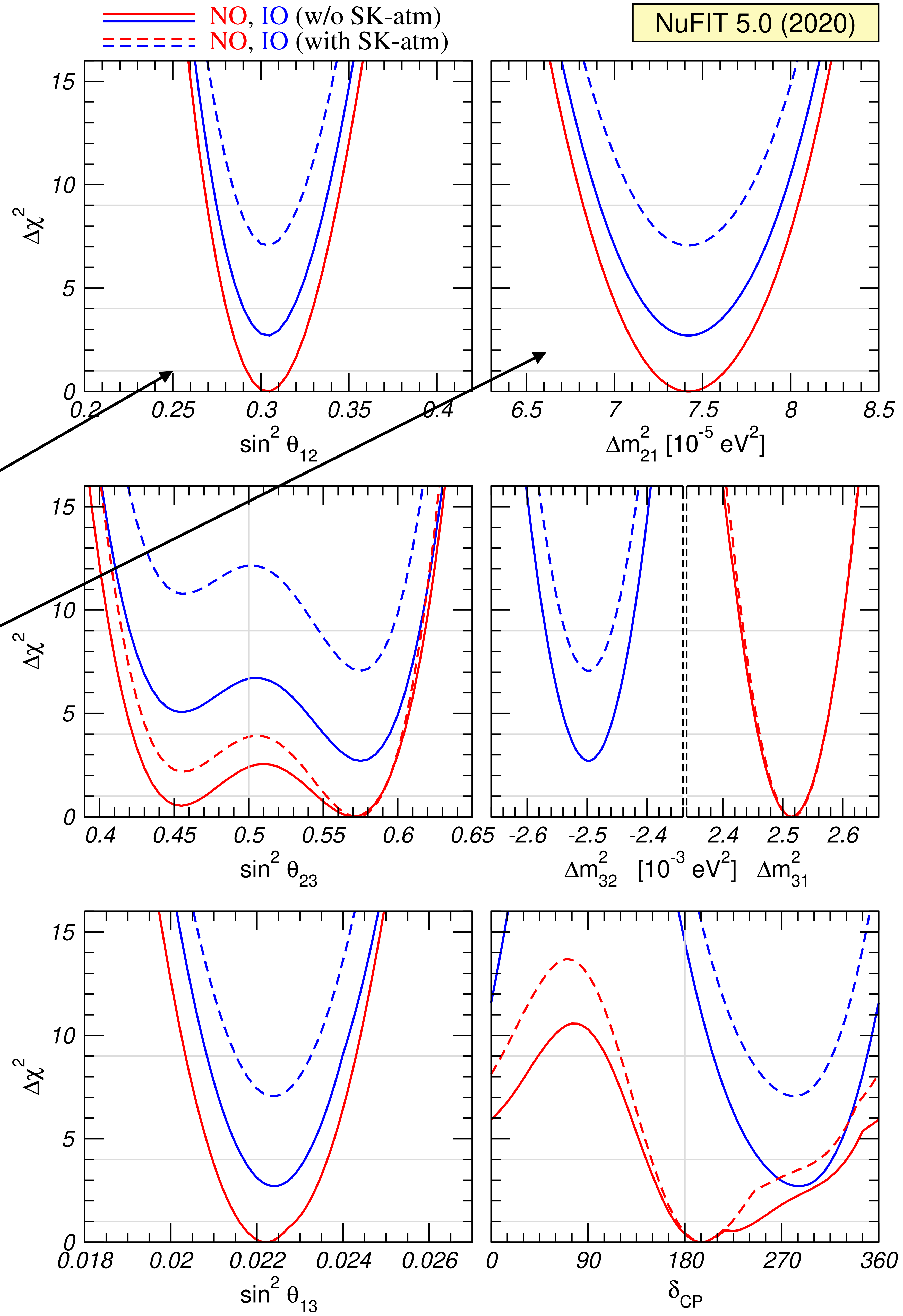
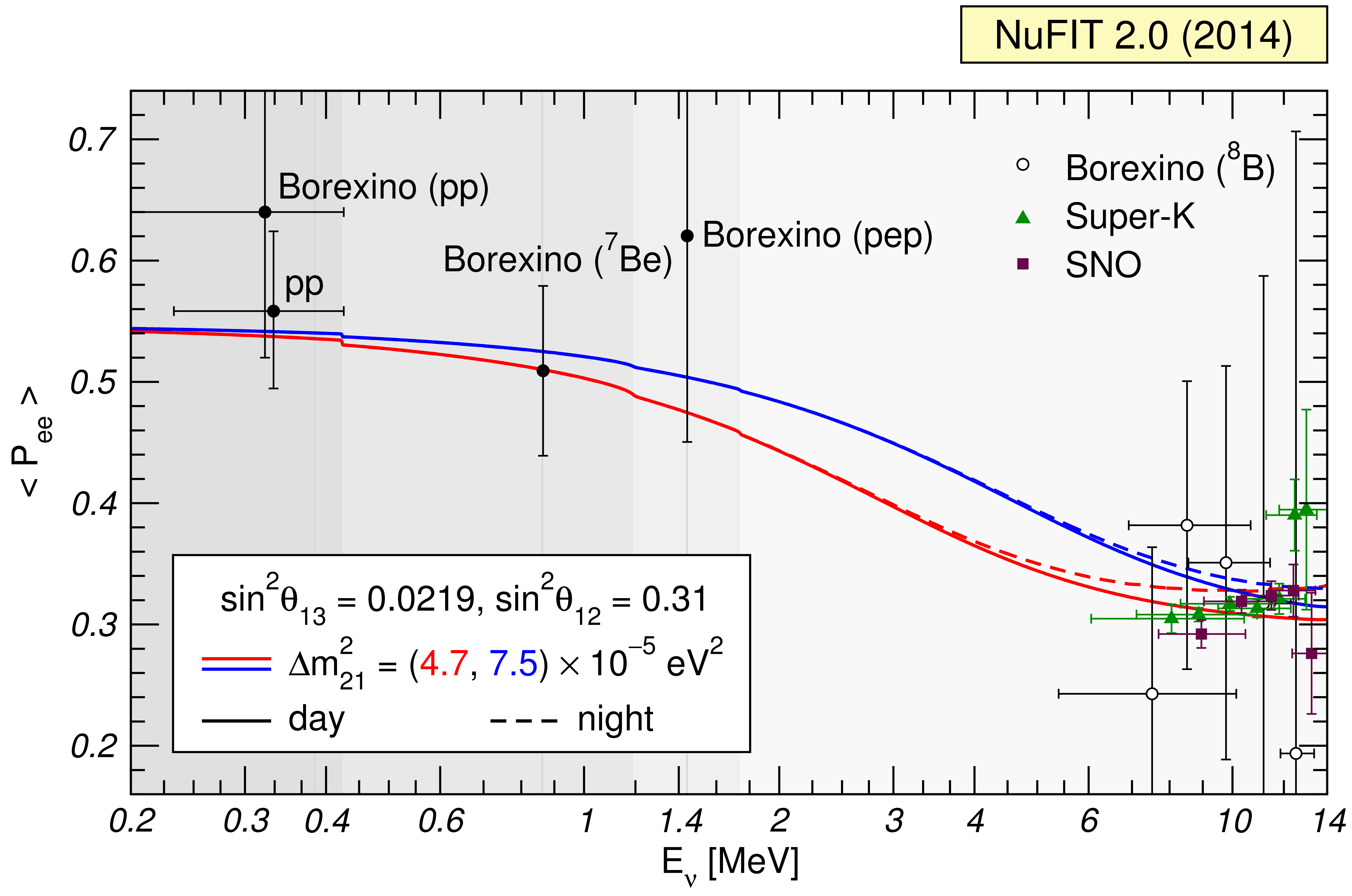
$$\Delta m^2_{21} \qquad (16\%)$$

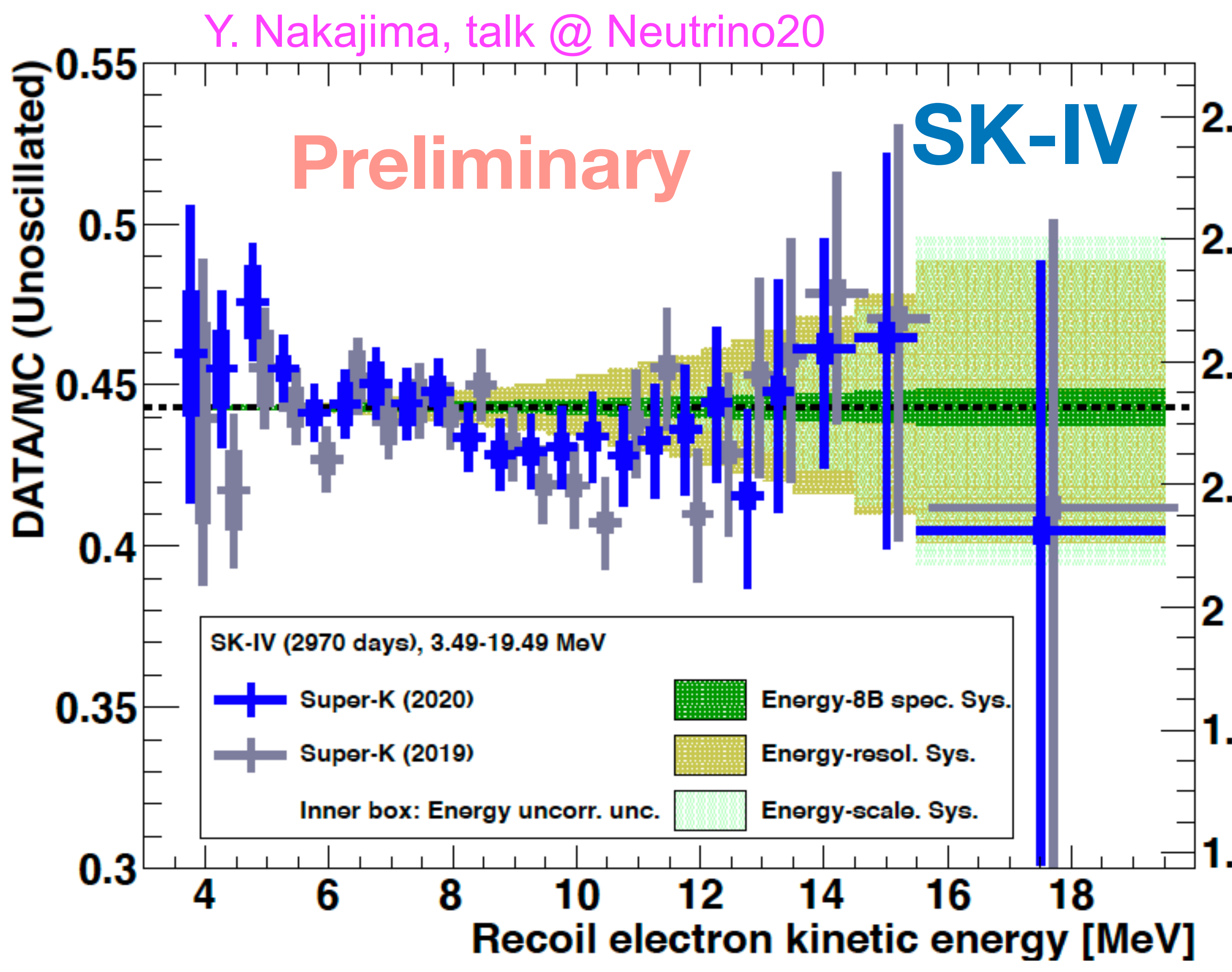


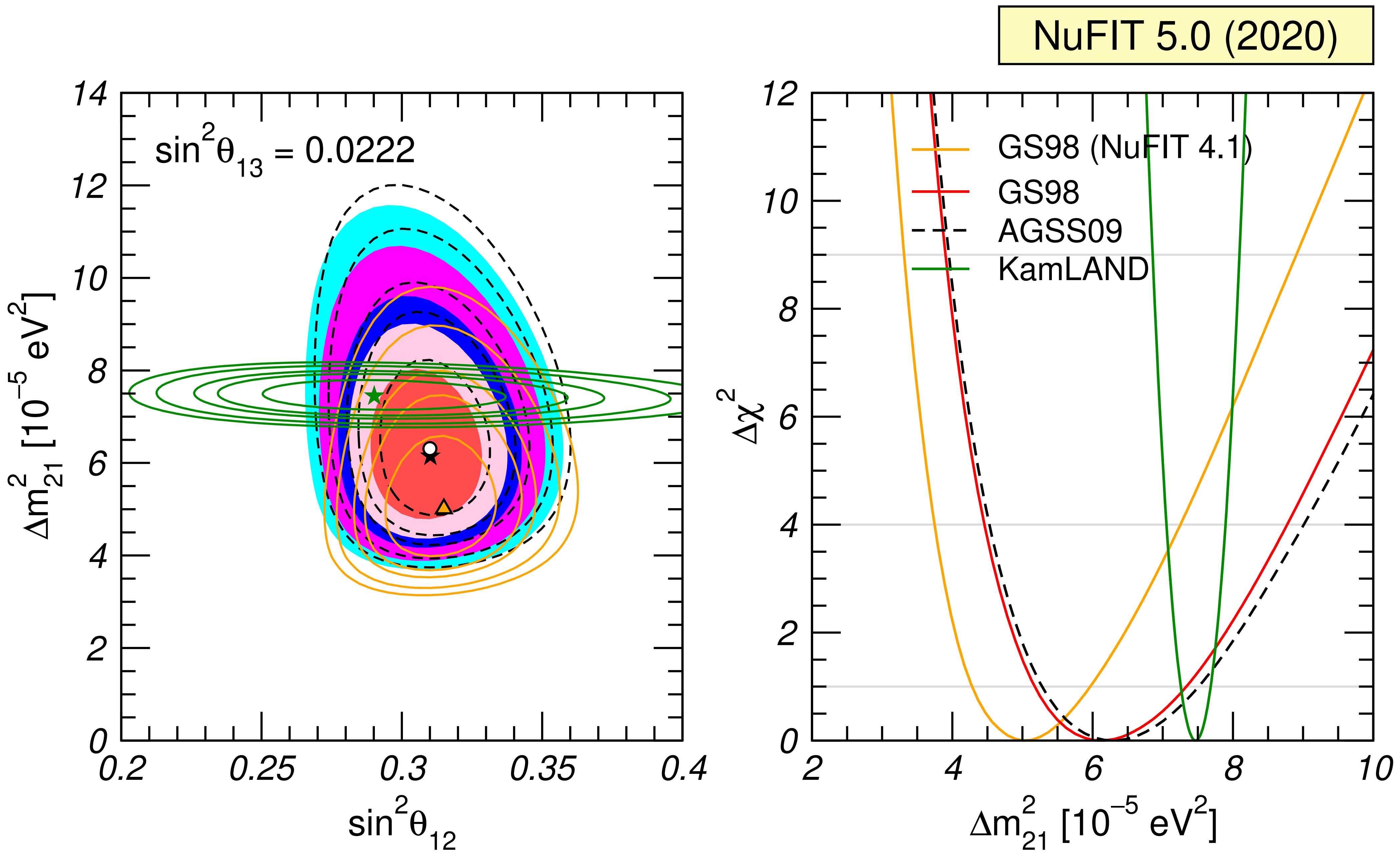
Long-standing tension between Δm² from KamLAND and solar neutrinos (2σ):



- missing up-turn of high-energy solar neutrino spectrum
- too large day-night effect

Long-standing tension between Δm² from KamLAND and solar neutrinos (2σ): resolved!

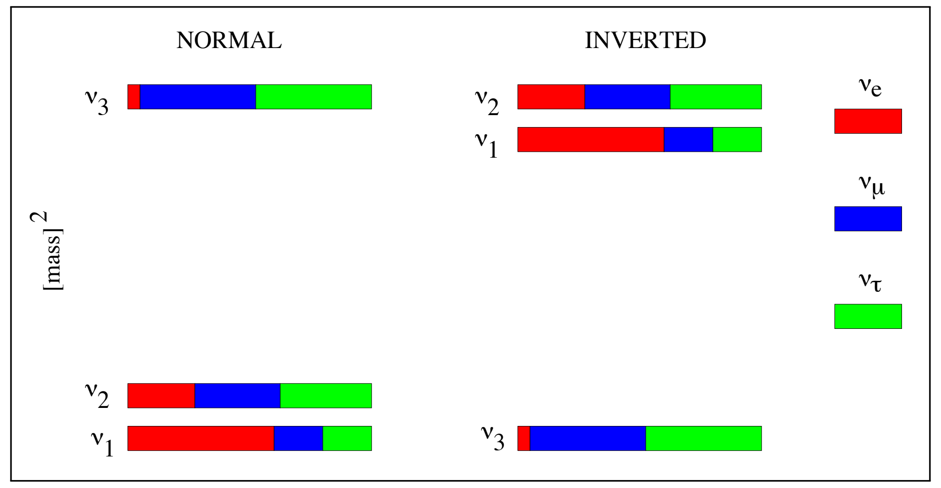




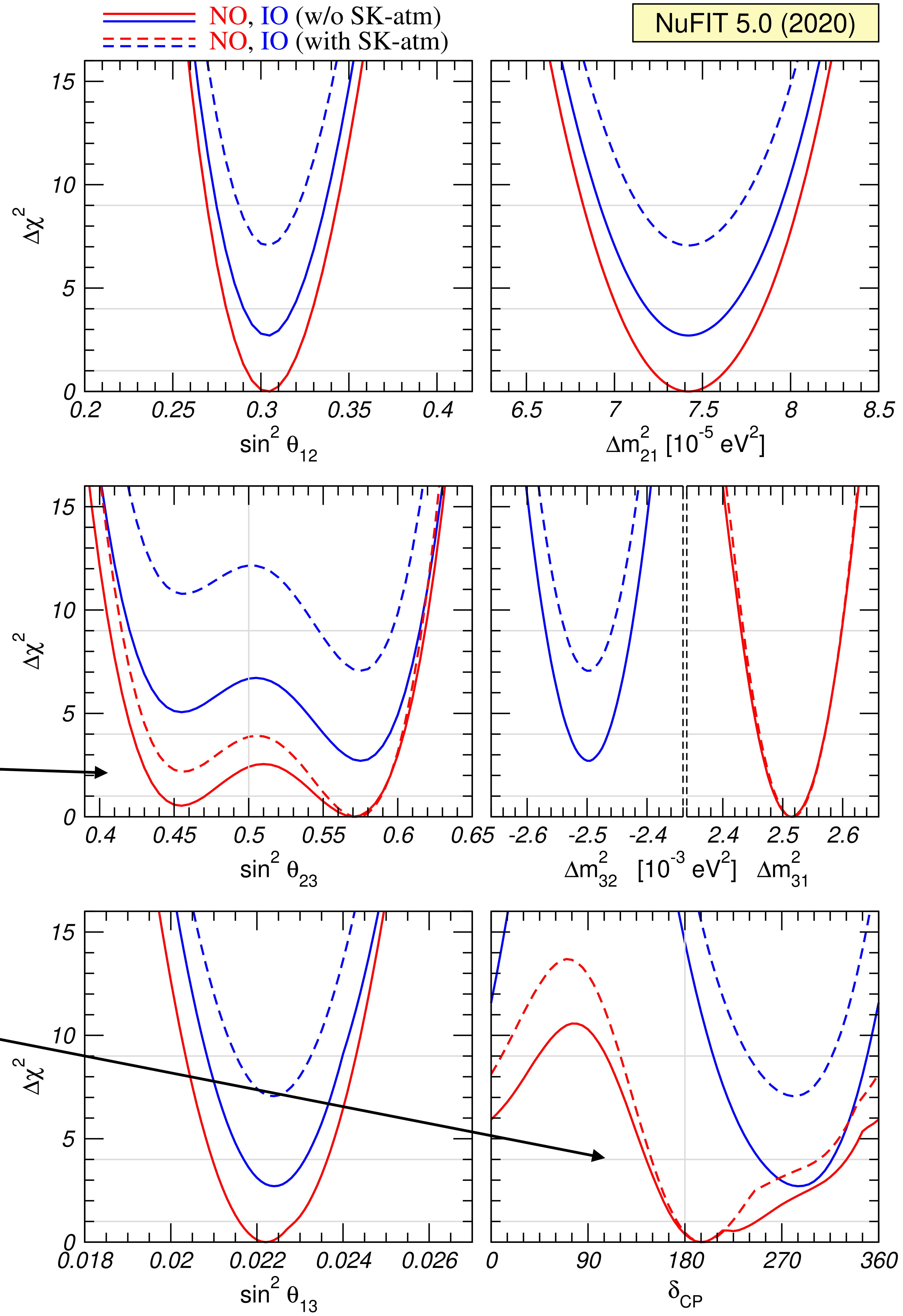
- new SuperK solar neutrino data @ Neutrino20:
  - spectrum better compatible with KamLAND prediction
  - day/night asym.: $A_{DN}^{Fit} = (-3.6 \pm 1.6(stat) \pm 0.6(syst))\,\%$ → $A_{DN}^{Fit} = (-2.1 \pm 1.1)\,\%$
- solar neutrino and KamLAND data compatible at 1.1σ

The unknowns:

- neutrino mass ordering (red vs blue curves)



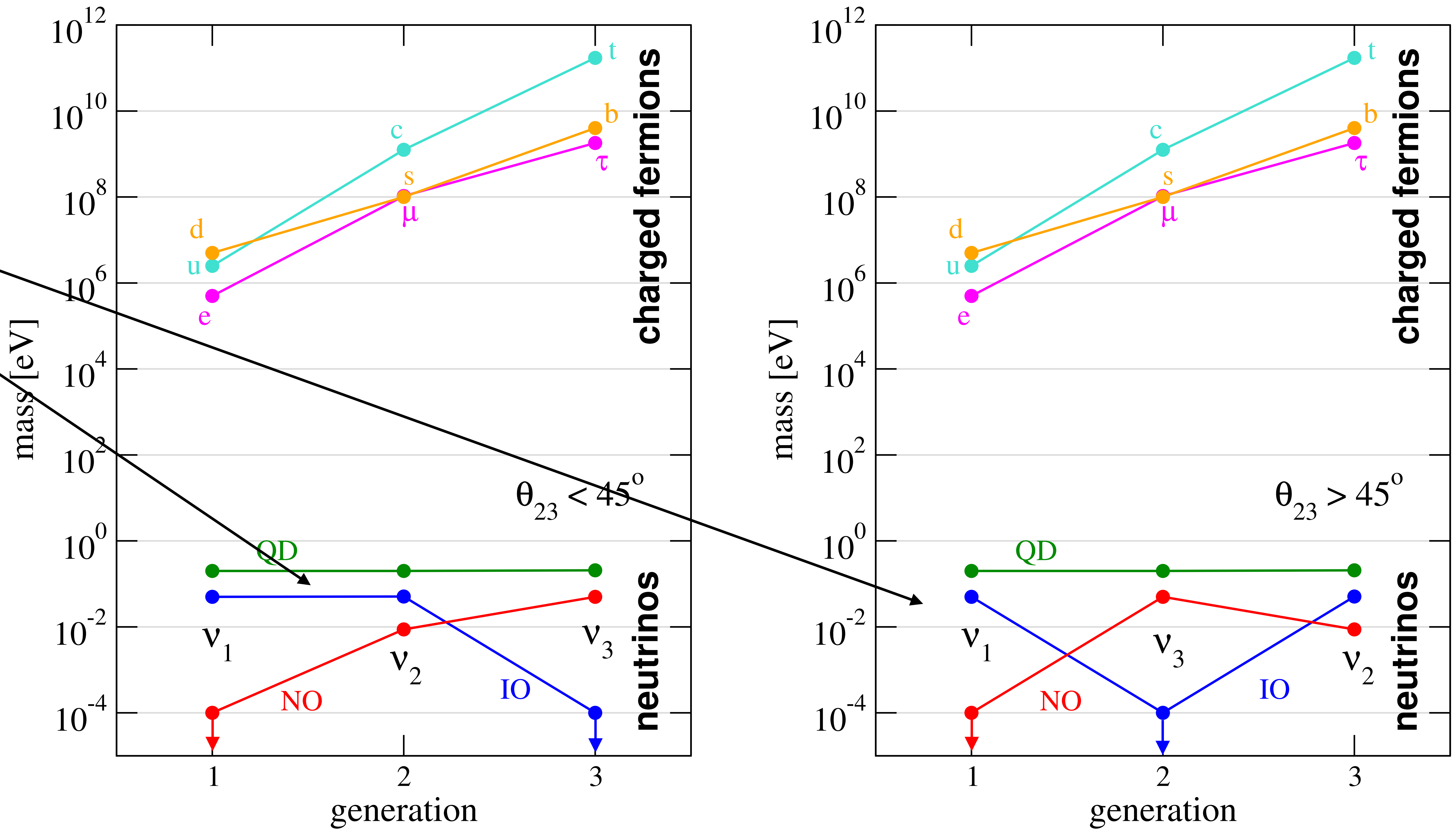
- octant of θ_{23}
- status of leptonic CP violation



Mass ordering and θ_{23}-octant:

- which of these options are realised in Nature?

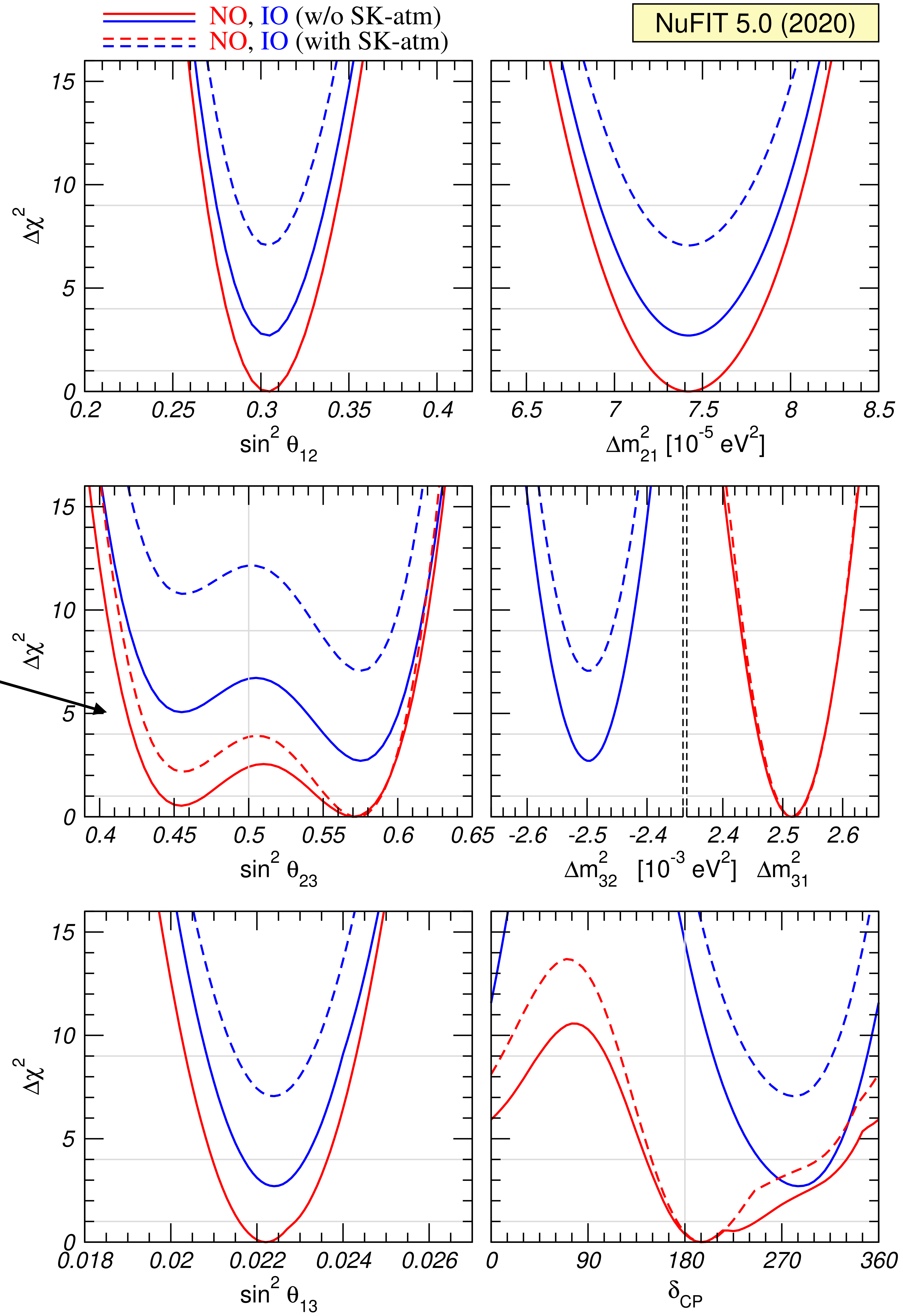
IO and/or 2nd octant would imply a neutrino mass spectrum very different from charged fermions



The least known mixing angle

NuFIT 5.0 results www.nu-fit.org

- broad allowed range for θ_{23} (24%)
- ambiguity in the octant
  - fragile with respect to atmospheric neutrino analysis



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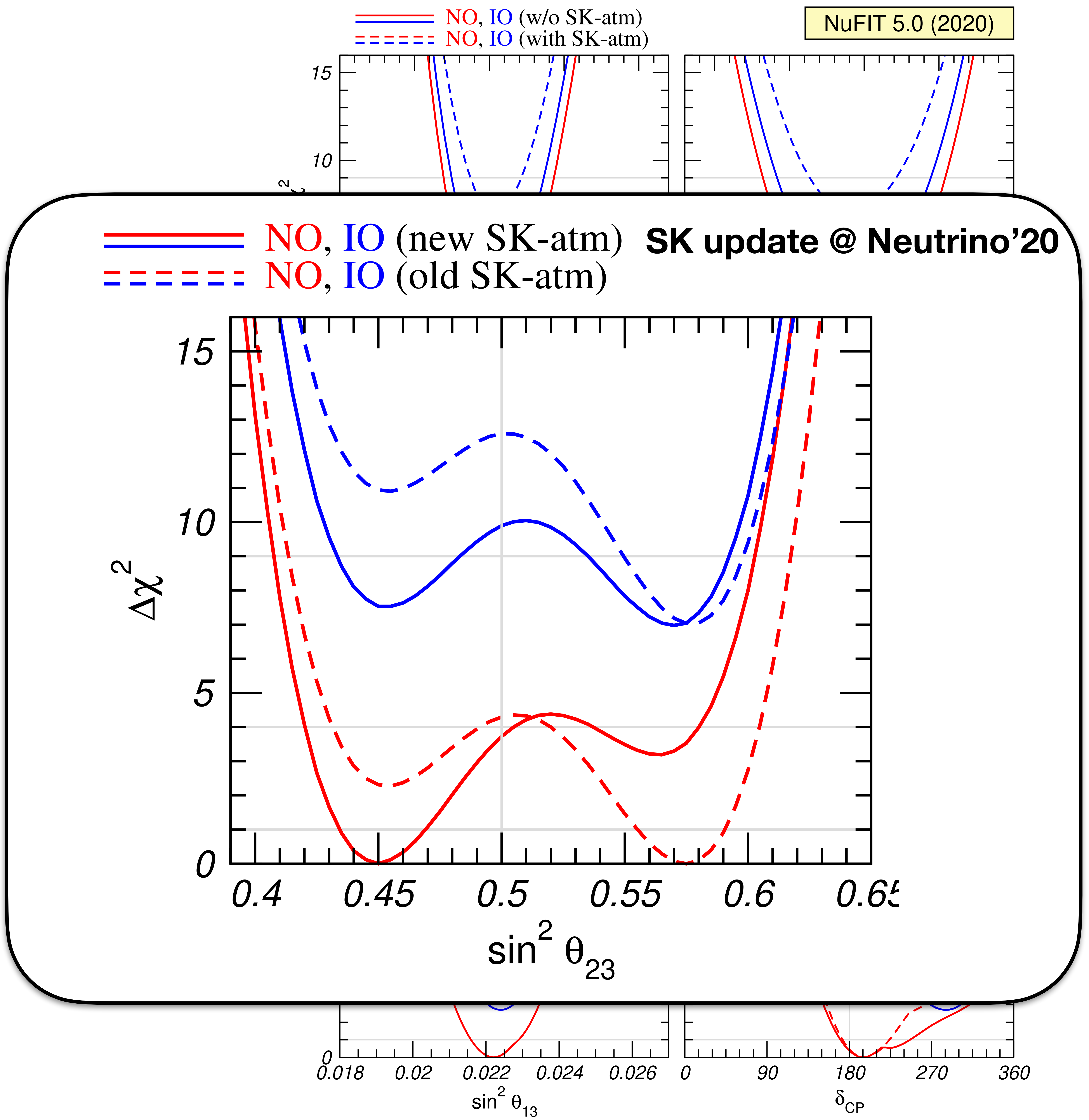
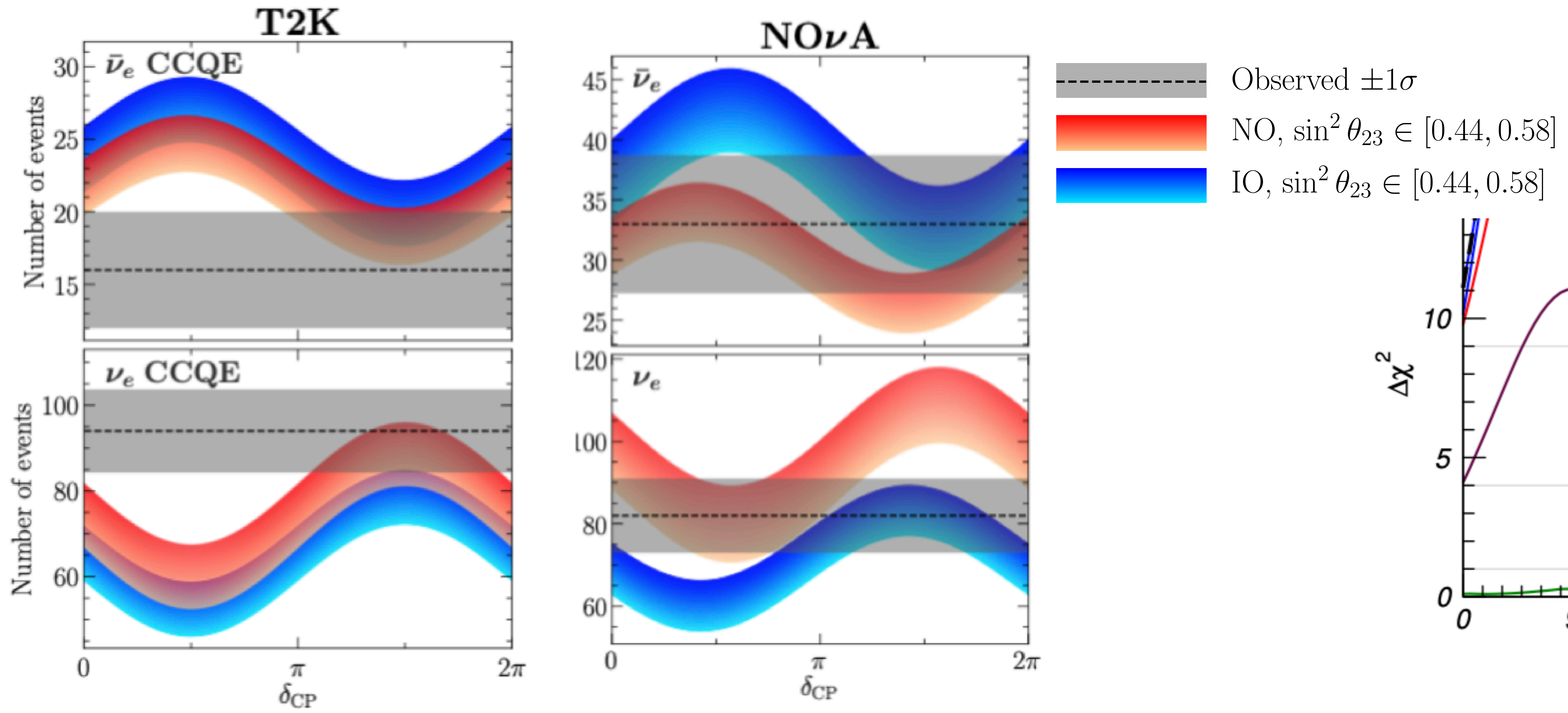
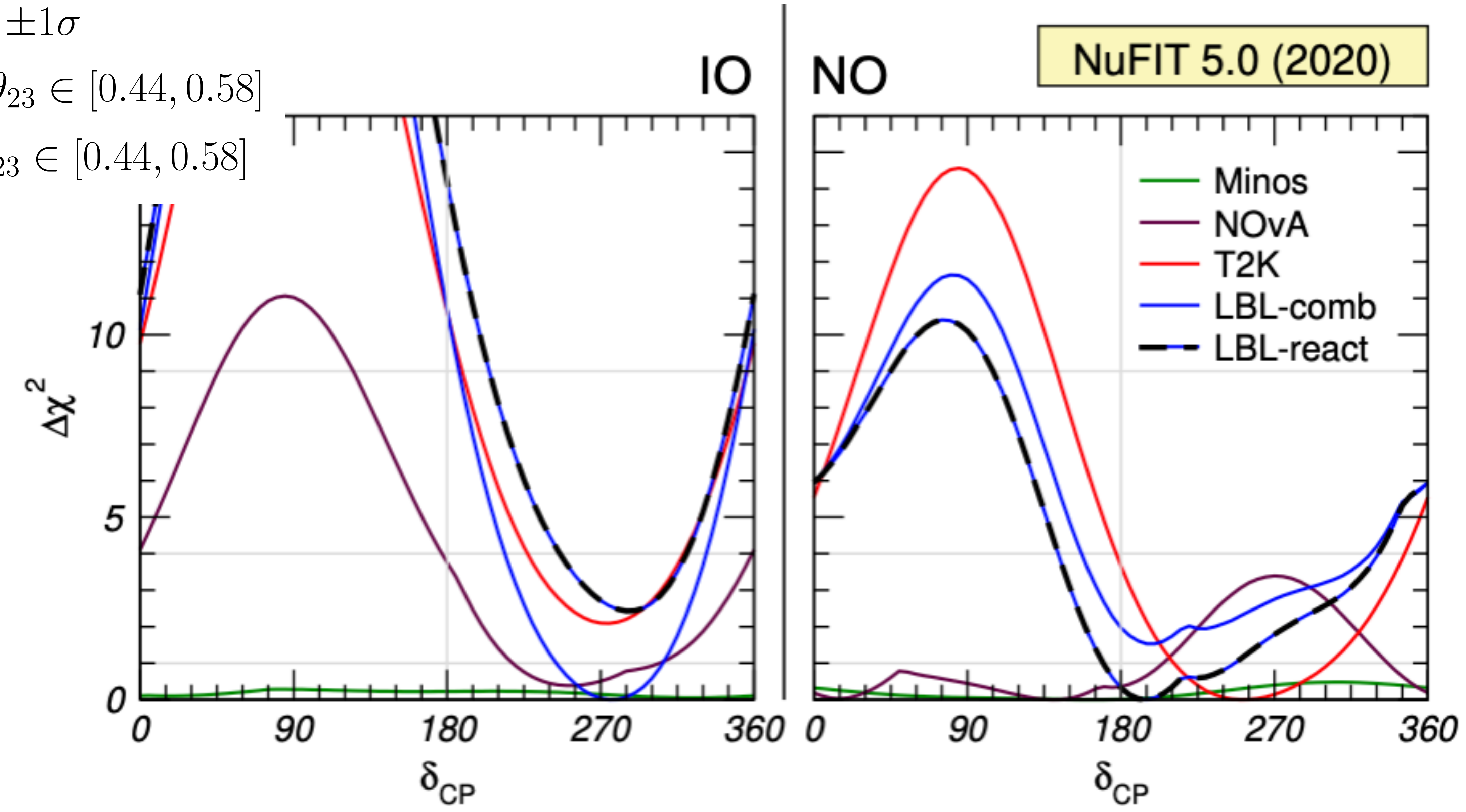


Mass ordering and CP phase: LBL accelerator & reactor data





- T2K and NOvA better compatible for IO → LBL combination best fit for IO

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T2K and NOvA are statistically consistent for both orderings

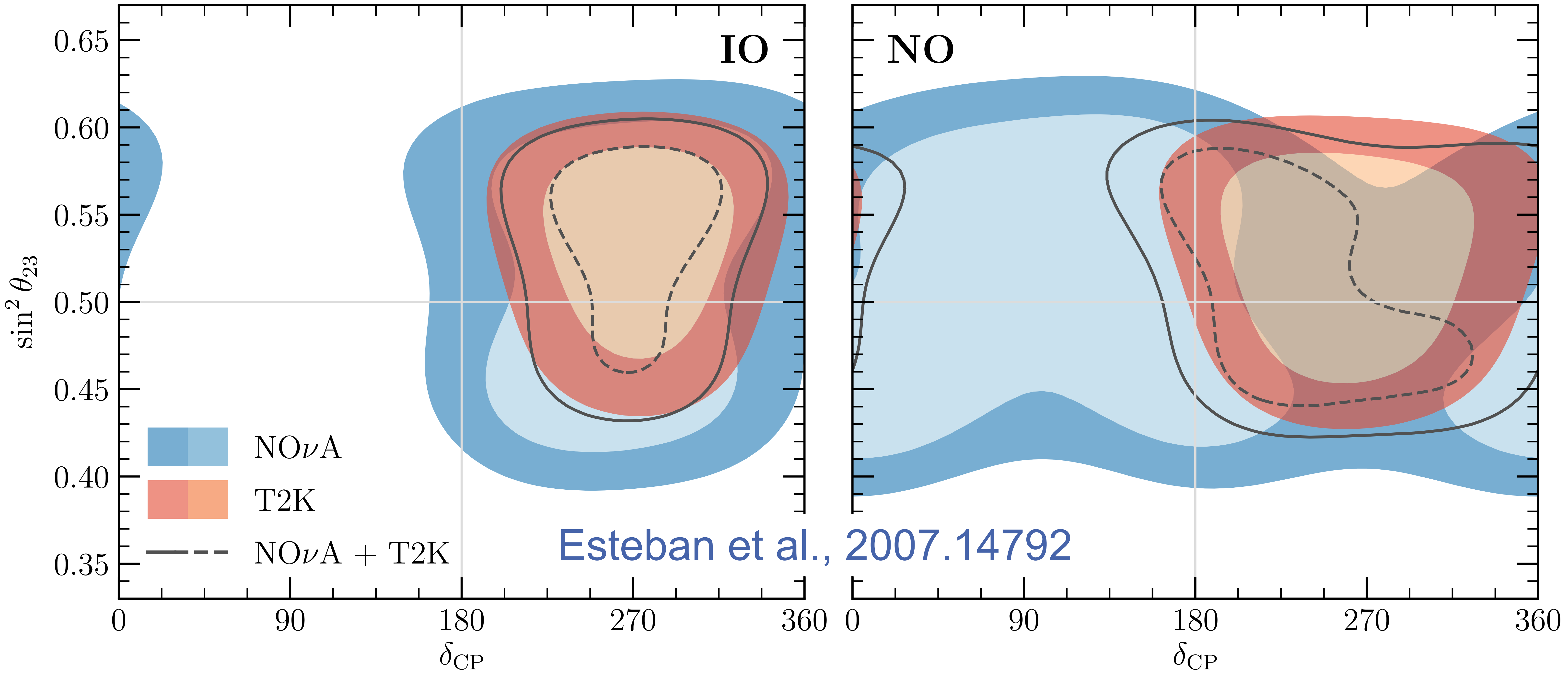

Figure 3. 1σ and 2σ allowed regions (2 dof) for T2K (red shading), NOvA (blue shading) and their combination (black curves). Contours are defined with respect to the local minimum for IO (left) or NO (right). We are fixing $\sin^2\theta_{13} = 0.0224$, $\sin^2\theta_{12} = 0.310$, $\Delta m^2_{21} = 7.40 \times 10^{-5}$ eV^2 and minimize with respect to $|\Delta m^2_{3\ell}|$.

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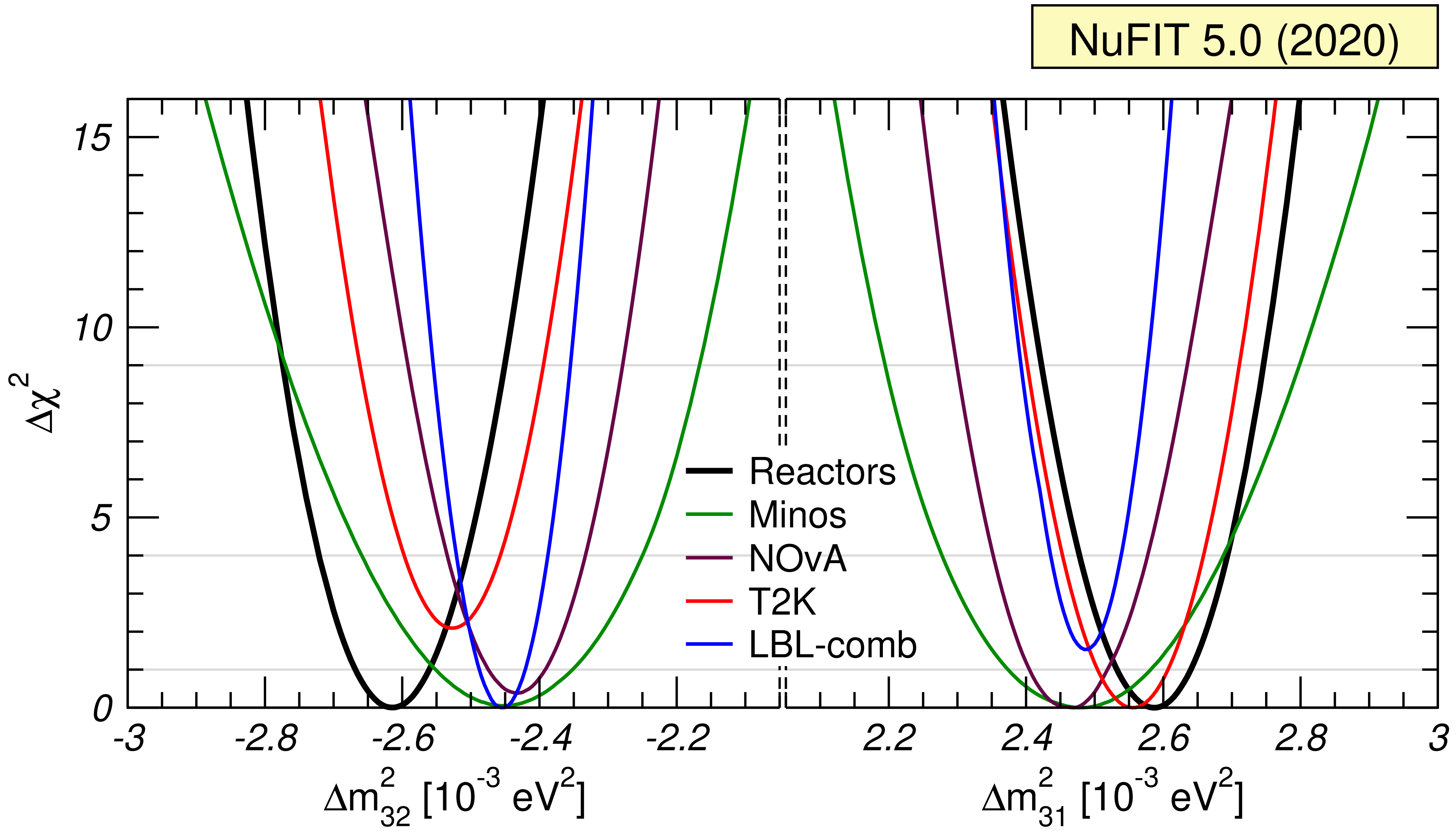

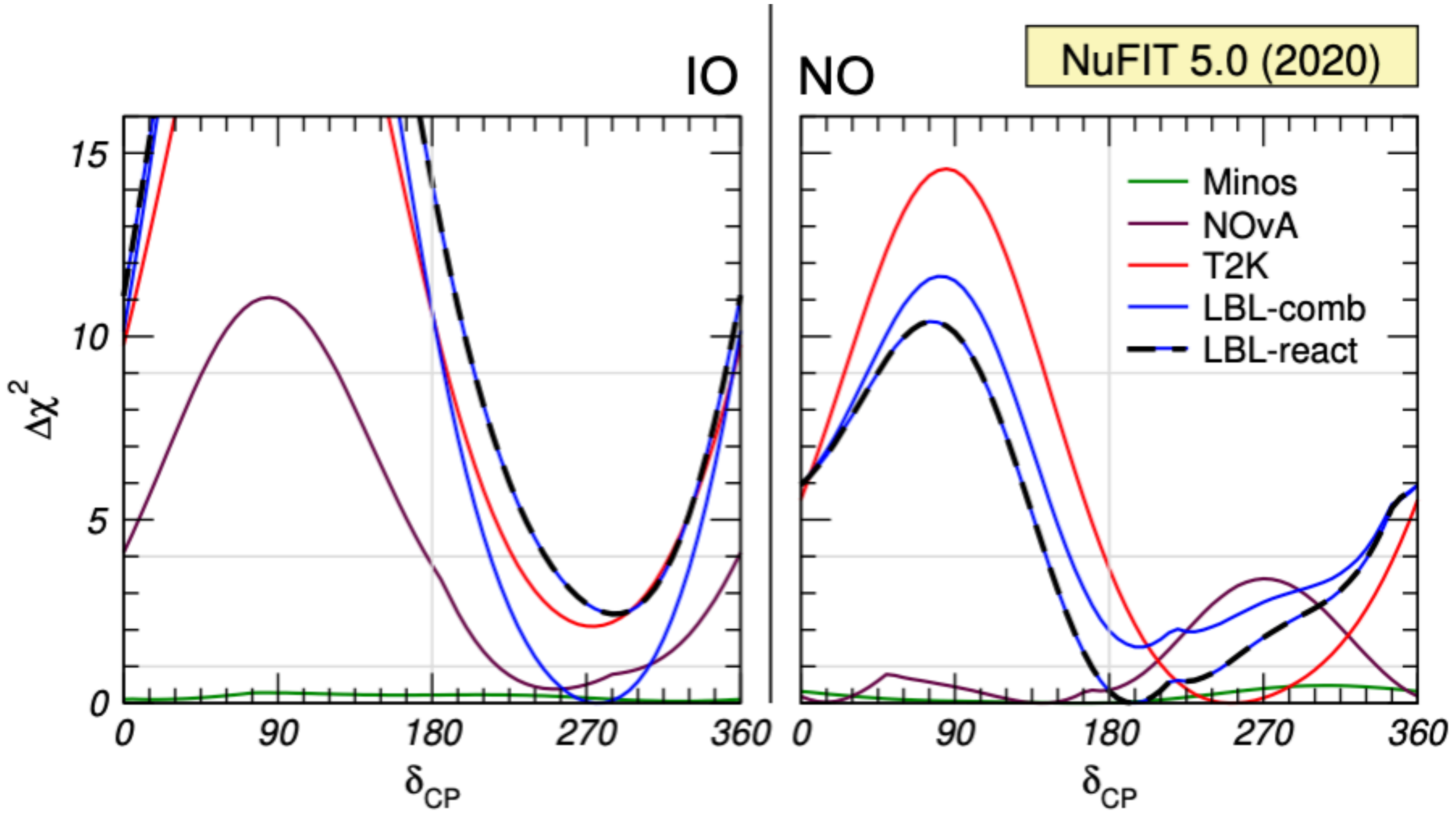

- T2K and NOvA better compatible for IO → LBL combination best fit for IO
- LBL/reactor complementarity in $|\Delta m^2_{31}|$ determination → combination prefers NO

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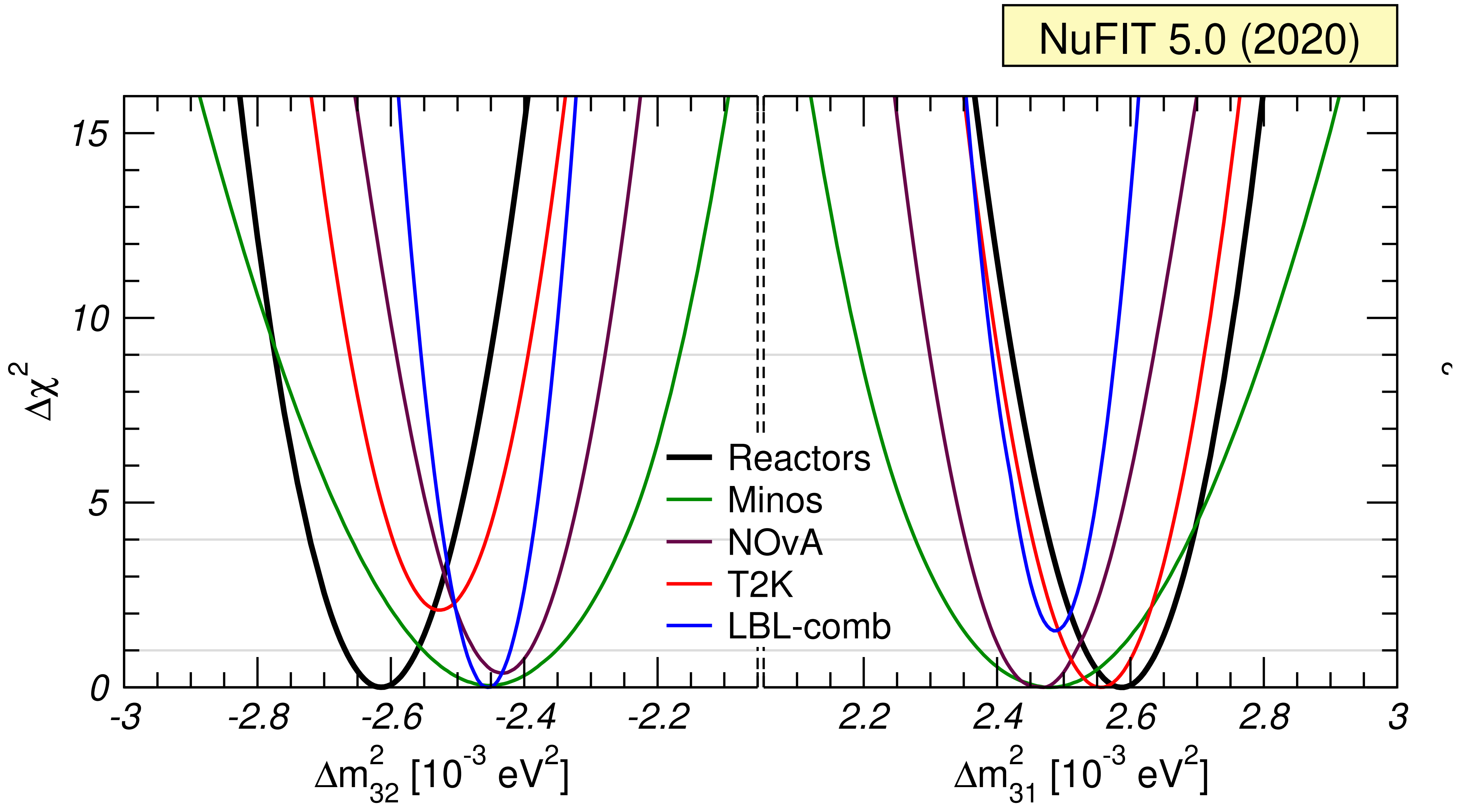

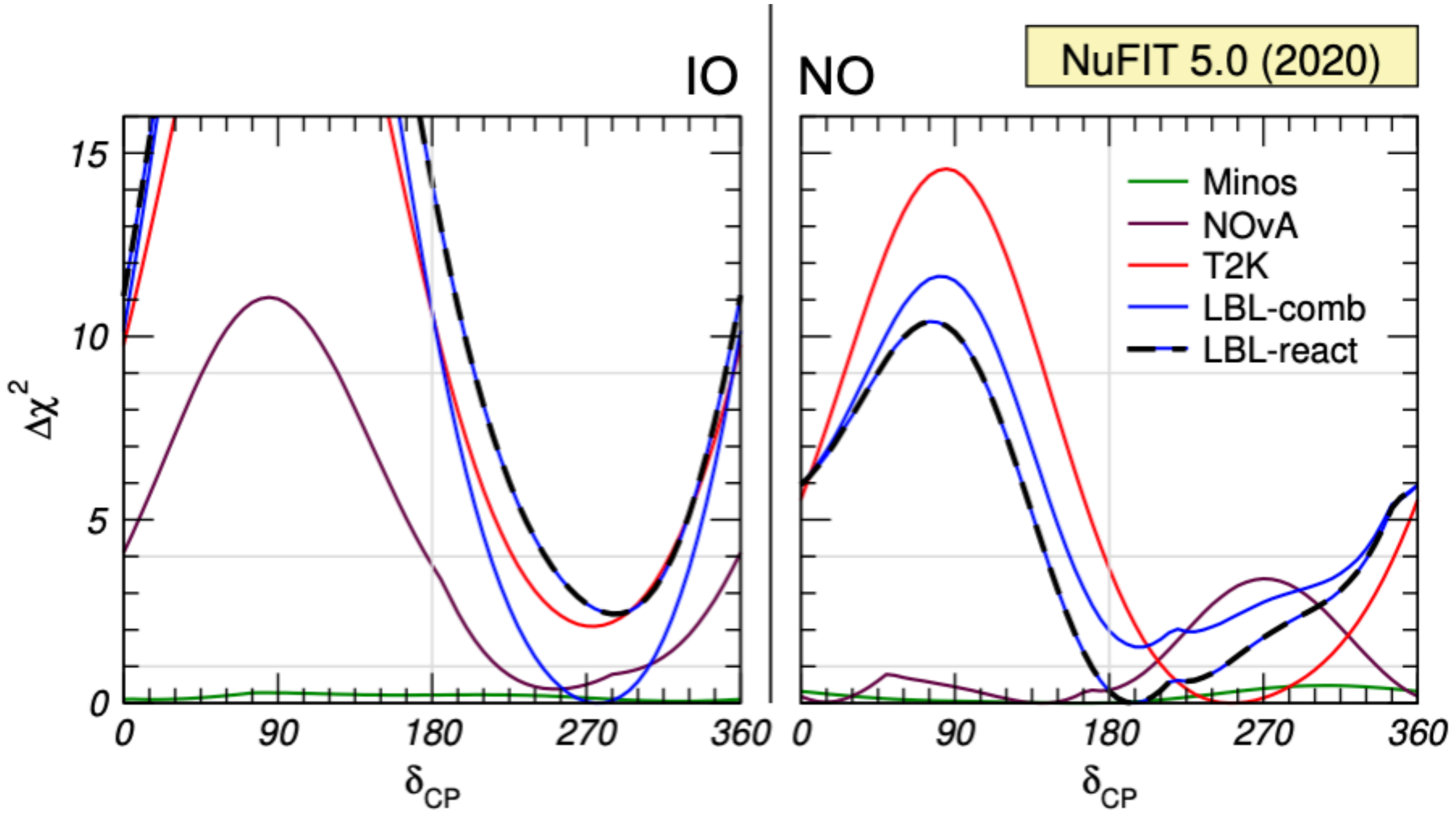

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- this effect will be very power full in the future [Blennow, TS, 2013], by combining reactor data from JUNO with atmospheric data from IceCube [1911.06745] or KM3NET/ORCA [2108.06293]

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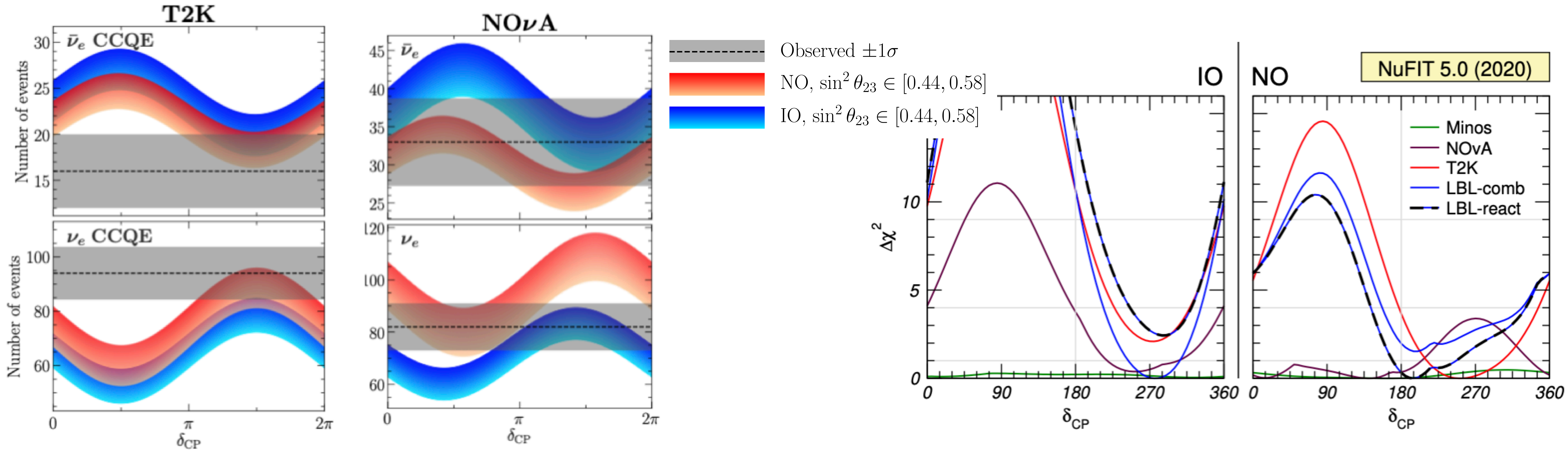
Mass ordering and CP phase: LBL accelerator & reactor data



- 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

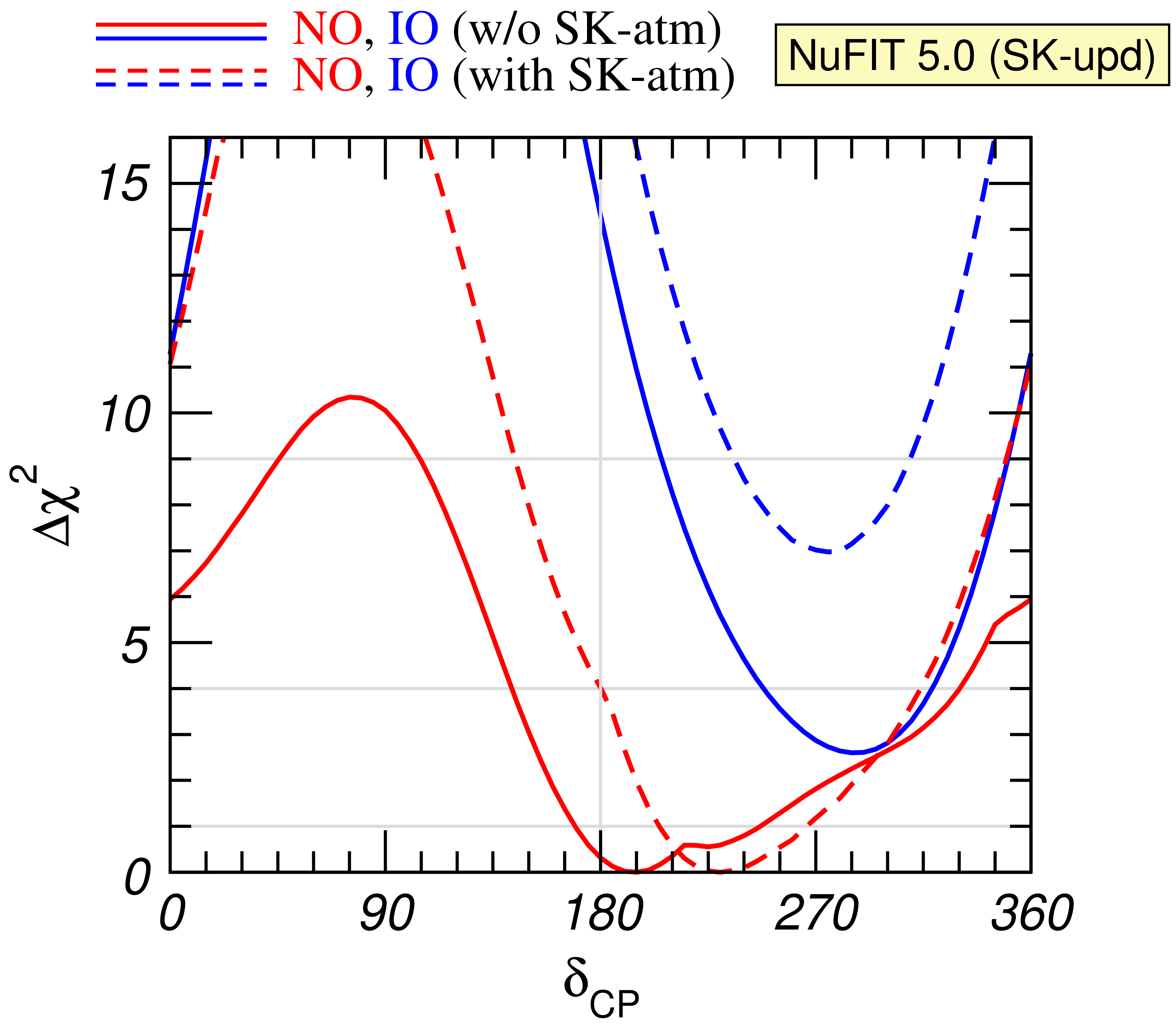
Mass ordering and CP phase: atmospheric neutrinos

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

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

- added to global fit via χ^2 table:
  $\chi^2(\mathrm{IO}) - \chi^2(\mathrm{NO}) = 2.7$ (no SK)
  $\rightarrow$ 7.1 (w SK) 2.7σ

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



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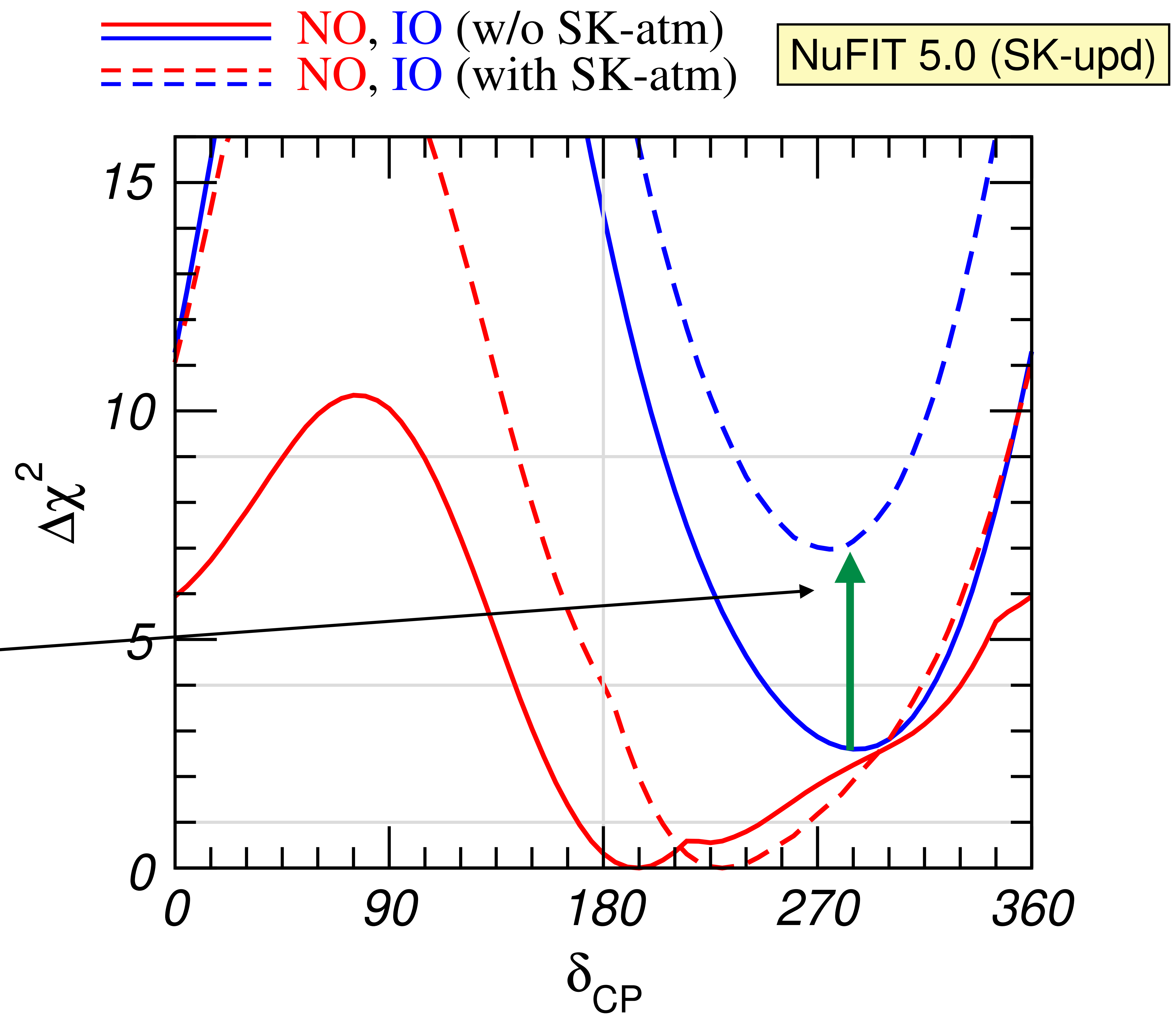

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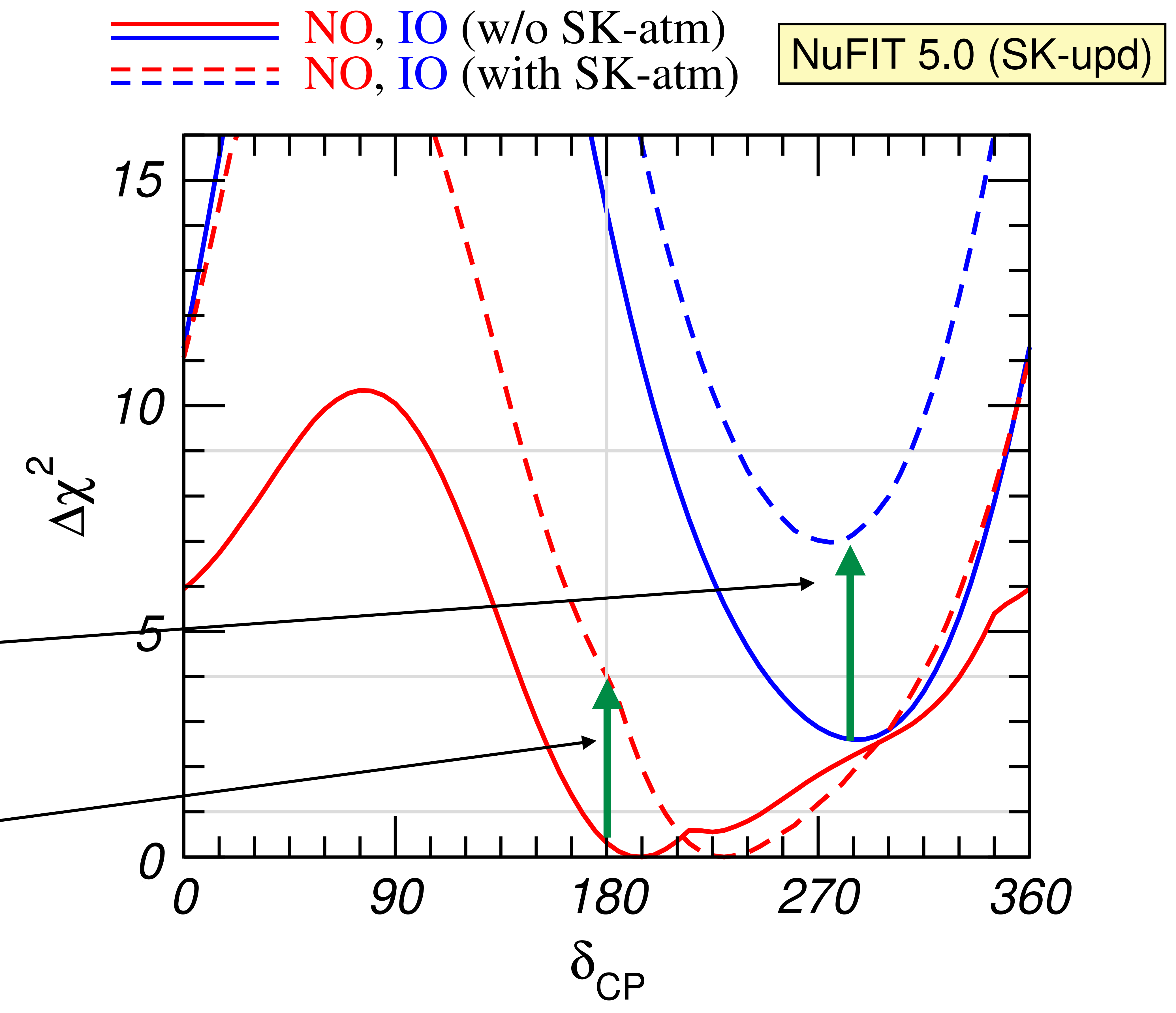

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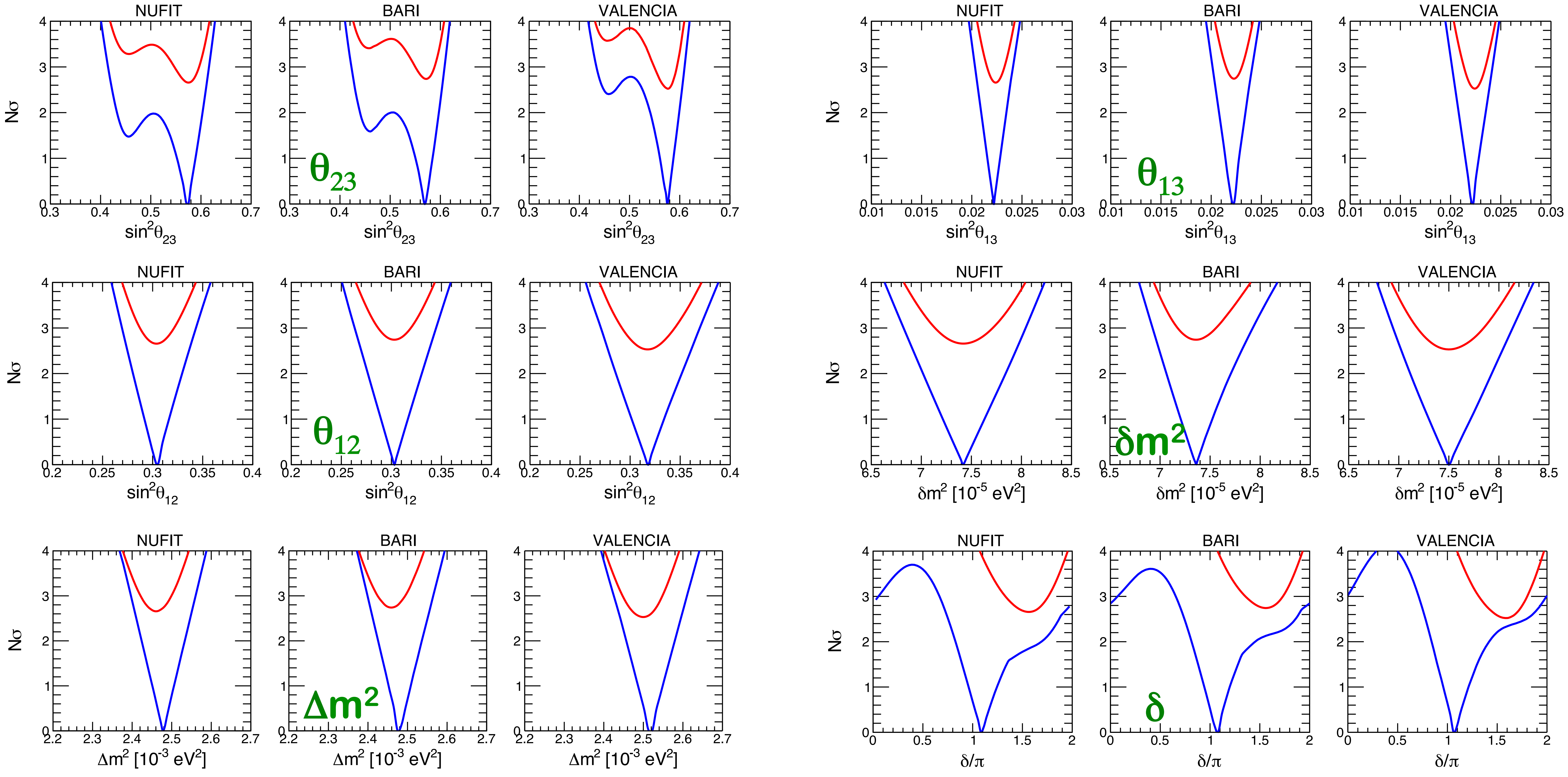
Intermediate summary:

- updated results from global 3-flavour 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	$\Delta\chi^2$(MO)	best fit δ_{CP}	$\Delta\chi^2$(CPC)	oct. θ_{23}	$\Delta\chi^2$(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**

Comparison of independent global analyses



From E. Lisi, talk @ Invisibles2021

BARI: 2003.08511 [updated for this Workshop]
NUFIT: 2007.19742 [with Δm^2_{13} and Δm^2_{23} converted to our Δm^2]
VALENCIA: 2006.11237v2 [with Δm^2_{13} and Δm^2_{23} converted to our Δm^2]

Search for deviations from standard 3-flavour paradigm

- sterile neutrinos / right-handed neutrinos / heavy neutral leptons
  from eV / keV / MeV / GeV / TeV → GUT scale
- EFT: non-standard neutrino interactions $\mathscr{L} \sim G_F \epsilon_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu \nu_\beta)(\bar{f} \gamma_\mu f)$
  (generalized mass ordering / dark-LMA degeneracy)
- EFT: magnetic moment operators $\mathscr{L} \sim d_{\alpha\beta} \bar{\nu}_\alpha \sigma^{\mu\nu} \nu_\beta F_{\mu\nu}$
- general non-unitarity in lepton mixing
- light-new physics coupled to neutrinos, e.g. *Z'*, (pseudo-)scalars
- neutrino decay
- …

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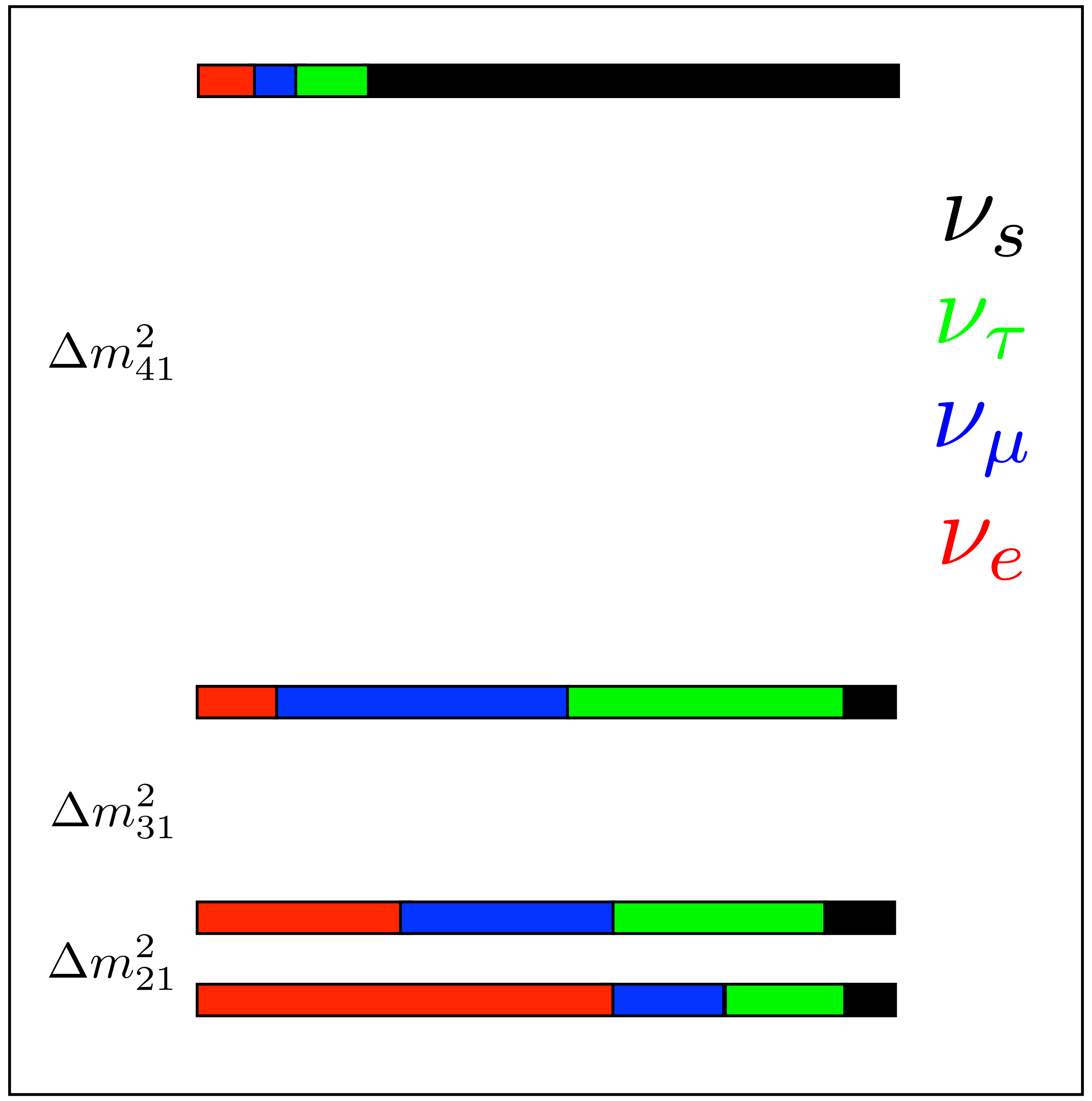
Sterile neutrinos at the eV scale?

- Reactor anomaly ($\bar{\nu}_e$ disappearance)
  - predicted vs measured rate
  - distance dependent spectral distortions
- Gallium anomaly (ν_e disappearance)
- LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$ appearance)
- MiniBooNE ($\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$ appearance)



Reactor anomaly

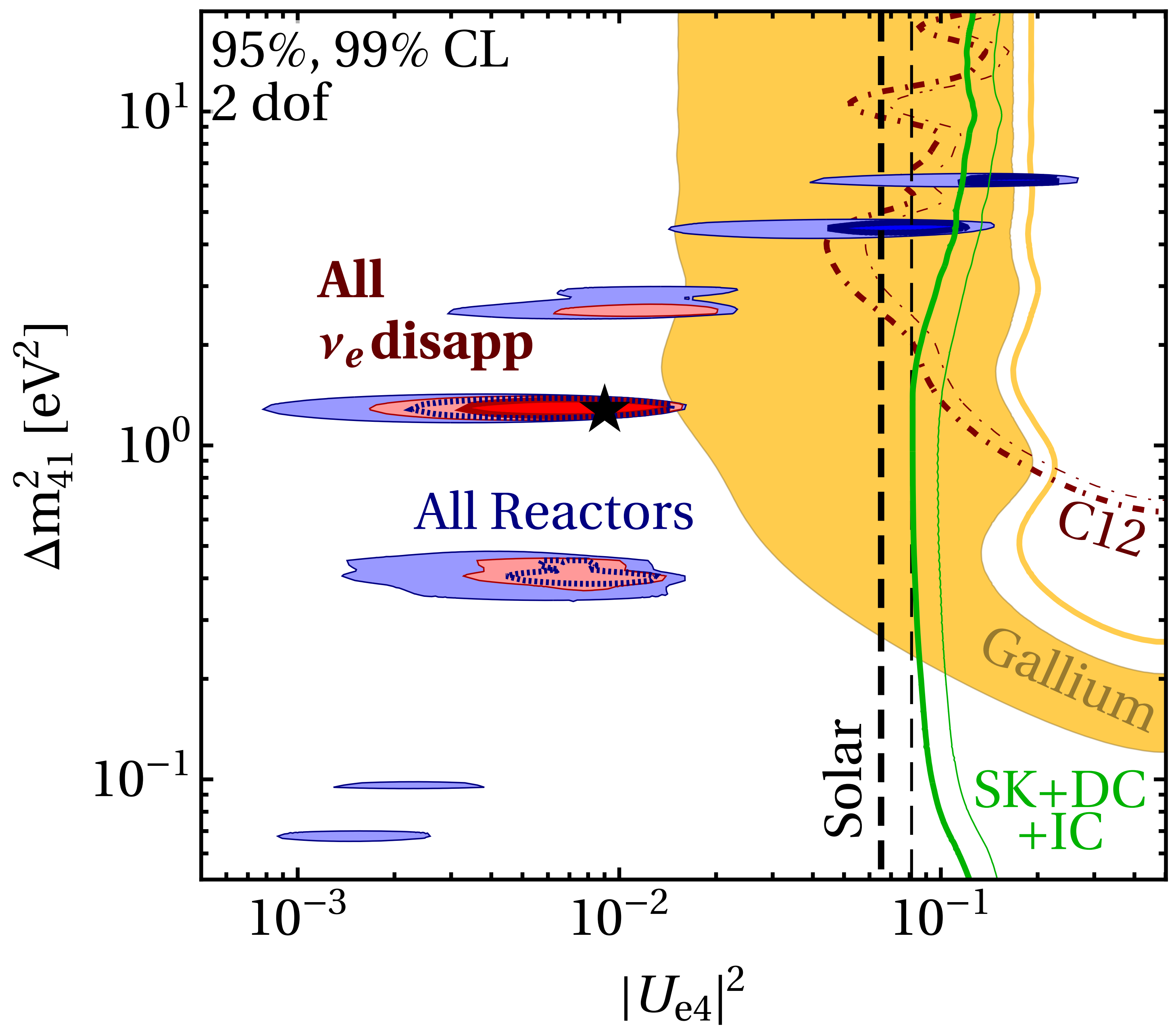
- tension between „predicted“ and observed neutrino rates at nuclear reactors
- dominated by systematic/theoretical uncertainty, status „unclear“

Berryman, Huber, 1909.09267

	Analysis	$\chi^2_{3\nu}$	$\chi^2_{\rm min}$	$n_{\rm data}$	p	$n\sigma$
Huber, Muller, 2011	HM Rates	41.4	33.5	40	2.0×10^{-2}	2.3
Estienne et al., 1904.09358	*Ab Initio* Rates	39.2	37.0	40	0.34	0.95
Hayen et al., 1908.08302	HKSS Rates	58.1	47.5	40	5.0×10^{-3}	2.8
	Spectra	184.9	172.2	212	1.8×10^{-3}	3.1
	DANSS + NEOS	98.9	84.7	84	8.1×10^{-4}	3.3

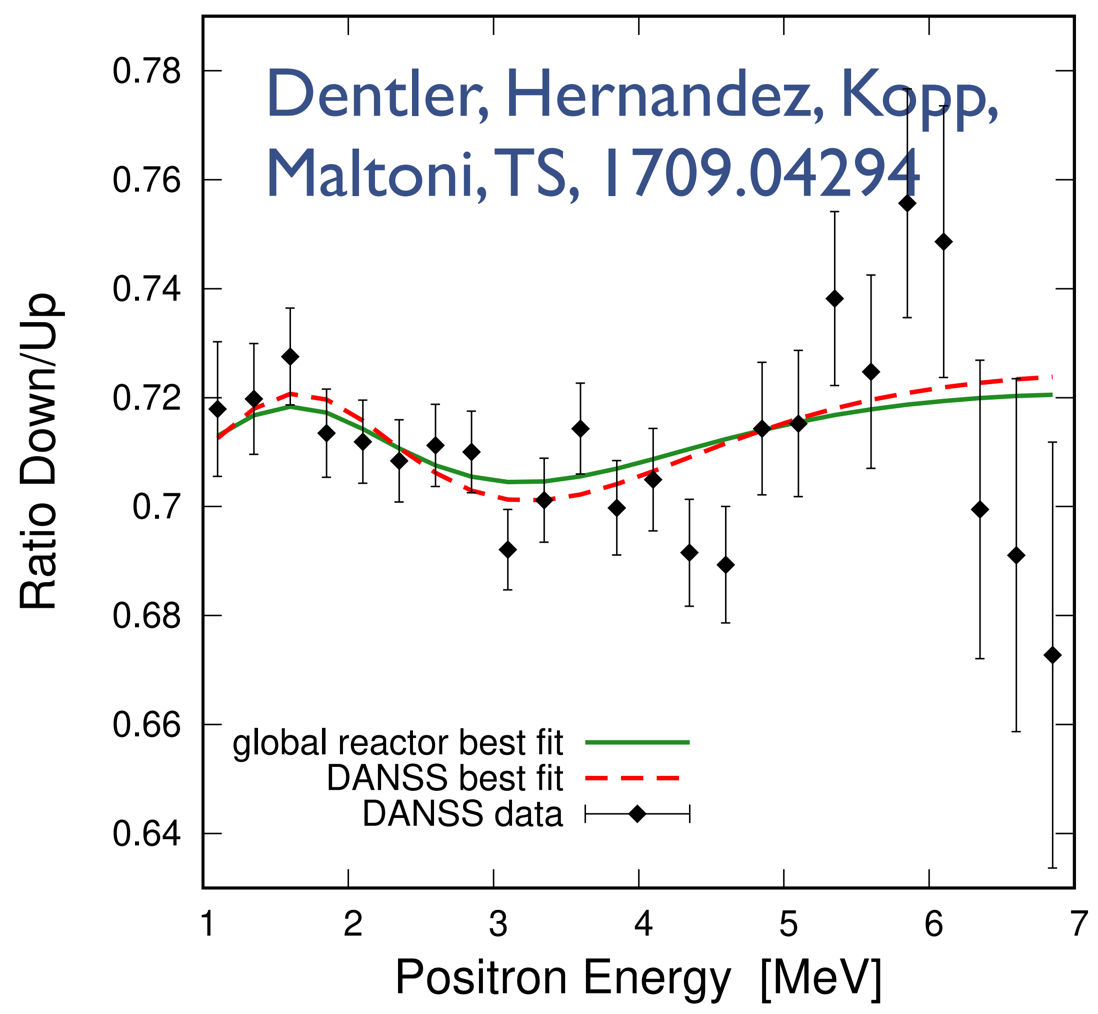
flux-independent analyses

Dentler et al., 1803.10661



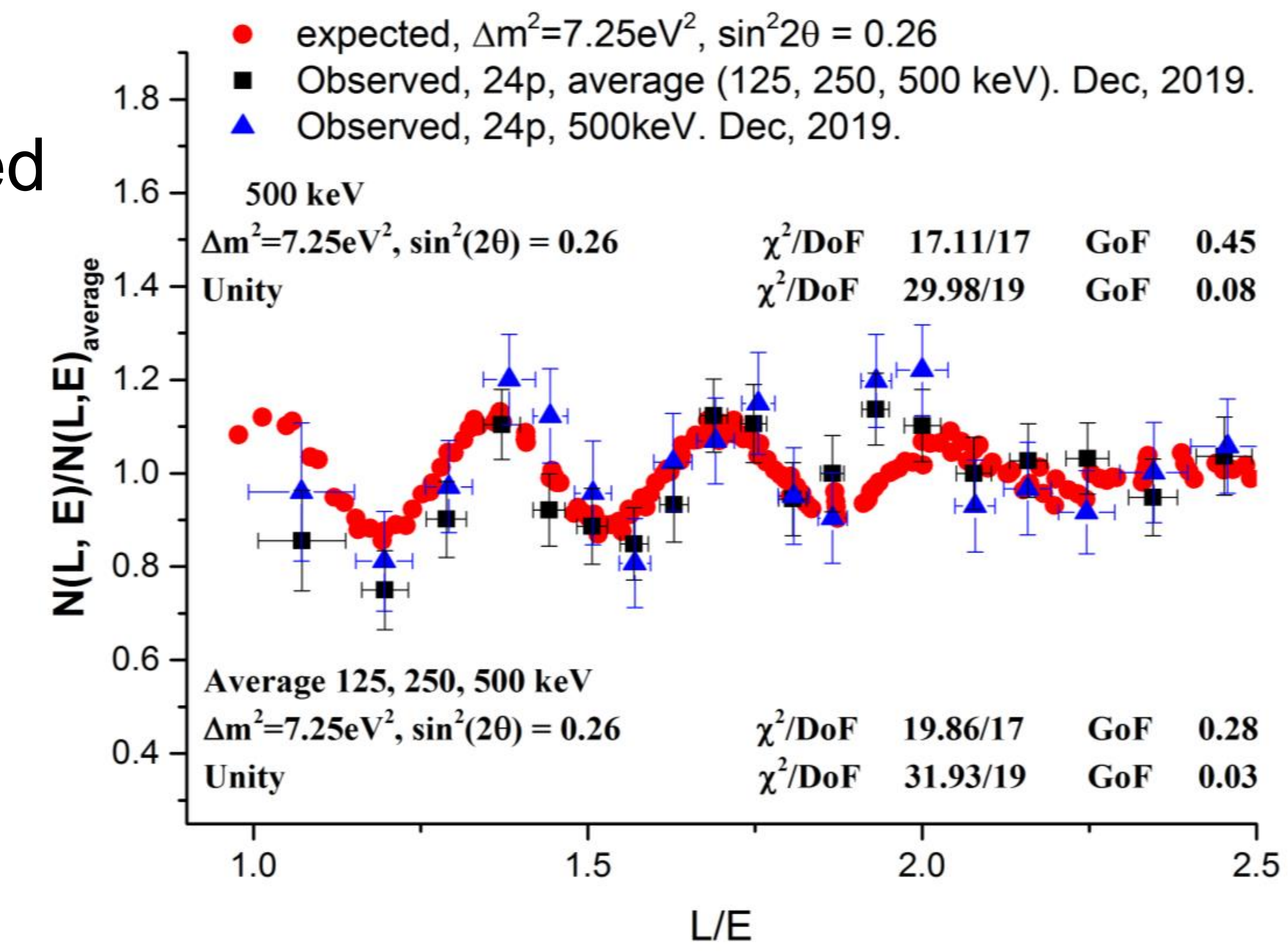
hint for sterile neutrino oscillations @ ~3.2σ independent of reactor flux calculations!

Recent relative spectral measurments

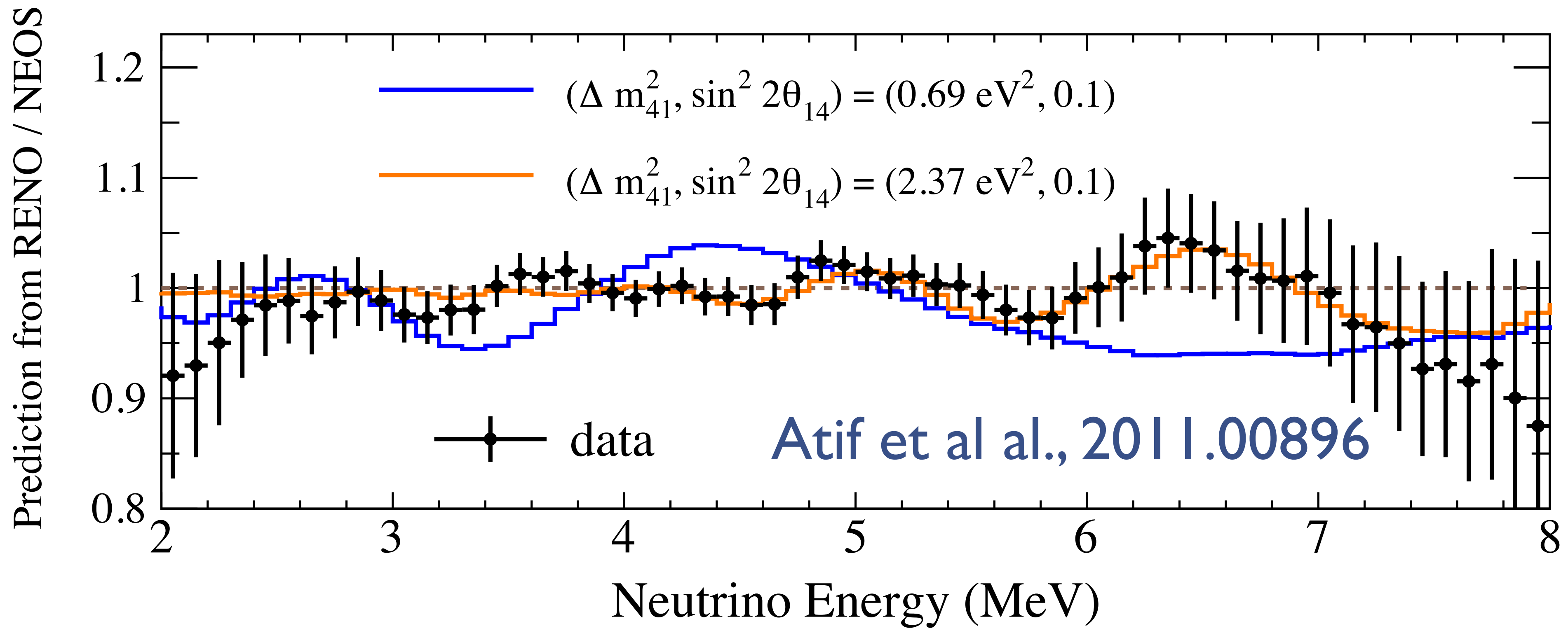


$\color{green}{\text{DANSS}}$: relative spectra @ L = 10.7 and 12.7 m
prev. ~ 2σ hint decr. ~1.5σ
DANSS talk @ ICHEP20 (update at EPS-HEP21)

Neutrino4 2005.05301



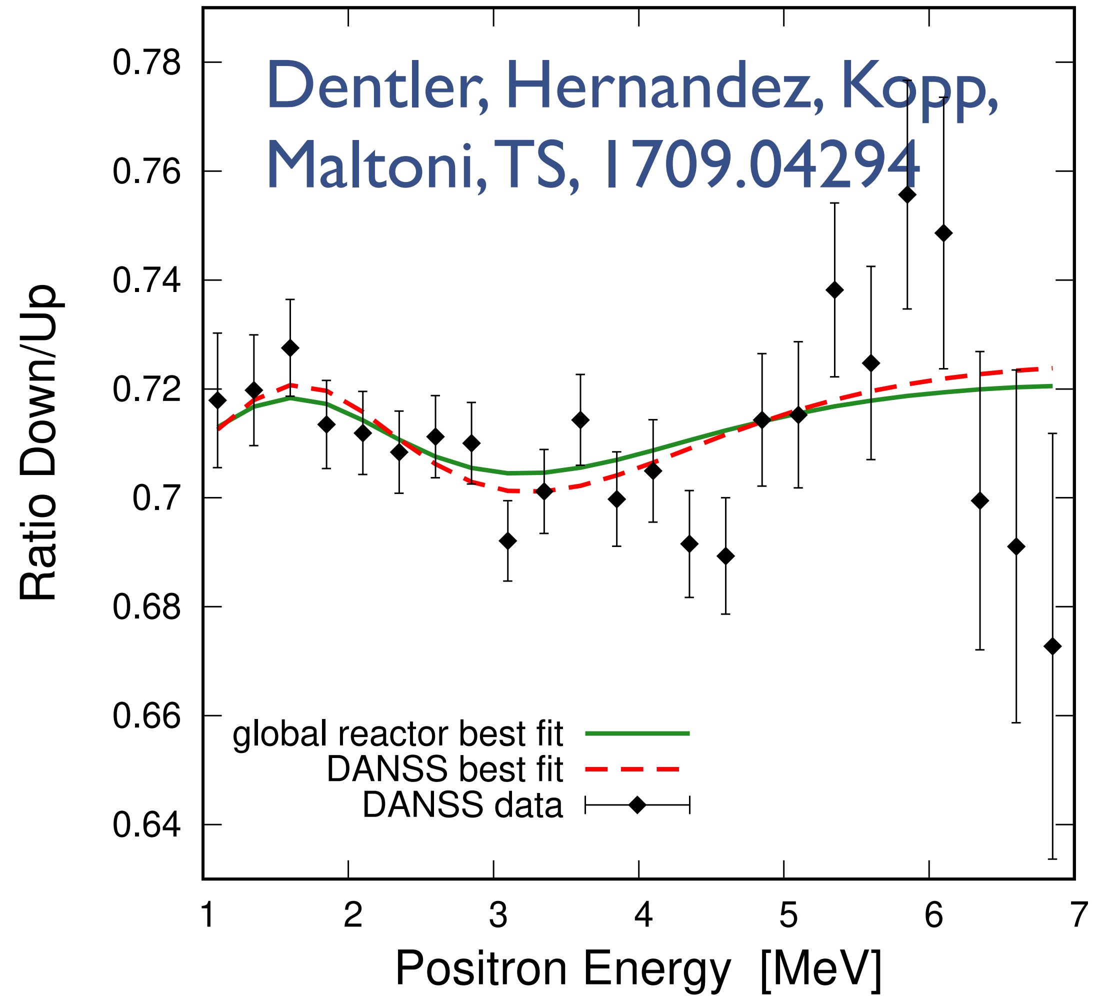
Neutrino4: segmented detector, L = 6.25 to 11.9 m, 216 bins in L/E „3σ“ indication



segmented detectors:
STEREO [arXiv:1912.06582]
L = 9 to 11 m $\Delta\chi^2$(no osc) ≈ 9
PROSPECT [arXiv:2006.11210]
L = 6.7 to 9.2 m

NEOS: spectrum at L = 24 m, relative to RENO (or DayaBay) near detectors: $\Delta\chi^2$(no osc) = 11.7

Recent relative spectral measurments



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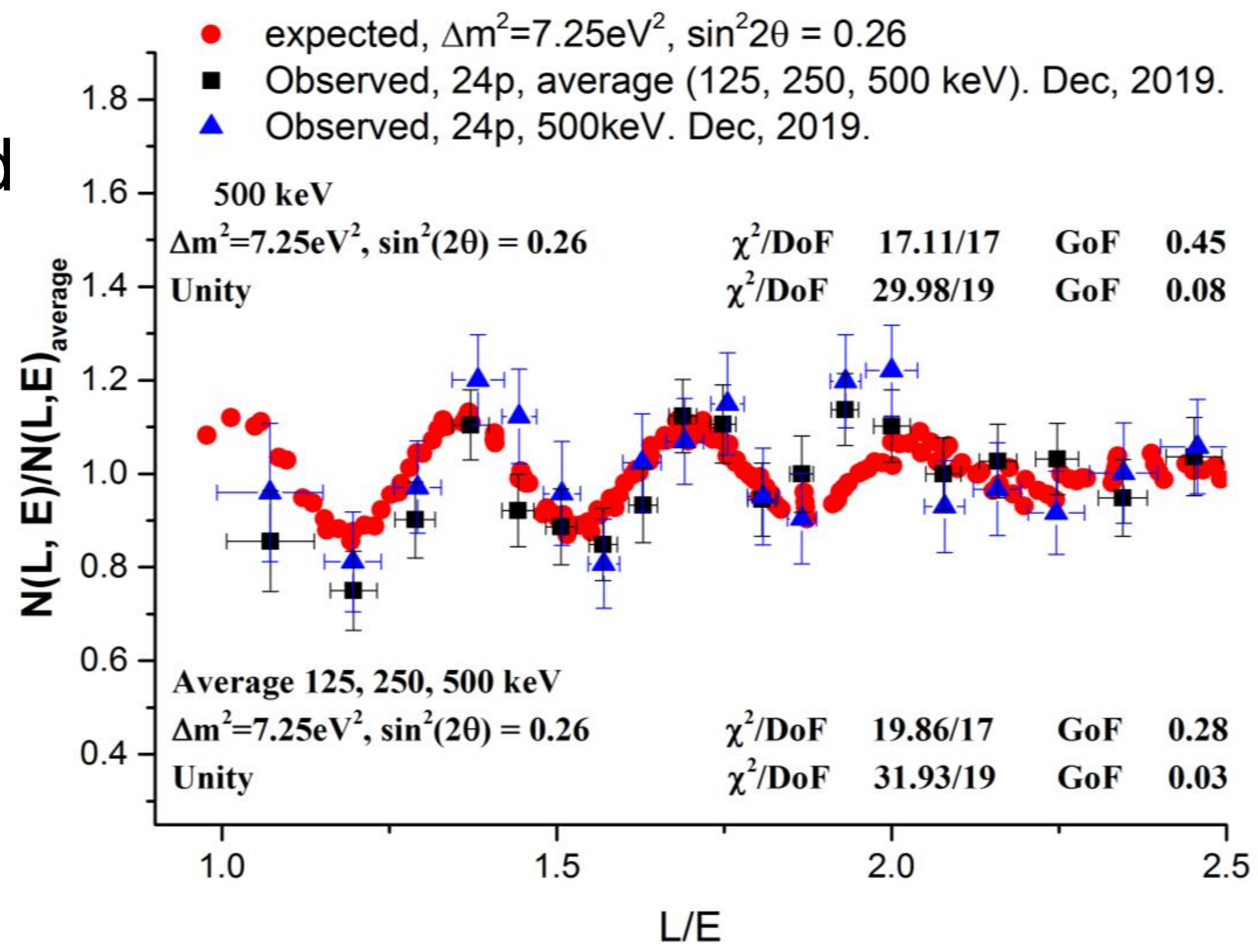

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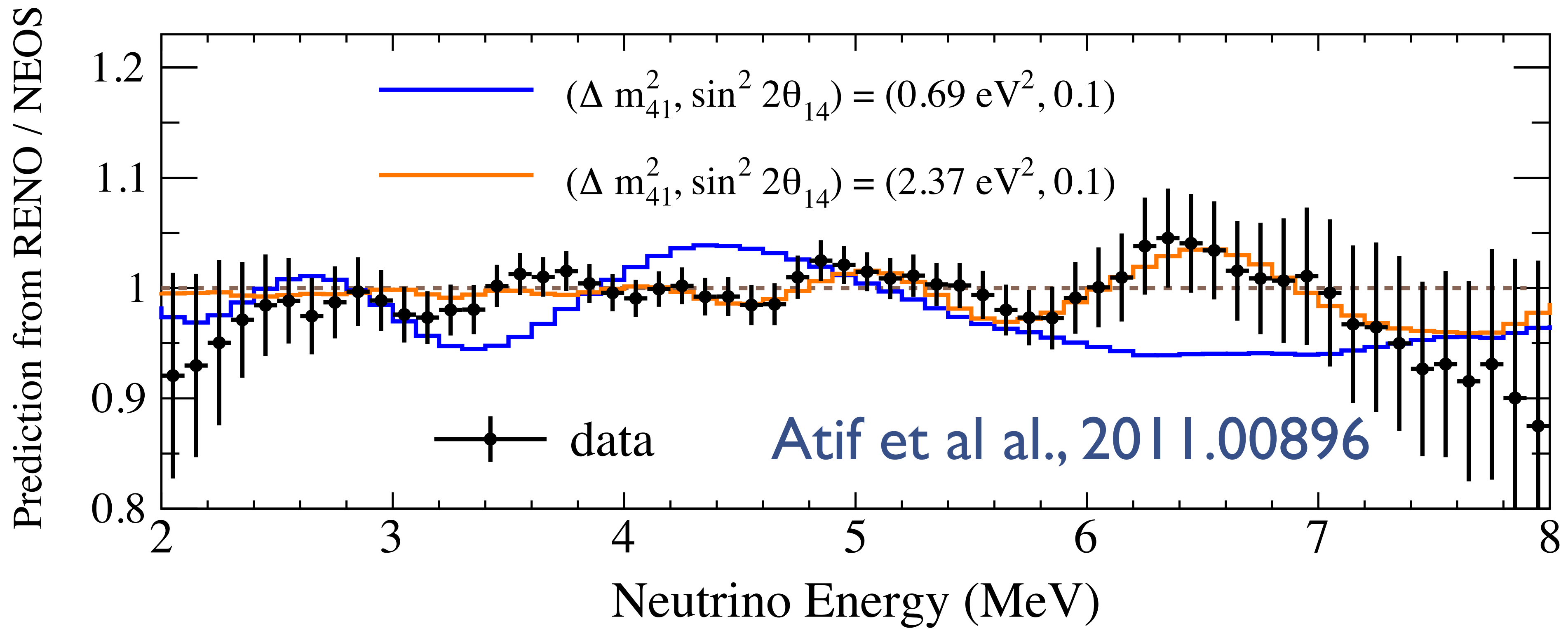

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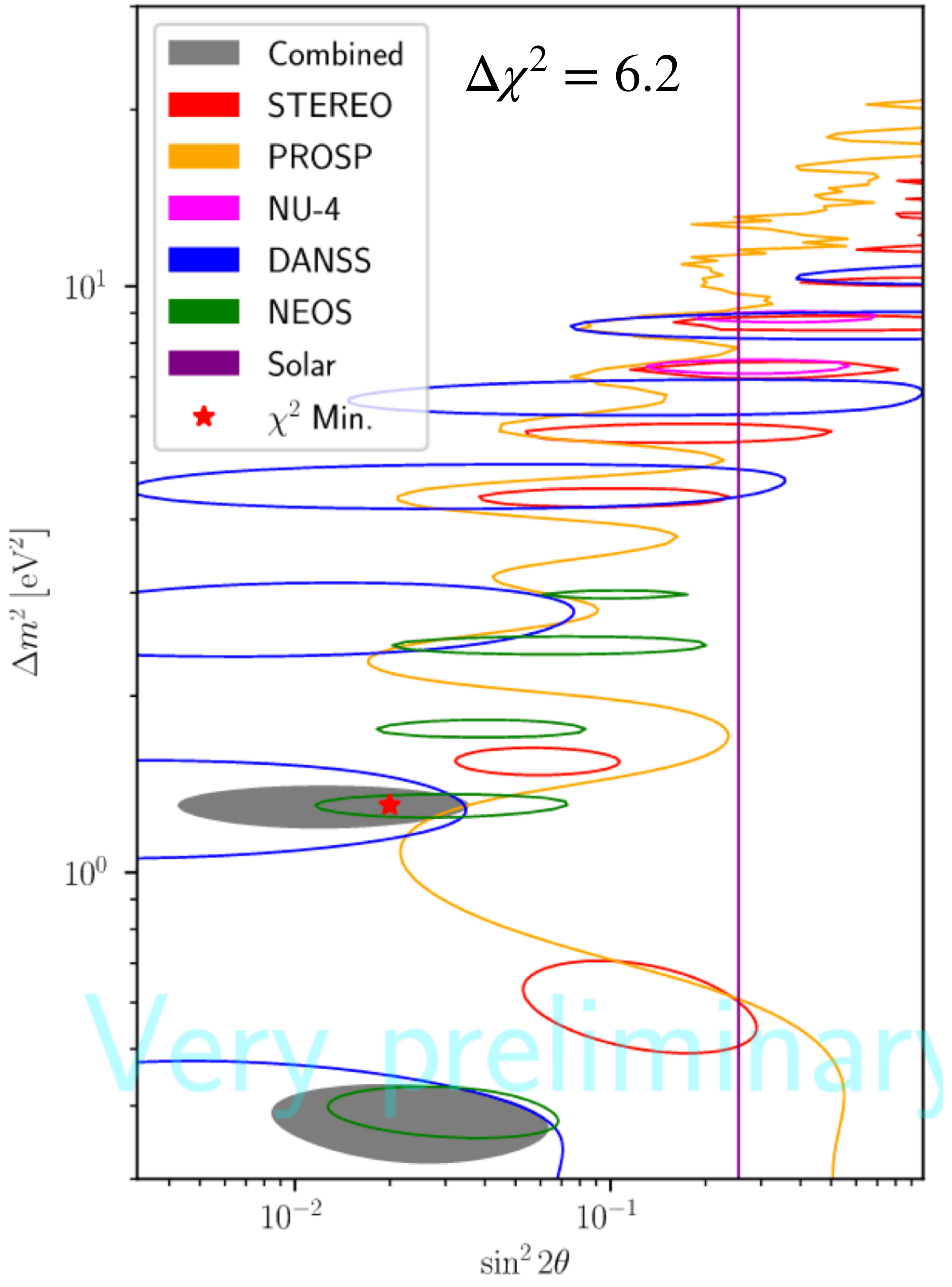
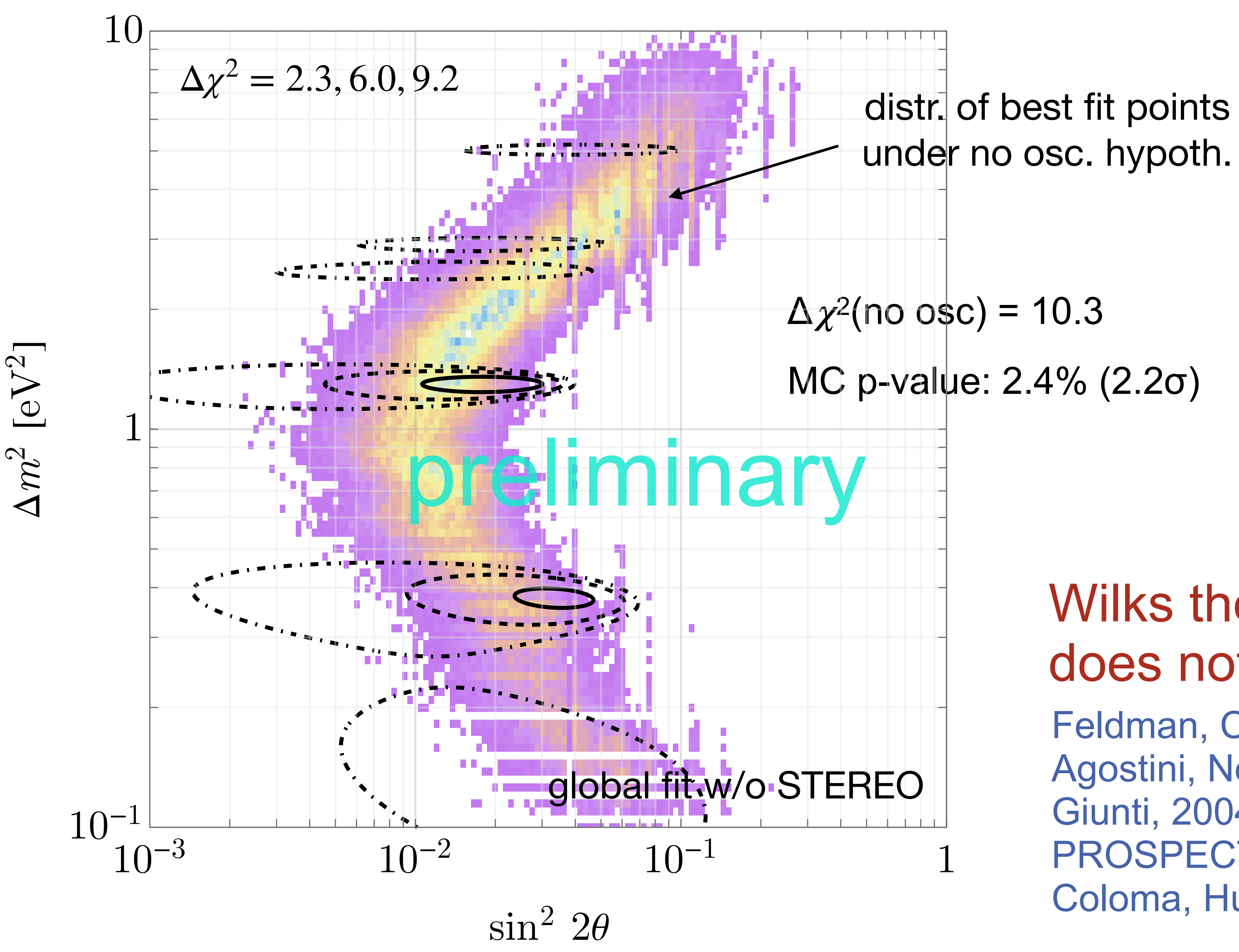
Are hints consistent with each other?

Berryman, Coloma, Huber, TS, Zhou, in prep.





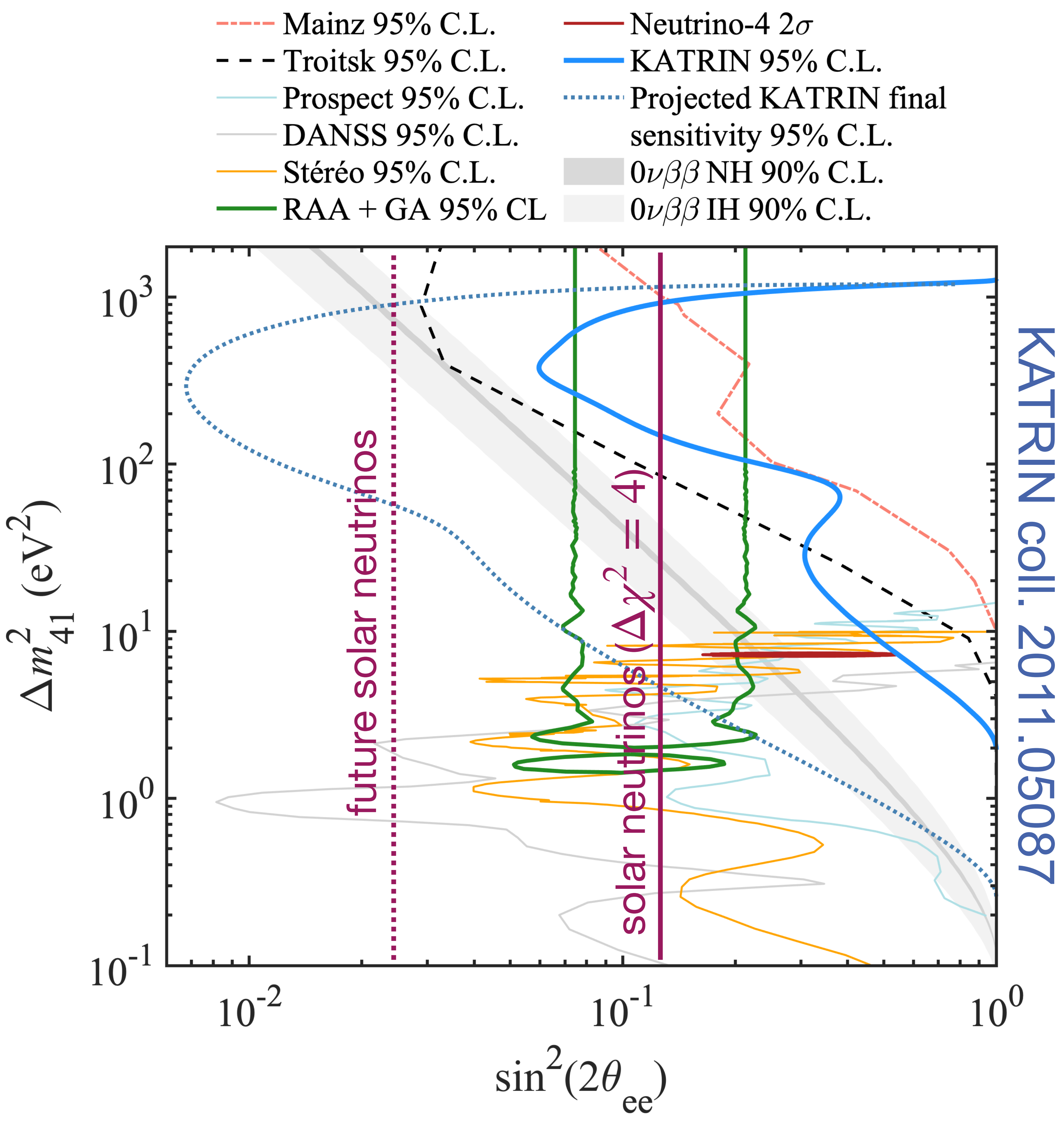
Wilks theorem does not apply

Feldman, Cousins, 98
Agostini, Neumair, 1906.11854
Giunti, 2004.07577
PROSPECT&STEREO 2006.13147
Coloma, Huber, TS 2008.06083

Testing the anomaly with complementary data

- beta decay spectrum: KATRIN
  talk by M. Schlösser

- solar neutrinos
  e.g. Dentler et al., 1803.10661;
  Giunti et al., 2101.06785;
  Berryman,Coloma,Huber,TS,Zhou, in prep.



Hints for $\nu_\mu \rightarrow \nu_e$ appearance

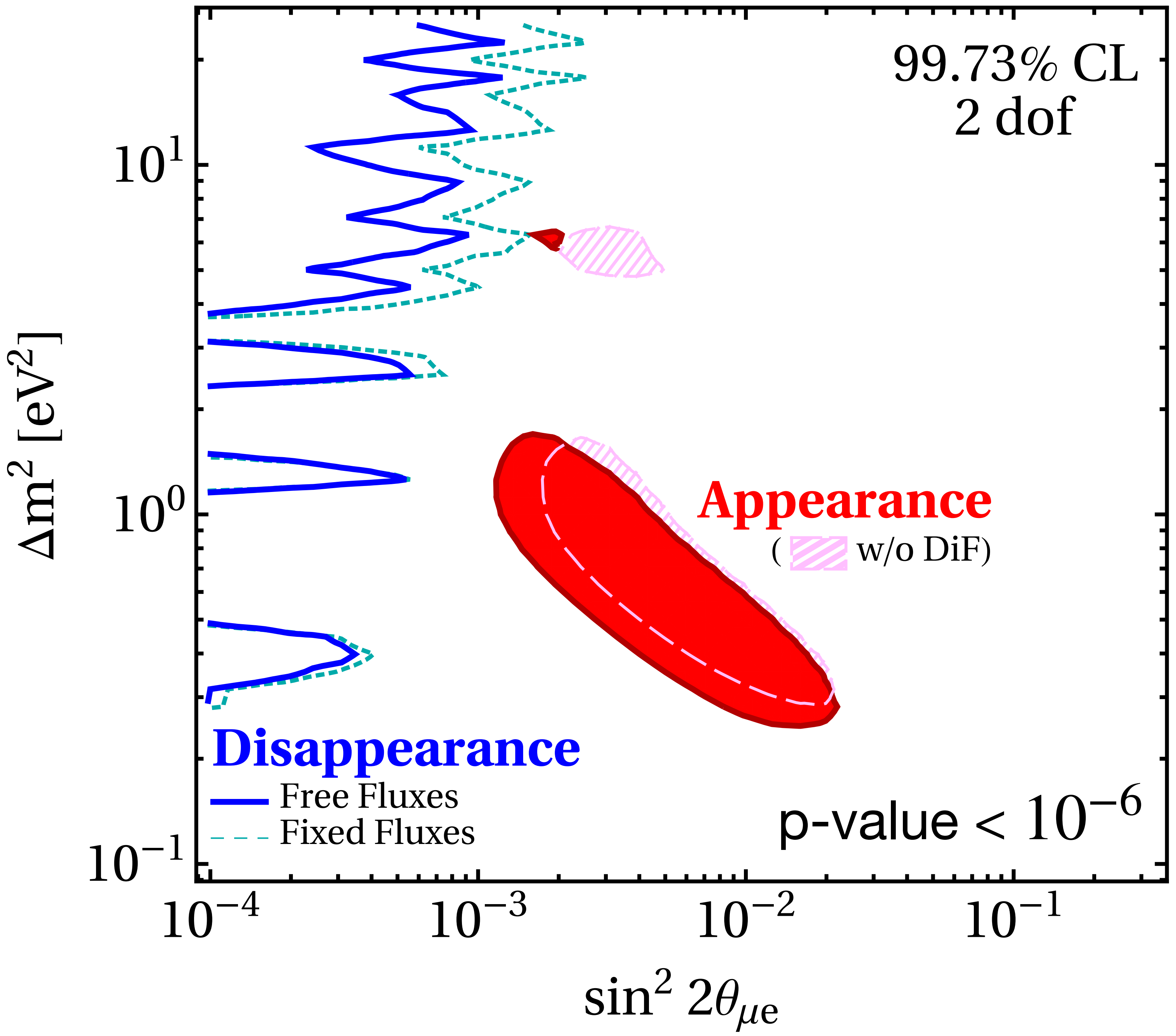
- LSND 2001: signal for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions (3.8σ)
- MiniBooNE 2020: neutrino+antineutrino excess: 638.0±132.8 events (4.8σ)

strong tension between appearance and disappearance data in the eV-sterile osc. framework
(non-observation of ν_μ disappearance)

$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

sterile oscillation explanation of LSND/MiniB robustly disfavoured

Dentler et al., 1803.10661



Other BSM explanations?

incomplete and outdated list:

- 3-neutrinos and CPT violation
  Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, TS 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
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- Lorentz violation Kostelecky et al., 04, 06; Gouvea, Grossman 06
- mass varying ν Kaplan,Nelson,Weiner 04; Zurek 04; Barger,Marfatia,Whisnant 05
- shortcuts of sterile νs in extra dim Paes, Pakvasa, Weiler 05; Doring, Pas, Sicking, Weiler, 18
- decaying sterile neutrino Palomares-Riuz, Pascoli, TS 05; Gninenko 09, 10;
  Bertuzzo, Jana, Machado, Zukanovich, 18; Ballett, Pascoli, Ross-Lonergan, 18; Fischer, Hernandez, TS, 19; Dentler, Esteban, Kopp, Machado, 19; deGouvea, Peres, Prakash, Stenico, 19; Abdallah, Gandhi, Roy, 20
- energy dependent quantum decoherence Farzan, TS, Smirnov 07; Bakhti, Farzan, TS, 15
- sterile neutrinos and new gauge boson Nelson, Walsh 07
- sterile ν with energy dependent mass or mixing TS 07
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many of them excluded by some data

MiniBooNE and a decaying sterile neutrino

Palomares, Pascoli, TS, hep-ph/0505216; Gninenko, 0902.3802, 1009.5536; Bertuzzo, Jana, Machado, Zukanovich, 1807.09877; Ballett, Pascoli, Ross-Lonergan, 1808.2915; Arguelles, Hostert, Tsai, 1812.08768; Fischer, Hernandez, TS, 1909.09561; Dentler, Esteban, Kopp, Machado, 1911.01427; deGouvea, Peres, Prakash, Stenico, 1911.01447; Brdar, Fischer, Smirnov, 2007.14411; Abdallah, Gandhi, Roy, 2010.06159;…

- sterile neutrino *N* with m_N ~ keV to ~500 MeV
- produce *N* either by mixing or by up-scattering
- decay:
  - $N \to \phi\, \nu_e$ with standard neutrino interaction in detector
  - electromagn. decay inside MB detector $N \to \nu\gamma \,/\, \nu e^{\pm} \,/\, \nu\pi^0 \,/\, \ldots$ (no LSND)
- exciting new physics / rich phenomenology / predict signatures in existing (near detectors) and/or upcoming experiments (e.g., Fermilab SBN, DUNE, HK, IceC)

Search for deviations from standard 3-flavour paradigm

- sterile neutrinos / right-handed neutrinos / heavy neutral leptons
  from eV / keV / MeV / GeV / TeV $\to$ GUT scale
- EFT: non-standard neutrino interactions $\mathscr{L} \sim G_F \epsilon_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu \nu_\beta)(\bar{f} \gamma_\mu f)$
  (generalized mass ordering / dark-LMA degeneracy)
- EFT: magnetic moment operators $\mathscr{L} \sim d_{\alpha\beta} \bar{\nu}_\alpha \sigma^{\mu\nu} \nu_\beta F_{\mu\nu}$
- general non-unitarity in lepton mixing
- light-new physics coupled to neutrinos, e.g. Z', (pseudo-)scalars
- neutrino decay
- …

Non-standard neutrino interactions

low-energy EFT for neutrino interaction:

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta} \sum_{f=u,d} \epsilon^f_{\alpha\beta} (\overline{\nu}_{\alpha L}\gamma^\mu \nu_{\beta L})(\overline{f}\gamma_\mu f)$$

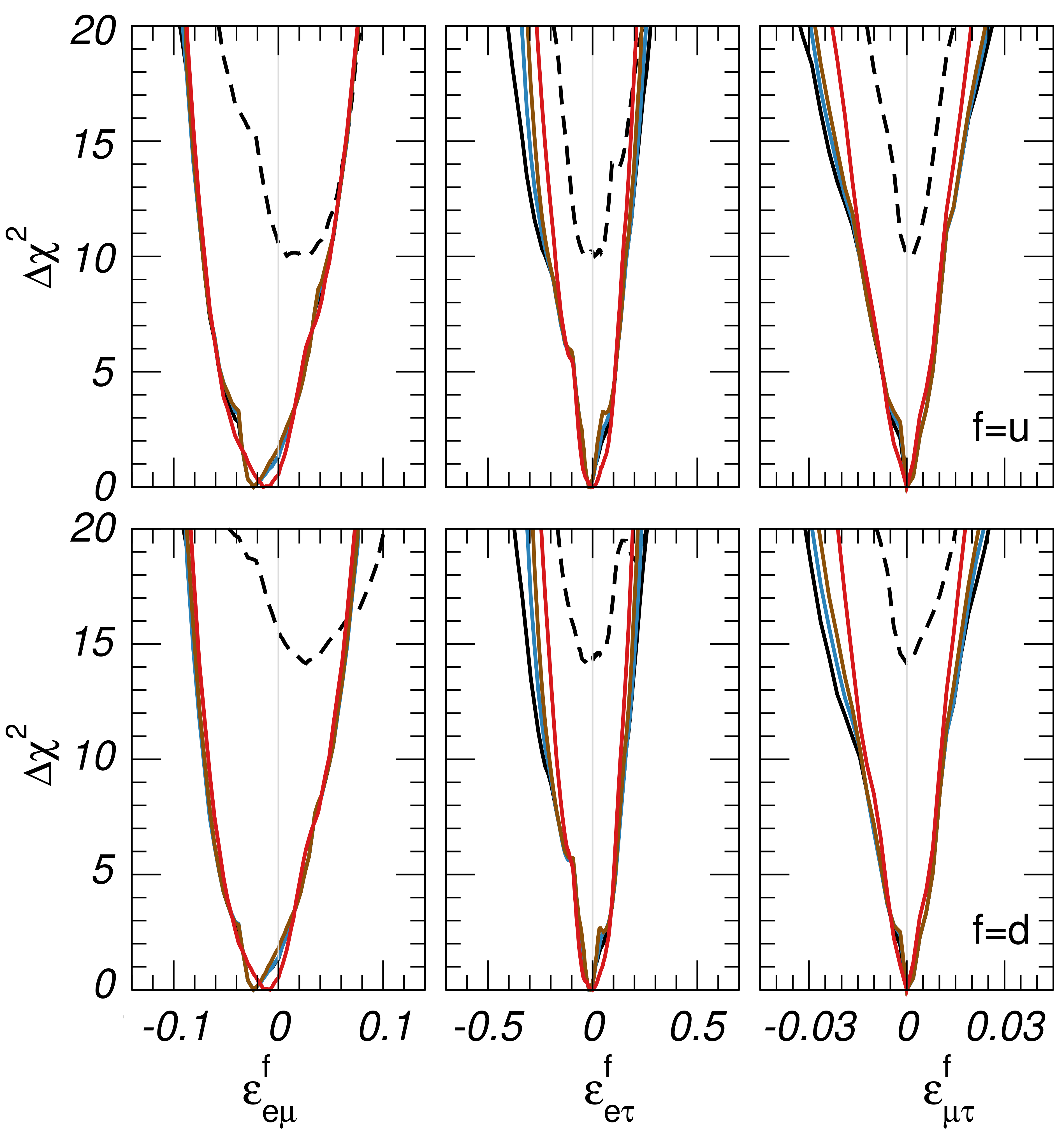
strength of new interaction relative to weak interaction

$$\epsilon^p_{\alpha\beta} = 2\epsilon^u_{\alpha\beta} + \epsilon^d_{\alpha\beta} = \sqrt{5}\epsilon^\eta_{\alpha\beta}\cos\eta\,, \quad \epsilon^n_{\alpha\beta} = 2\epsilon^d_{\alpha\beta} + \epsilon^u_{\alpha\beta} = \sqrt{5}\epsilon^\eta_{\alpha\beta}\sin\eta\,.$$

global fit of osc + NC NSI (5+7 params.), oscillation data + COHERENT

Coloma, Esteban, Gonzalez-Garcia, Maltoni, 1911.09109 [Neutrino20 updated]

off-diagonal NSI limits at the % level:



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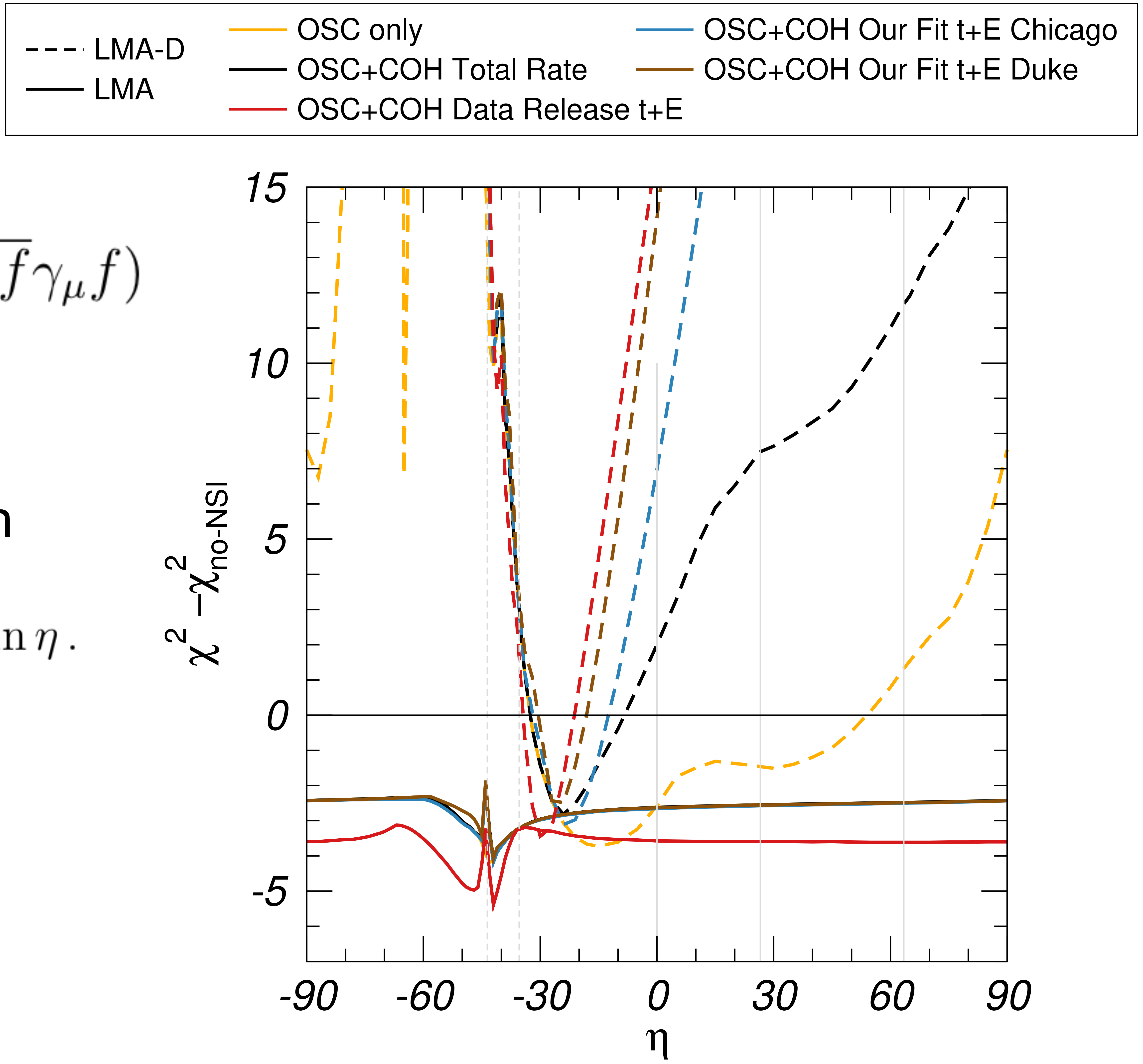

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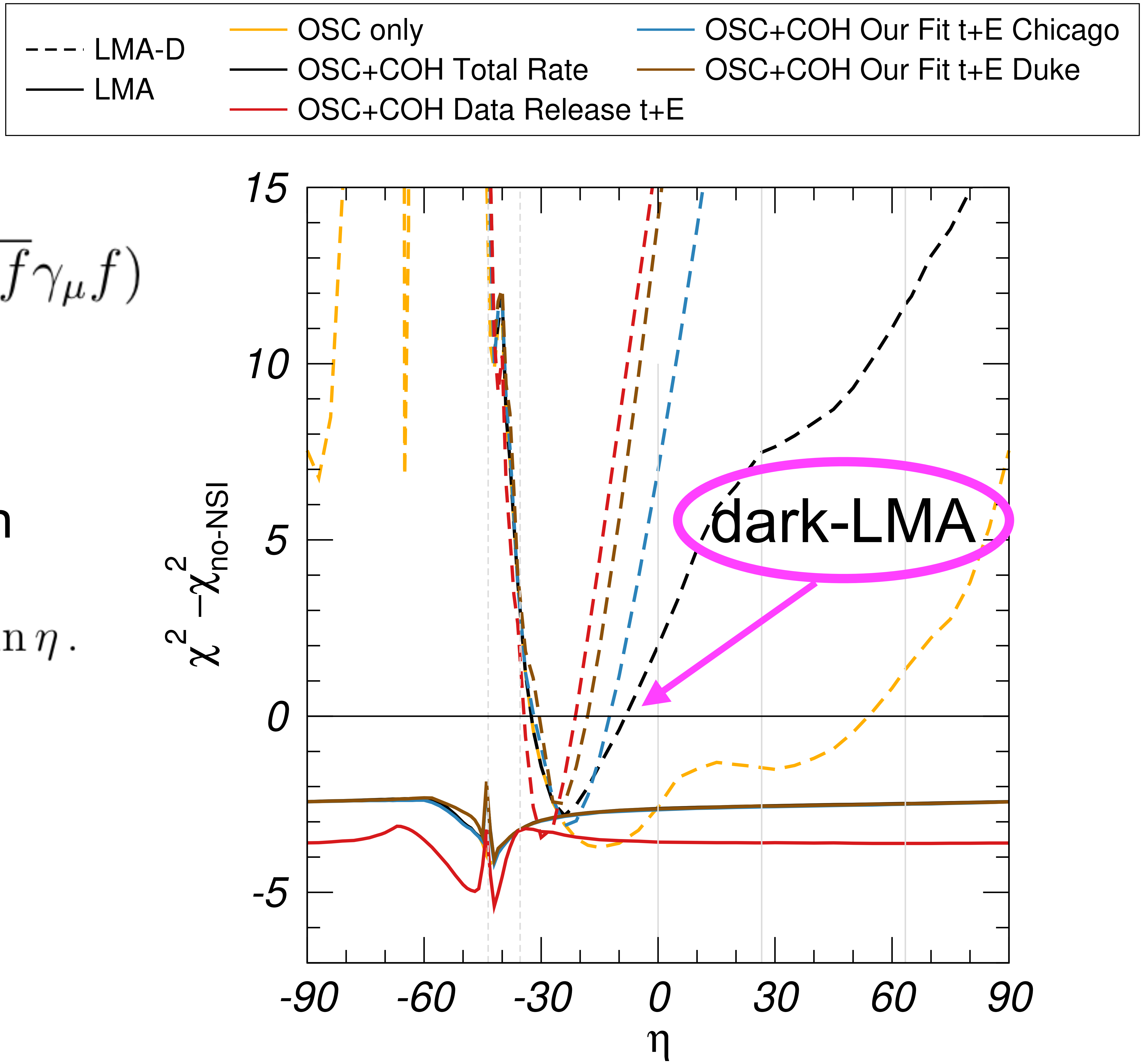

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Dark-LMA / generalised MO degeneracy

- solution with $\theta_{12} > 45°$: „dark-LMA“
  Miranda, Tortola, Valle, hep-ph/0406280
- implies flipping of the mass ordering:
  „generalised MO degeneracy“ Coloma, TS, 16

$\Rightarrow$

- requires NSI ~ G_F
- O(1) modification of mixing pattern
- makes determination of MO by oscillation experiments impossible

based on an exact symmetry of the Hamilton operator of the neutrino evolution equation (CPT):

$$H \to -H^*$$

$$\Delta m^2_{31} \to -\Delta m^2_{32}\,,$$

$$\theta_{12} \to \pi/2 - \theta_{12}\,,$$

$$\delta_{\rm CP} \to \pi - \delta_{\rm CP}\,,$$

$$(\epsilon^Y_{ee} - \epsilon^Y_{\mu\mu}) \to -(\epsilon^Y_{ee} - \epsilon^Y_{\mu\mu}) - 2\,,$$
$$(\epsilon^Y_{\tau\tau} - \epsilon^Y_{\mu\mu}) \to -(\epsilon^Y_{\tau\tau} - \epsilon^Y_{\mu\mu})\,,$$
$$\epsilon^Y_{\alpha\beta} \to -(\epsilon^Y_{\alpha\beta})^* \qquad (\alpha \neq \beta)\,.$$

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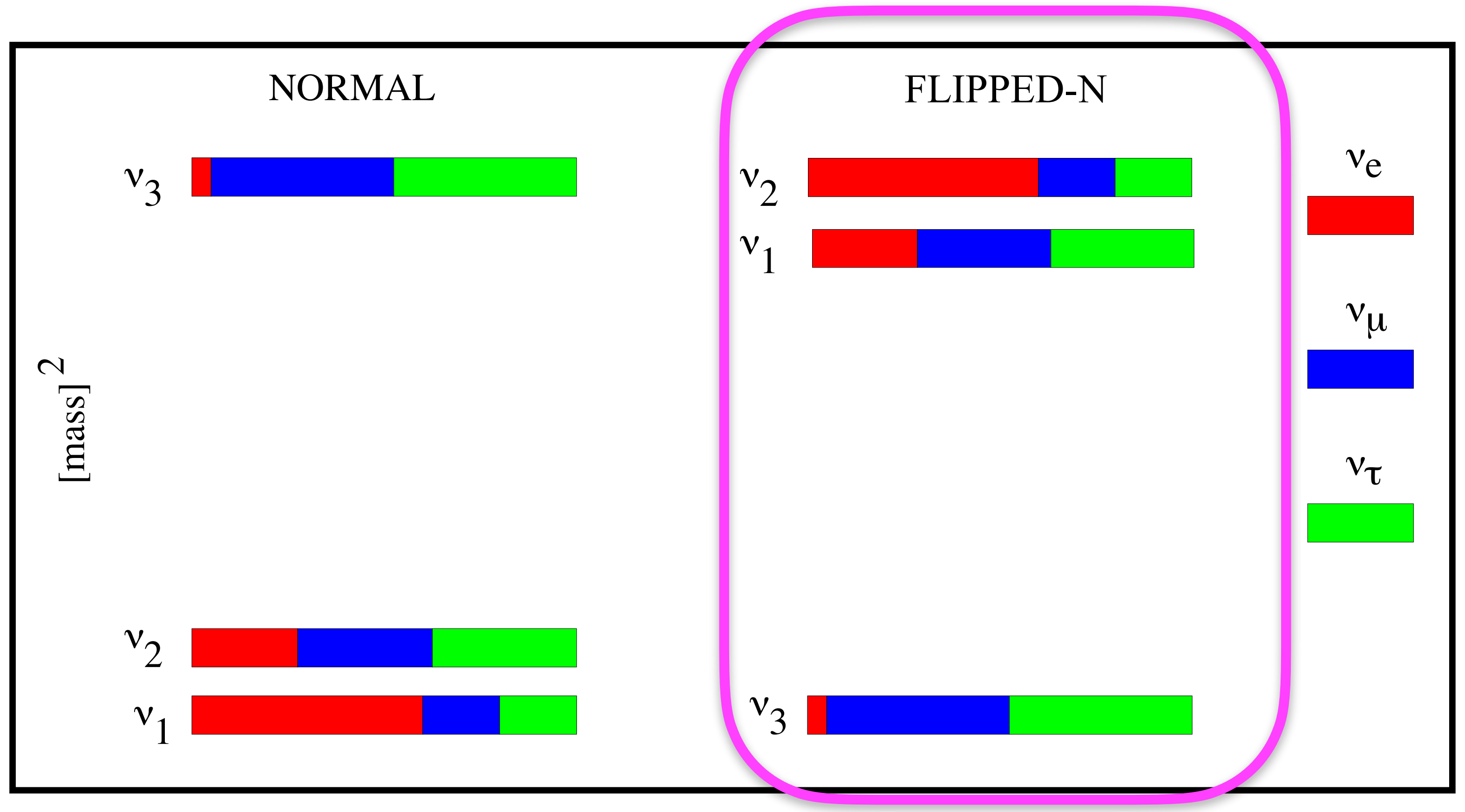
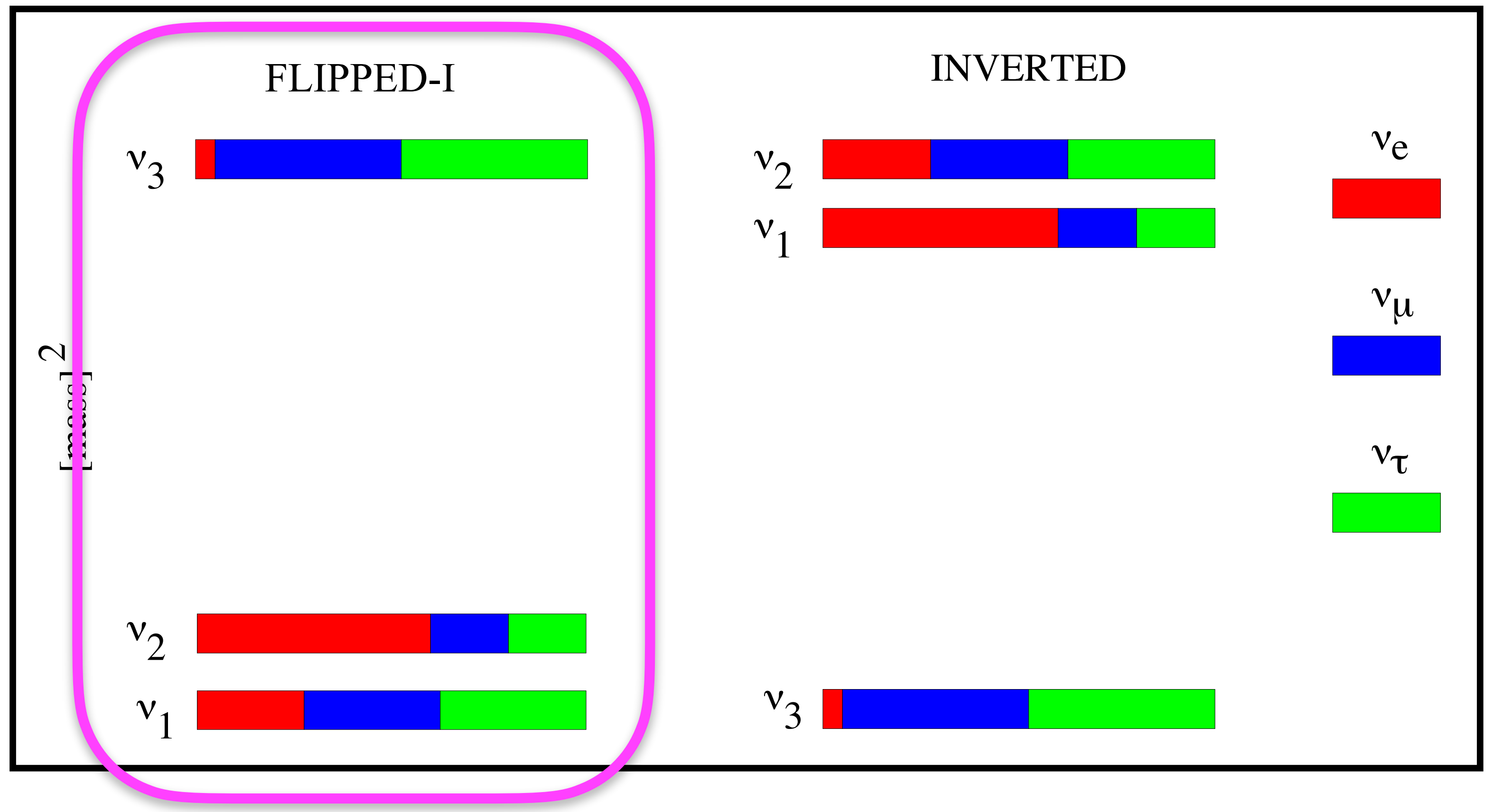




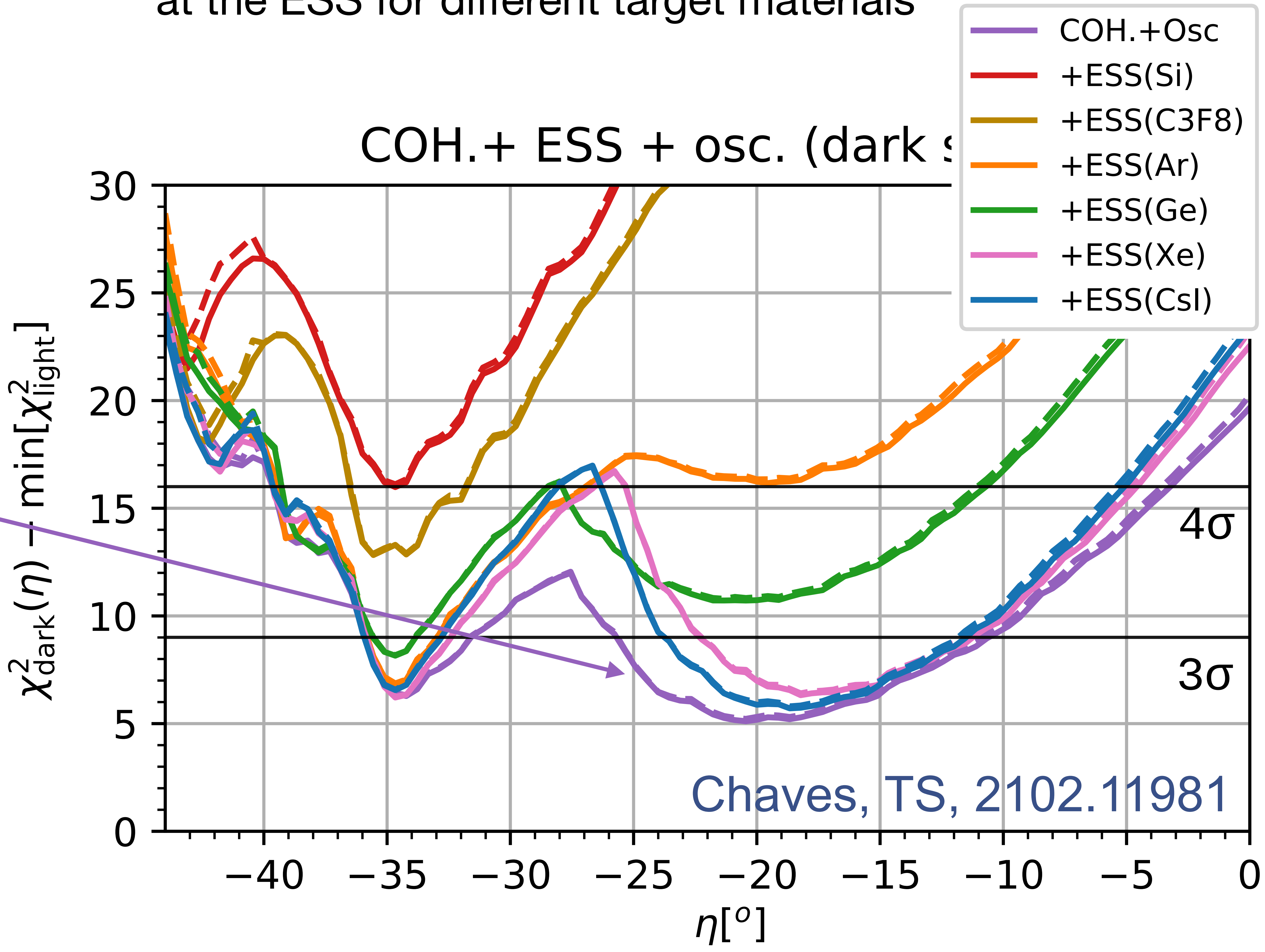
Dark-LMA and coherent neutrino-nucleus scattering

- Coherent neutrino-nucleus scat. crucial test of dark-LMA
  Coloma et al.1708.02899; Giunti, 1909.00466; Coloma et al., 1911.09109…

- recent COHERENT data on Ar disfavours dark-LMA at ~2σ; three islands:

$$\eta \approx -20^\circ\,, \qquad \epsilon^\eta_{ee} \approx -0.2\,, \qquad \epsilon^\eta_{\mu\mu} \approx 1.2\,,$$
$$\eta \approx -35^\circ\,, \qquad \epsilon^\eta_{ee} \approx -1.8\,, \qquad \epsilon^\eta_{\mu\mu} \approx 1.5\,,$$
$$\eta \approx -35^\circ\,, \qquad \epsilon^\eta_{ee} \approx 2.5\,, \qquad \epsilon^\eta_{\mu\mu} \approx 6.0\,.$$

sensitivity to dark-LMA of future CEvNS experiment at the ESS for different target materials



Dark-LMA and coherent neutrino-nucleus scattering

- significant rejection requires data from targets with different Z/N, to avoid „blind spot“ e.g. CsI vs Si

$$\epsilon_{\alpha\beta}^{Y,\eta} = \epsilon_{\alpha\beta}^{p} + Y\epsilon_{\alpha\beta}^{n} = \sqrt{5}\epsilon_{\alpha\beta}^{\eta}(\cos\eta + Y\sin\eta)$$

Target	Z	Y	η_{blind}
C_3F_8	8.2	1.081	$-42.8°$
Si	14	1.006	$-44.8°$
Ar	18	1.235	$-39.0°$
Ge	32	1.270	$-38.2°$
CsI	54	1.405	$-35.4°$
Xe	54	1.431	$-35.0°$

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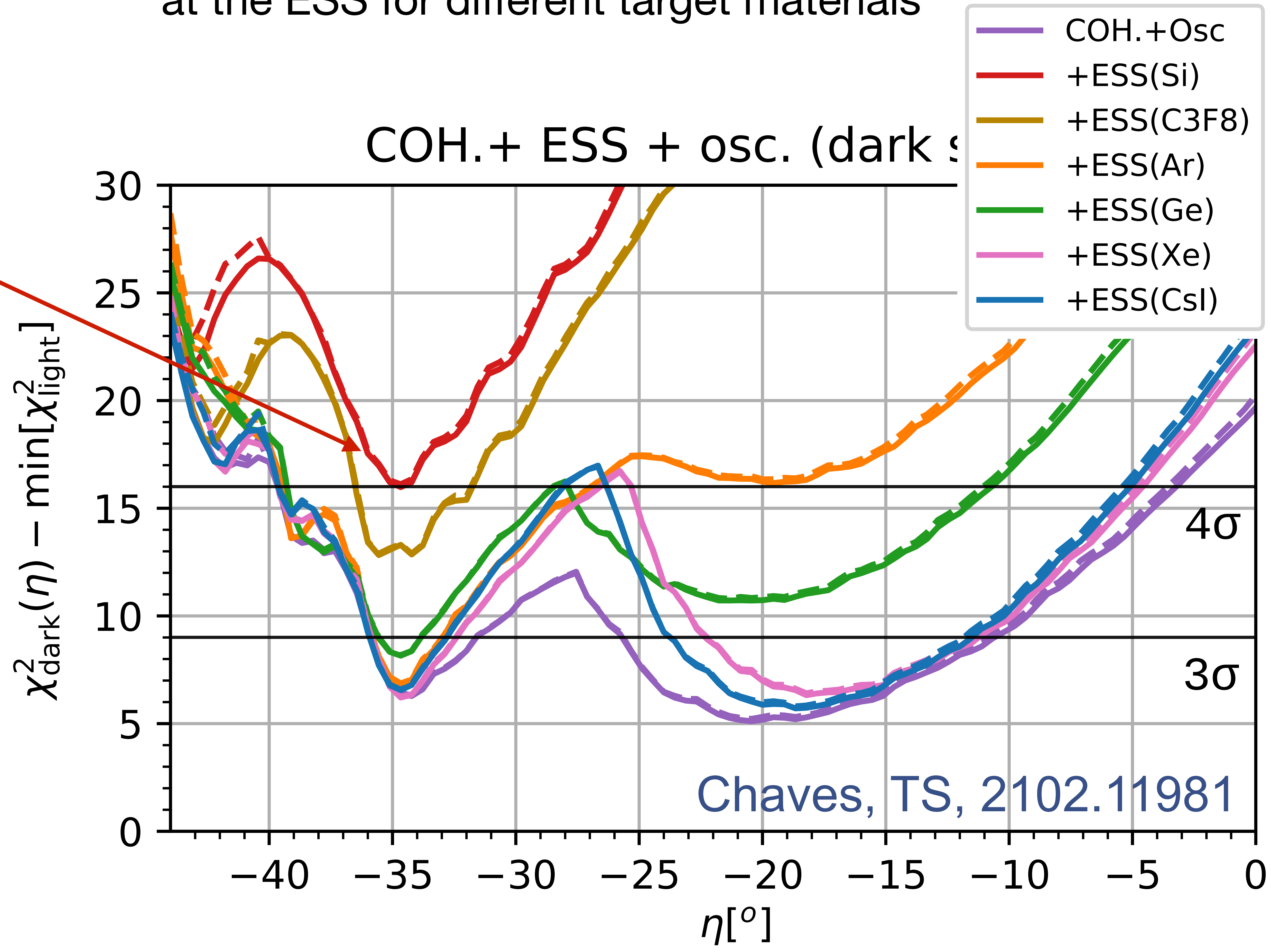

Summary

- updated results from global 3-flavour fit
  - determination of mass-ordering, θ_{23}-octant, CP phase: interplay of accelerator / reactor / atmospheric data — hints not yet statistically significant
- eV sterile neutrinos
  - hints from reactor experiments are disappearing
  - explaining LSND/MiniBooNE requires more elaborate new physics
  - strong constraints from cosmology
- non-standard neutrino interactions (EFT)
  - currently no indications in data
  - but O(1) NSI cannot be excluded: dark-LMA degeneracy: qualitative distortion of mixing pattern allowed at 2σ
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Thank you for your attention!