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HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

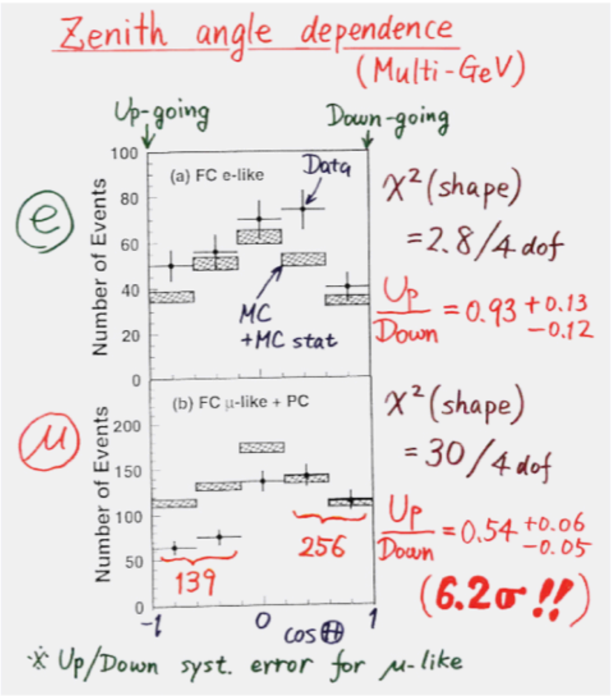
Recent developments in neutrino oscillations from a phenomenology perspective

Thomas Schwetz-Mangold

KAT Strategietreffen — 4. Dez. 2020

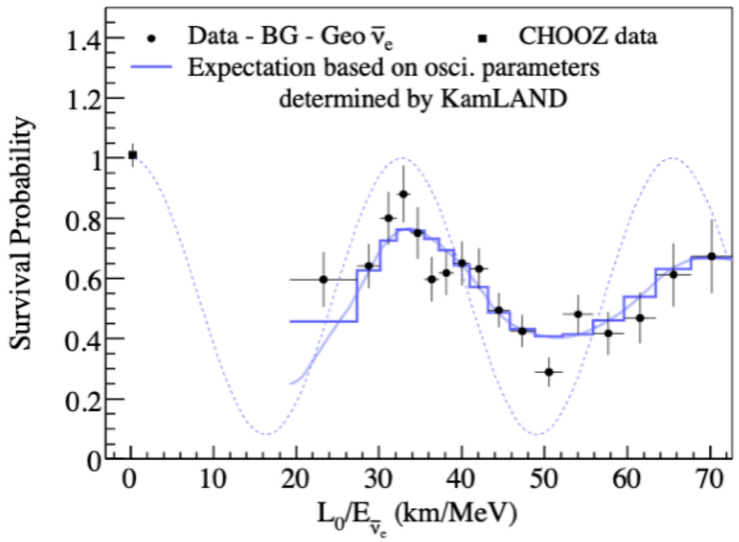
Neutrinos oscillate!

SuperK 1998 atmospheric neutrinos



KamLAND 2006

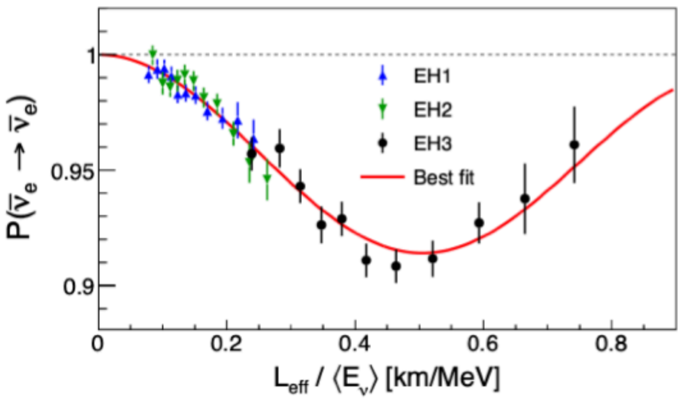
reactor neutrinos ~ 180 km



neutrinos have mass → Standard Model of particle physics needs to be extended!

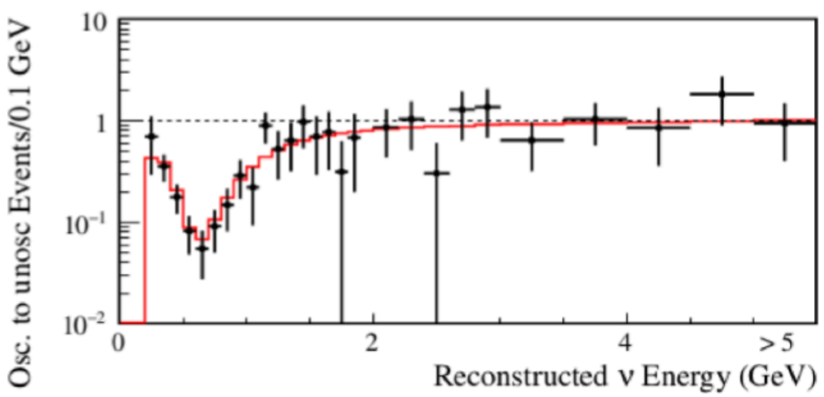
DayaBay, 2015

$\bar{\nu}_e \to \bar{\nu}_e$, $\langle L \rangle \sim 2$ km



T2K, 2015

$\nu_\mu \to \nu_\mu$, $\langle L \rangle \sim 295$ km



3-flavour neutrino parameters

- 3 masses: Δm^2_{21}, Δm^2_{31}, m_0
- 3 mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$
- 3 phases: 1 Dirac (δ), 2 Majorana (α_1, α_2)

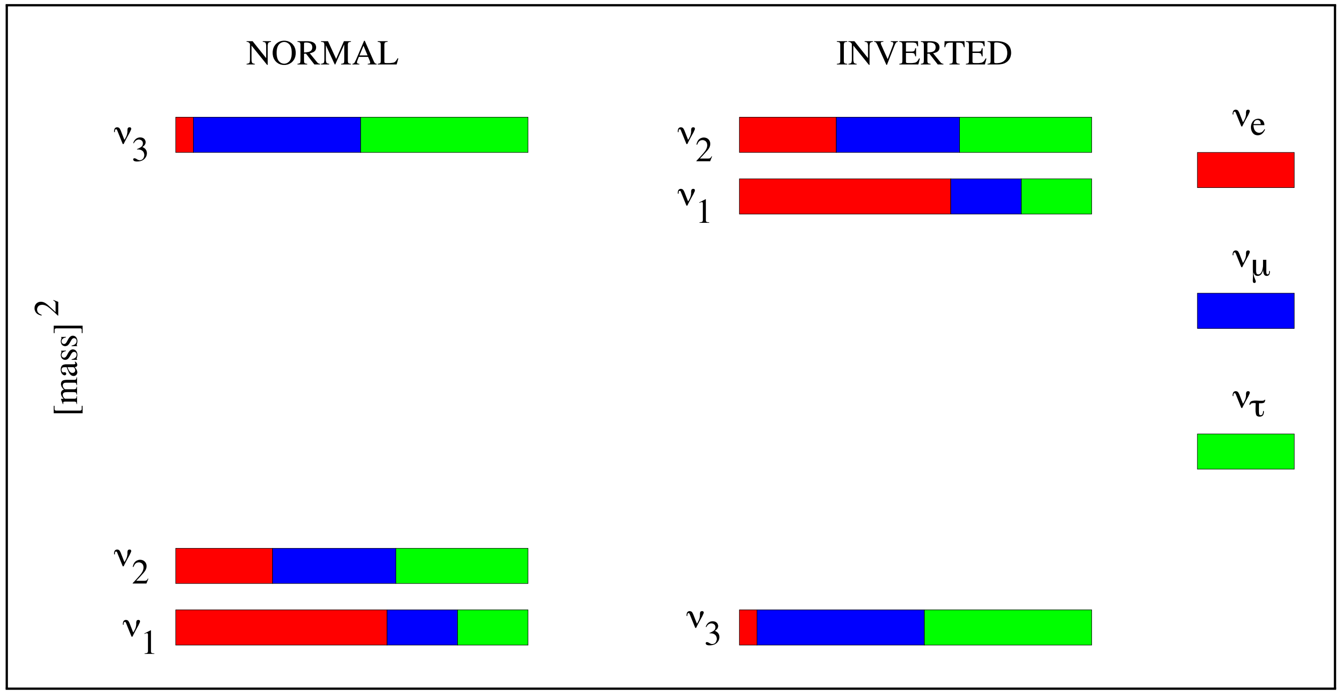
neutrino oscillations
absolute mass observables
lepton-number violation

$$U = \begin{array}{ccc} \Delta m^2_{31} & & \Delta m^2_{21} \\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} & \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} & \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ \text{atm+LBL(dis)} & \text{react+LBL(app)} & \text{solar+KamLAND} \end{array}$$

3-flavour effects are suppressed: $\Delta m^2_{21} \ll \Delta m^2_{31}$ and $\theta_{13} \ll 1$ ($U_{e3} = s_{13} e^{-i\delta}$)

$\Rightarrow$ dominant oscillations are well described by effective two-flavour oscillations
$\Rightarrow$ present data is already sensitive to sub-leading effects

The rough picture



- the two mass-squared differences are separated roughly by a factor 30:

$$\Delta m^2_{21} \approx 7 \times 10^{-5}\text{eV}^2\,, \quad |\Delta m^2_{31}| \approx |\Delta m^2_{32}| \approx 2.4 \times 10^{-3}\text{eV}^2$$

- at least two neutrinos are massive — two possible orderings
- mixing angles are large

$\sin\theta_{13} = \lvert U_{e3}\rvert$	$(\nu_e$ component in $\nu_3) = (\nu_3$ component in $\nu_e)$	$\theta_{13} \approx 9^\circ$
$\tan\theta_{12} = \frac{\lvert U_{e2}\rvert}{\lvert U_{e1}\rvert}$	ratio of ν_2 and ν_1 component in ν_e	$\theta_{12} \approx 33^\circ$
$\tan\theta_{23} = \frac{\lvert U_{\mu 3}\rvert}{\lvert U_{\tau 3}\rvert}$	ratio of ν_μ and ν_τ component in ν_3	$\theta_{23} \approx 45^\circ$

Complementarity of global oscillation data

param	experiment	comment
θ_{12}	SNO, SuperK, (KamLAND)	resonant matter effect in the Sun
θ_{23}	SuperK, T2K, NOvA	ν_μ disappearance atmospheric (accelerator) neutrinos
θ_{13}	DayaBay, RENO, D-Chooz (T2K, NOvA)	$\bar{\nu}_e$ disappearance reactor experiments @ ~ 1 km
Δm^2_{21}	KamLAND, (SNO, SuperK)	$\bar{\nu}_e$ disappearance reactor @ ~ 180 km (spectrum)
$\lvert\Delta m^2_{31}\rvert$	MINOS, T2K, NOvA, DayaBay	ν_μ and $\bar{\nu}_e$ disapp (spectrum)
δ	T2K, NOvA + DayaBay	combination of $(\nu_\mu \to \nu_e) + \bar{\nu}_e$ disap

⇒ **global analysis** (especially sub-leading 3-flavour effects)

NuFit collaboration: www.nu-fit.org with M.C. Gonzalez-Garcia, M. Maltoni, et al.
NuFIT 5.0: Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, 2007.14792

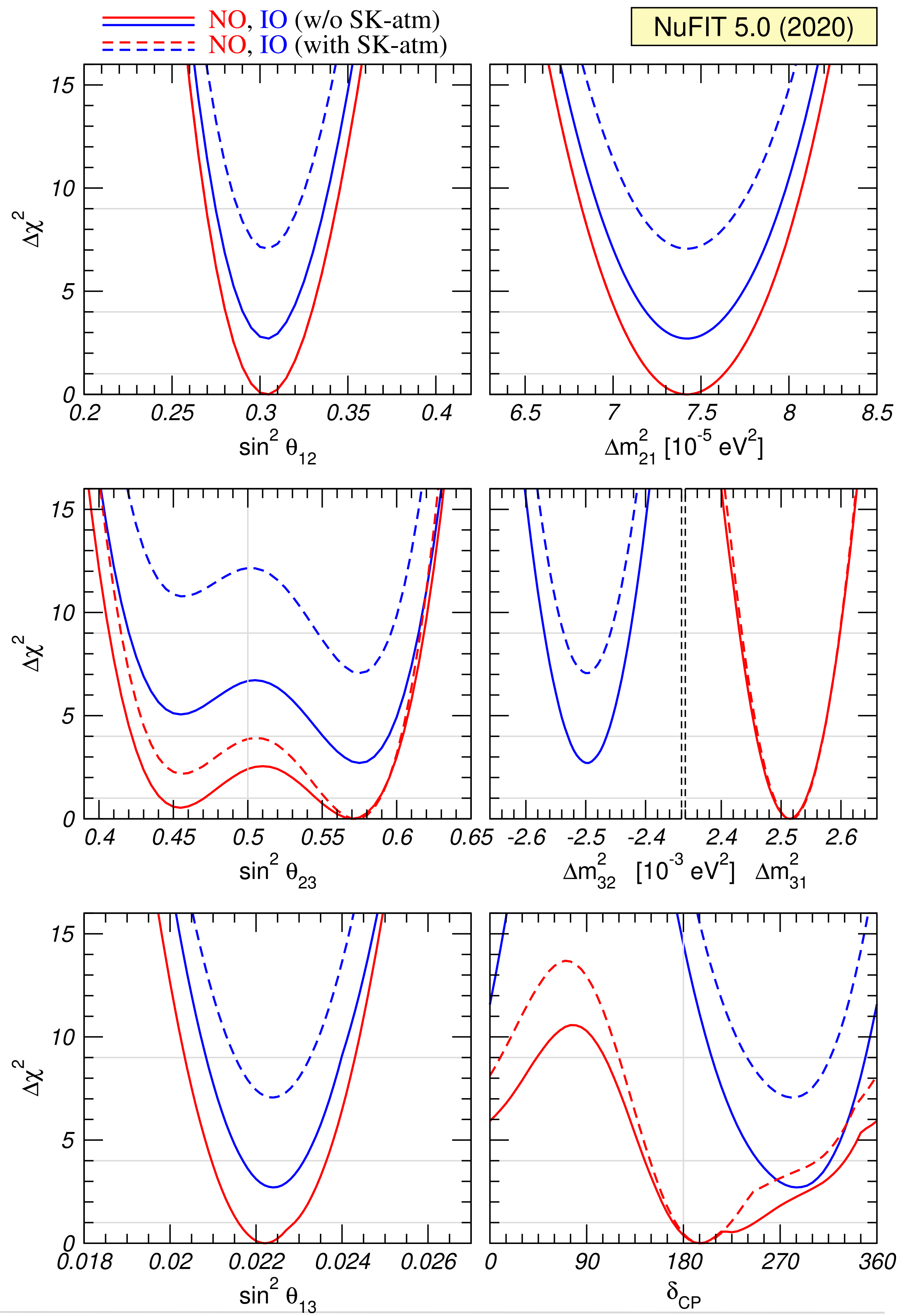
compatible results from Bari (Lisi et al.) and Valencia (Tortola et al.) groups

NuFit 5.0 results

www.nu-fit.org

NuFIT 5.0 (2020)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
	$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
	$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{\mathrm{CP}}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$
		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	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{\mathrm{CP}}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$



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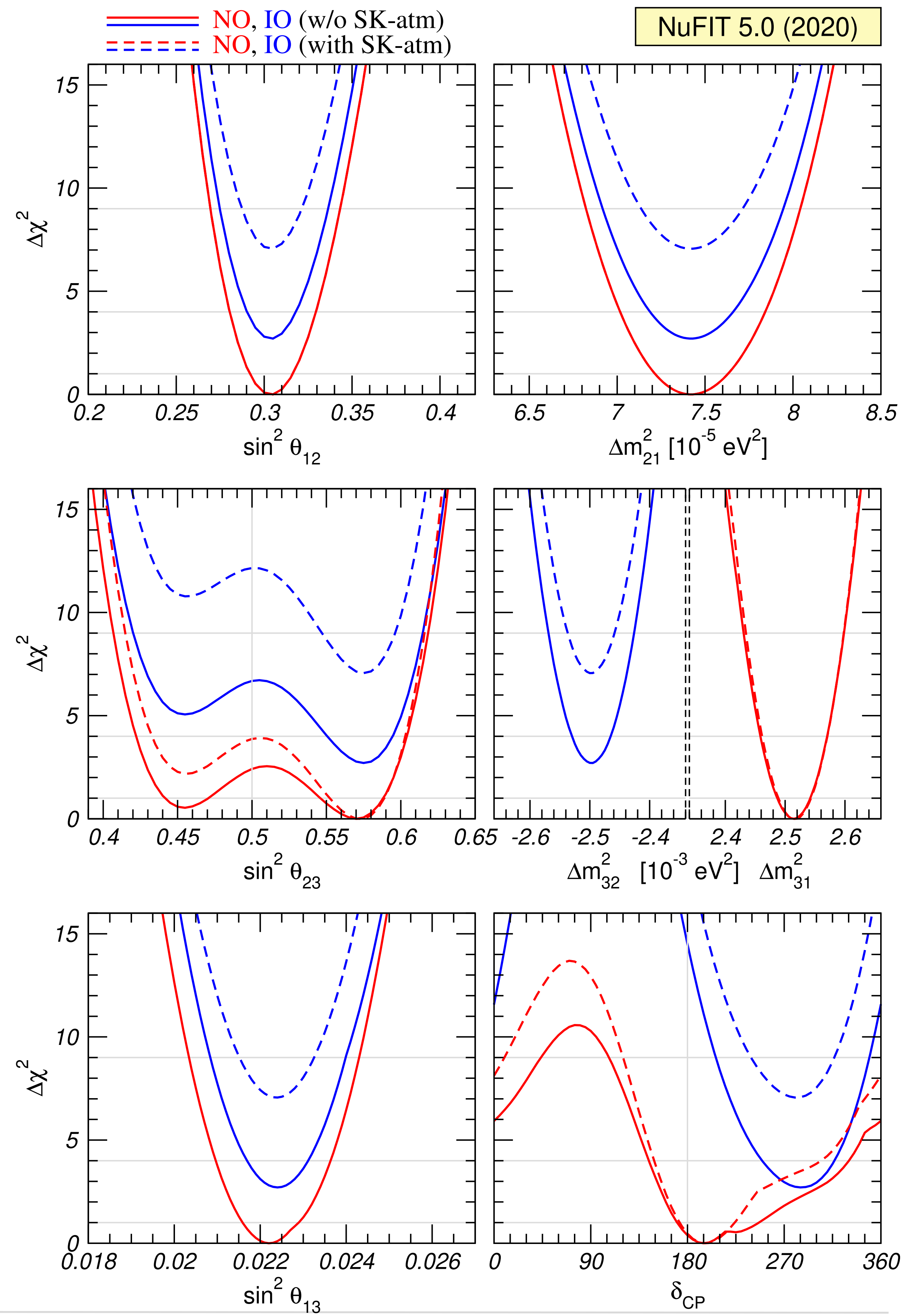
NuFit 5.0 results

- robust determination (relat. precision at 3σ):

$$\theta_{12}\,(14\%)\;,\quad \theta_{13}\,(9\%)$$
$$\Delta m^2_{21}\,(16\%)\,,\quad |\Delta m^2_{3\ell}|\,(6.7\%)$$

- broad allowed range for $\theta_{23}\,(27\%)$, non-significant indications for non-maximality/octant
- ambiguity in sign of $\Delta m^2_{3\ell}$ $\rightarrow$ mass ordering
- values of $\delta_{\mathrm{CP}} \simeq 90^\circ$ disfavoured



CP violation and mass ordering

status about one year ago:

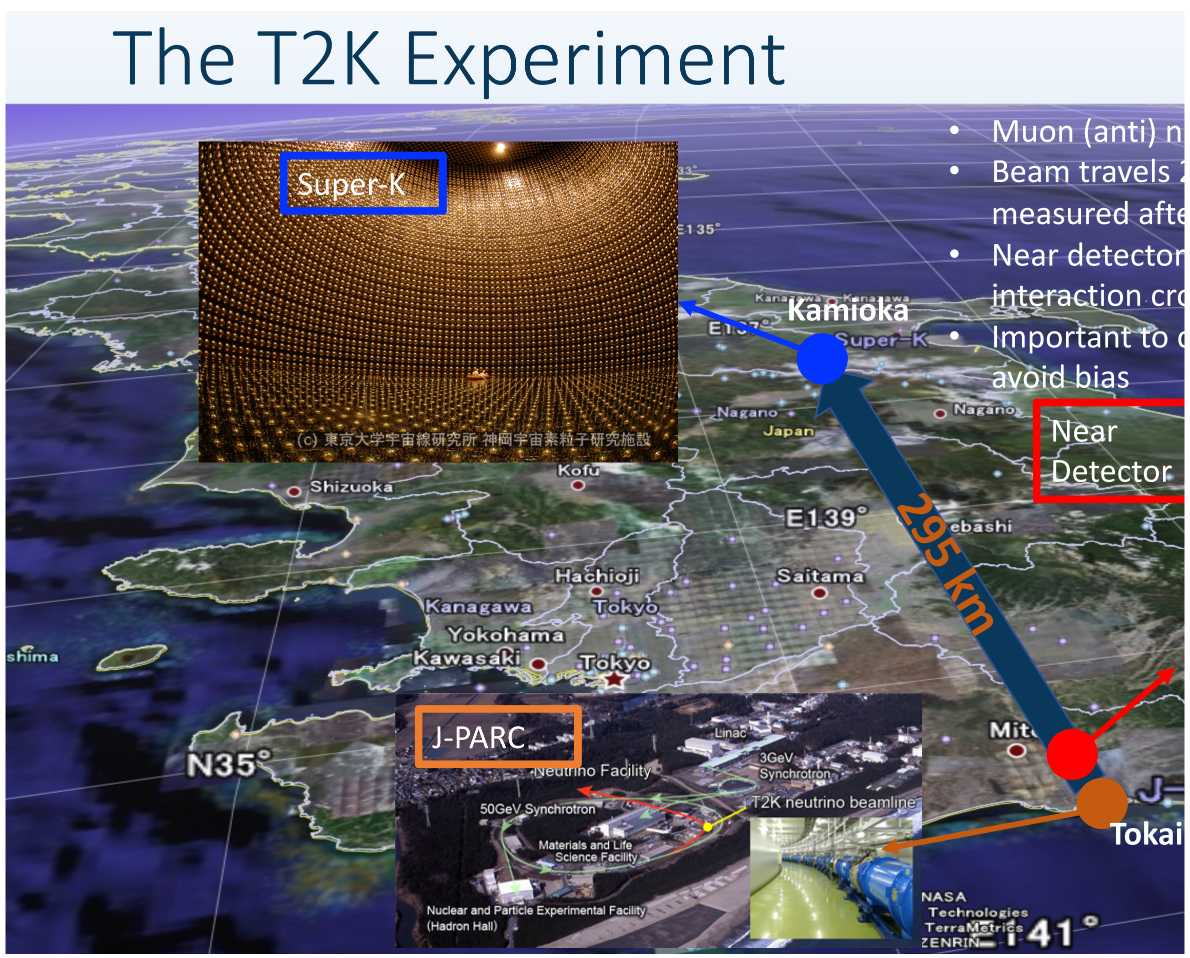
- preference for normal mass ordering ~3σ
  (subtle interplay of global data)

- hints for „large“ CP violation ~2-3σ
  (mostly driven by T2K versus DayaBay)

New data from T2K and NOvA at Neutrino20 (June 2020)
neutrino samples increased by 32% / 54% resp.

T2K and NOvA accelerator experiments

- $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ disappearance
- $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance



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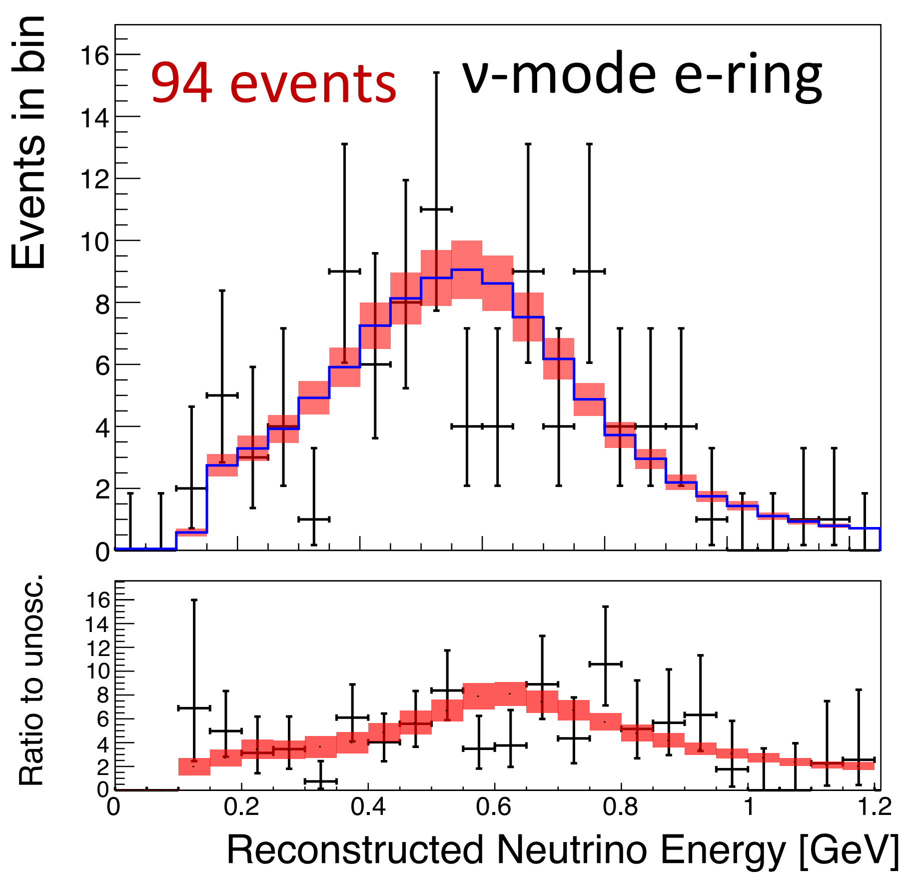
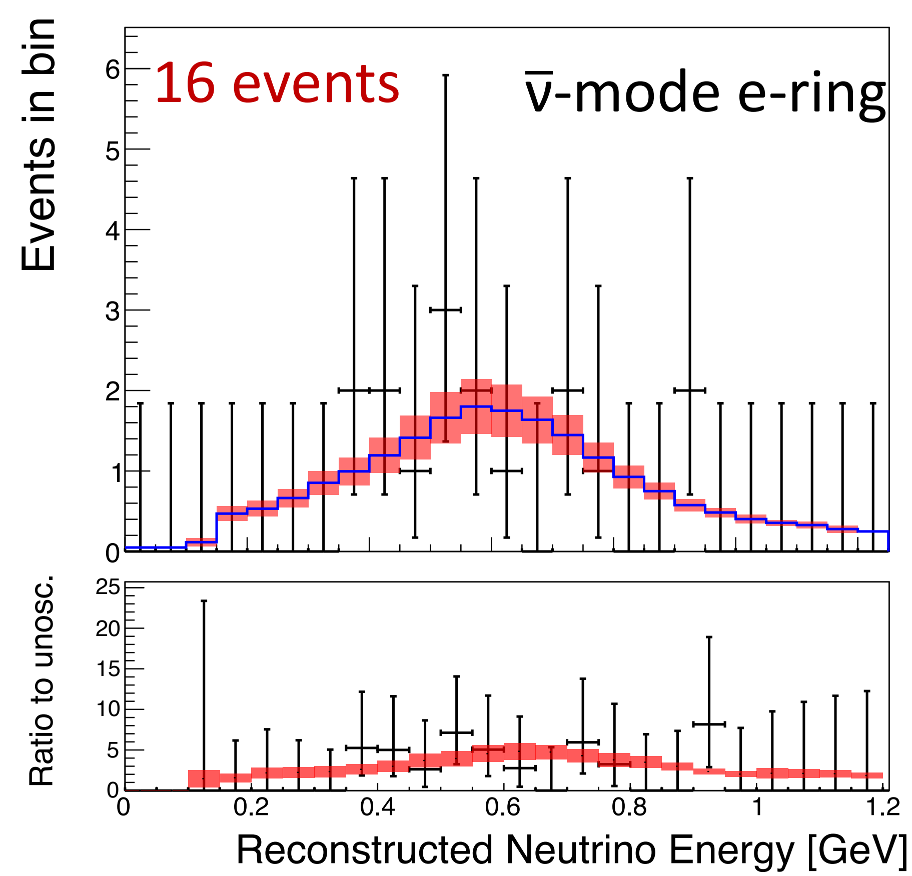
T2K and NOvA Neutrino20 $\nu_\mu \rightarrow \nu_e$ appearance results

T2K Run 1-10 Preliminary



T2K Run 1-10 Preliminary



NOvA neutrino

Total Observed	82	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28

NOvA anti-neutrino

Total Observed	33	Range
Total Prediction	33.2	25-45
Wrong-sign	2.3	1.0-3.2
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd.	14.0	13-15

>4σ evidence of $\bar{\nu}_e$ appearance

Latest results from T2K and NOvA

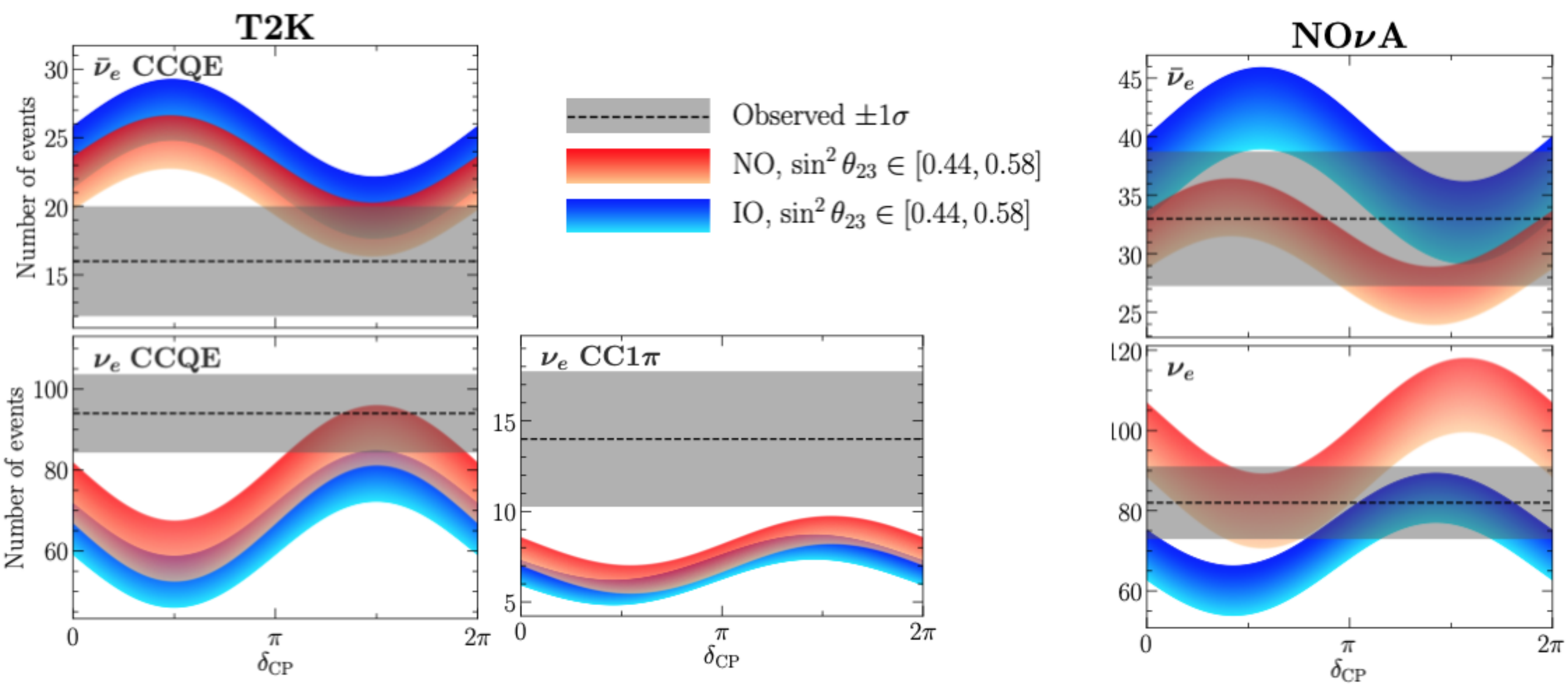
determined by DayaBay, RENO, DoubleChooz

$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(1-A)\Delta}{(1-A)^2} + \sin 2\theta_{13}\, \hat{\alpha}\, \sin 2\theta_{23} \frac{\sin(1-A)\Delta}{1-A} \frac{\sin A\Delta}{A} \cos(\Delta + \delta_{\rm CP})$$

$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}$$

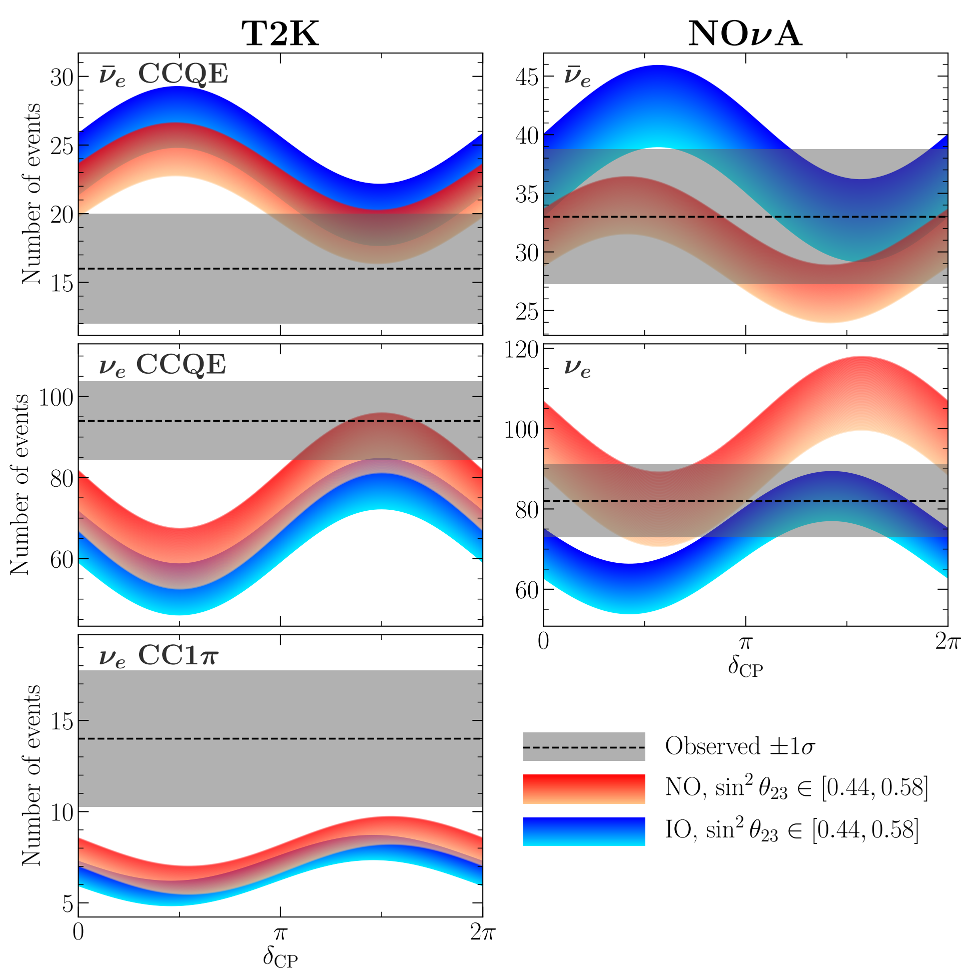
$$\hat{\alpha} \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sin 2\theta_{12}$$

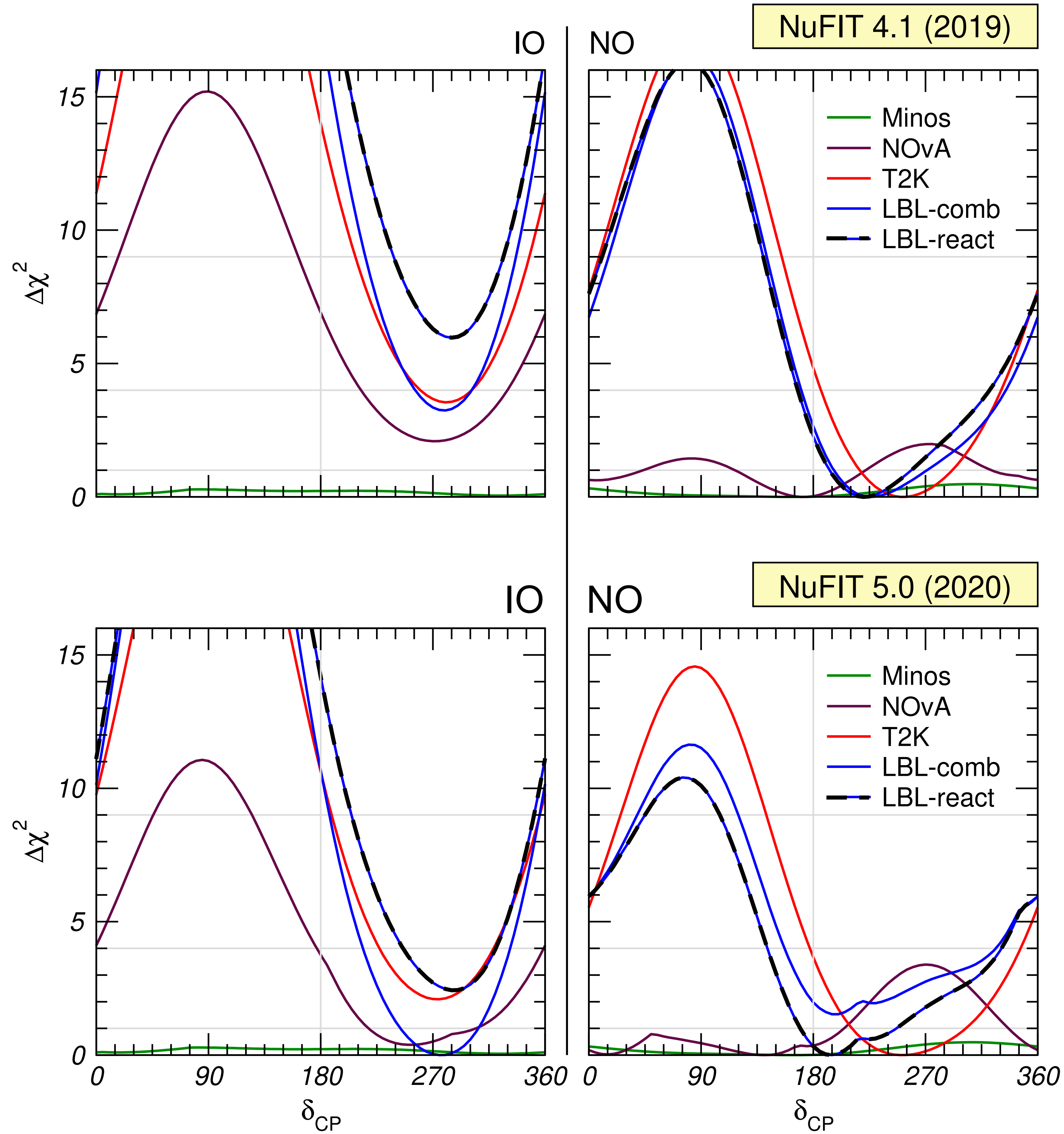
$$A \equiv \frac{2E_\nu V}{\Delta m^2_{31}}$$



Status of mass ordering and CP phase

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

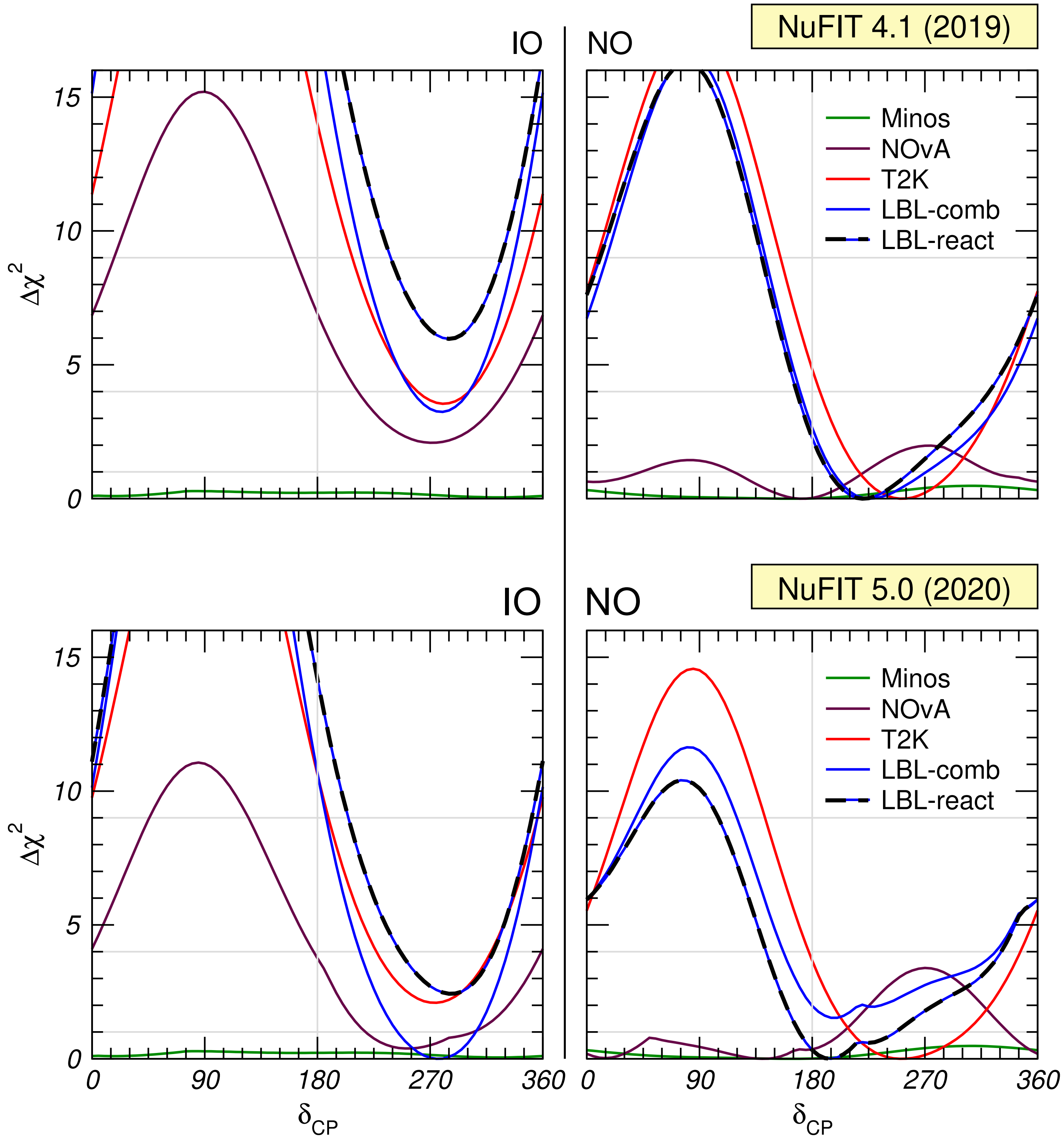




Esteban et al., 2007.14792

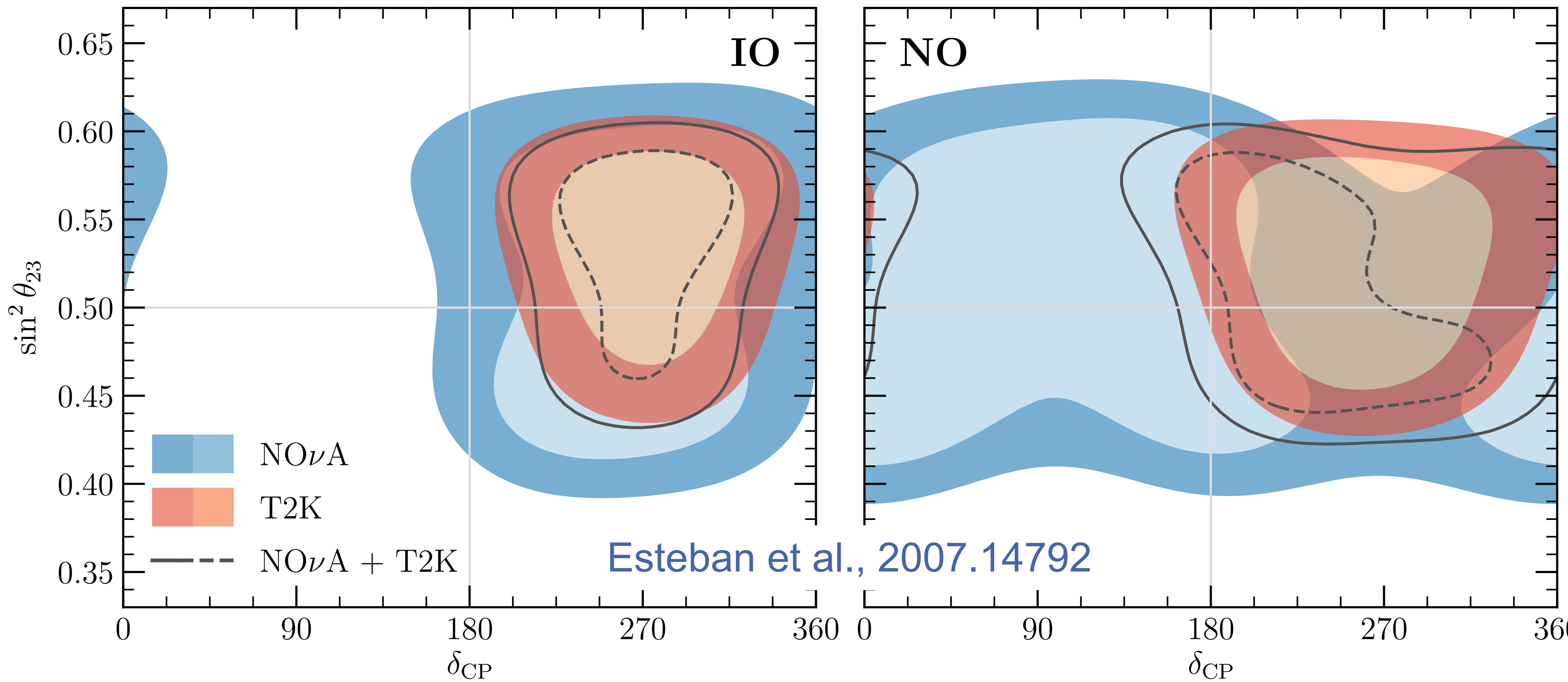
Status of mass ordering and CP phase

- T2K and NOvA better compatible for IO → LBL combination best fit for IO
- 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 conserv. disfavoured at 3σ



Esteban et al., 2007.14792

T2K and NOvA are statistically consistent for both orderings



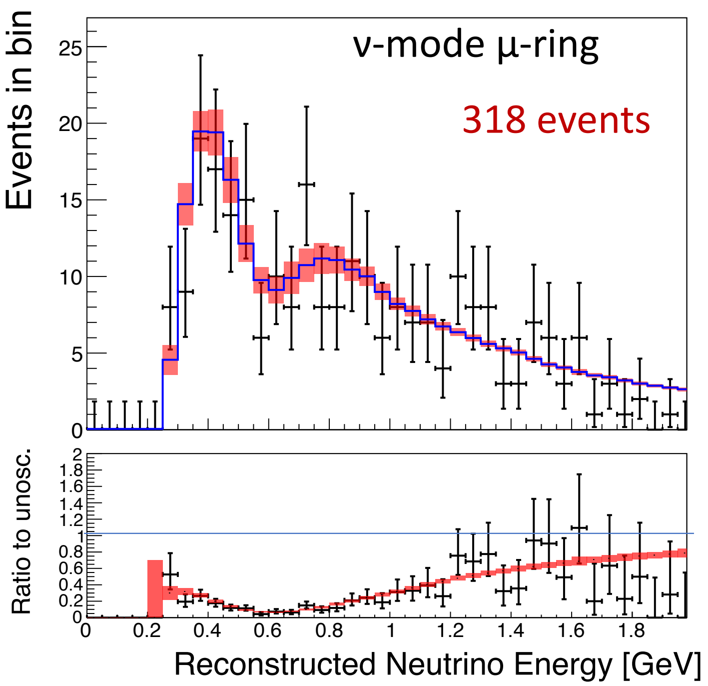
Esteban et al., 2007.14792

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 $|\Delta m^2_{3\ell}|$.

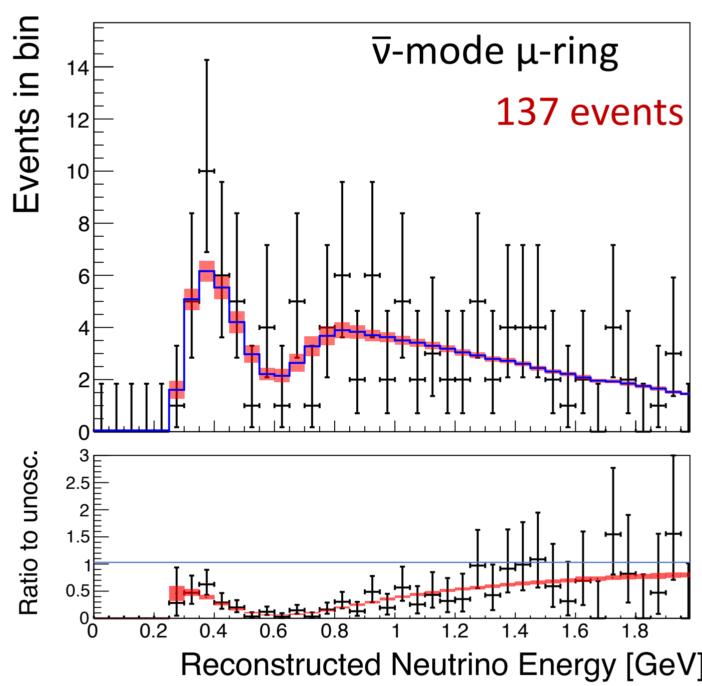
μ and e disappearance

T2K @ Neutrino20

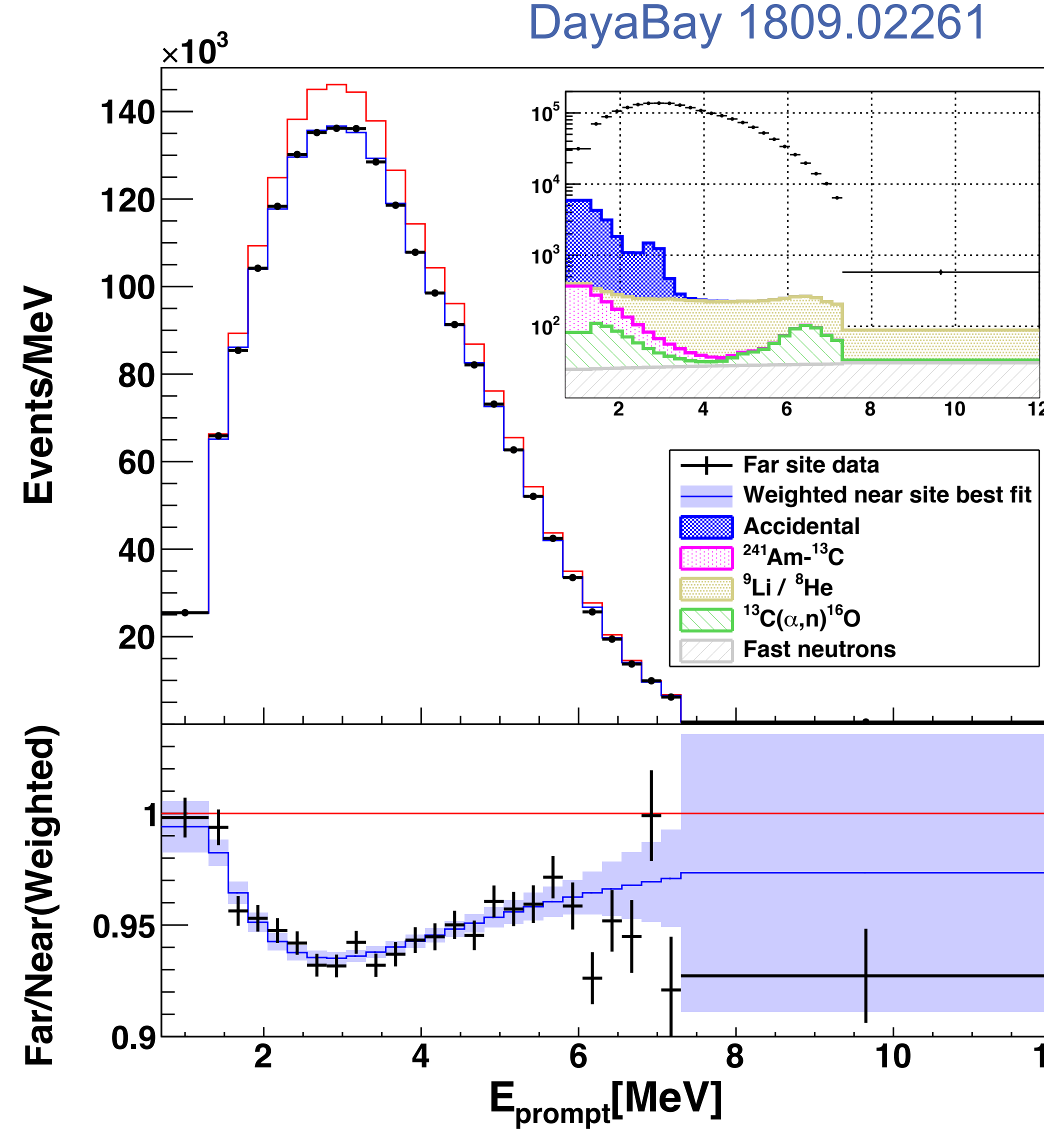
T2K Run 1-10 Preliminary



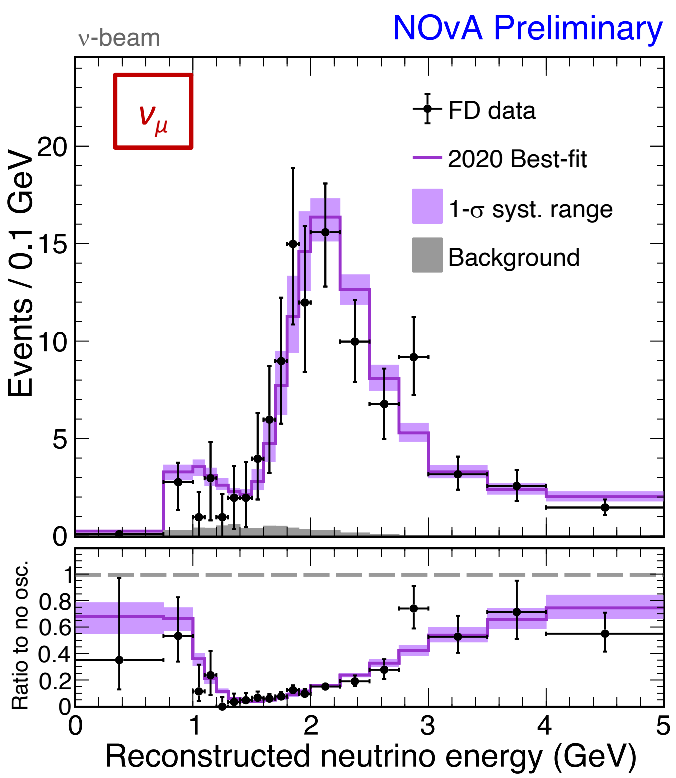
T2K Run 1-10 Preliminary

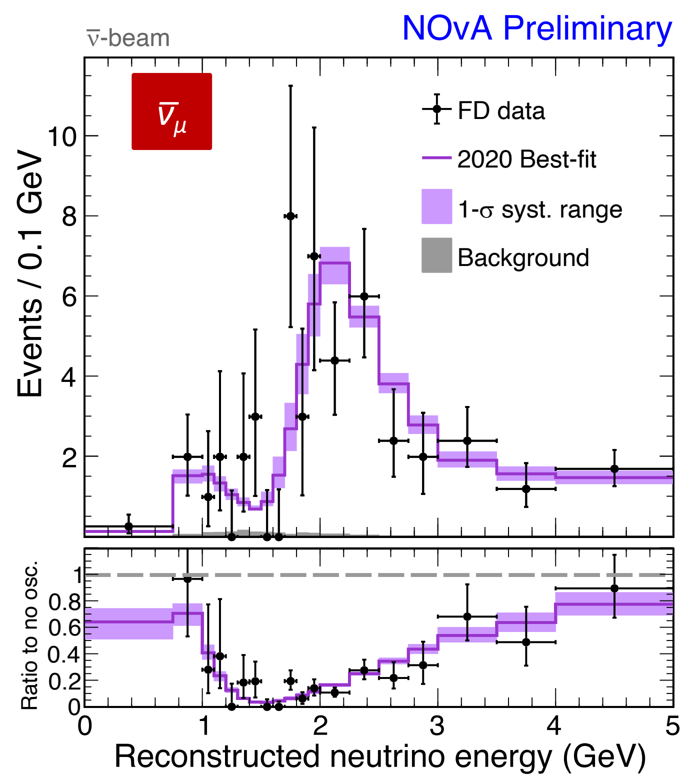


DayaBay 1809.02261



NOvA @ Neutrino20

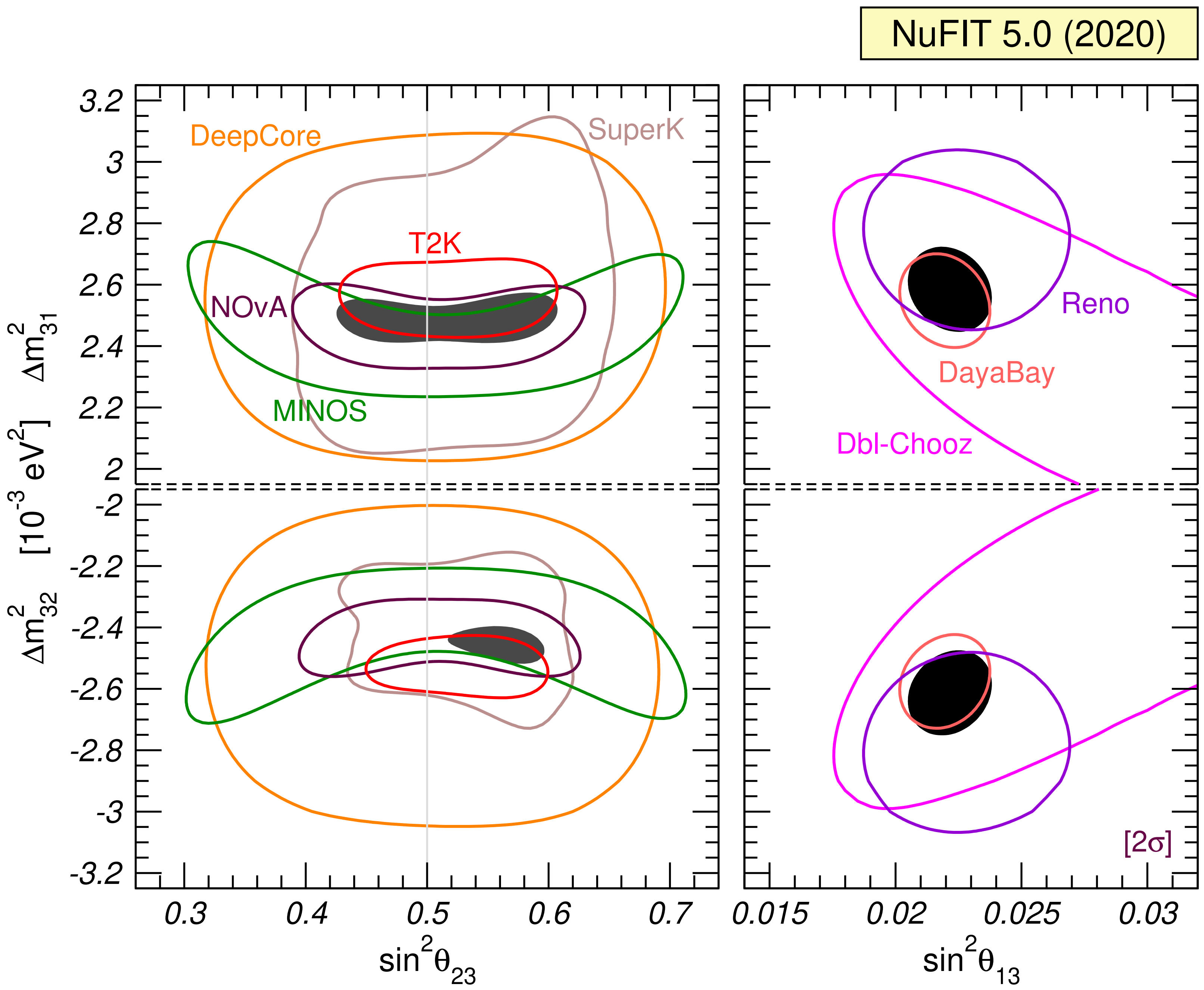




211 events, 8.2 background

105 events, 2.1 background

Consistency of μ and e disappearance

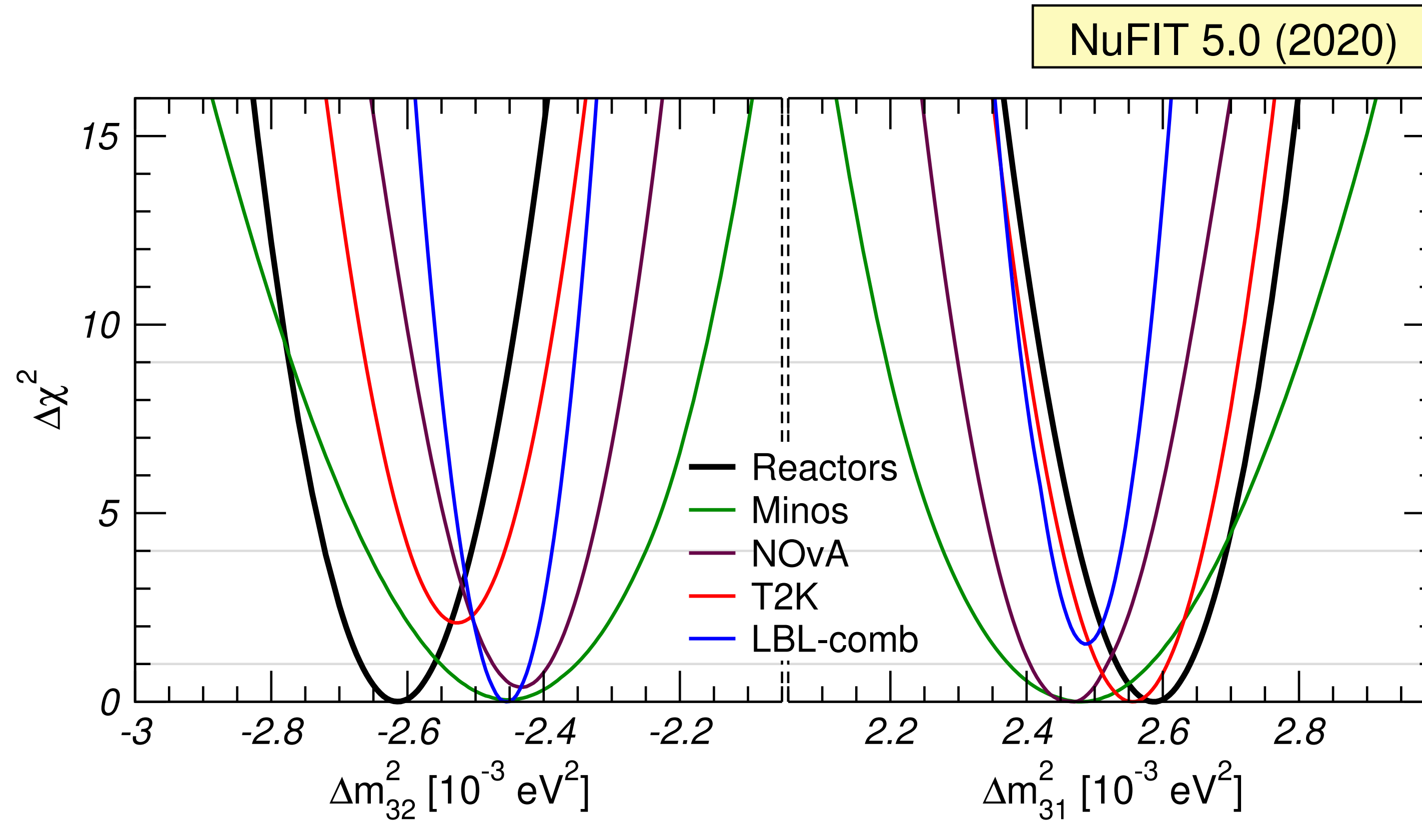


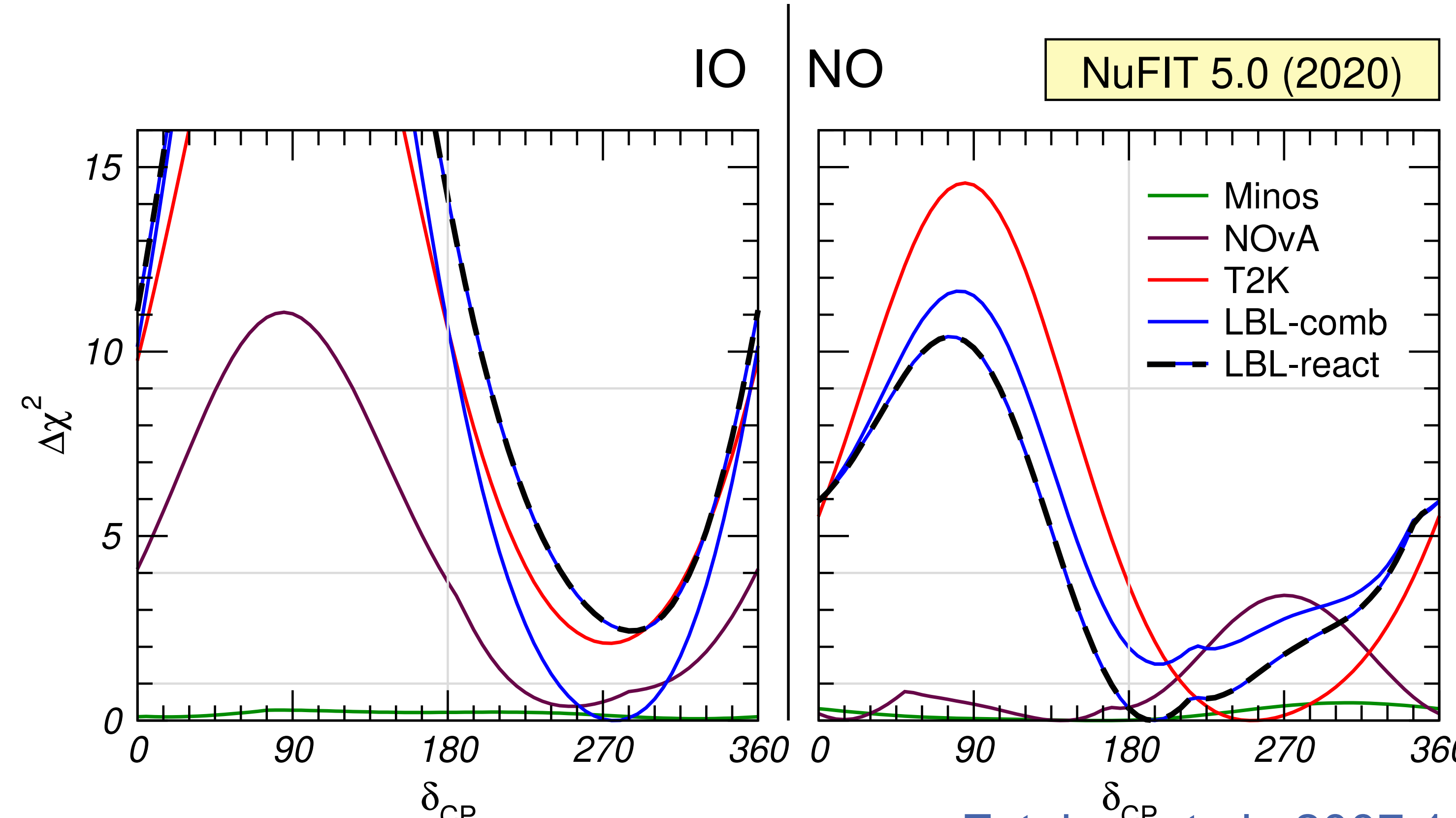
$$|\Delta m^2_{\mu\mu}| = |\Delta m^2_{ee}| \mp \Delta m^2_{21} \left[\cos 2\theta_{12} - \cos\delta \sin\theta_{13} \sin 2\theta_{12} \tan\theta_{23}\right]$$

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

Status of mass ordering

- T2K and NOvA better compatible for IO → LBL combination best fit for IO
- LBL/reactor determ of Δm^2 better for NO →
- overall preference for NO with $\Delta\chi^2 = 2.7$ (was 6.2 in 2019)

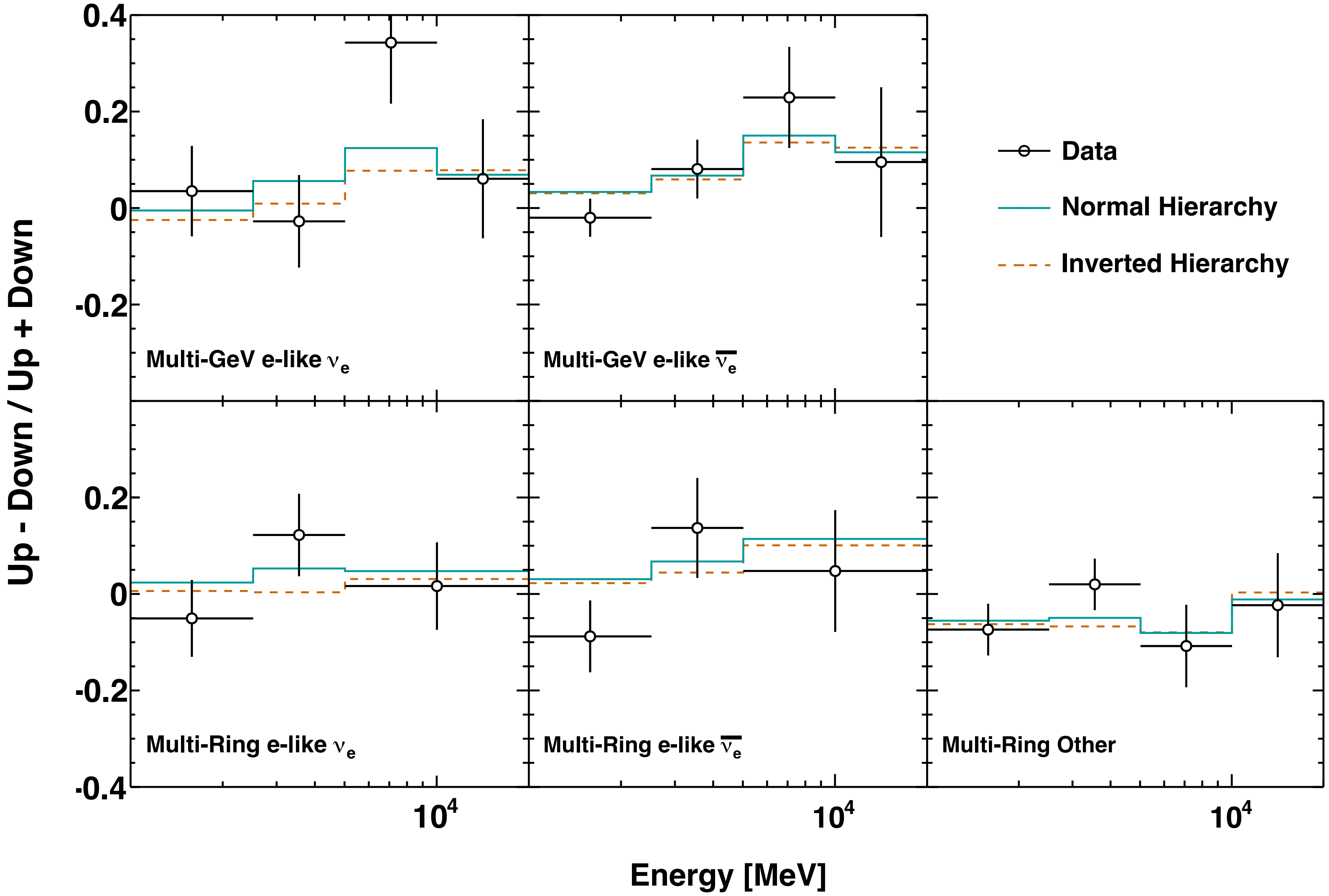


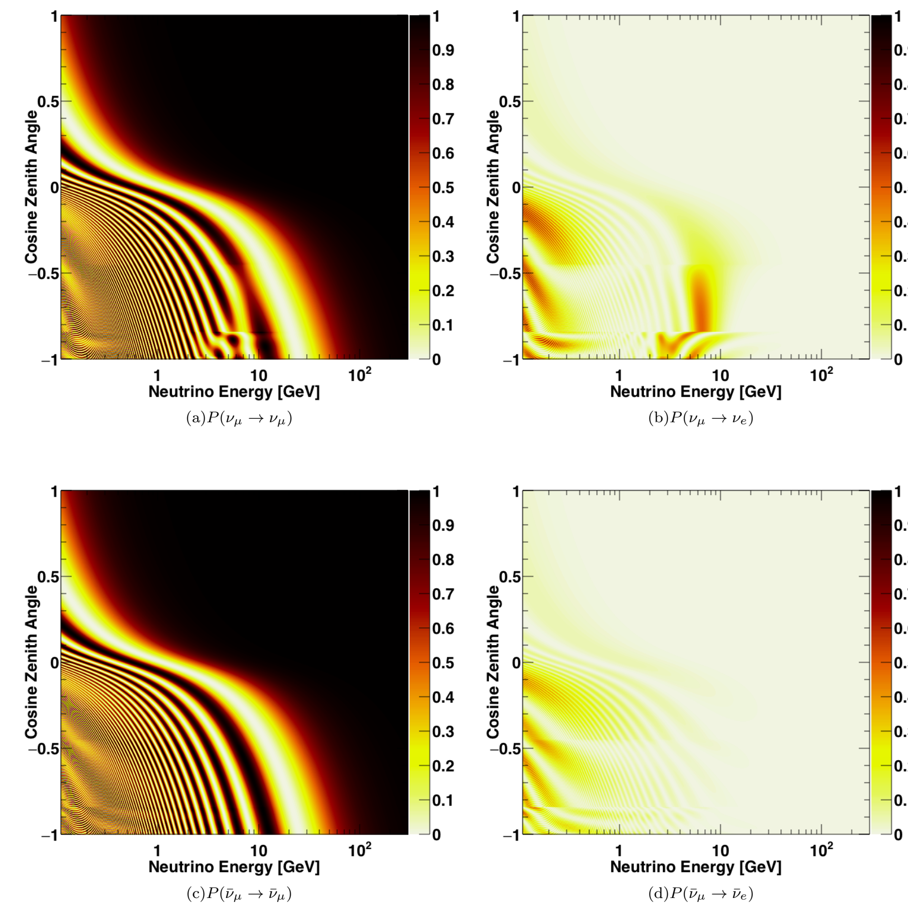


Esteban et al., 2007.14792

Mass ordering - atmospheric neutrinos

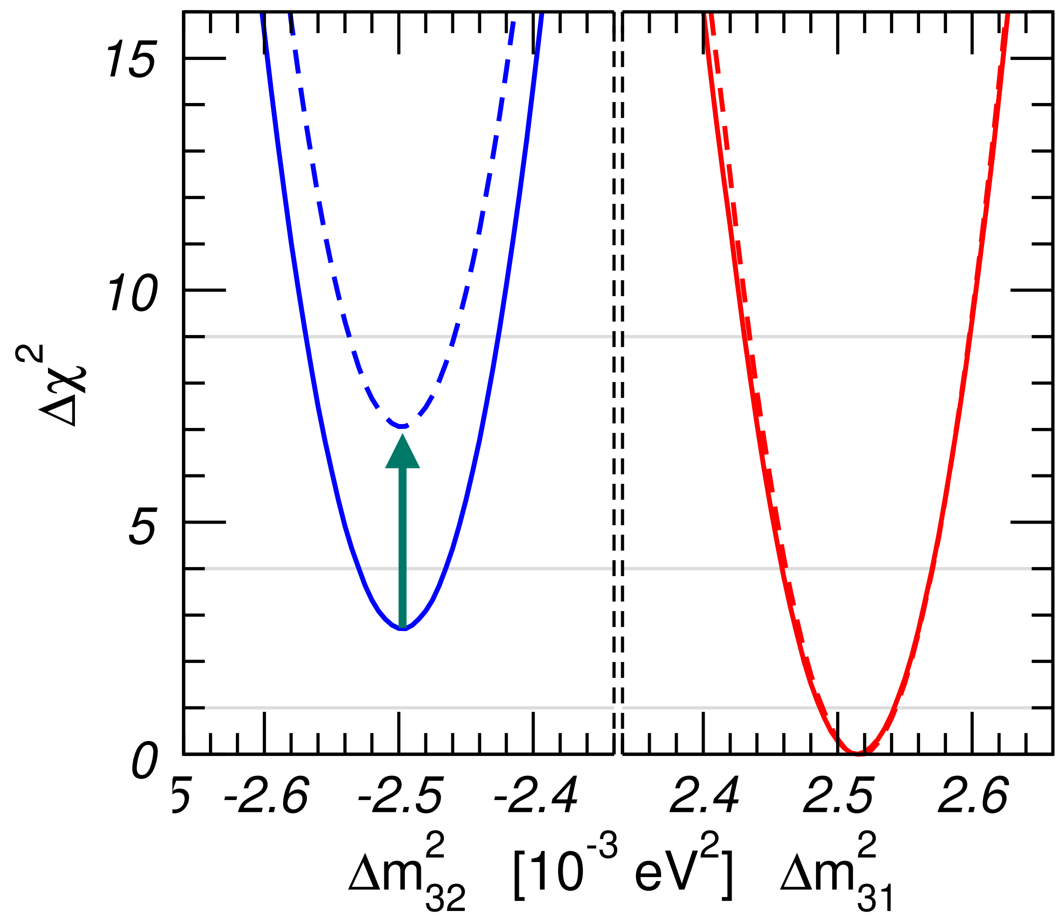
Super-Kamiokande I-IV, 1710.09126





- $\chi^2_{(IO)} - \chi^2_{(NO)} = 4.3$
- analysis not reproducable outside SK
- add χ^2 table to global fit („black box“)

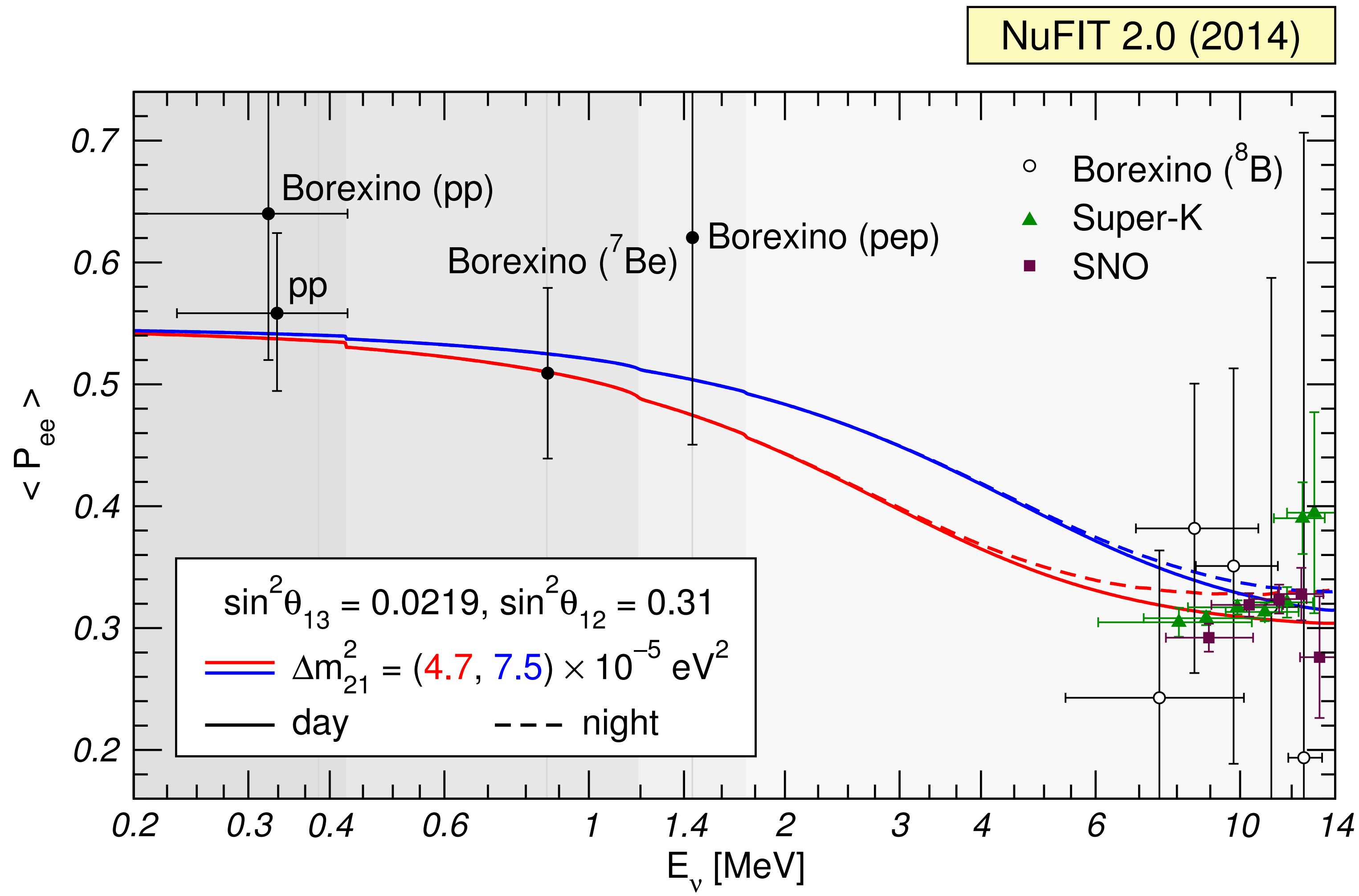
Mass ordering - atmospheric neutrinos



- global analysis (using SK I-IV, 1710.09126):
  χ^2(IO) - χ^2(NO) = 2.7 (no SK) → 7.1 (w SK) 2.7σ was 10.4 (3.2σ) in 2019

- NOTE: recent SK update @ Neutrino20: improved analysis:
  χ^2(IO) - χ^2(NO) = 4.3 → 3.2 (χ^2 table not available yet)

Small „tension“ (2σ) in 12 sector

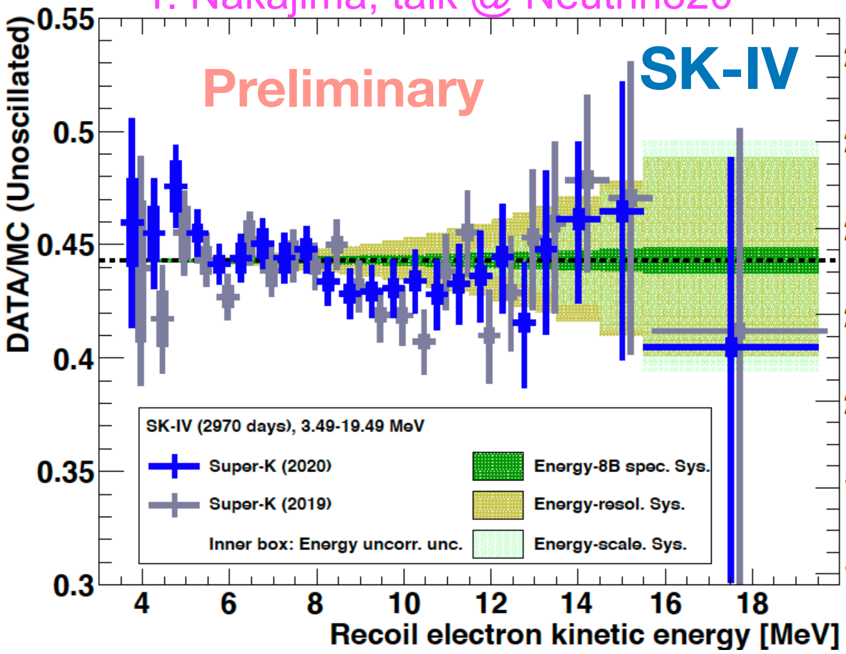


long-standing tension between Δm² from KamLAND and solar neutrinos:

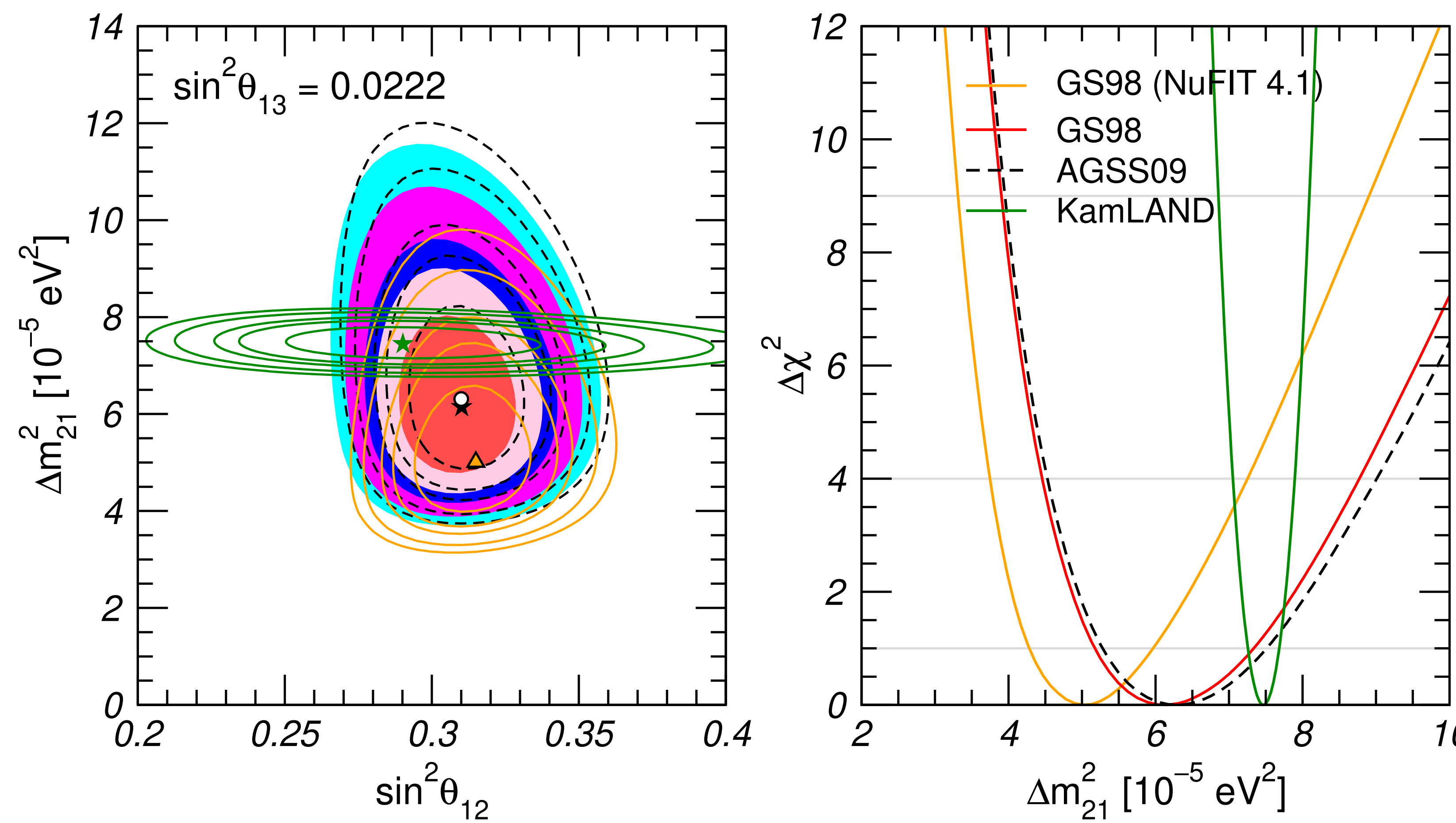
- missing up-turn of high-energy solar neutrino spectrum
- too large day-night effect

Small „tension“ (2σ) in 12 sector: RESOLVED

Y. Nakajima, talk @ Neutrino20



NuFIT 5.0 (2020)



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

Summary

- 3-flavour oscillation paradigm very successful
  excellent description of global data

- previous hints for CP violation disappeared
  mostly due to new T2K and NOvA results:
  - CP cons. @ 0.6σ
  - if restricted to inverted ordering: CPV preferred at ~3σ

- previous hints for normal ordering decreased:
  - $\Delta\chi^2_{(IO)}$ = 2.7 (no SK atm) / 7.1 (w SK atm)

    opposite tendencies in different sets of experiments
  - preference for NO from SK atm is decreasing

- previous tension between solar and KamLAND data resolved with
  latest SuperK solar neutrino data

Thank you for your attention!

Supplementary slides

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T2K, NOvA, and reactors are consistent with each others

data sets	normal ordering			inverted ordering		
	$\chi^2_{\rm PG}/n$	p-value	$\#\sigma$	$\chi^2_{\rm PG}/n$	p-value	$\#\sigma$
T2K vs NOvA	6.7/4	0.15	1.4σ	3.6/4	0.46	0.7σ
T2K vs React	0.3/2	0.87	0.2σ	2.5/2	0.29	1.1σ
NOvA vs React	3.0/2	0.23	1.2σ	6.2/2	0.045	2.0σ
T2K vs NOvA vs React	8.4/6	0.21	1.3σ	8.9/6	0.18	1.3σ
T2K vs NOvA	6.5/3	0.088	1.7σ	2.8/3	0.42	0.8σ
T2K vs NOvA vs React	7.8/4	0.098	1.7σ	7.2/4	0.13	1.5σ

Table 2. Testing the consistency of different data sets shown in the first column assuming either normal or inverted ordering. "React" includes Daya-Bay, RENO and Double-Chooz. In the analyses above the horizontal line, θ_{13} is a free parameter, whereas below the line we have fixed $\sin^2\theta_{13} = 0.0224$. See text for more details.

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, 2007.14792