Global analysis of neutrino oscillation results

Thomas Schwetz

www.nu-fit.org

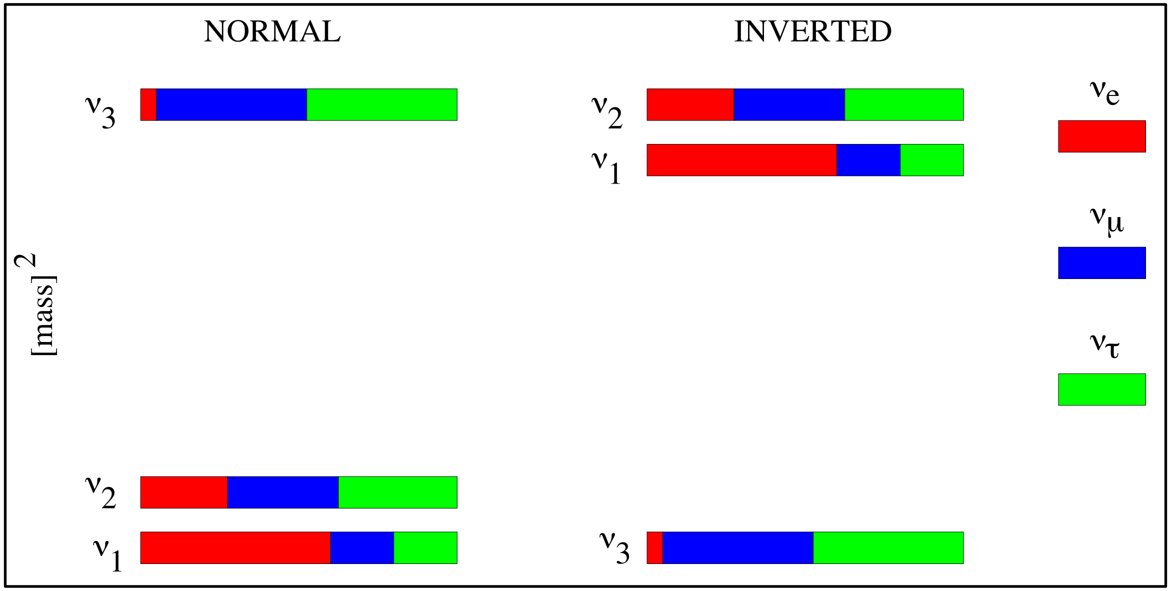
Colloquium Towards CP violation in neutrino Physics, 24-25 Oct 2019, Prague

Karlsruher Institut für Technologie

elusives neutrinos, dark matter &

The 3-flavour paradigm

- 3 masses: Δm^2_{21} , Δm^2_{31}, m_0
- 3 mixing angles θ_{12} θ_{13} θ_{23}
- 3 phases (1 Dirac, 2 Majorana)



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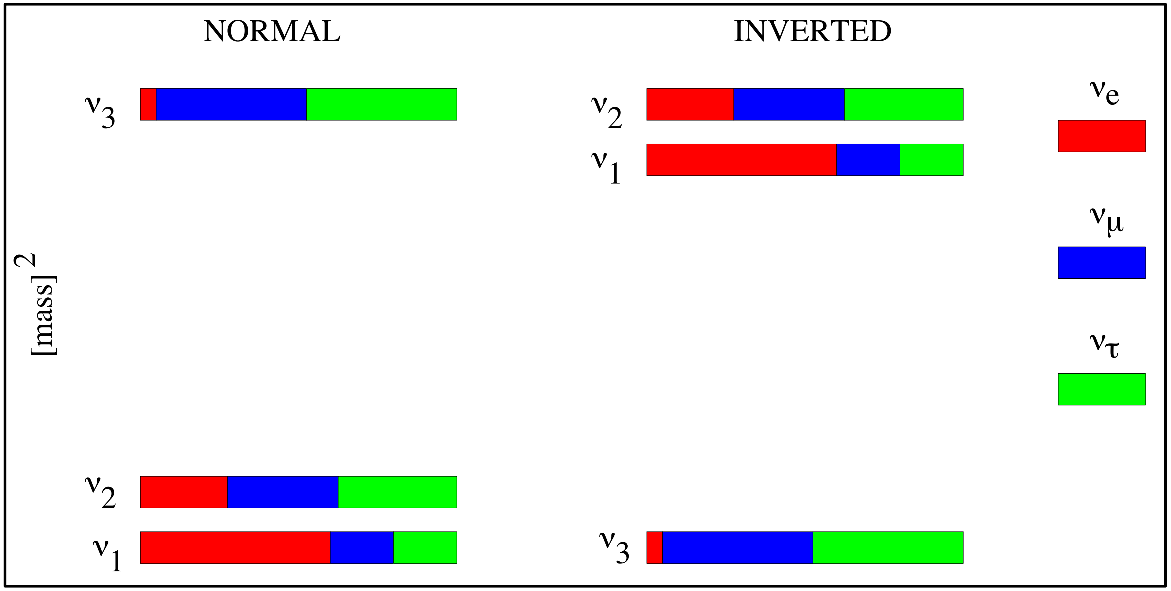

The 3-flavour paradigm

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- 3 mixing angles θ_{12} θ_{13} θ_{23} ← neutrino oscillations
- 3 phases (1 Dirac, 2 Majorana)

- each parameter determined by several (classes of) experiments
- especially true for not-so-well determined parameters (θ_{23}, MO, Dirac-phase)
- interplay of different data sets → global analyses

NuFit 4.1 (2019)

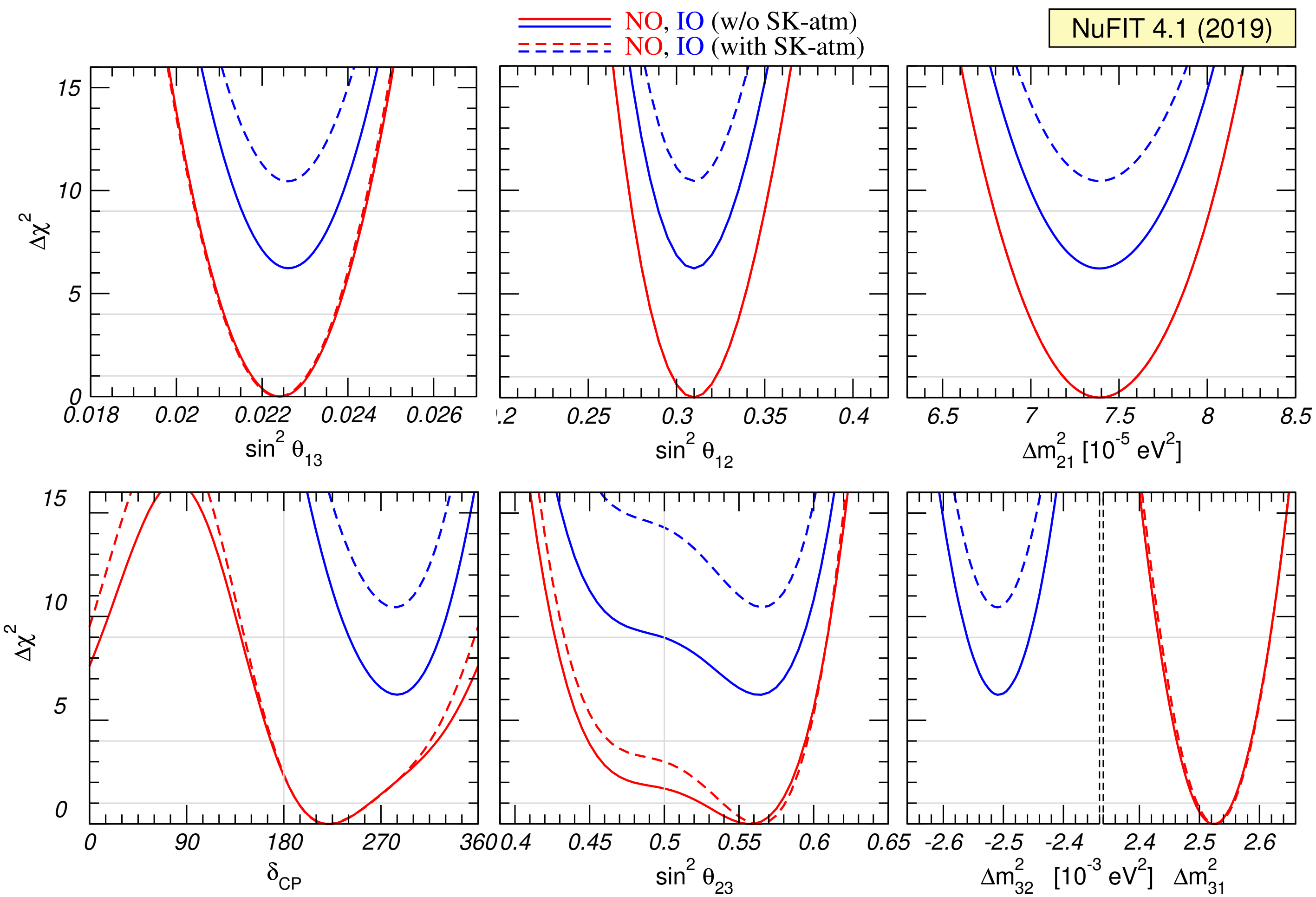
www.nu-fit.org

I. Esteban, C. Gonzalez-Garcia, A. Hernandez, M. Maltoni, TS, arXiv:1811.05487, JHEP 19

- http://www.nu-fit.org
- data available till July 2019
- full list of data see http://www.nu-fit.org/sites/default/files/v41.release-notes.pdf
- T2K: 14.93e20 pot neutrino, 17e20 pot antineutrino
  NOvA: 8.85e20 pot neutrino, 12.33e20 pot antineutrino

global fits from Bari (Fogli, Lisi et al) and Valencia (Tortola, Valle et al) groups with similar results

NuFit 4.1 (2019)



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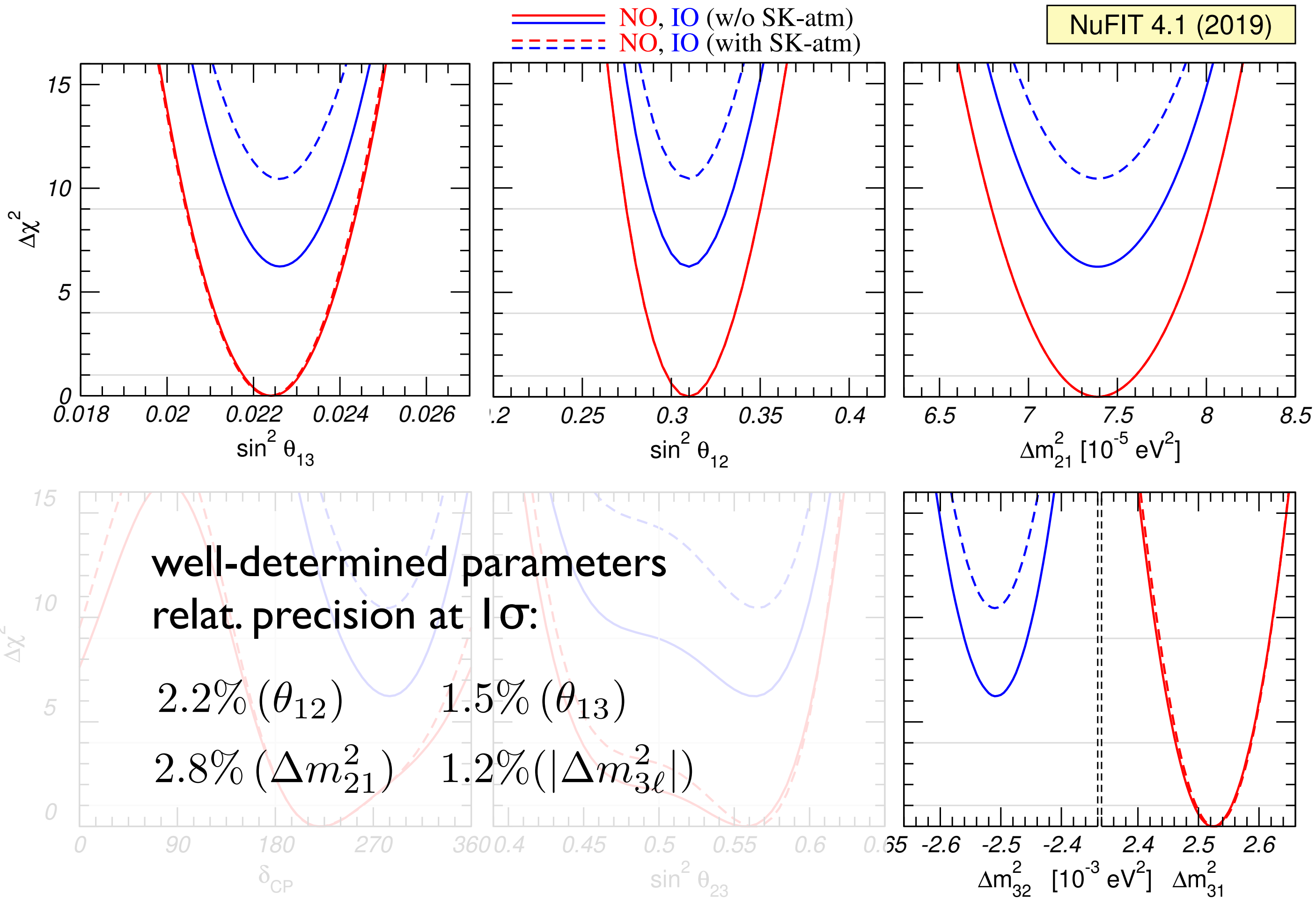
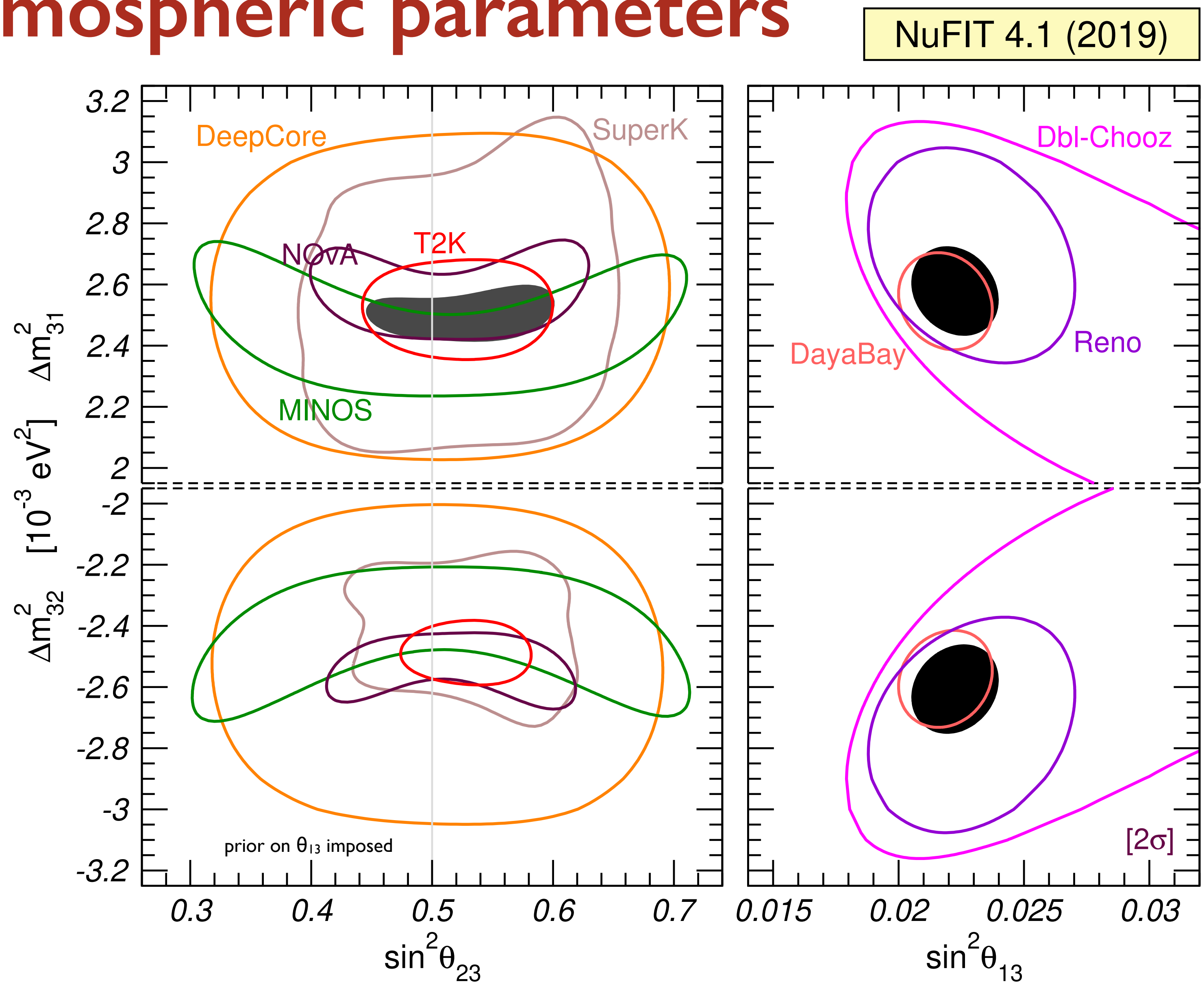


well-determined parameters
relat. precision at 1σ:

$2.2\%\ (\theta_{12})$ $1.5\%\ (\theta_{13})$

$2.8\%\ (\Delta m^2_{21})$ $1.2\%(|\Delta m^2_{3\ell}|)$

Atmospheric parameters

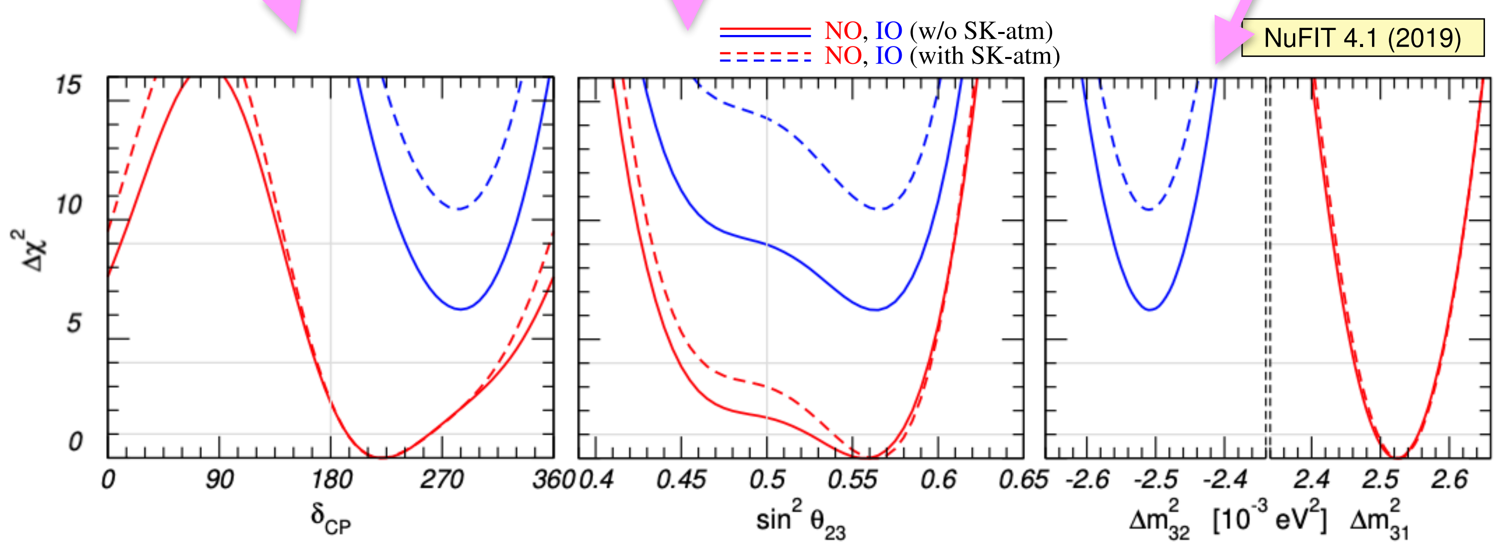


not-so-well determined

CP phase

Determination of θ_{23}

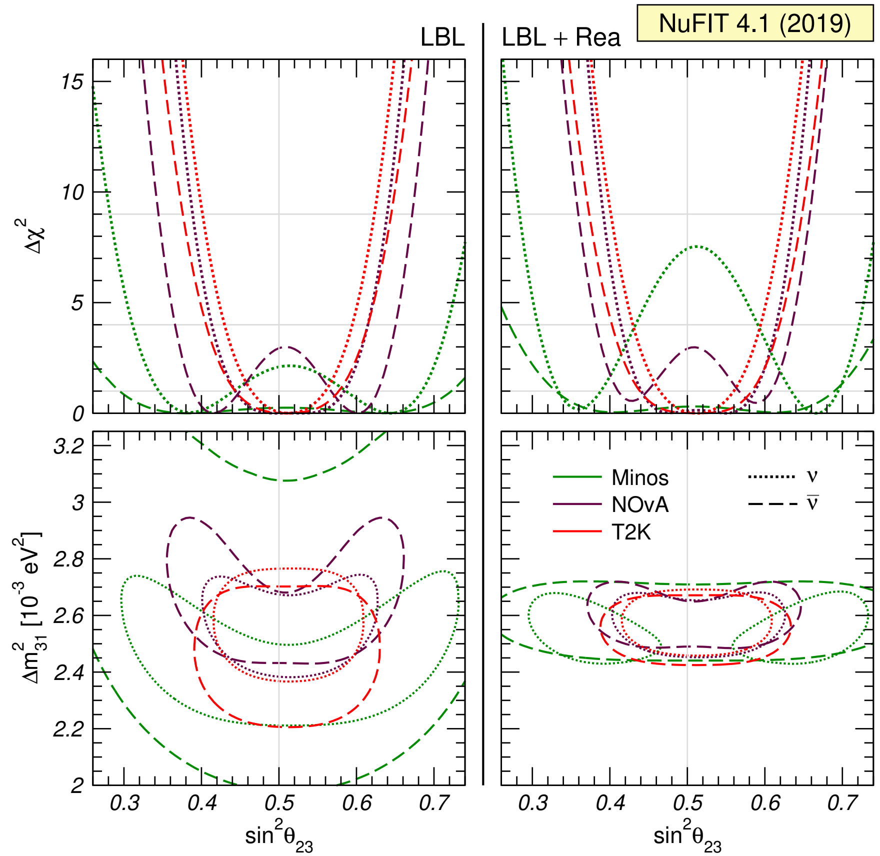
Mass ordering



LBL disappearance results

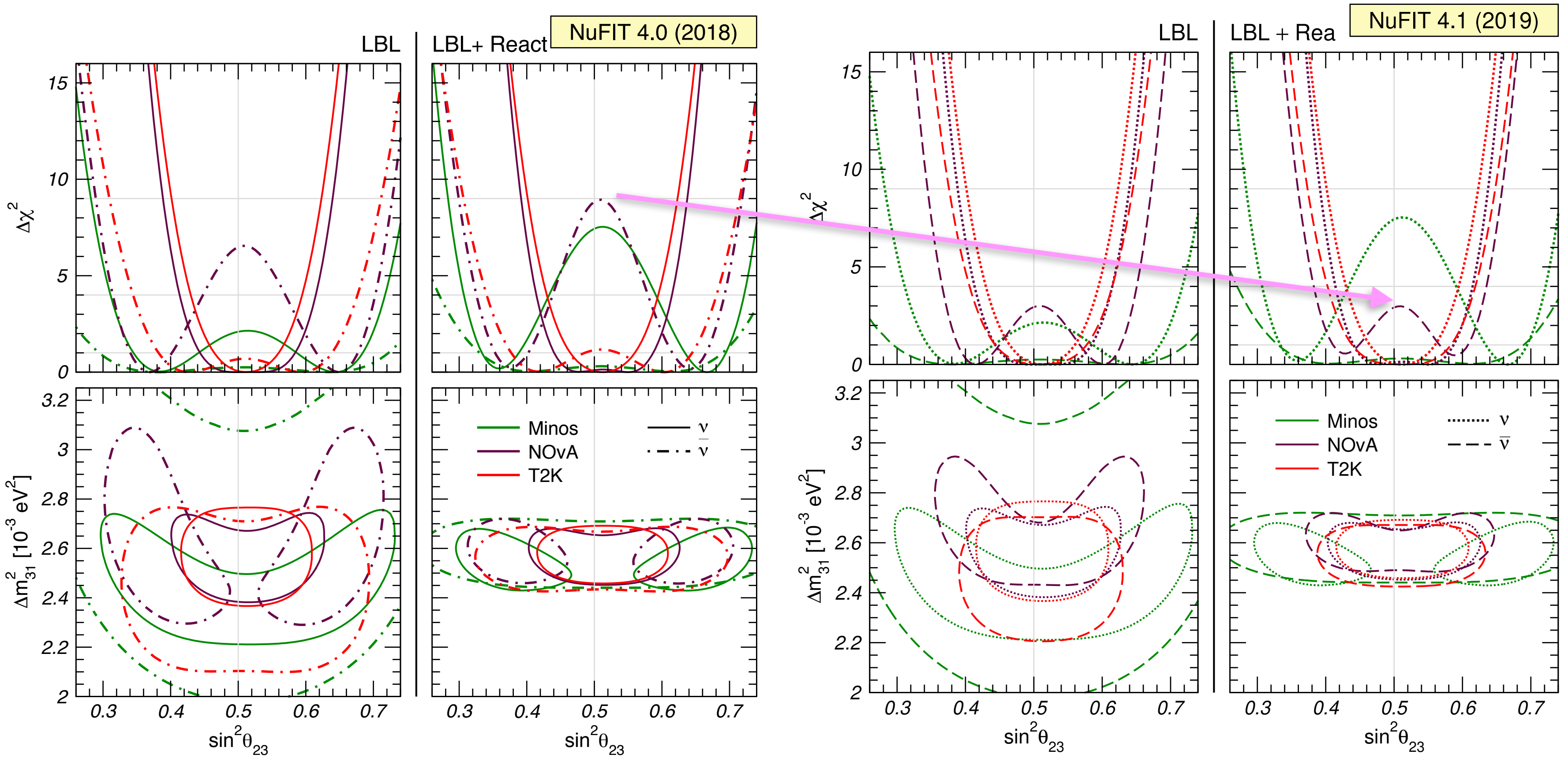
$$P_{\mu\mu} \approx 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E_\nu}$$

$$\sin^2\theta_{\mu\mu} = \cos^2\theta_{13}\sin^2\theta_{23}\,,$$
$$\Delta m^2_{\mu\mu} = \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \cos\delta_{CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}$$



2σ contours, normal ordering, prior on θ_{13} imposed

LBL disappearance results



NOvA anti-nu update 6.9 → 12.3 pot

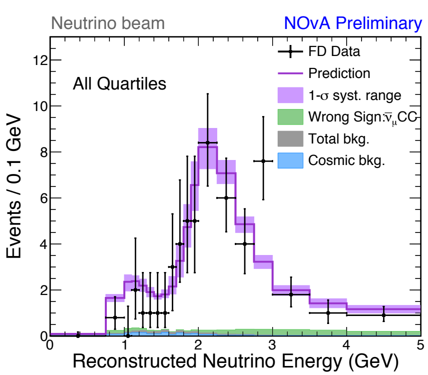
2σ contours, normal ordering, prior on θ_{13} imposed

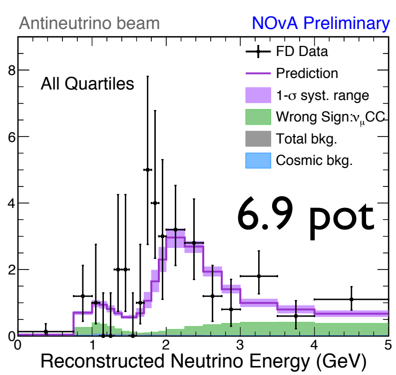
LBL disappearance results

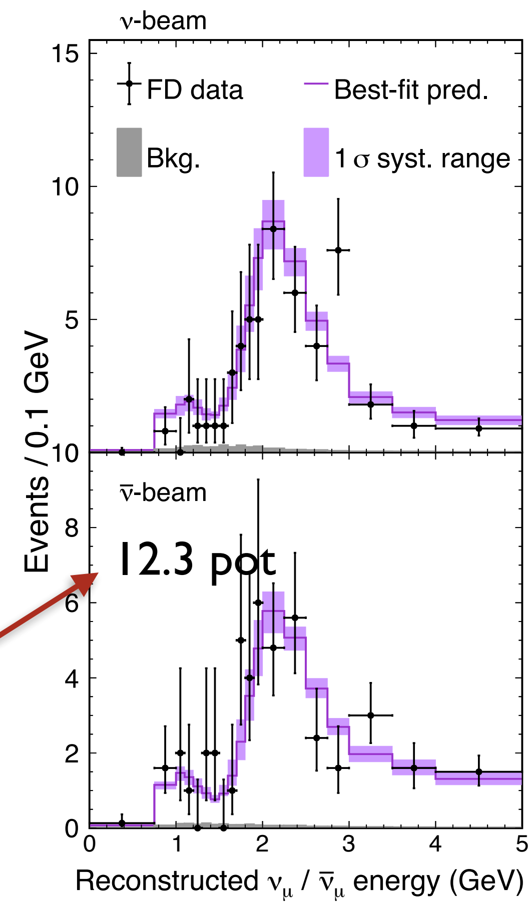
NOvA 2019 update 1906.04907

$$P_{\mu\mu} \approx 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E_\nu}$$

$$\begin{aligned} \sin^2\theta_{\mu\mu} &= \cos^2\theta_{13}\sin^2\theta_{23}\,, \\ \Delta m^2_{\mu\mu} &= \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} \\ &\quad + \cos\delta_{\rm CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21} \end{aligned}$$







M. Sanchez, Neutrino18

LBL appearance data

following Elevant, Schwetz, 15

$$N_{\nu_e} \approx \mathcal{N}_\nu \left[2s_{23}^2(1+2oA) - C' \sin\delta_{\rm CP}(1+oA)\right]$$
$$N_{\bar\nu_e} \approx \mathcal{N}_{\bar\nu} \left[2s_{23}^2(1-2oA) + C' \sin\delta_{\rm CP}(1-oA)\right]$$

$$C' \approx 0.28$$
$$o \equiv \mathrm{sgn}(\Delta m_{3\ell}^2)$$
$$A \equiv \left|\frac{2EV}{\Delta m_{3\ell}^2}\right| \approx \begin{cases} 0.05 & \text{T2K} \\ 0.1 & \text{NOvA} \end{cases}$$

	T2K CCQE (ν)	T2K CC1π (ν)	T2K CCQE ($\bar\nu$)	NOvA (ν)	NOvA ($\bar\nu$)
$\mathcal{N}$	40	3.8	11	34	11
$N_{\rm obs} - N_{\rm bck}$	61.4	13.6	6.1	43.6	13.8

2018 numbers

trend persists in recent T2K update

- Both neutrino and anti-neutrino events are enhanced by increasing s_{23}^2.
- Values of $\sin\delta_{\rm CP} \simeq +1\,(-1)$ suppress (increase) neutrino events, and have the opposite effect for anti-neutrino events.
- For NO (IO) neutrino events are enhanced (suppressed) due to the matter effect, whereas anti-neutrino events are suppressed (enhanced).
- For NO (IO) the matter effect increases (decreases) the impact of $\delta_{\rm CP}$ for neutrinos, while the opposite happens for anti-neutrinos.

θ_{23} octant

$$N_{\nu_e} \approx \mathcal{N}_\nu \left[2s_{23}^2(1+2oA) - C'\sin\delta_{\rm CP}(1+oA)\right]$$
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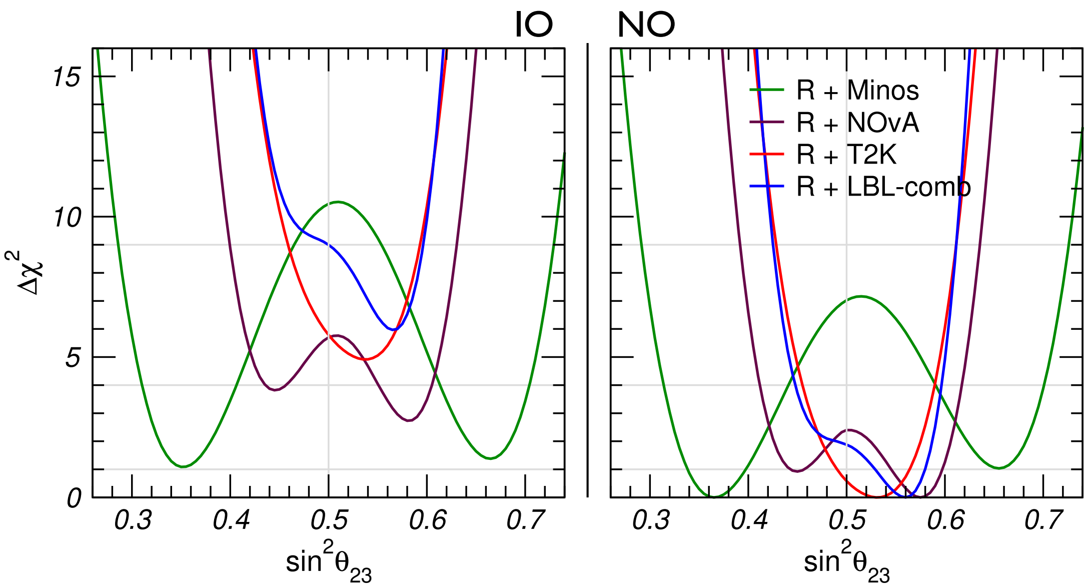
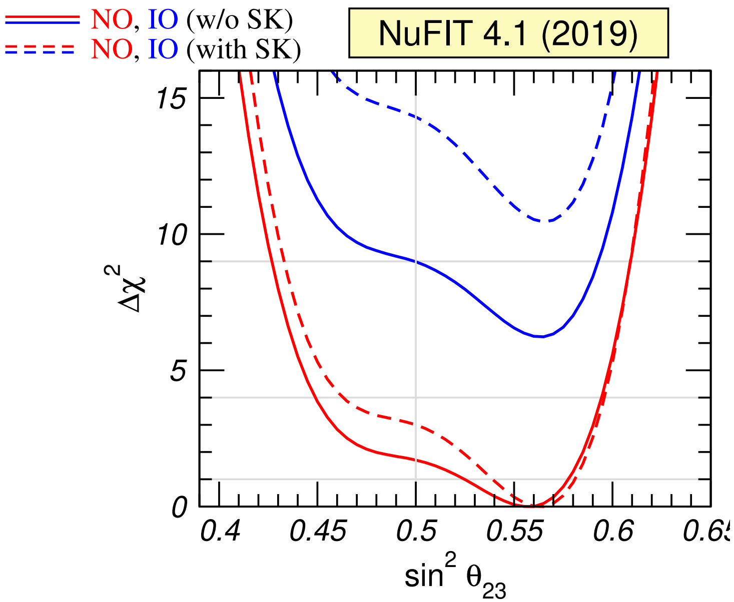
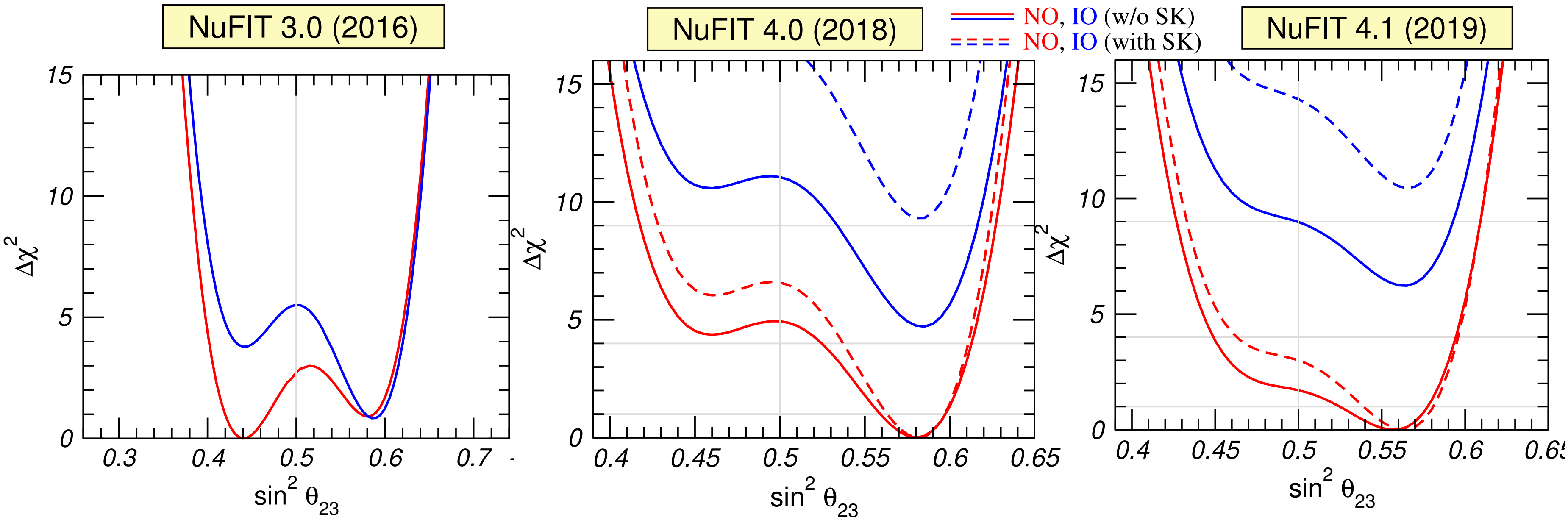


θ_{23} octant — summary



- preference for second octant, bf at $\sin^2\theta_{23} = 0.56$
  $\sin^2\theta_{23} < 0.5$ disfavoured with $\Delta\chi^2 \approx 1.8$ (3.0) without (with) SK atm
- 2nd octant is good news for MO sensitivity of atm. and LBL experiments

θ_{23} octant — impact of recent data



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- 2nd octant is good news for MO sensitivity of atm. and LBL experiments
- hints for 2nd octant decreased with recent update

CP phase

$$N_{\nu_e} \approx \mathcal{N}_\nu \left[2s^2_{23}(1+2oA) - C'\sin\delta_{\rm CP}(1+oA)\right]$$
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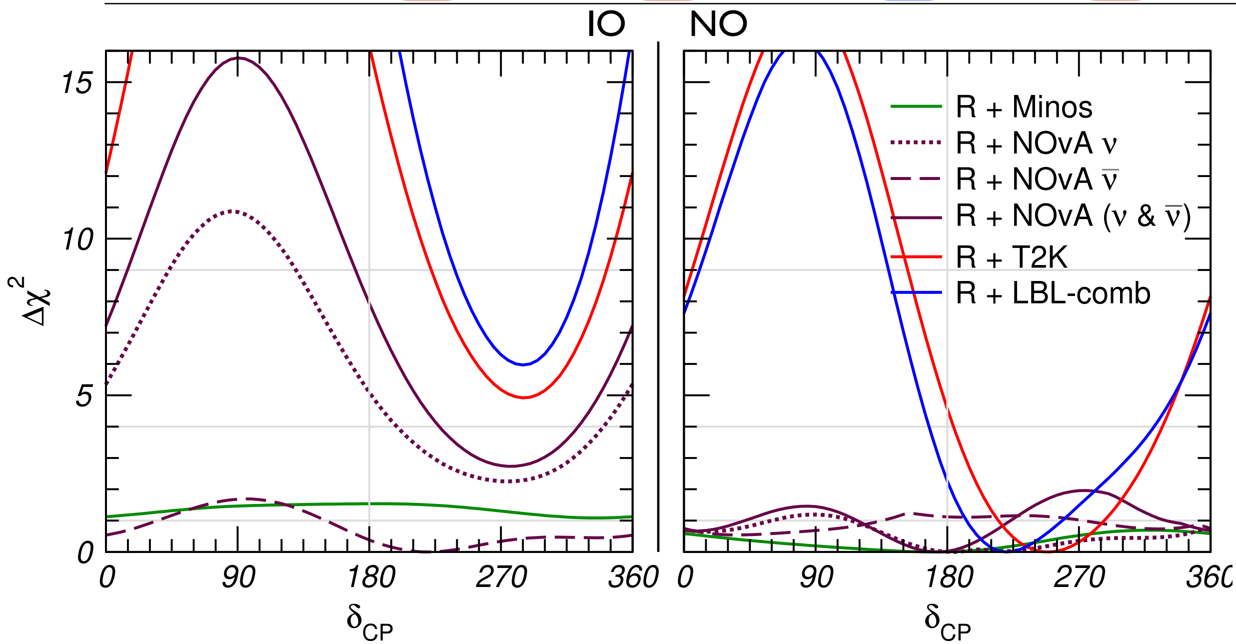
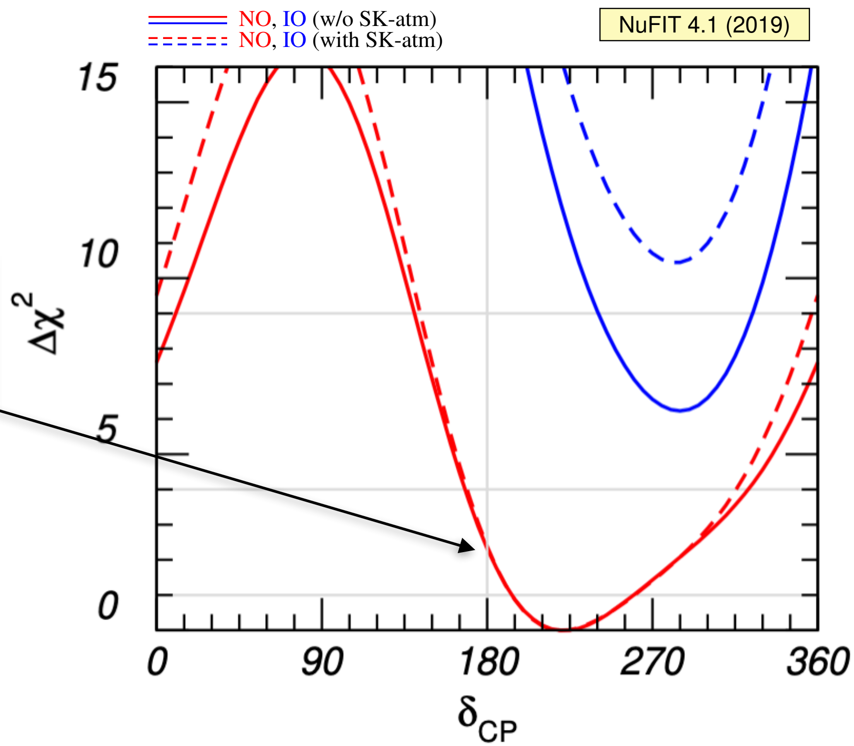


CP sens. driven by T2K

NOvA results for NO inconclusive

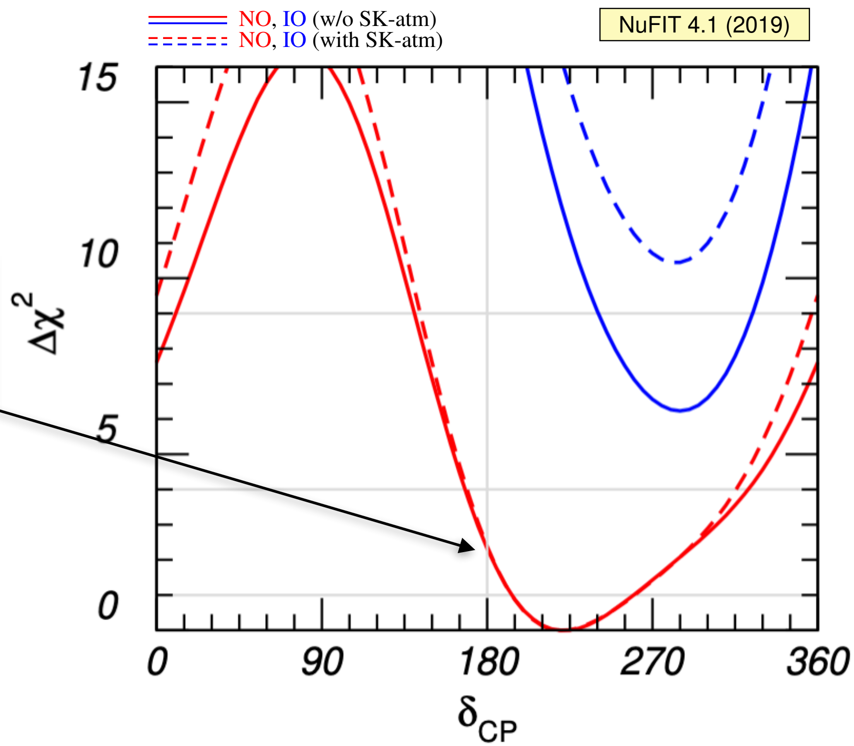
CP phase



CP conservation at $\Delta\chi^2 = 2.2$

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 10.4$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\delta_{CP}/^\circ$	221^{+39}_{-28}	$144 \to 357$	282^{+23}_{-25}	$205 \to 348$

CP phase



CP conservation at $\Delta\chi^2 = 2.2$

for IO, CP conservation excluded at >3σ (due to some „tension" in the data)

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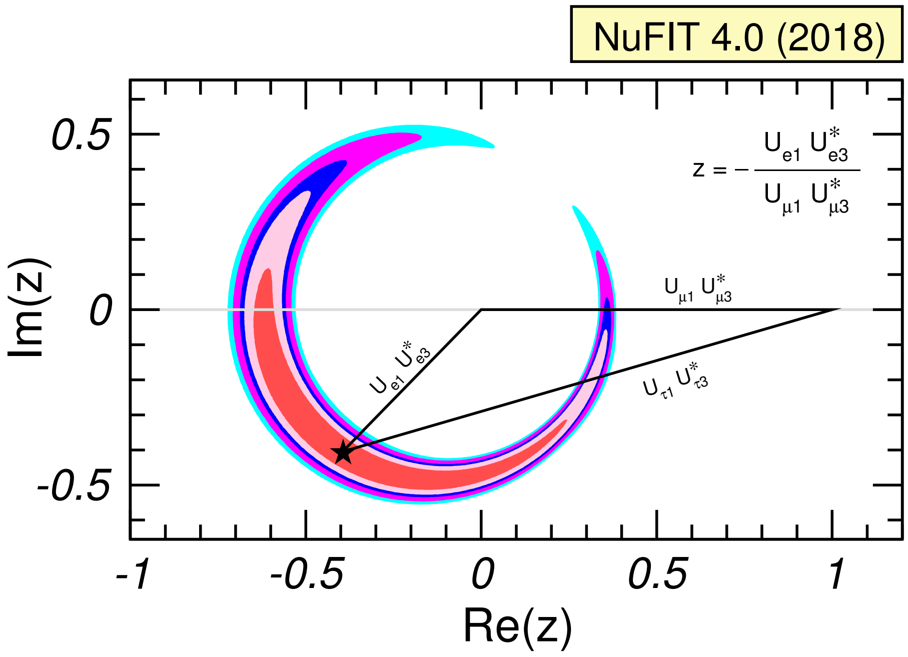
Leptonic CP violation

Jarlskog invariant:

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

$$J^{\max}_{\text{CP}} = 0.0333 \pm 0.0006\,(\pm 0.0019) \text{ at } 1\sigma\ (3\sigma)$$



Leptonic CP violation

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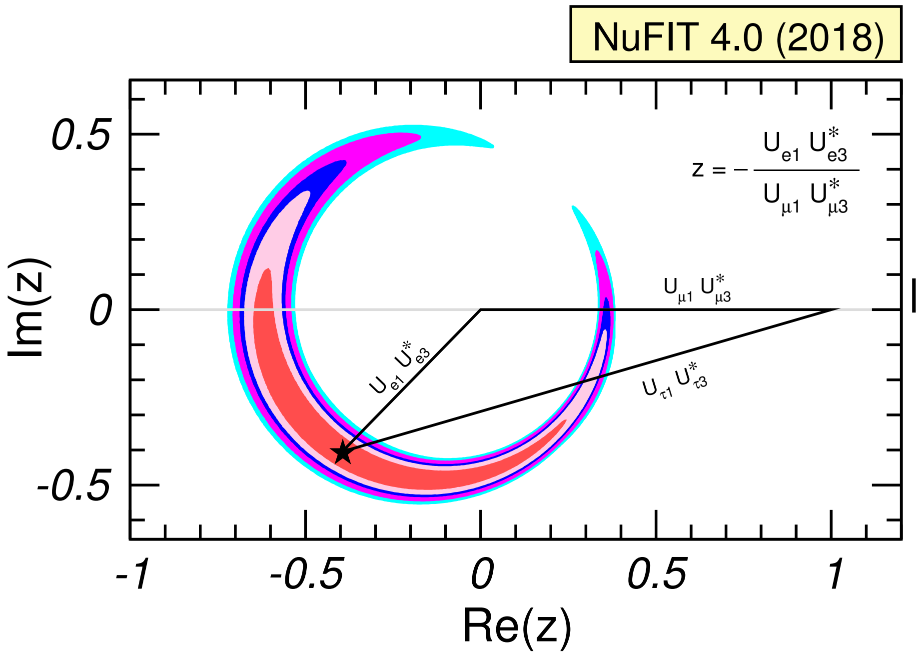
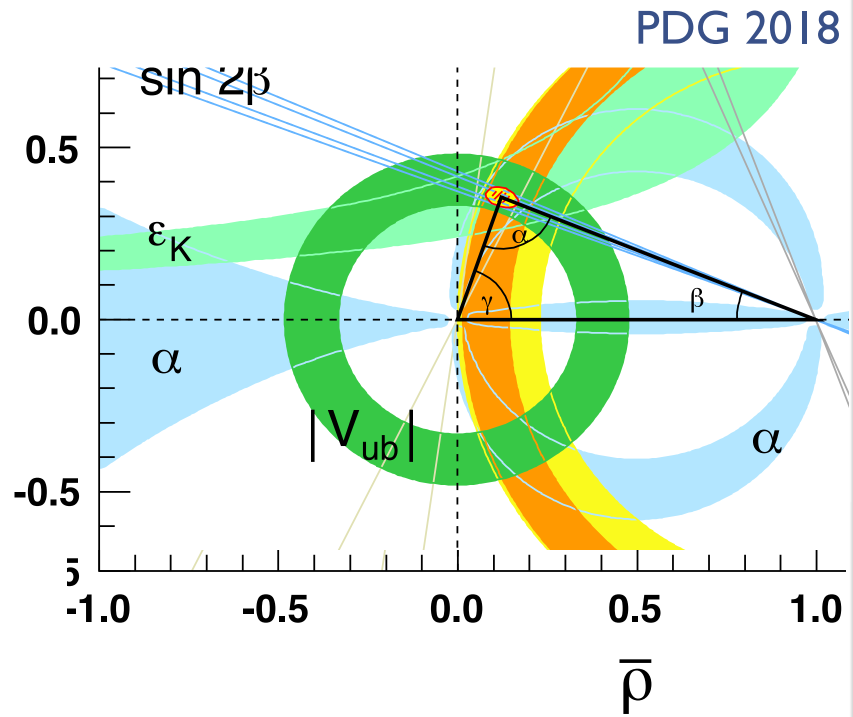
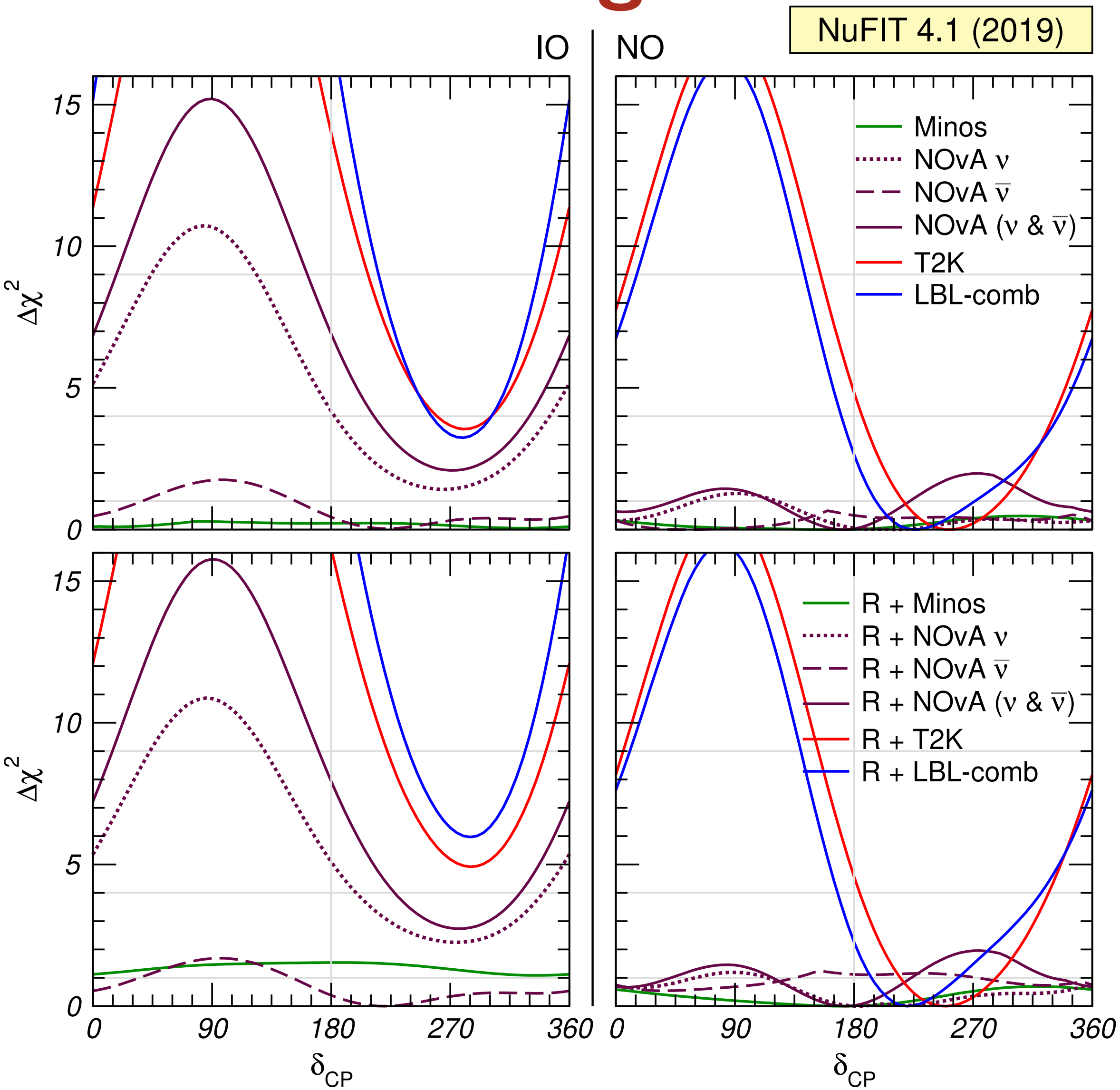
$$J^{\max}_{\mathrm{CP}} = 0.0333 \pm 0.0006\,(\pm 0.0019) \text{ at } 1\sigma\ (3\sigma)$$

$$J^{\mathrm{quarks}}_{\mathrm{CP}} = (3.18 \pm 0.15) \times 10^{-5}$$





Mass ordering



no reactor data, but θ_{13} prior added

T2K: $\Delta\chi^2$(IO) ≈ 3.6

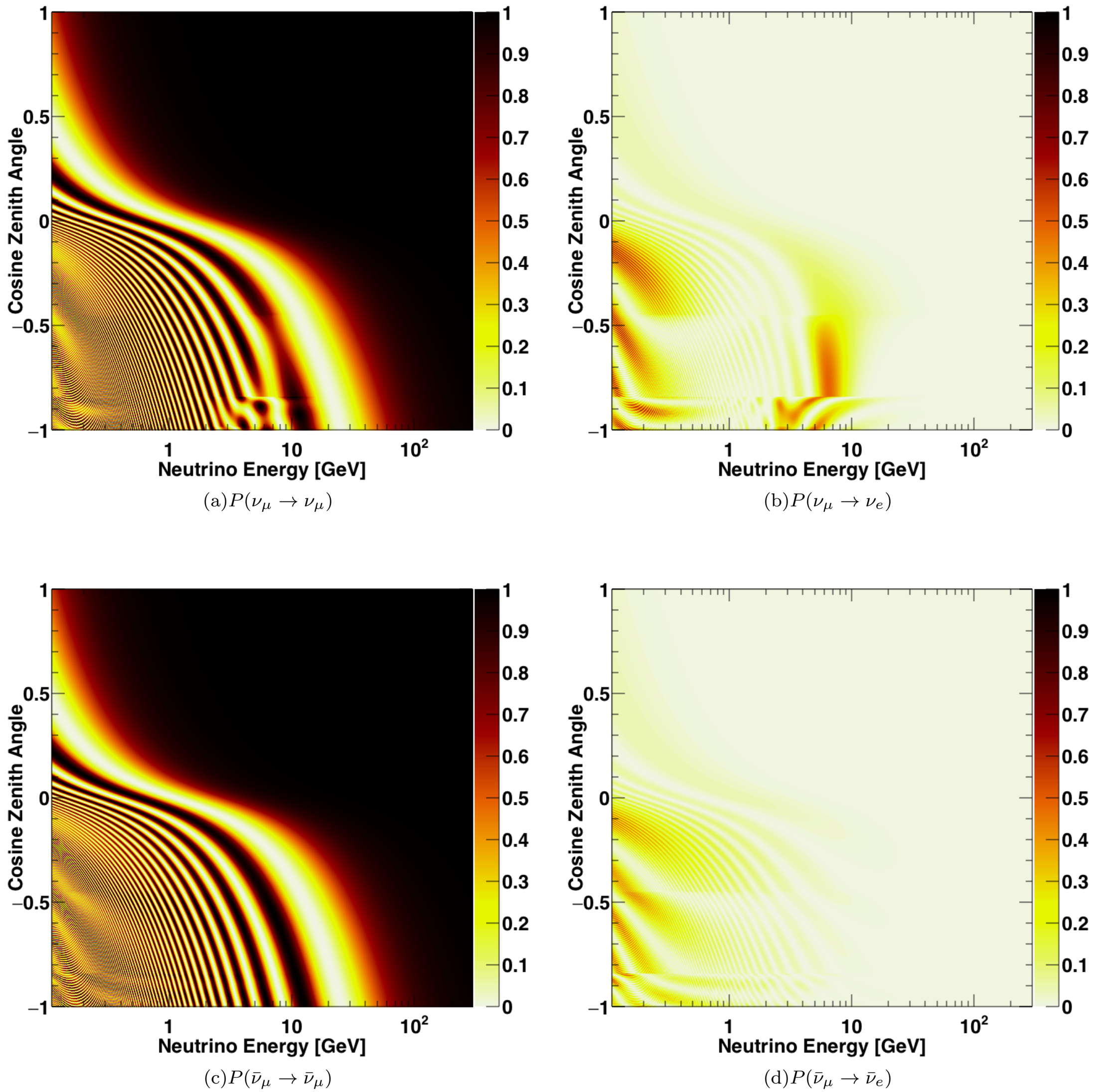
adding NOvA: $\Delta\chi^2$(IO) ≈ 3.2

adding reactors: $\Delta\chi^2$(IO) = 6.2

ν_e and ν_μ disappearance: slightly different effective mass-squared differences

Nunokawa, Parke, Zukanovich, 05, 06
Blennow, TS, 13

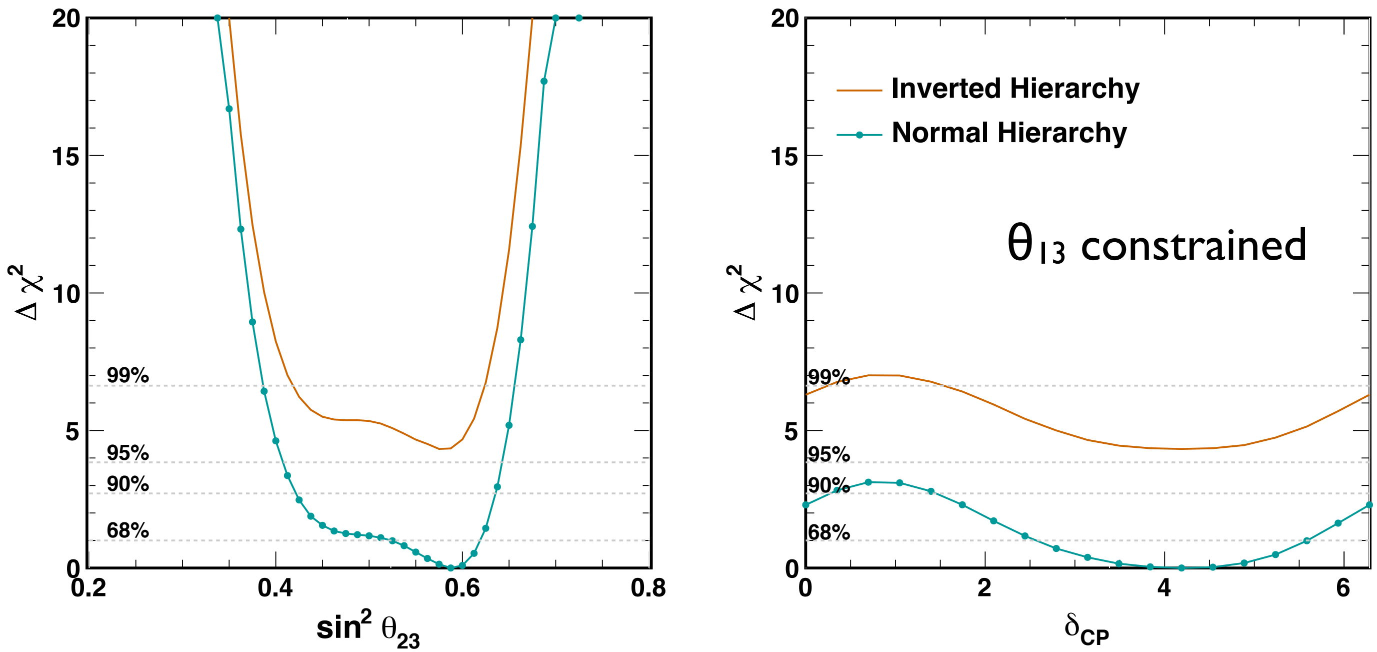
Mass ordering - atmospheric neutrinos



1710.09126

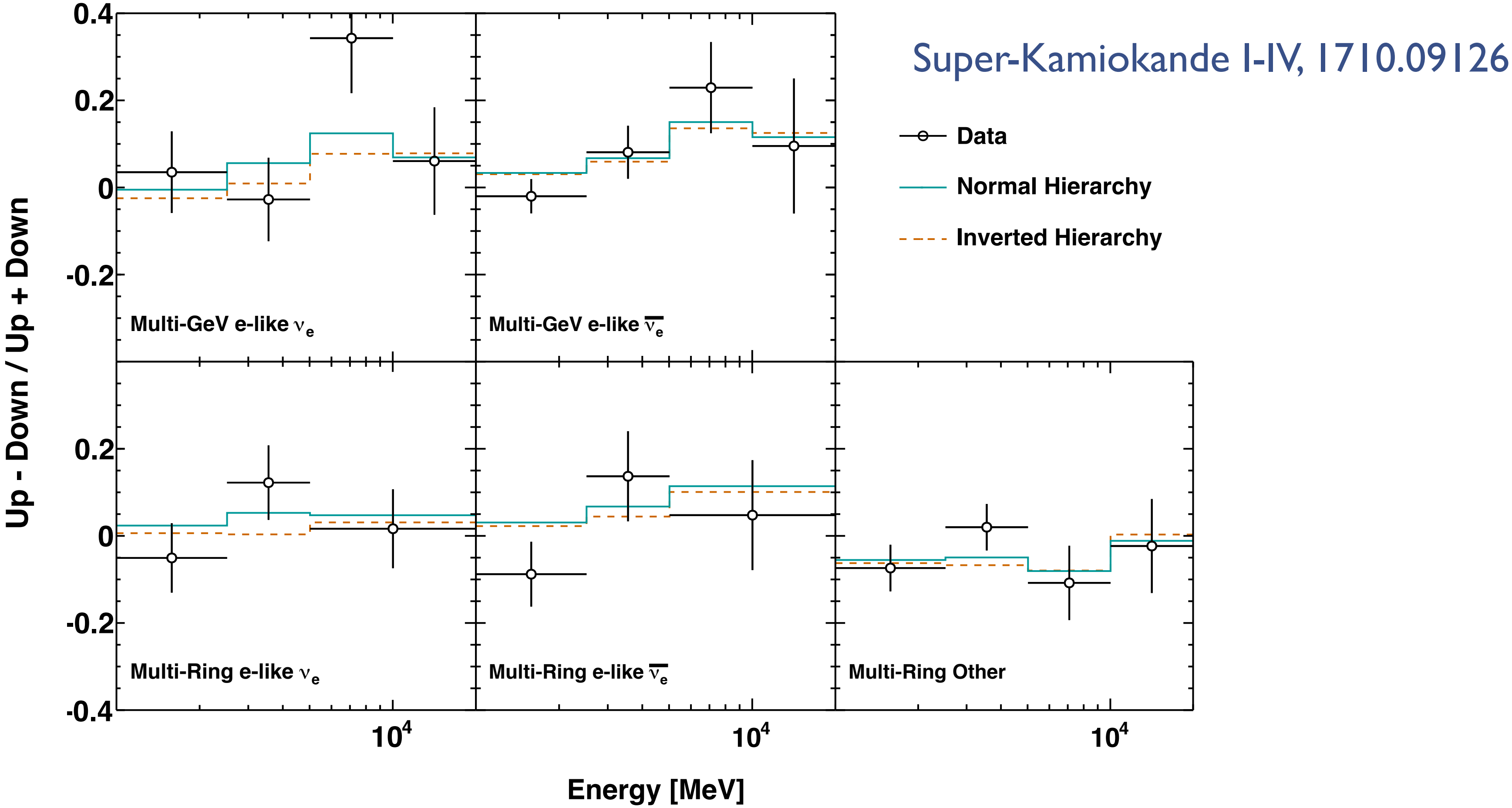
Mass ordering - atmospheric neutrinos

Super-Kamiokande I-IV, 1710.09126



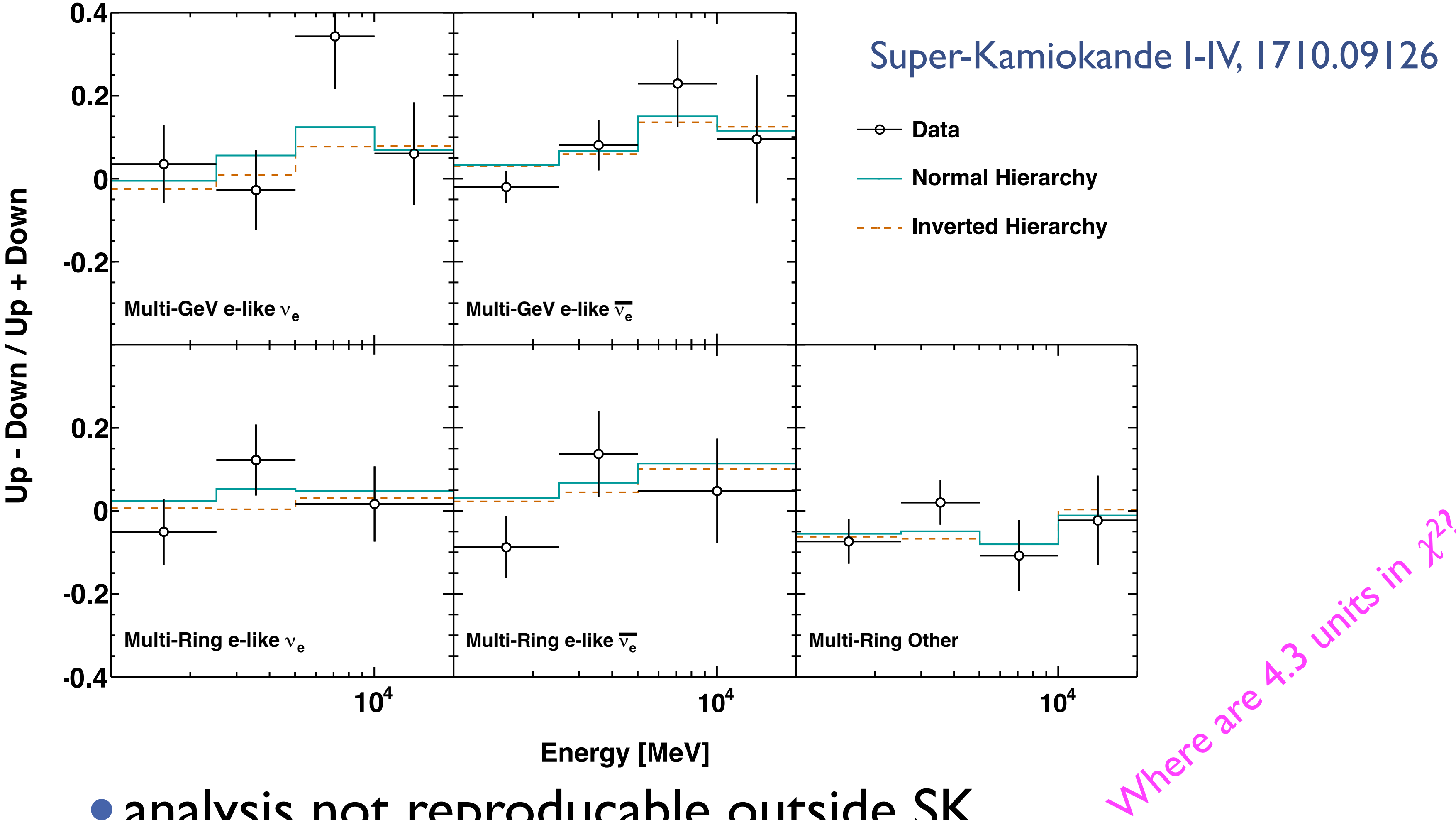
- prefers 2nd θ_{23} octant and $\pi < \delta < 2\pi$
- $\chi^2(IO) - \chi^2(NO) = 4.3$

Mass ordering - atmospheric neutrinos



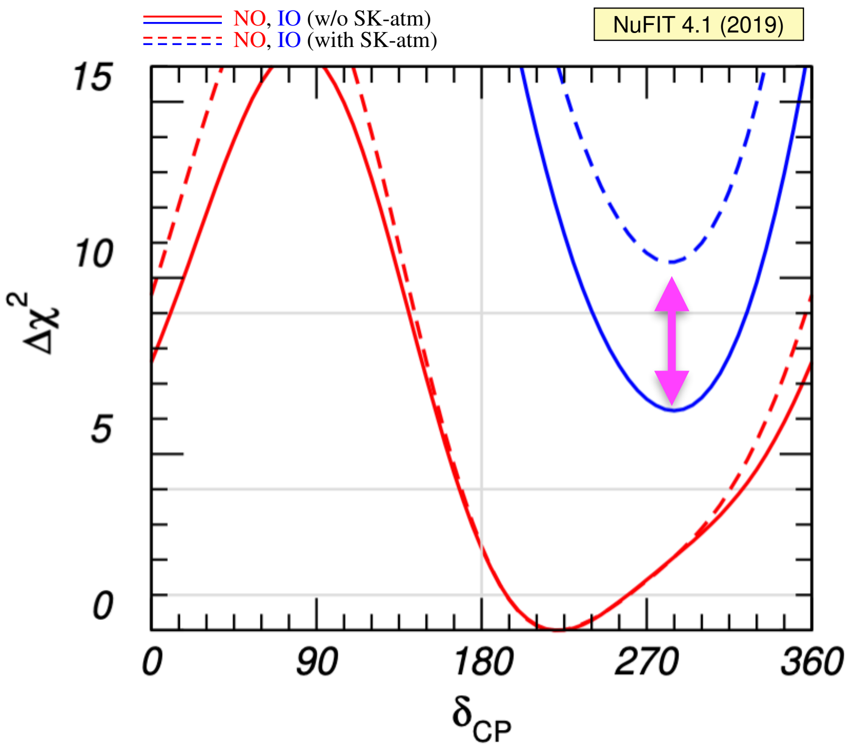
- analysis not reproducable outside SK
- add χ^2 table to global fit („black box")

Mass ordering - atmospheric neutrinos



- analysis not reproducable outside SK
- add χ^2 table to global fit („black box“)

Mass ordering incl. atmospherics



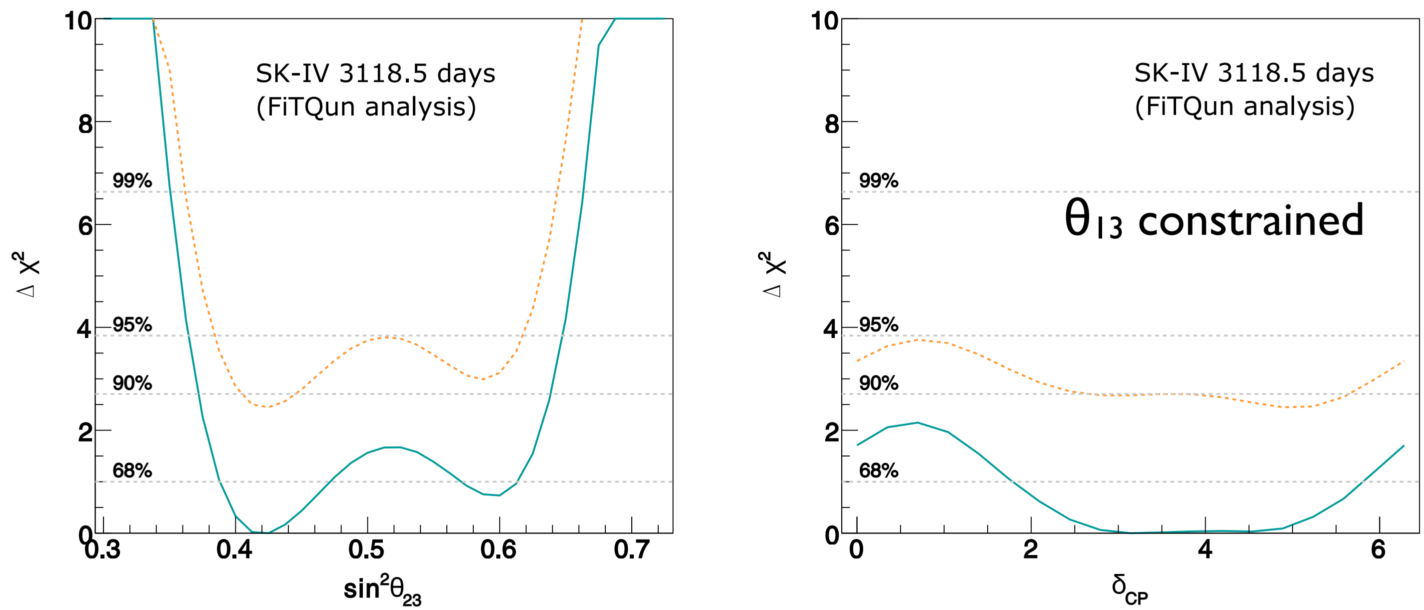
adding SuperK I-IV atm χ^2 table to the global fit → inverted ordering becomes disfavoured at >3σ

(contribution of IceCube to MO still very small)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 10.4$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\delta_{CP}/°$	221^{+39}_{-28}	$144 \to 357$	282^{+23}_{-25}	$205 \to 348$

Mass ordering - atmospheric neutrinos

Atmospheric Neutrino Oscillation Analysis With Improved Event Reconstruction in Super-Kamiokande IV, 1901.03230

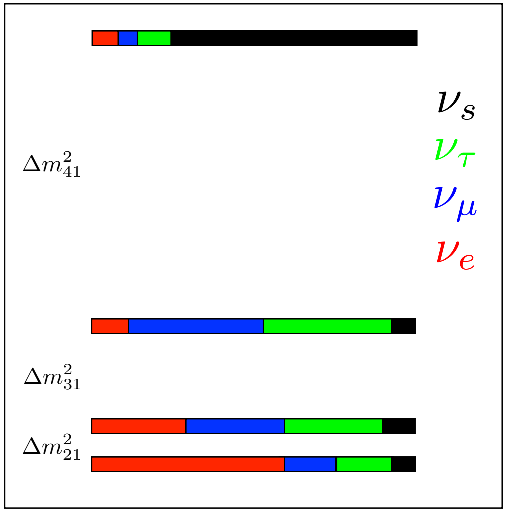


- χ^2(IO) - χ^2(NO) = 2.45 (compared to 4.3 from SK I-IV 2017)
- effective exposure 254 kt yr only 23% smaller (32% larger fiducial volume) (compared to 328 kt yr of SK I-IV 2017)

Anomalies inconsistent with 3-flavour paradigm

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

Huber, Muller, 2011 → HM Rates

Estienne et al., 1904.09358 → *Ab Initio* Rates

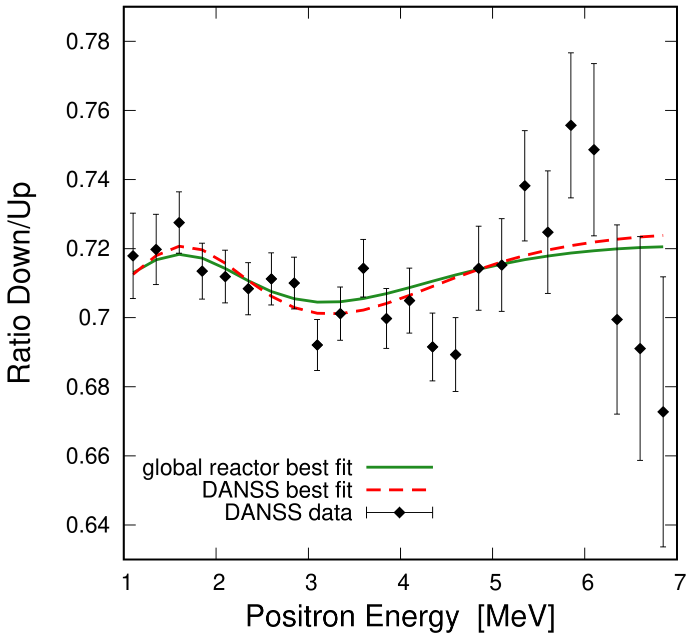
Hayen et al., 1908.08302 → HKSS Rates

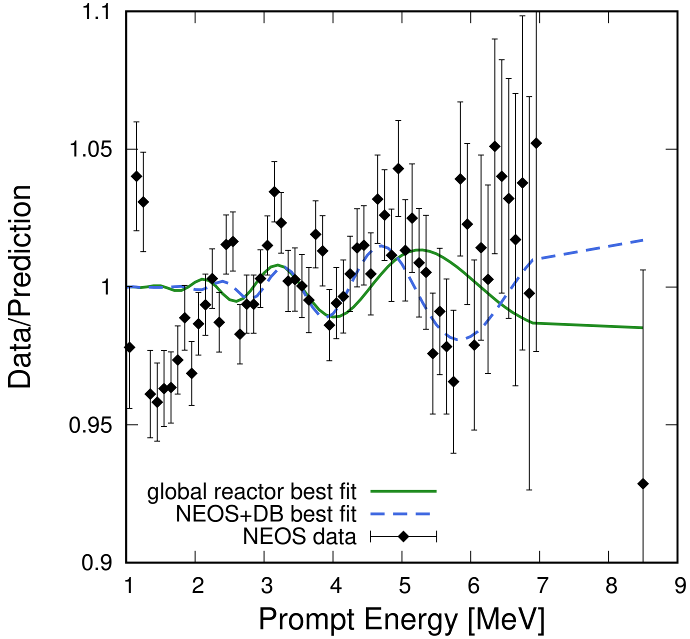
Berryman, Huber, 1909.09267

Analysis	$\chi^2_{3\nu}$	$\chi^2_{\rm min}$	$n_{\rm data}$	p	$n\sigma$
HM Rates	41.4	33.5	40	2.0×10^{-2}	2.3
Ab Initio Rates	39.2	37.0	40	0.34	0.95
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

Relative spectral distortions

Dentler, Hernandez, Kopp, Maltoni, TS, 1709.04294





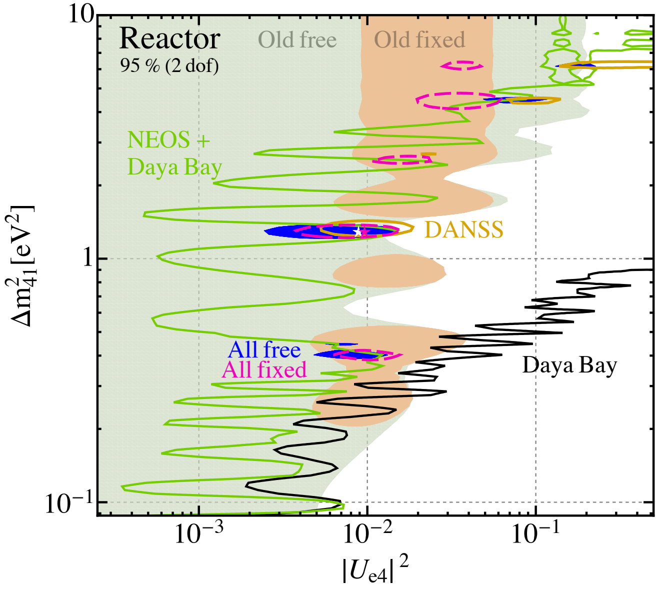
DANSS: relative spectra @ detector locations with $L = 10.7$ and 12.7 m

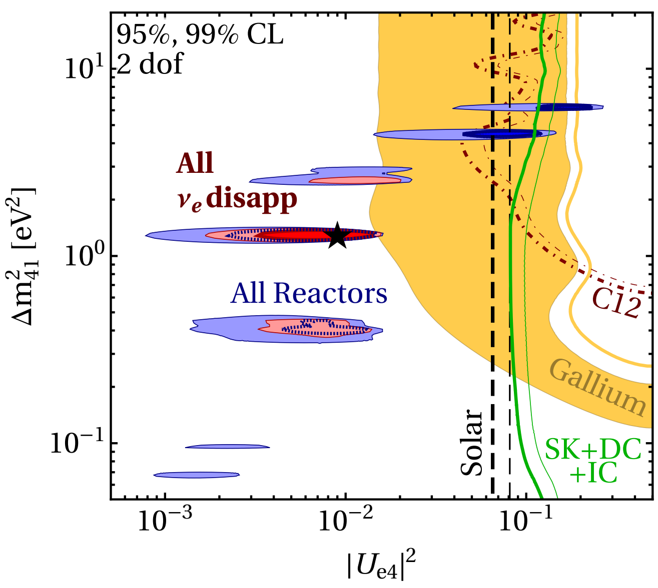
NEOS: spectrum at $L = 24$ m, relative to prediction based on Daya Bay near detector spectrum

Combined ν_e disappearance analysis

Analysis	Δm^2_{41} [eV^2]	$\lvert U^2_{e4}\rvert$	$\chi^2_{\rm min}$/dof	$\Delta\chi^2$(no-osc)	significance
DANSS+NEOS	1.3	0.00964	74.4/(84 − 2)	13.6	3.3σ
all reactor (flux-free)	1.3	0.00887	185.8/(233 − 5)	11.5	2.9σ
all reactor (flux-fixed)	1.3	0.00964	196.0/(233 − 3)	15.5	3.5σ
$\overset{(-)}{\nu}_e$ disap. (flux-free)	1.3	0.00901	542.9/(594 − 8)	13.4	3.2σ
$\overset{(-)}{\nu}_e$ disap. (flux-fixed)	1.3	0.0102	552.8/(594 − 6)	17.5	3.8σ

Dentler et al., 1803.10661





~3σ hint for sterile neutrino oscillations, independent of reactor flux calculations!

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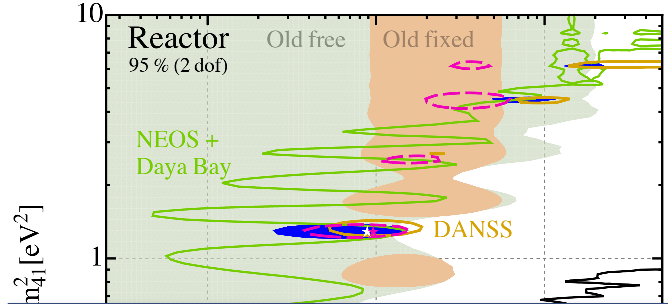
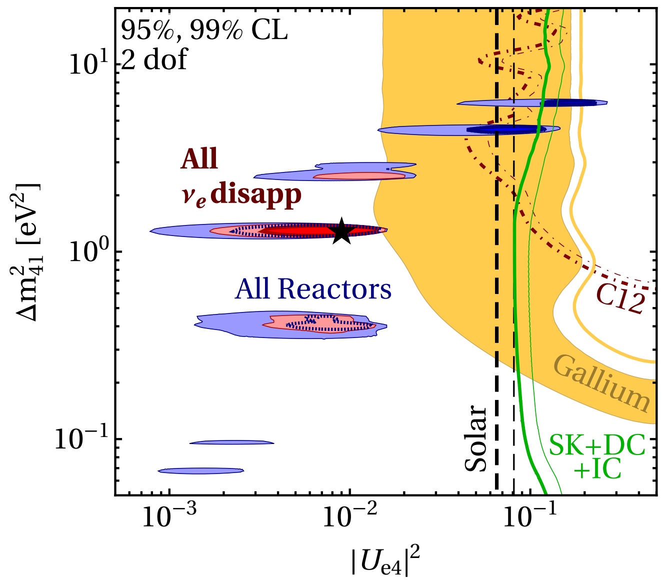


- PROSPECT/STEREO: limits too weak to test spectral hint
- Impact of latest DANSS results under investigation



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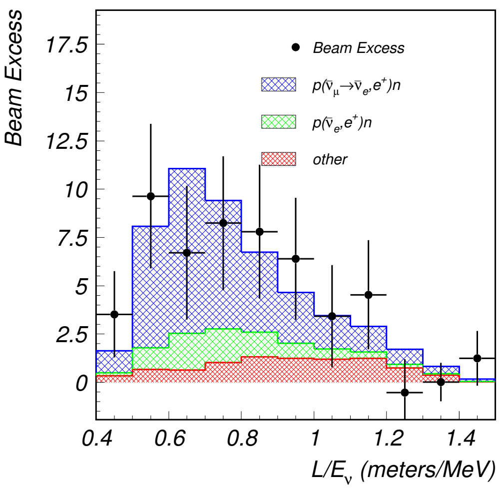
Hints for $\nu_\mu \to \nu_e$ appearance

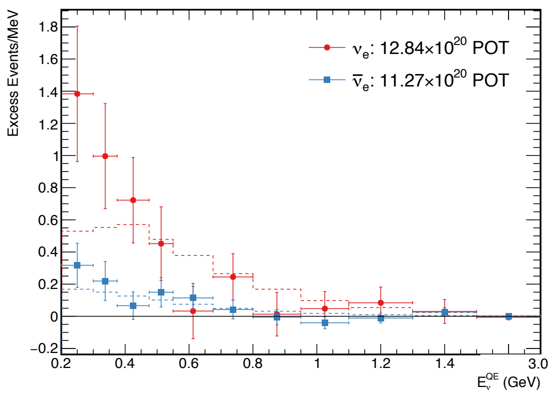
combined appearance data:

LSND, 2001



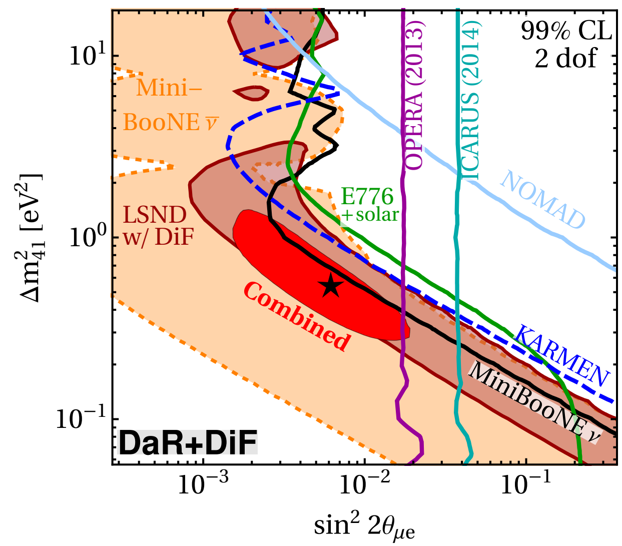
- signal for $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions (3.8σ)

MiniBooNE, 1805.12028



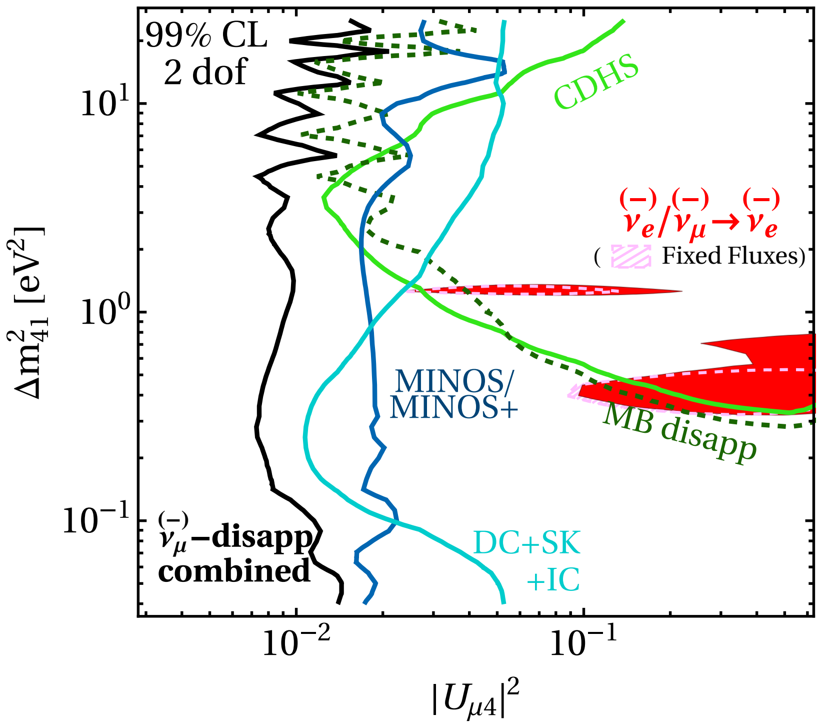
- neutrino mode excess: 381.2 ± 85.2 events (4.5σ)
- ν-$\bar{\nu}$ combined excess: 460.5 ± 95.8 events (4.8σ)

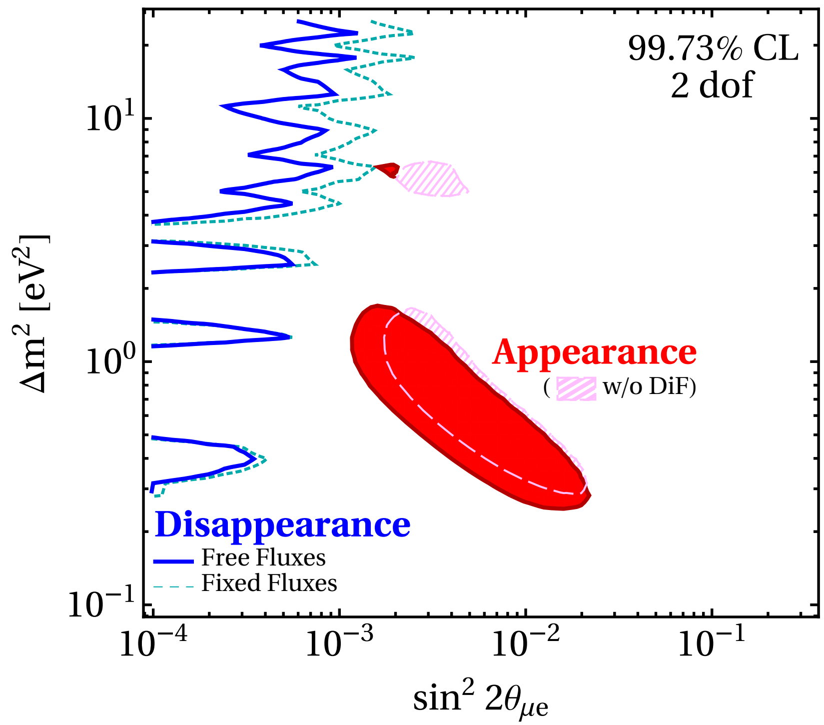
Dentler et al, 1803.10661



using pre-2018 MiniBooNE data, results quantitativley very similar

Strong tension btw appearance and disappearance





non-observation of oscillations in ν_μ disappearance (CDHS, MiniB, MINOS+, SK, IceCube)

consistency of appearance and disapp. data with a p-value $< 10^{-6}$

Dentler et al, 1803.10661

Strong tension btw appearance and disappearance

… robust result wrt to individual experiments

Analysis	$\chi^2_{\rm min,global}$	$\chi^2_{\rm min,app}$	$\Delta\chi^2_{\rm app}$	$\chi^2_{\rm min,disapp}$	$\Delta\chi^2_{\rm disapp}$	$\chi^2_{\rm PG}$/dof	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.71×10^{-7}
Removing anomalous data sets							
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
w/o MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
w/o reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
w/o gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
Removing constraints							
w/o IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
w/o MINOS(+)	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
w/o MB disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$ dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$ dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

reactor flux-free analysis — Dentler et al, 1803.10661

results for 2018 MiniB very similar (tension gets slightly worse)

MiniBooNE and a decaying sterile neutrino

Palomares, Pascoli, TS, hep-ph/0505216; Gninenko, 0902.3802, 1009.5536
Bertuzzo, et. al, 1807.09877; Ballett, Pascoli, Ross-Lonergan, 1808.2915

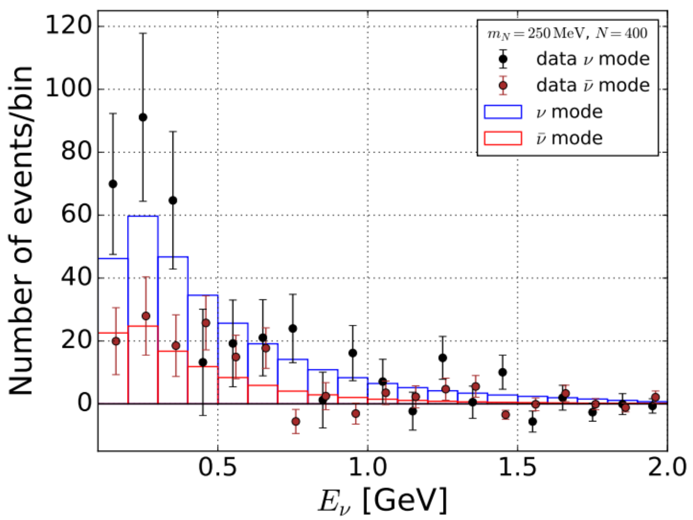
our recent proposal: Fischer, Hernandez, TS, 1909.09561

- sterile neutrino N with m_N ~ 250 MeV ($m_\pi < m_N < m_K$)
- produce N in kaon decays via mixing K → N μ/e
- decay inside MB detector N → νγ via

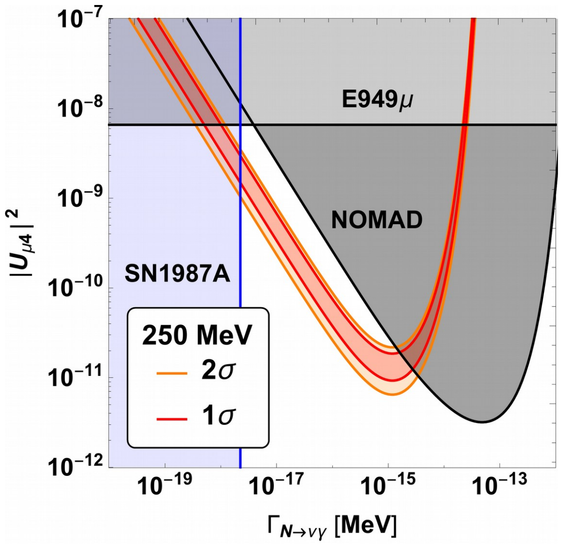
$$\mathcal{O}_{N\to\gamma\nu} = \frac{1}{\Lambda}\bar{N}\sigma^{\alpha\beta}\nu F_{\alpha\beta}$$

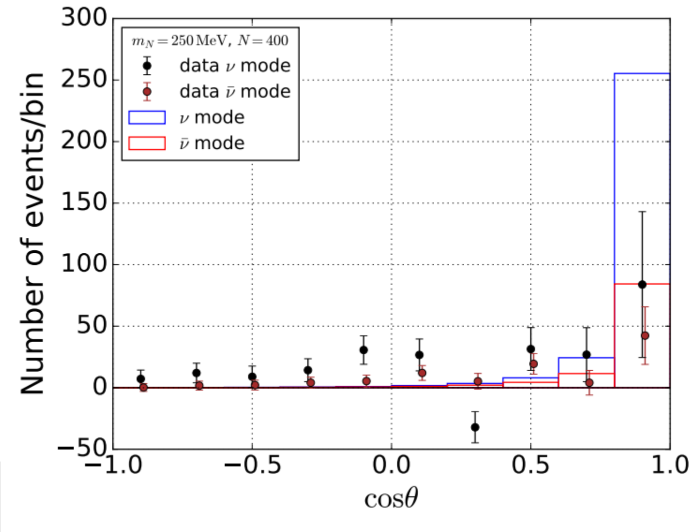
MiniBooNE and a decaying sterile neutrino

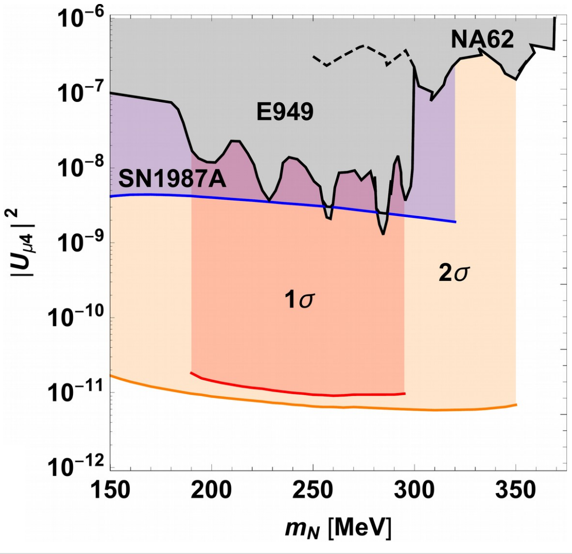
Fischer, Hernandez, TS, 1909.09561



$K \to N\mu$







MiniBooNE and a decaying sterile neutrino

Fischer, Hernandez, TS, 1909.09561

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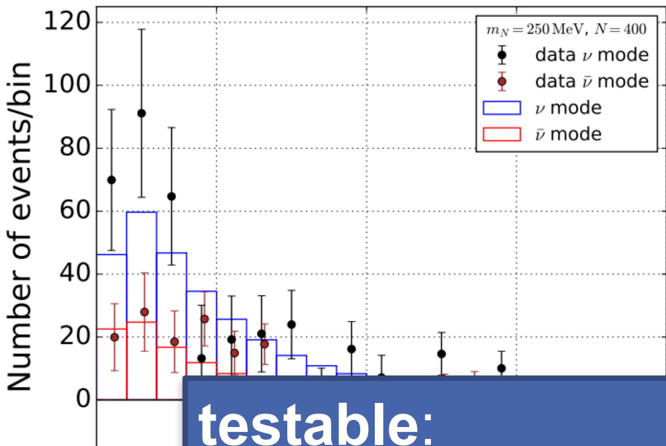
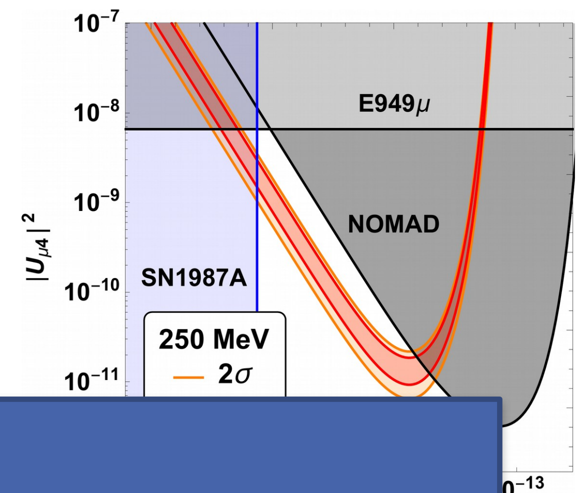
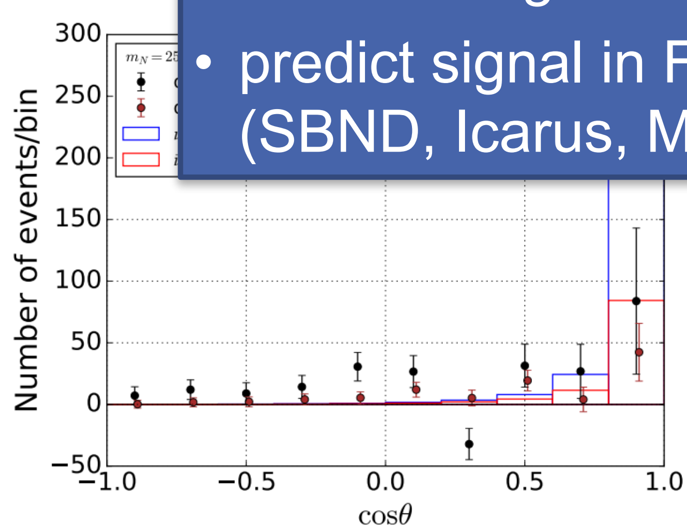
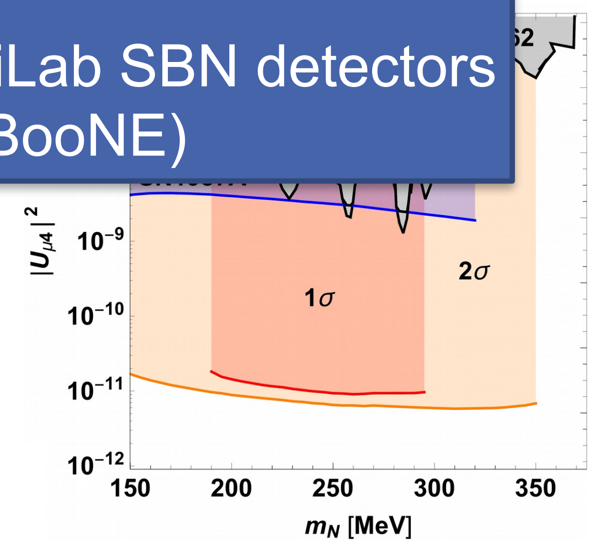




testable:

- event timing in MiniB
- predict signal in FermiLab SBN detectors (SBND, Icarus, MicroBooNE)





Summary 1: anomalies

- hints from relative reactor spectral distortions:

$$\Delta m^2_{41} \simeq 1.3 \text{ eV}^2, \ |U^2_{e4}| \simeq 0.01 \text{ at } \gtrsim 3\sigma$$

- Gallium anomaly: significance reduced to 2.3σ

Kostensalo, et al., 1906.10980

- LSND & MiniBooNE: eV-scale oscill. strongly disfavoured
- eV-scale neutrinos relevant for SBL oscillations are in strong tension with cosmology
- other BSM explanations of MiniBooNE and/or LSND? example: sterile neutrino decay (MeV to few 100 MeV)

Summary II: 3-flavour oscillations

- Octant of θ_{23}:
  weak preference for second octant, bf at $\sin^2\theta_{23} = 0.56$
  $\sin^2\theta_{23} < 0.5$ disfavoured with $\Delta\chi^2 \approx 1.8$ (3.0) without (with) SK atm

- mass ordering:
  NO preferred by $\Delta\chi^2 = 6.2$ (10.4) without (with) SK atm
  SK significance goes down with „improved" analysis
  global fit (incl. IceCube/ORCA & JUNO) may be fastest track to MO

- CP phase:
  CP conservation allowed at $\Delta\chi^2 = 2.2$, bf at $\delta = 221°$

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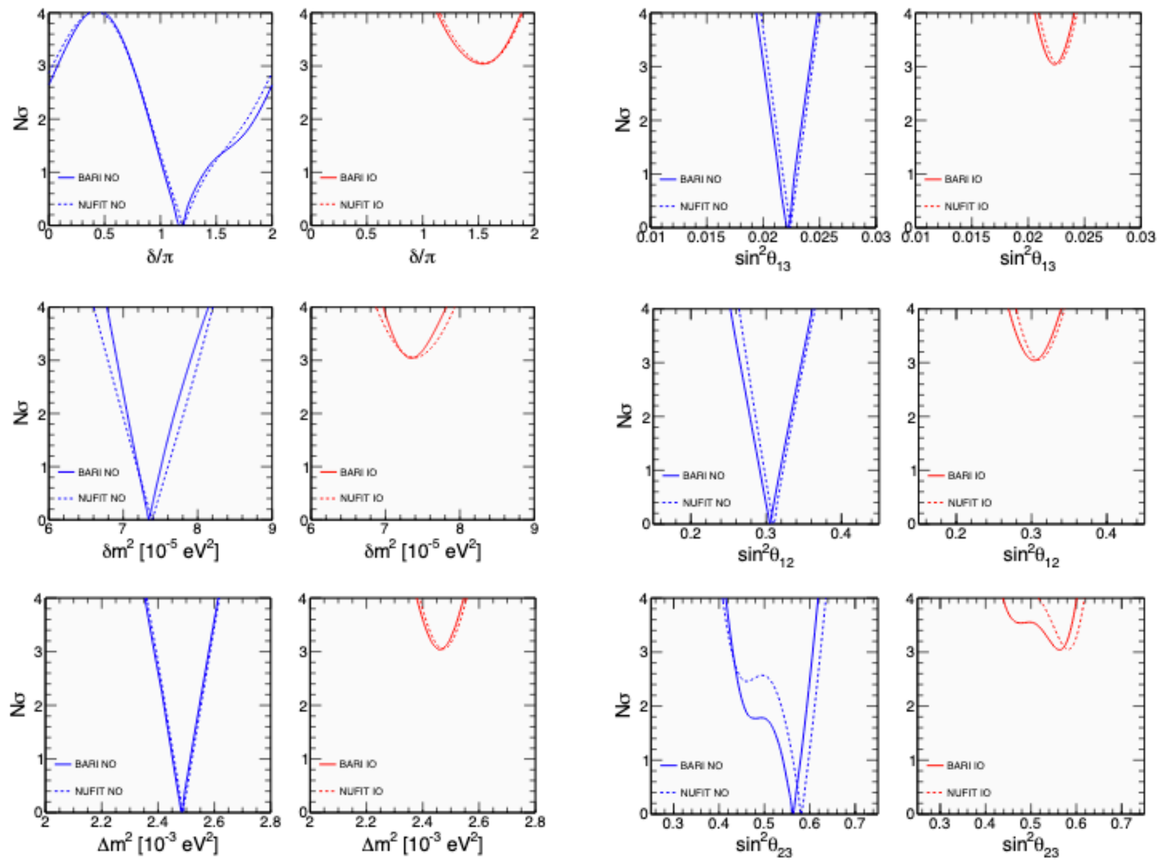
Thank you for your attention!

supplementary slides

Comparison of this 2019 partial update ("BARI") with NuFIT 4.0 results ("NUFIT")

[basically using the same relevant input data sets]



E. Lisi, ESPPU open symposium, Granada, 2019

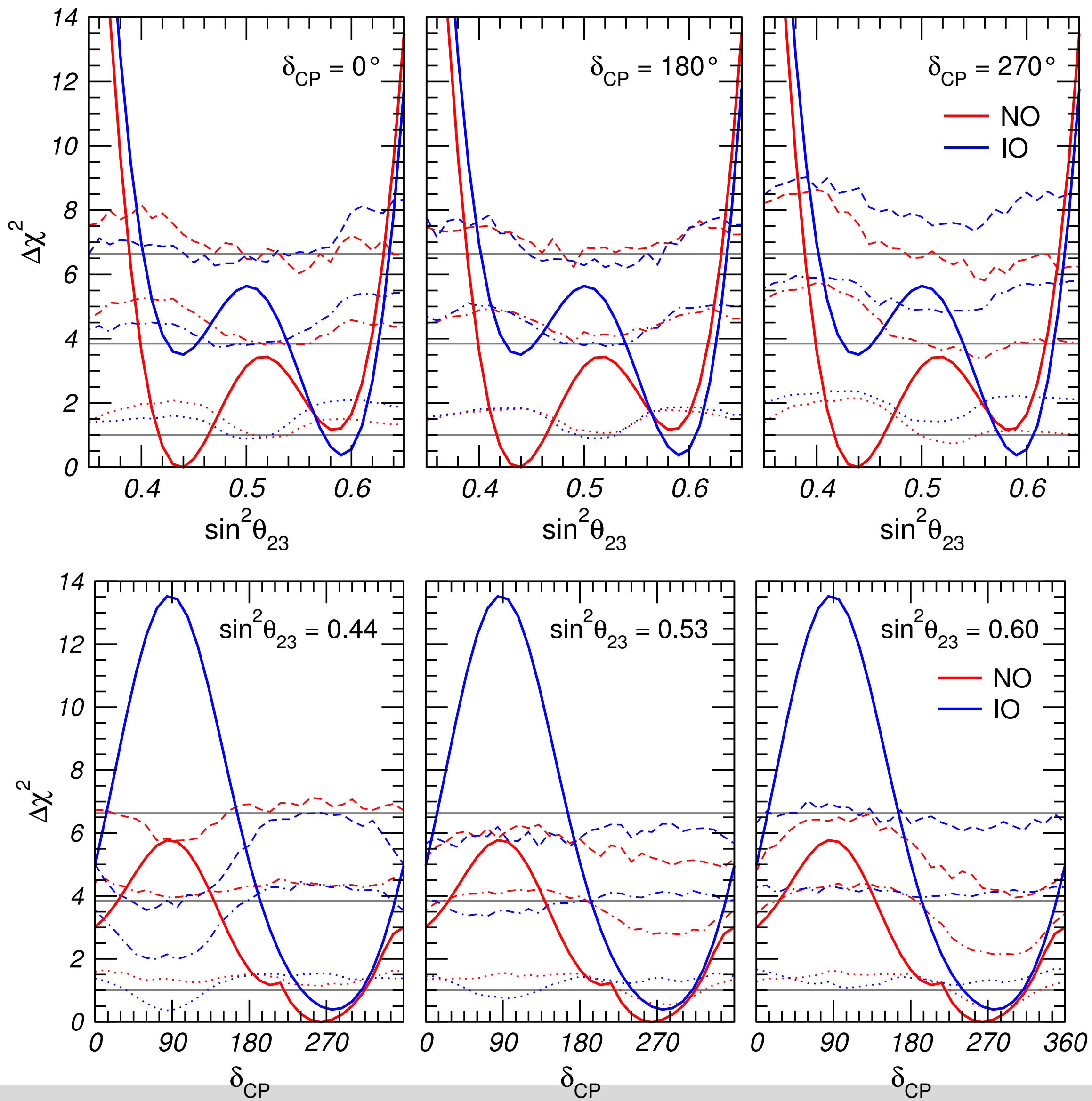
Agreement as good as it can be expected from independent phenom. analyses

[except perhaps for the "bimodal" -and relatively fragile- p.d.f. of $\sin^2\theta_{23}$]

similar results from „Valencia fit" [M. Tortola, et al]

KIT Karlsruher Institut für Technologie

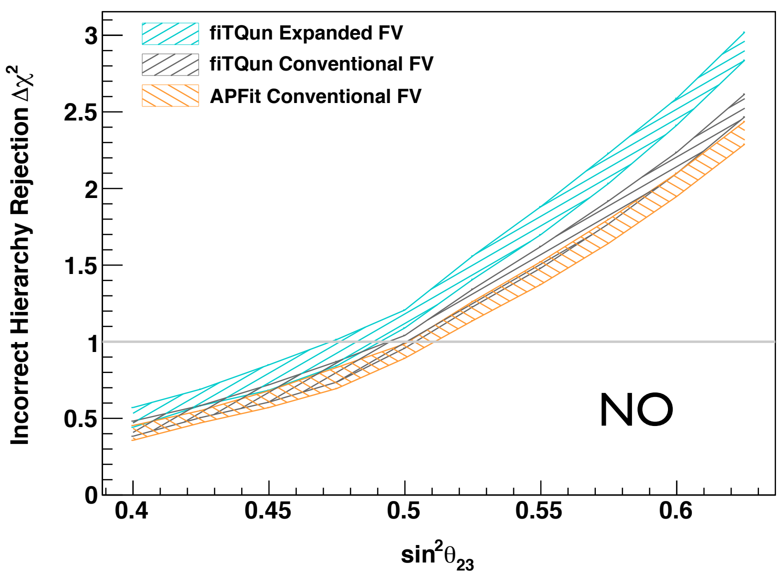
Monte Carlo simulation of χ^2 distribution

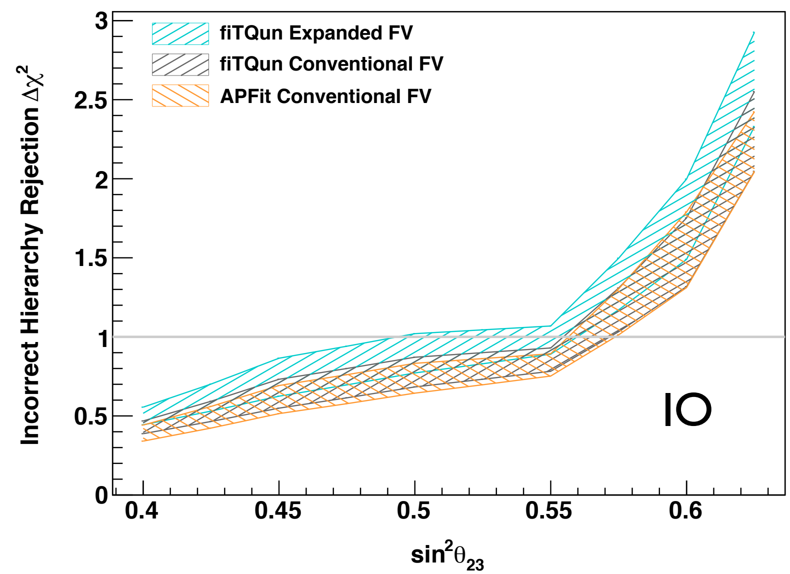


NuFit 3.0, Esteban et al., 1611.01514;
Elevant, TS, 1506.07685

Mass ordering - atmospheric neutrinos

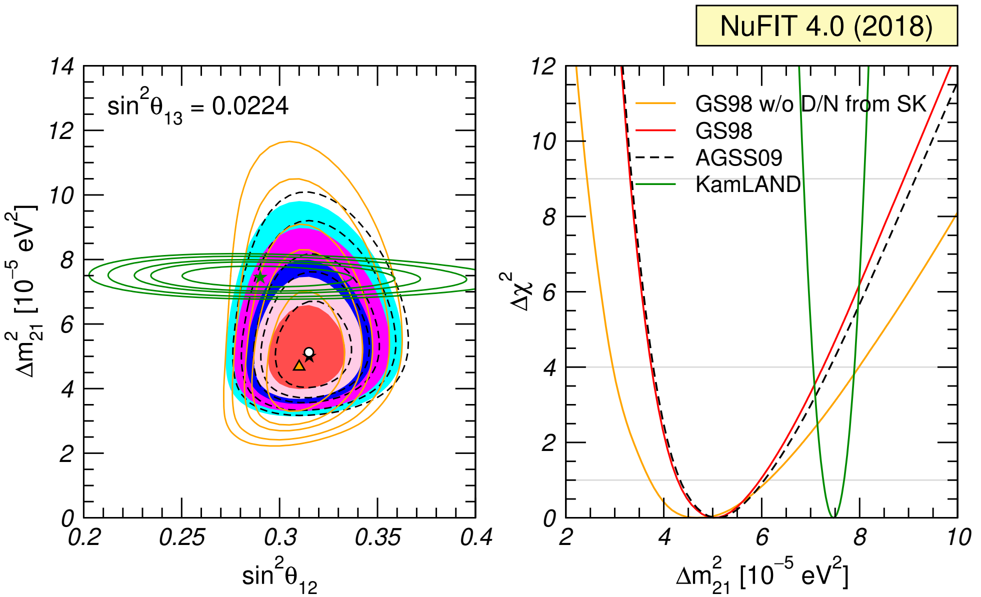
Atmospheric Neutrino Oscillation Analysis With Improved Event Reconstruction in Super-Kamiokande IV, 1901.03230

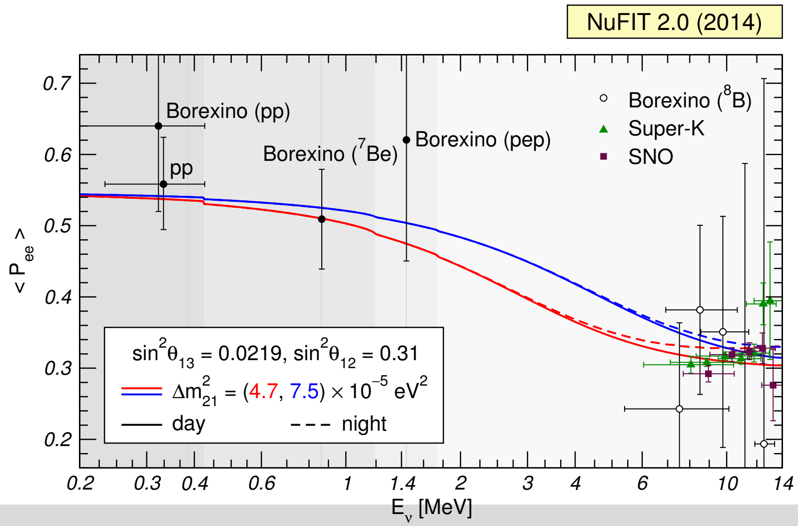




θ_{13} constrained — expected sensitivity

Solar parameters

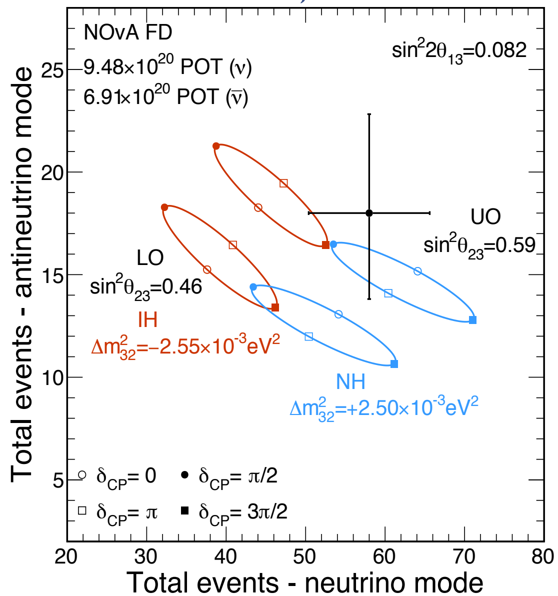


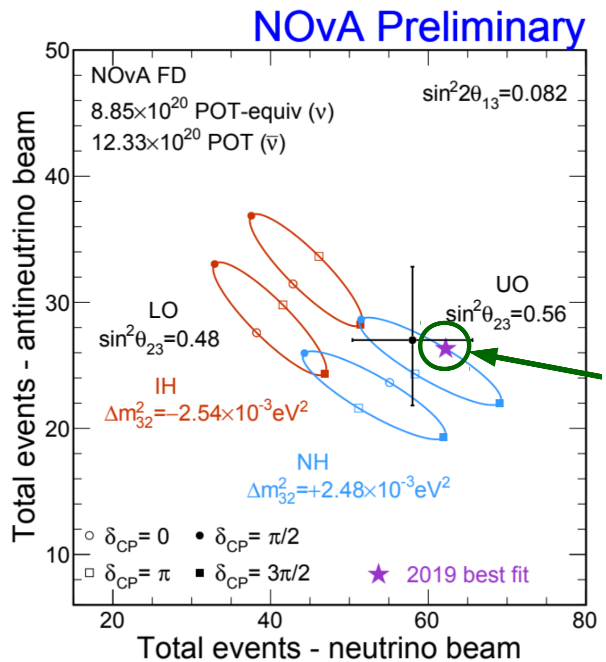


- using reconstructed fluxes from Daya-Bay in KamLAND analysis
- tension between solar and KamLAND remains at ~2σ
- robust wrt to solar models (abundances)
- driven by spectrum upturn and day/night data from SK

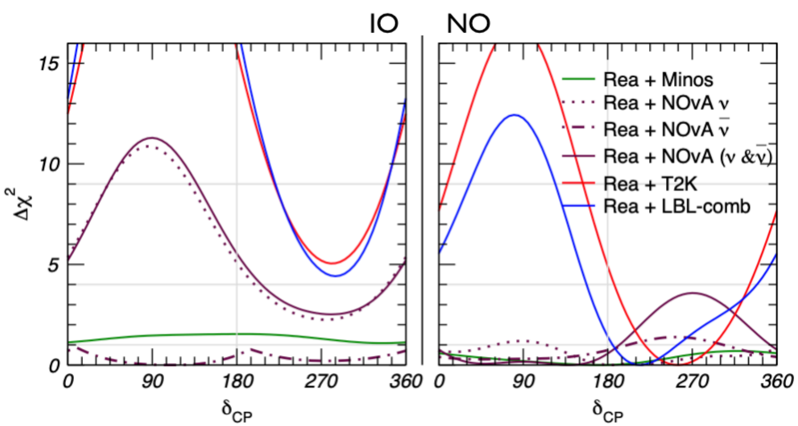
NOvA 2019 update

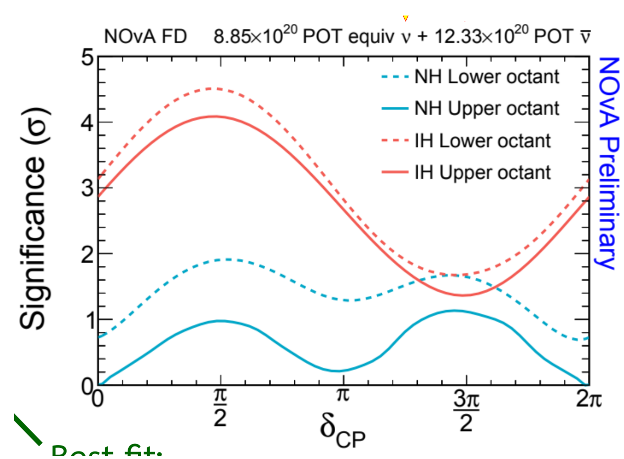
M. Sanchez, Neutrino18



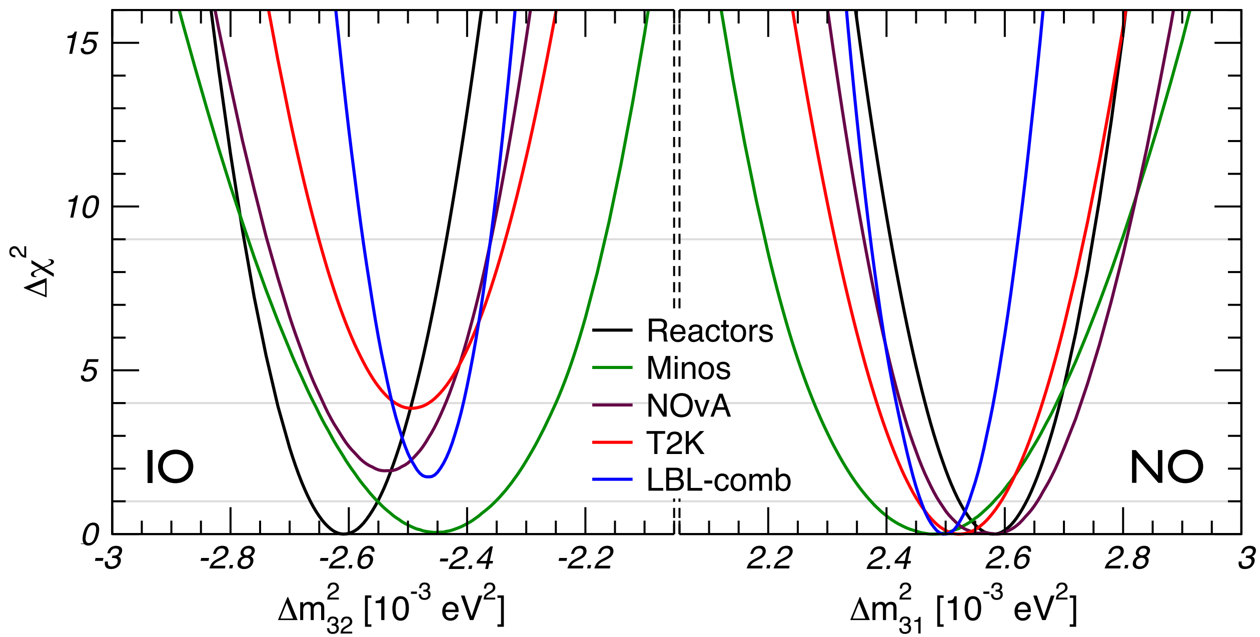


J. Wolcott, FNAL, 2019





Mass ordering



ν_e and ν_μ disappearance depend on slightly different effective mass-squared differences

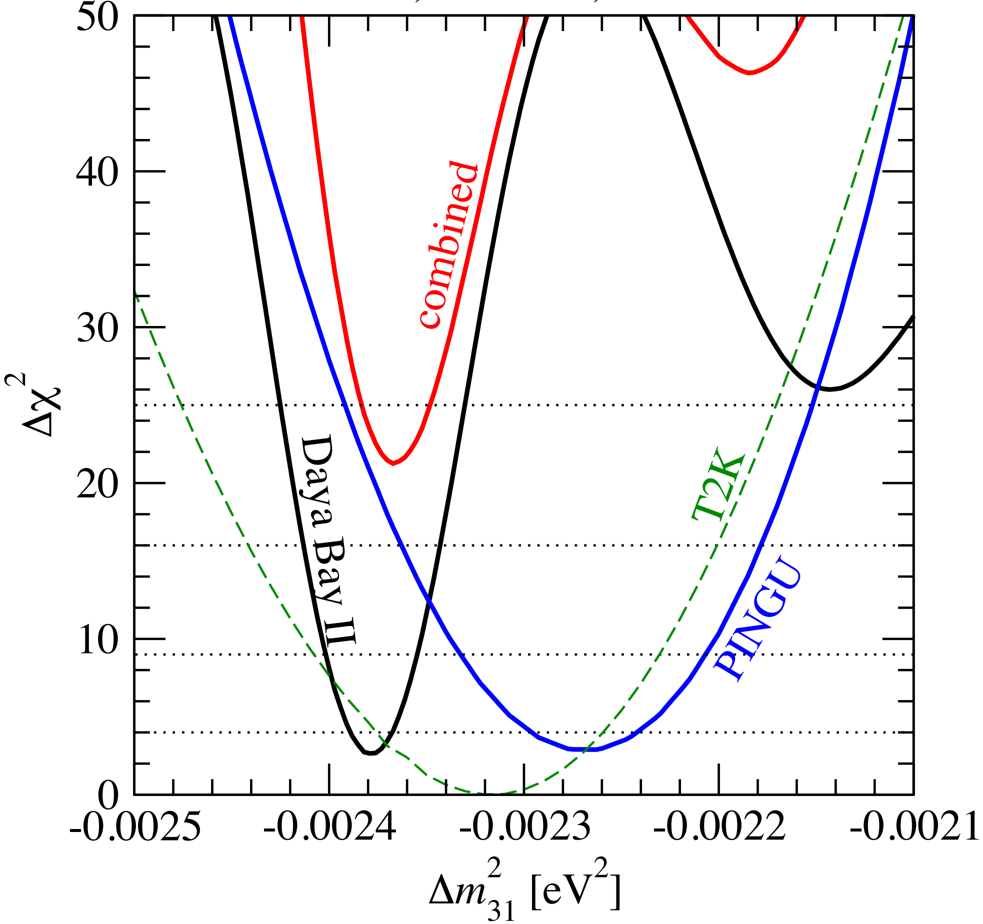
$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

$$\Delta m^2_{\mu\mu} = \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \cos\delta_{\rm CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}$$

Nunokawa, Parke, Zukanovich, 05, 06

ν_e and ν_μ disapp. complementarity in future

Blennow, Schwetz, 1306.3988

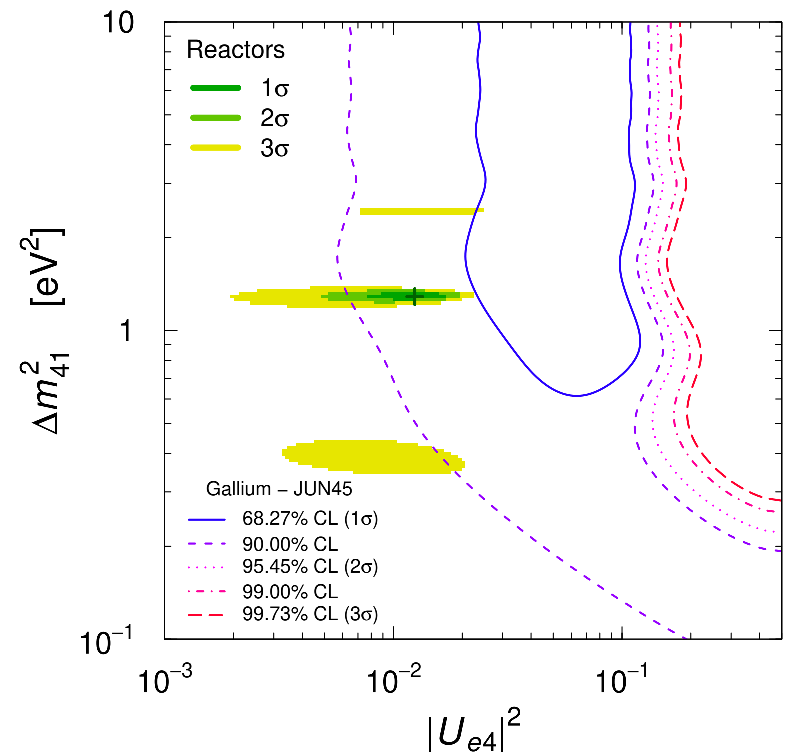


joint IceCube & JUNO paper
is in preparation

Update on Gallium anomaly

- improved shell-model cross section calculations
- significance decreases $3.0\sigma \rightarrow 2.3\sigma$
- smaller mixing angles, consistent with DANSS/NEOS spectral distortions

Kostensalo, Suhonen, Giunti, Srivastava, 1906.10980



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