Phenomenology of three-neutrino masses and mixings

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www.nu-fit.org

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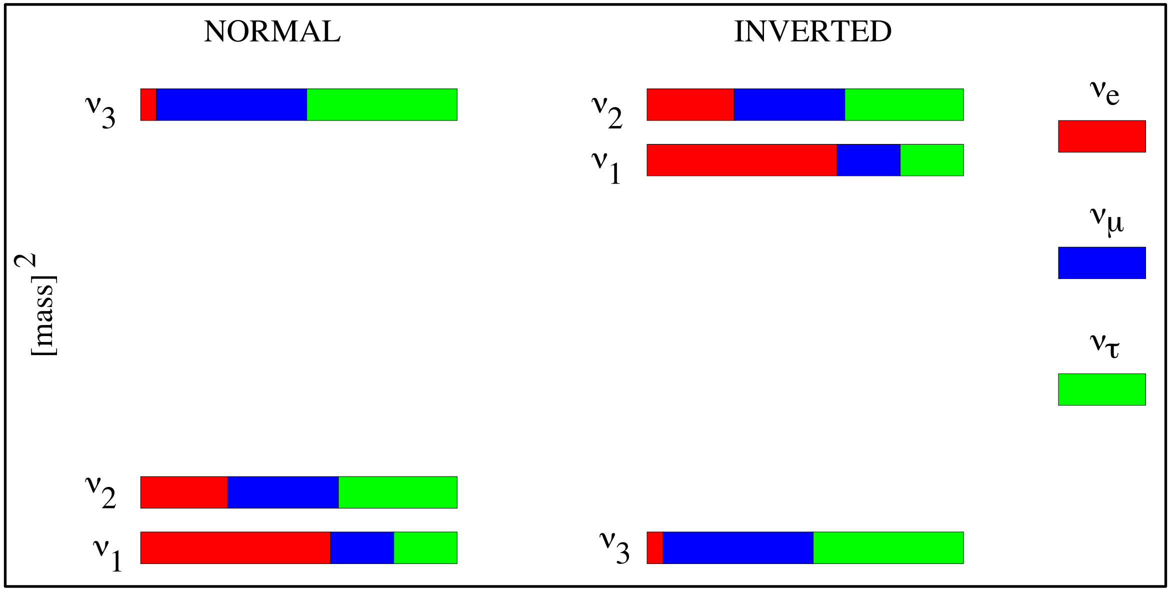
Karlsruher Institut für Technologie

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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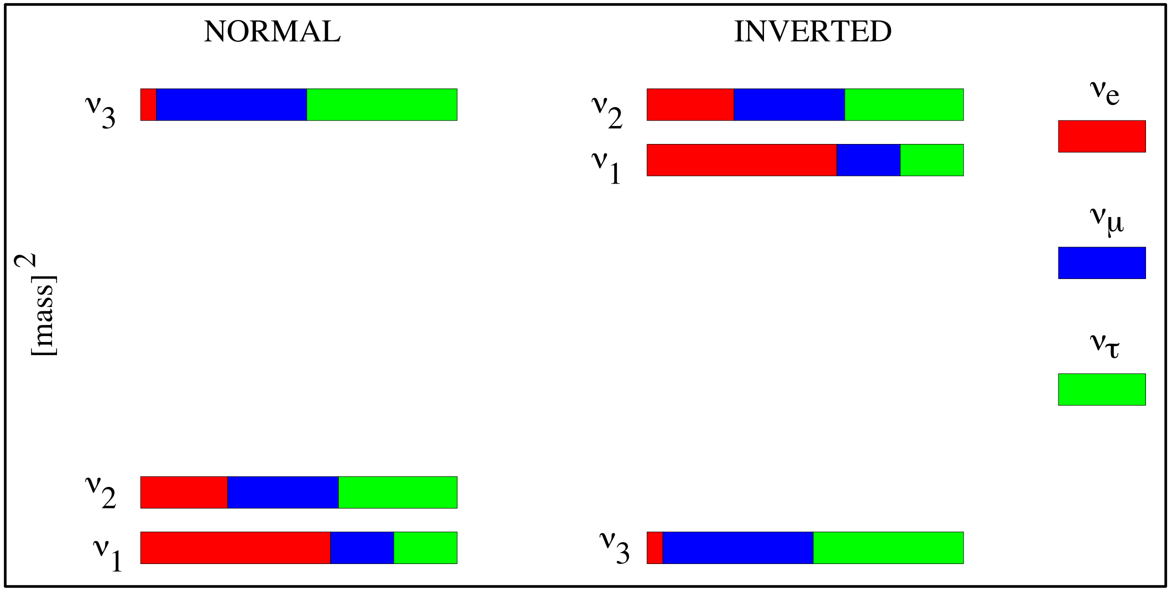
← neutrino oscillations



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The 3-flavour paradigm

- 3 masses: Δm^2_{21} , Δm^2_{31}, m_0
- 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

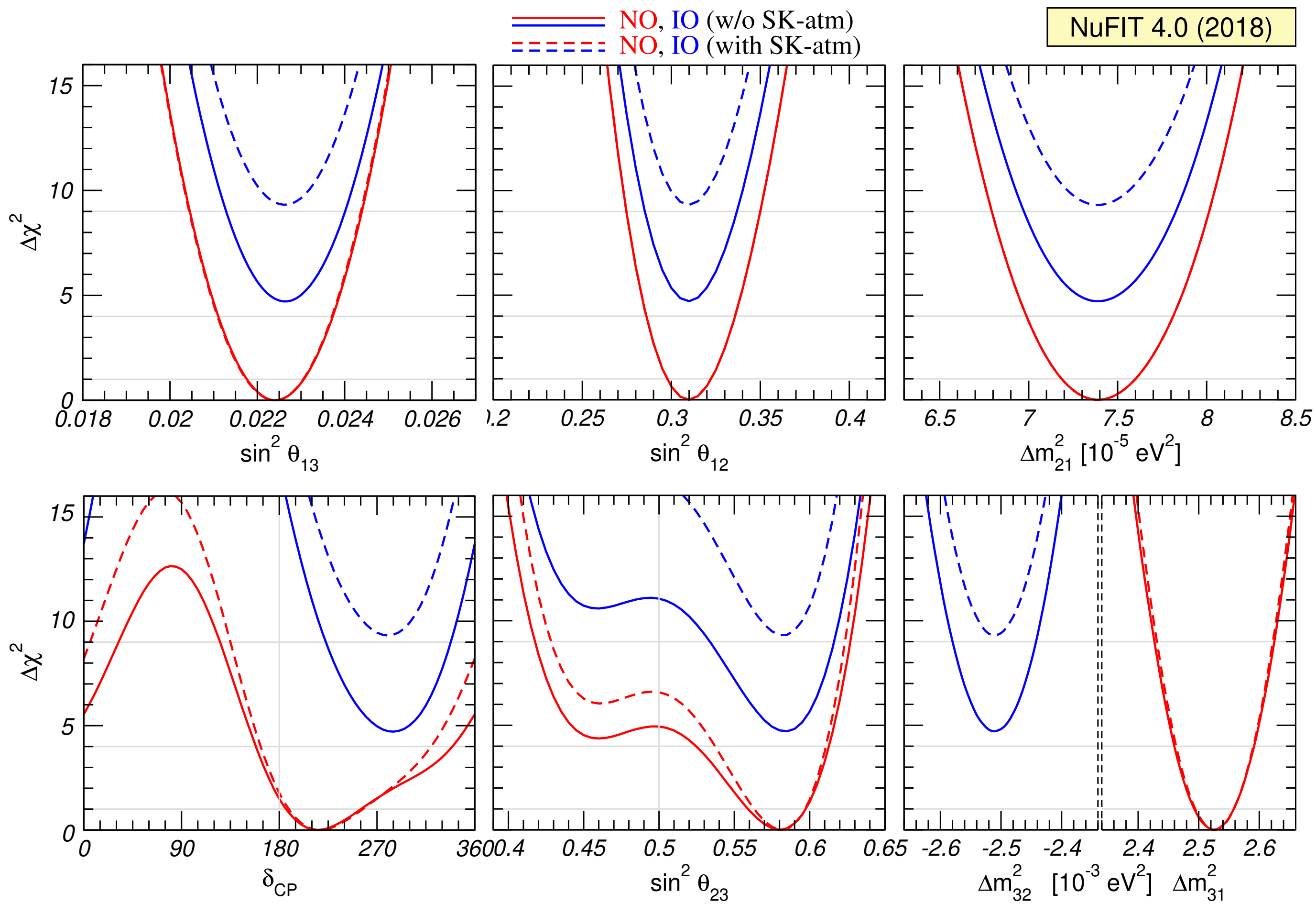
NuFit 4.0 (2018)

www.nu-fit.org

I. Esteban, C. Gonzalez-Garcia, A. Hernandez, M. Maltoni, T. Schwetz, 1811.05487, JHEP 19

- data available till Oct 2018 (incl. Neutrino 2018 releases)
- T2K:
  14.93e20 pot neutrino, 11.24e20 pot antineutrino
- NOvA:
  8.85e20 pot neutrino, 6.91e20 pot antineutrino
- full list of data see
  http://www.nu-fit.org/sites/default/files/v40.release-notes.pdf

NuFit 4.0 (2018)



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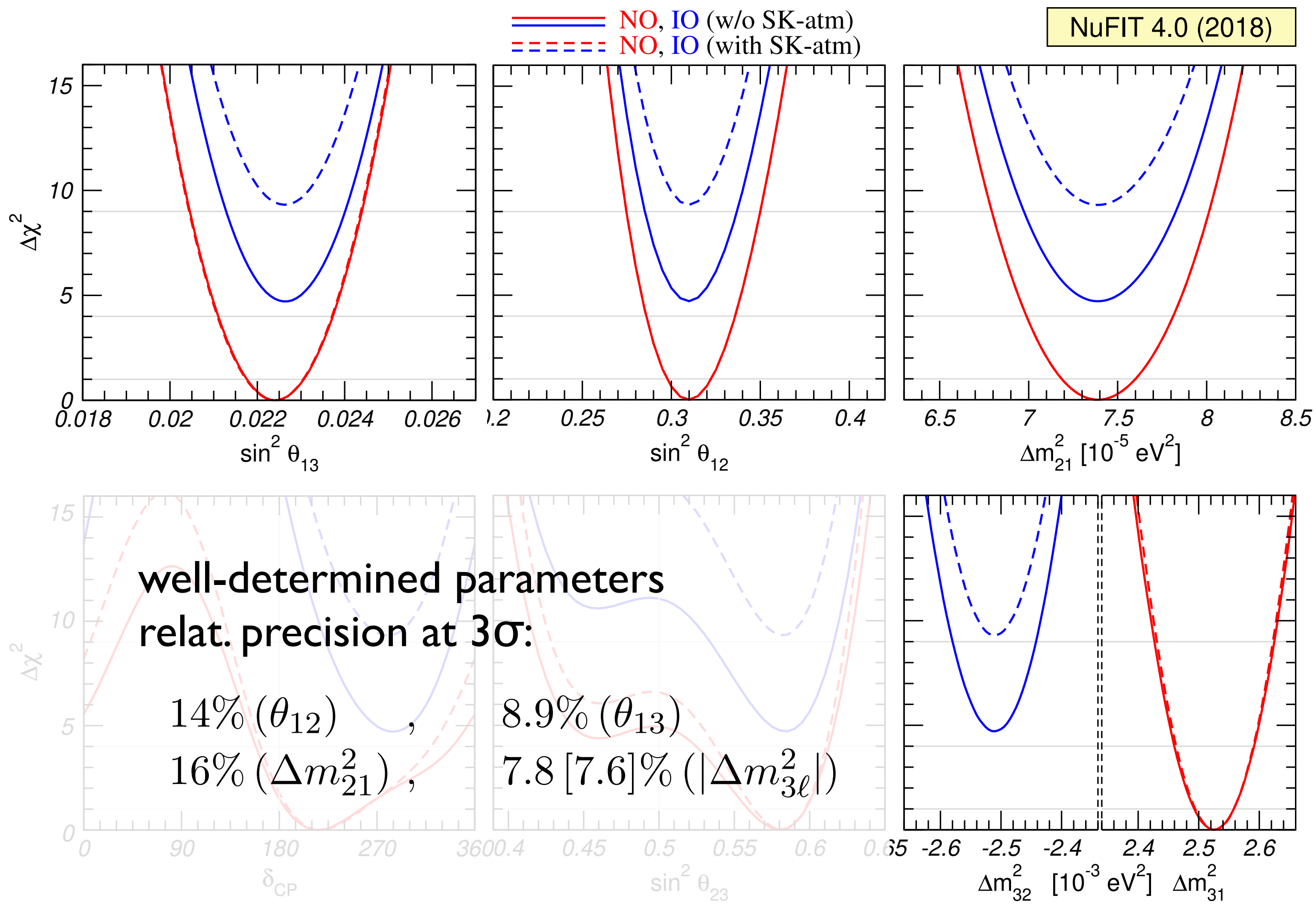
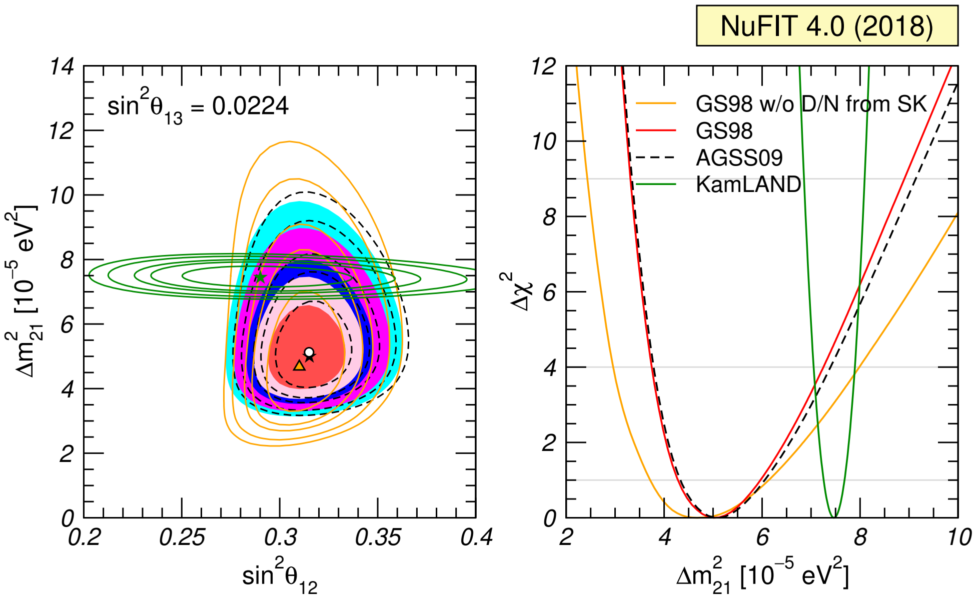


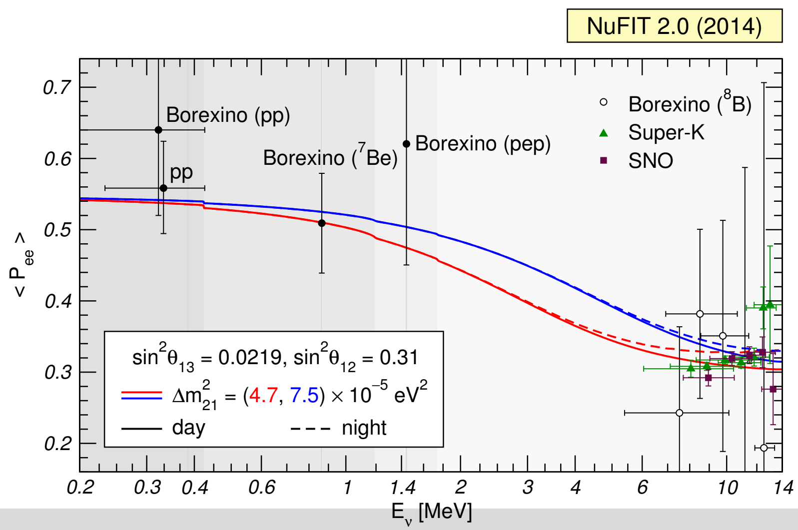
well-determined parameters
relat. precision at 3σ:

$14\%\ (\theta_{12})$, $8.9\%\ (\theta_{13})$

$16\%\ (\Delta m^2_{21})$, $7.8\ [7.6]\%\ (|\Delta m^2_{3\ell}|)$

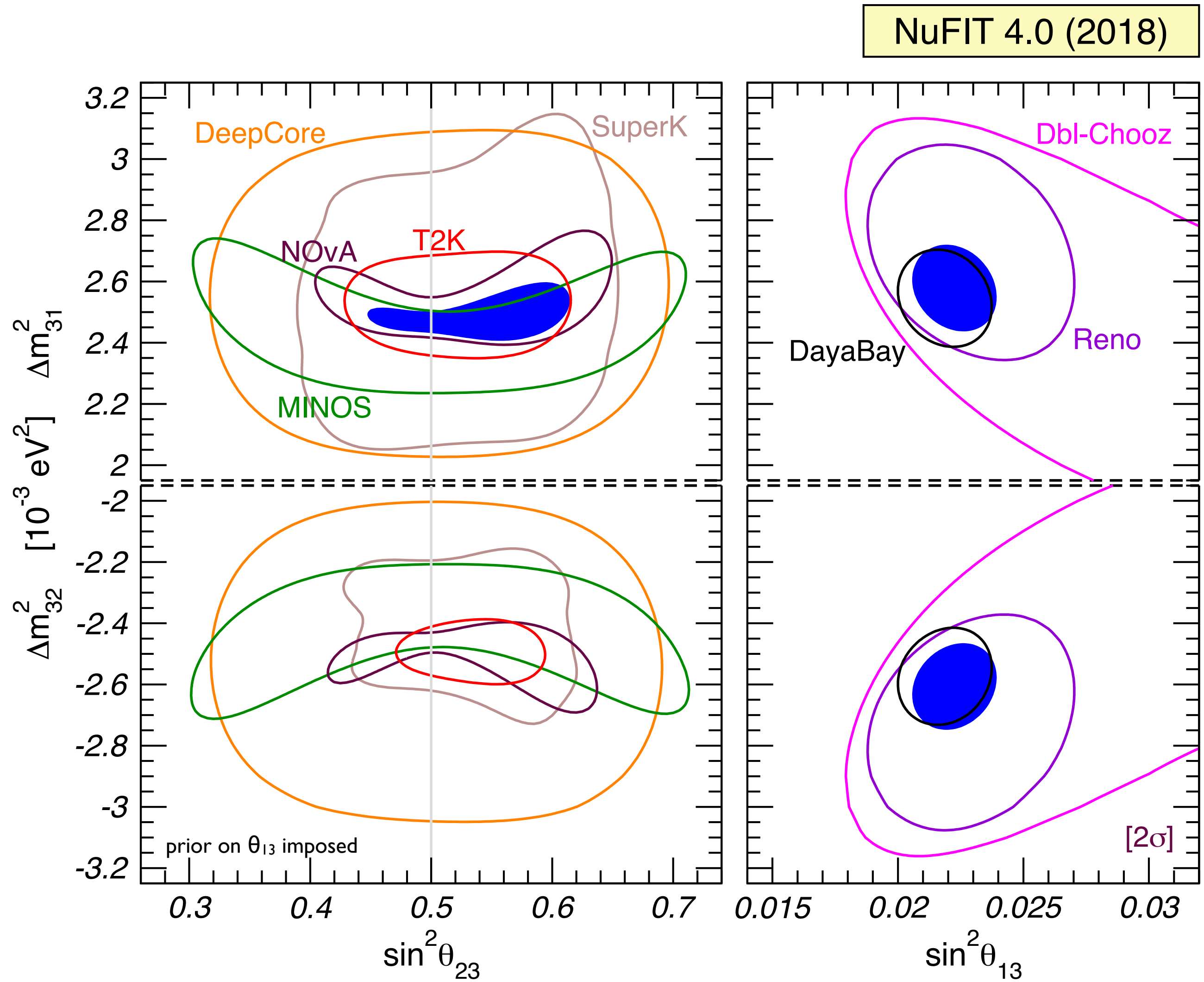
Solar parameters





- 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

Atmospheric parameters



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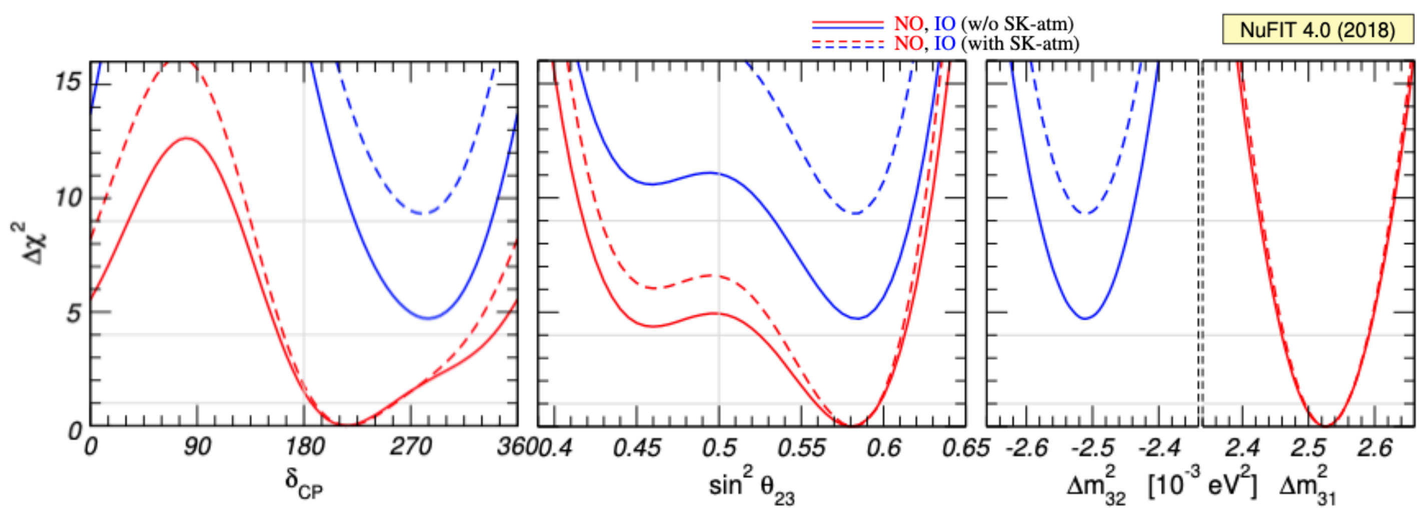
not-so-well determined

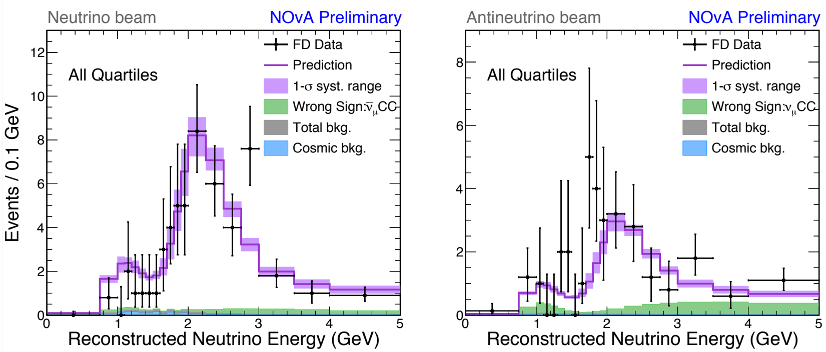
- preference for second octant of θ_{23}, bf at $\sin^2\theta_{23} = 0.58$
  $\sin^2\theta_{23} < 0.5$ disfavoured with $\Delta\chi^2 \approx 4.4$ (6.0) without (with) SK atm
- NO preferred over IO by $\Delta\chi^2 = 4.7$ (9.3) without (with) SK atm
- CP conservation allowed at $\Delta\chi^2 = 1.8$, bf at $\delta = 217°$



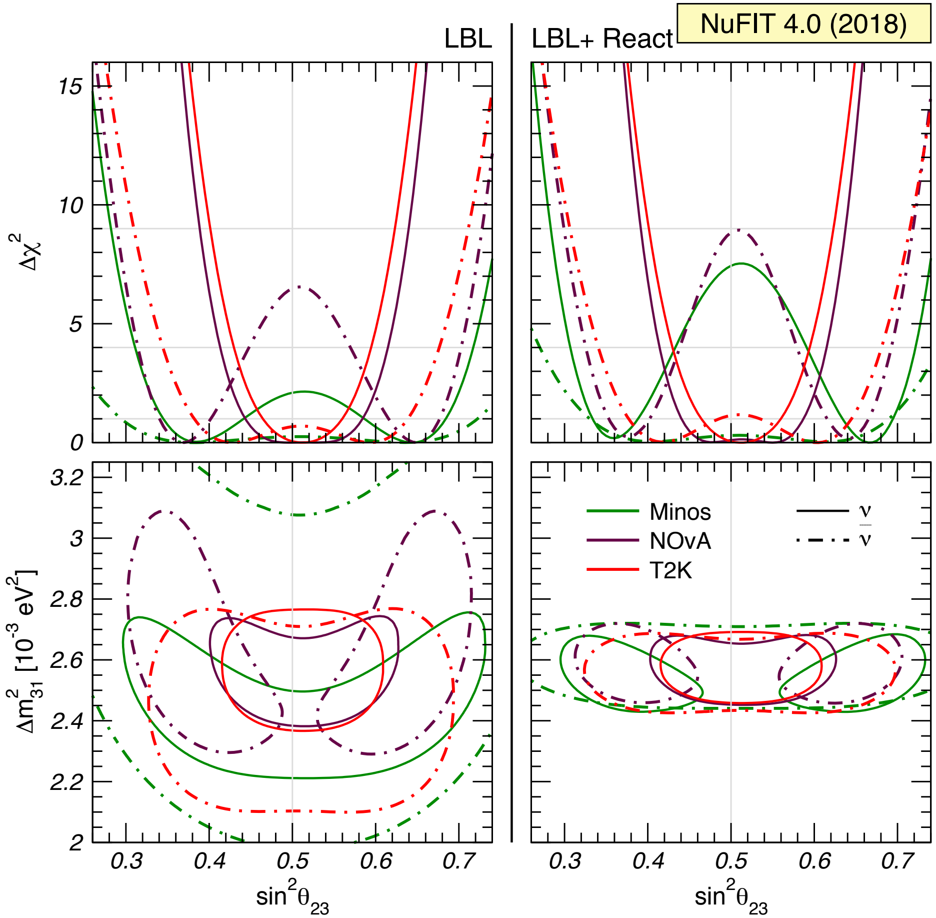
LBL disappearance results

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

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



M. Sanchez, Neutrino18



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

LBL appearance data

following Elevant, Schwetz, 15

$$C' \approx 0.28$$

$$o \equiv \mathrm{sgn}(\Delta m^2_{3\ell})$$

$$A \equiv \left|\frac{2EV}{\Delta m^2_{3\ell}}\right| \approx \begin{cases} 0.05 & \text{T2K} \\ 0.1 & \text{NOvA} \end{cases}$$

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

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

	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

- Both neutrino and anti-neutrino events are enhanced by increasing s^2_{23}.
- Values of $\sin\delta_{CP} \simeq +1\,(-1)$ 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 δ_{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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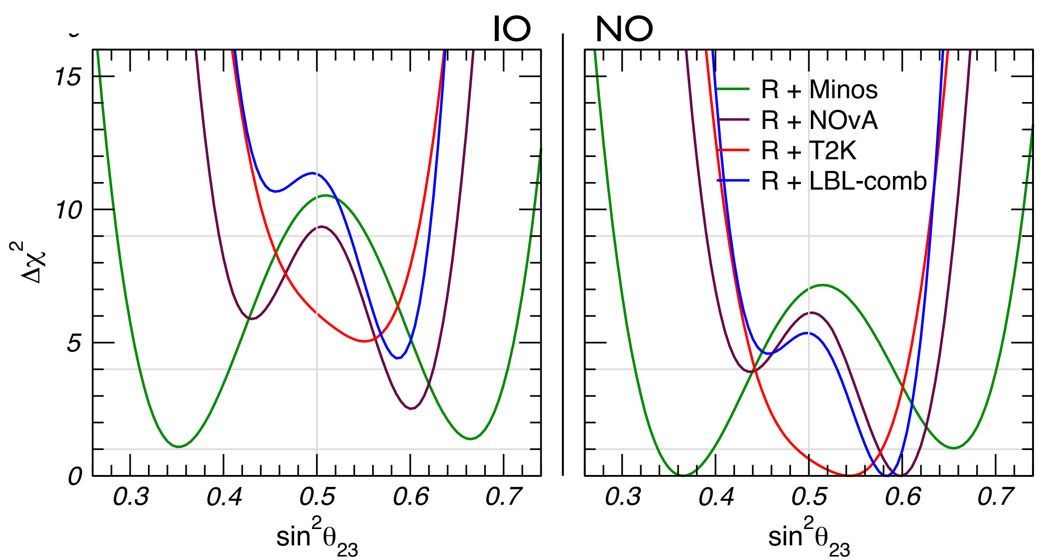

CP phase

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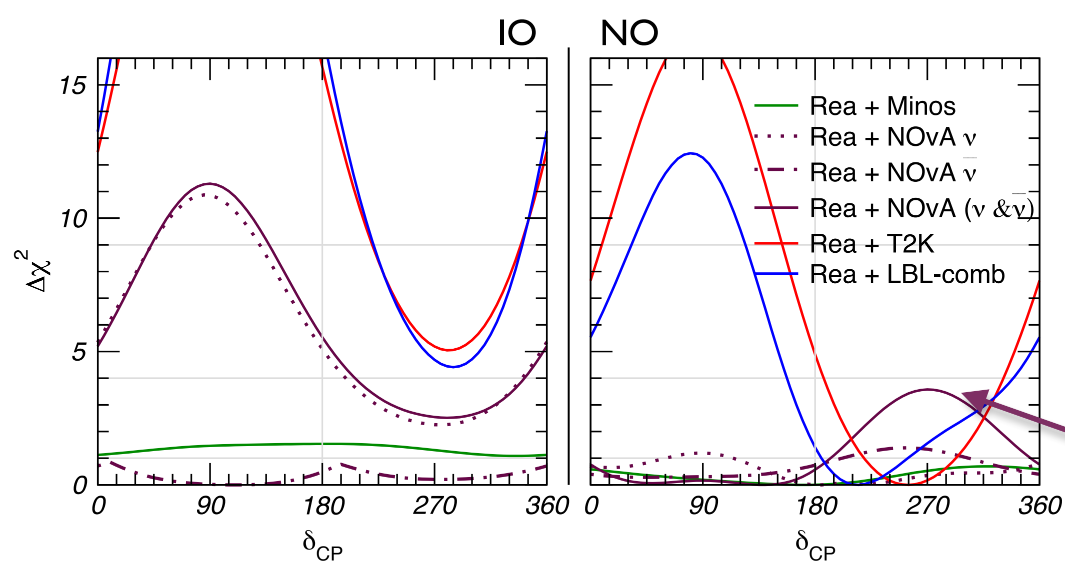
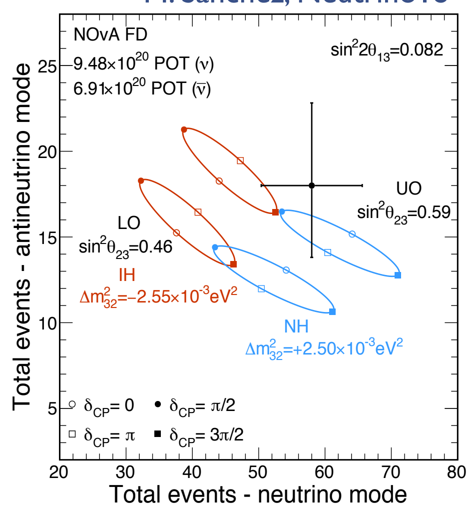
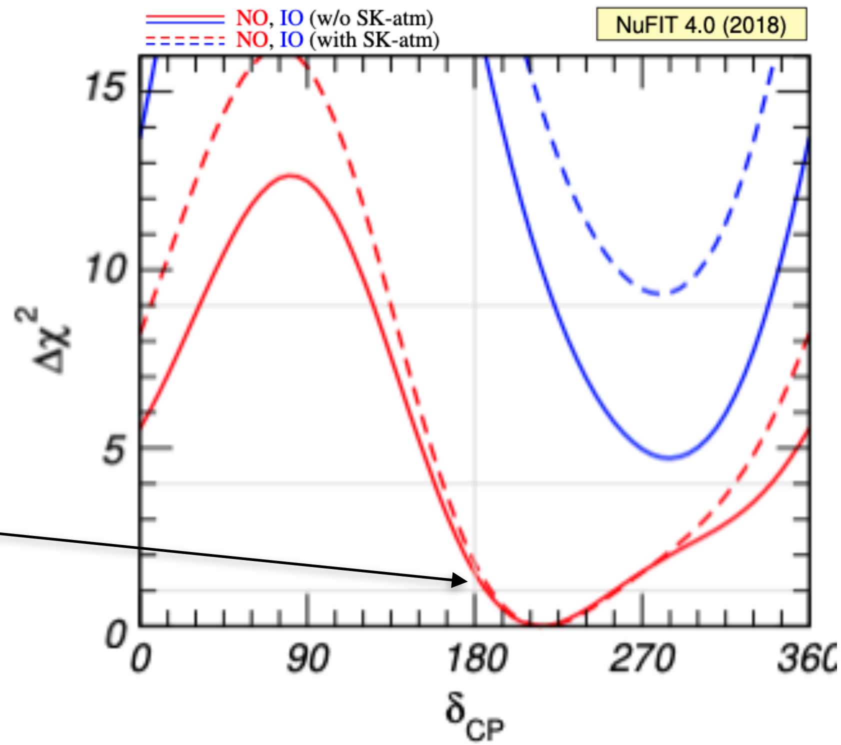


M. Sanchez, Neutrino18



NOvA: non-max θ_{23} from antineut. + matter enhancement predict too many neutrino events for $\delta \approx 270°$

CP phase



CP conservation
at $\Delta\chi^2 = 1.8$

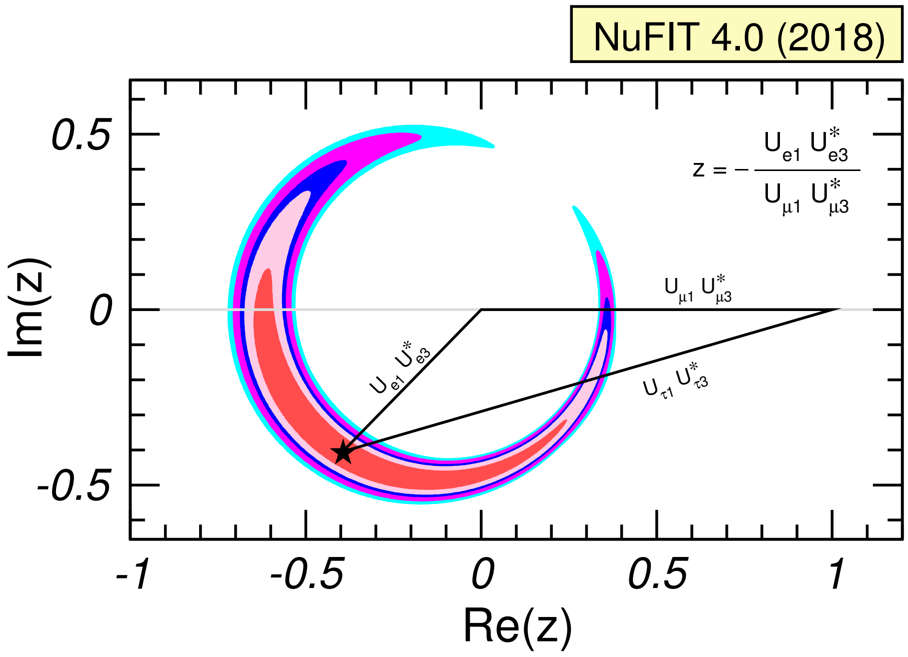
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\delta_{CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$

Leptonic CP violation

Jarlskog invariant:

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

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



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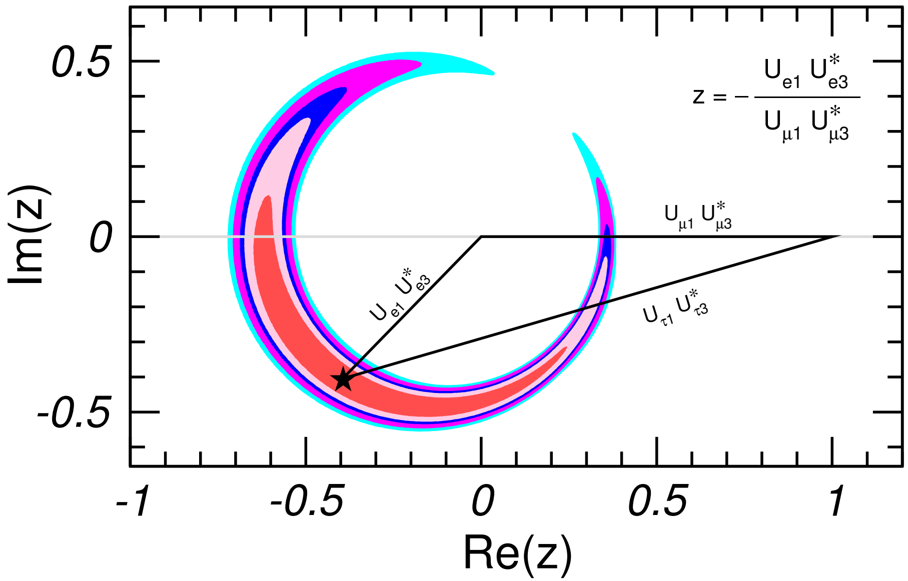
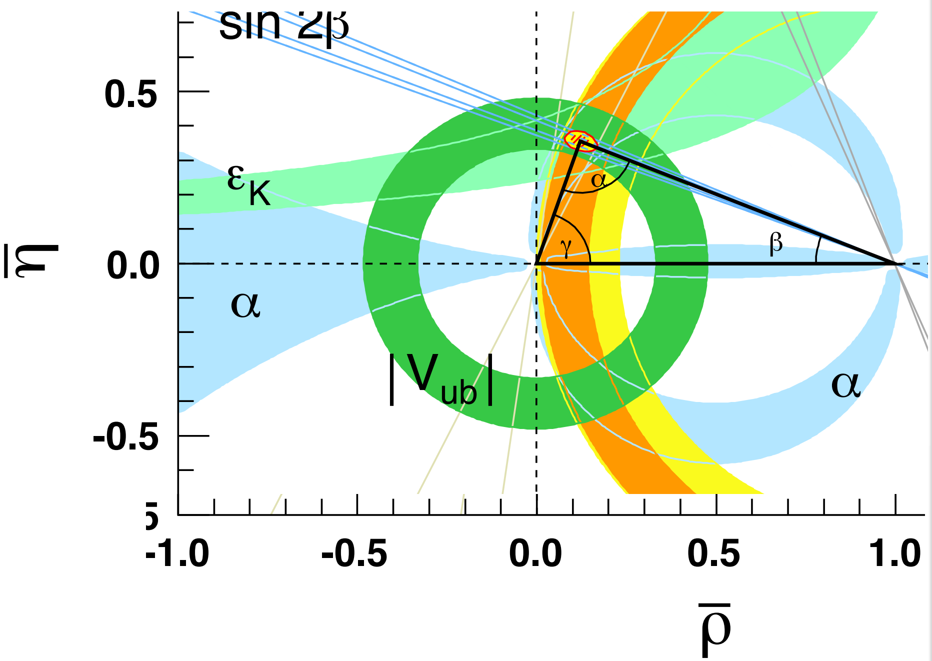
$$J^{\max}_{\rm CP} = 0.0333 \pm 0.0006\,(\pm 0.0019) \;\text{ at } 1\sigma\ (3\sigma)$$

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

NuFIT 4.0 (2018)



PDG 2018



Mass ordering

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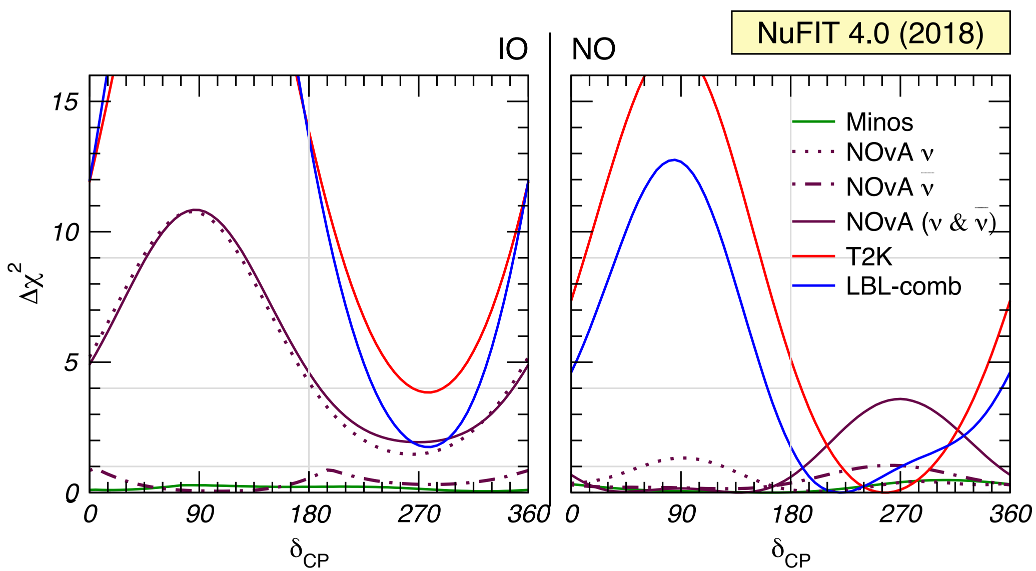
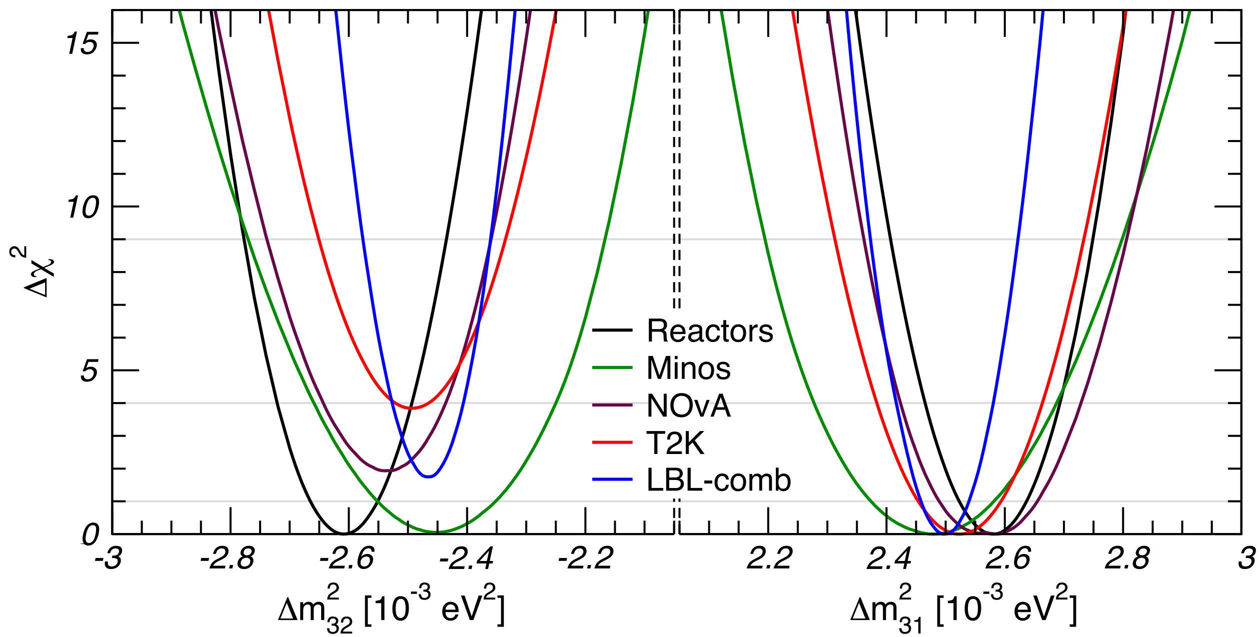


no reactor data, but θ_{13} prior added

T2K: $\Delta\chi^2$(IO) ≈ 4

adding NOvA: $\Delta\chi^2$(IO) ≈ 2

Mass ordering



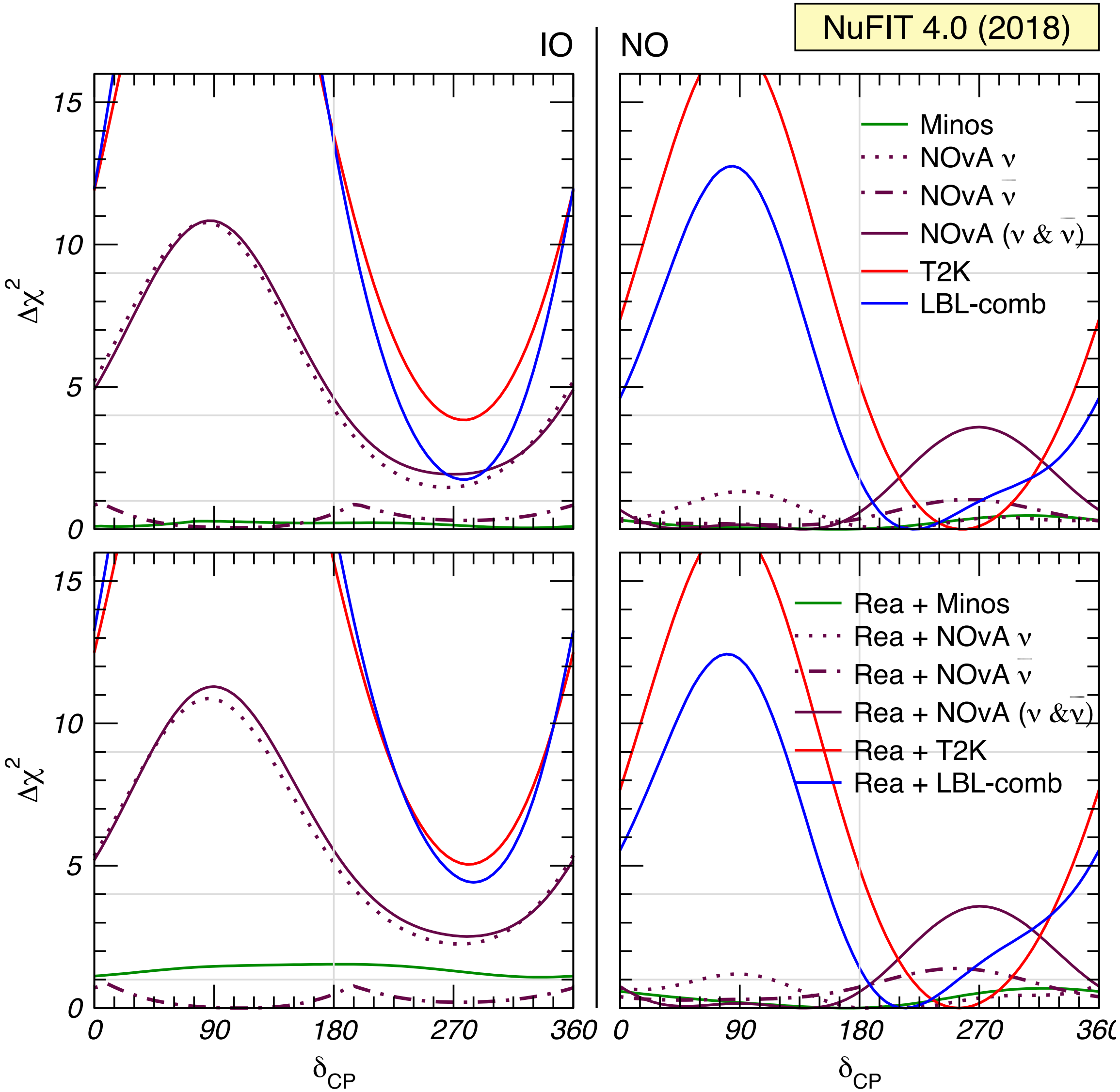
ν_e and ν_μ disappearance depend on slightly different effective mass-squared differences

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

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

Nunokawa, Parke, Zukanovich, 05, 06

Mass ordering



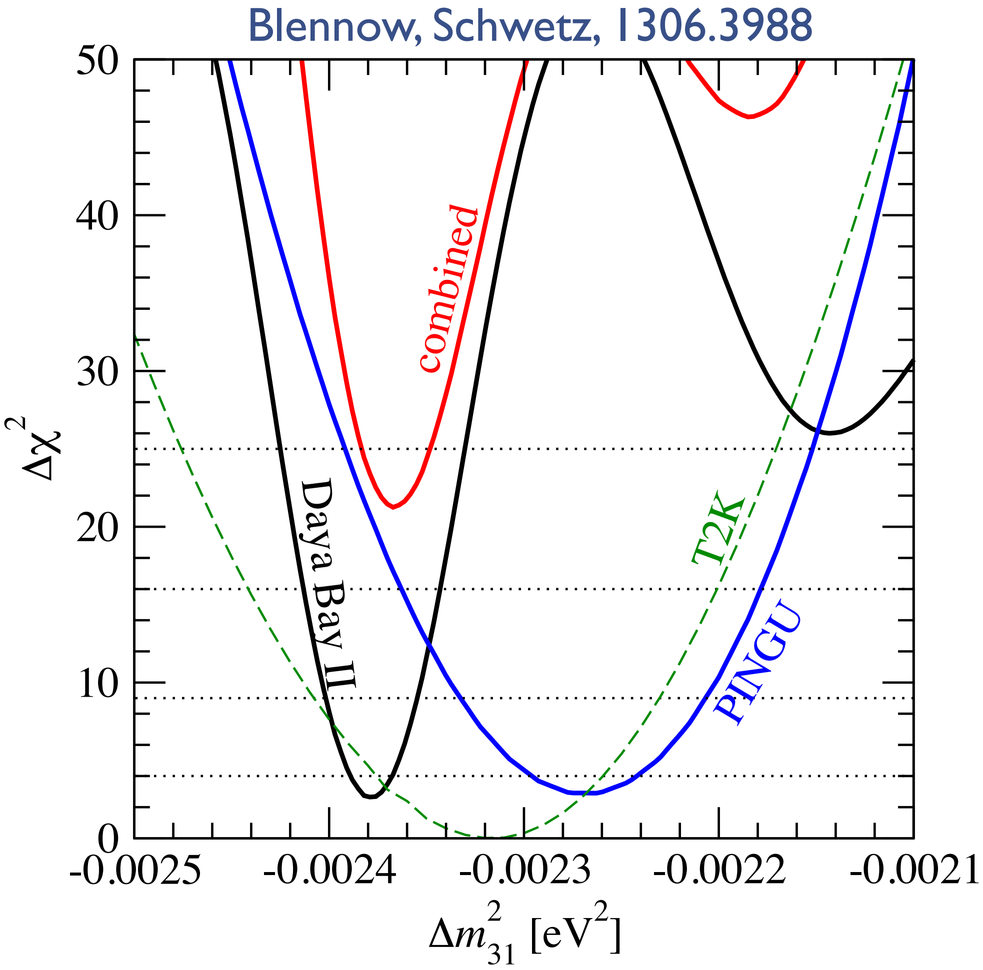
no reactor data, but θ_{13} prior added

T2K: $\Delta\chi^2(\mathrm{IO}) \approx 4$

adding NOvA: $\Delta\chi^2(\mathrm{IO}) \approx 2$

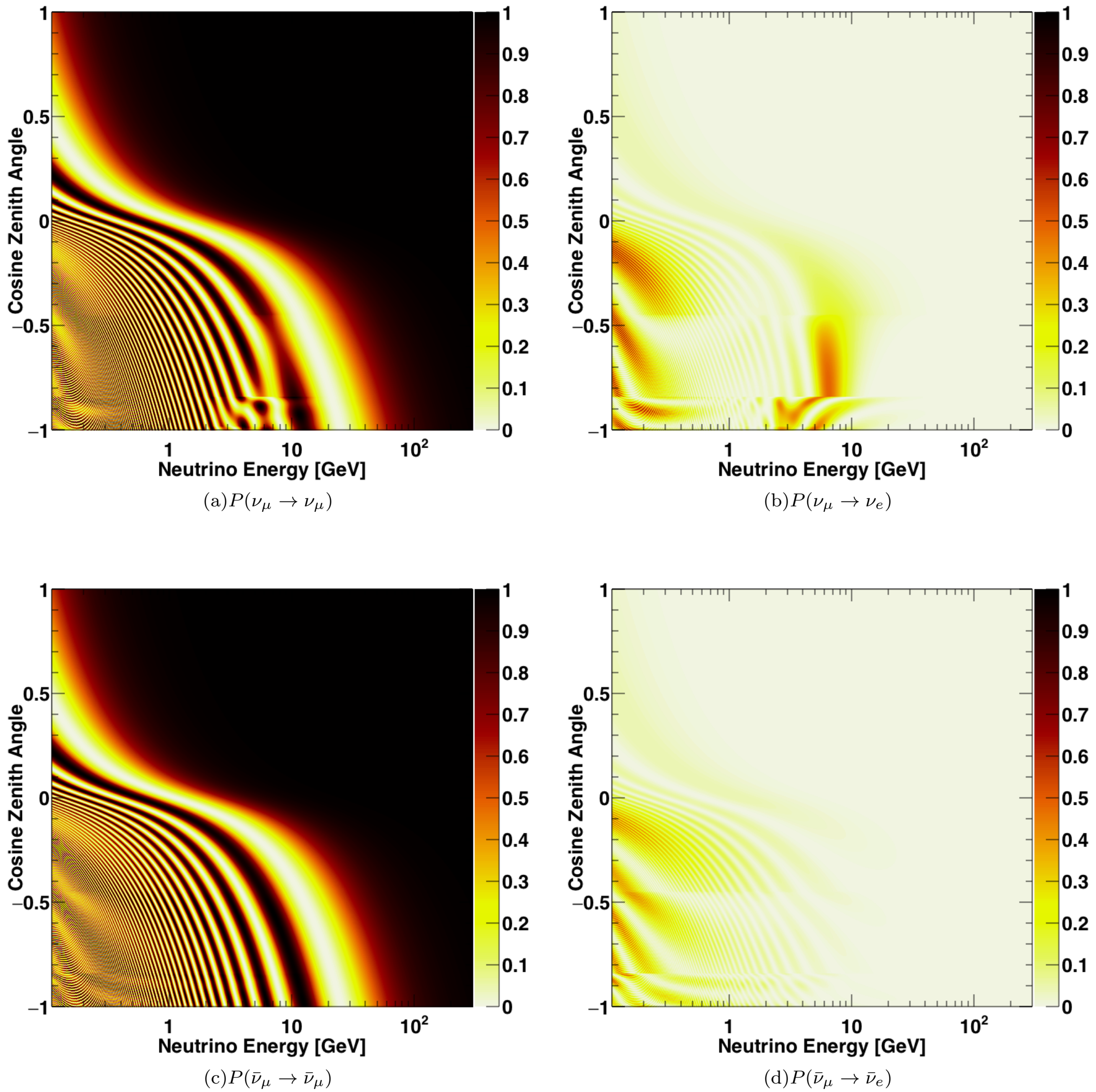
adding reactors: $\Delta\chi^2(\mathrm{IO}) \approx 4$

ν_e and ν_μ disapp. complementarity in future



joint IceCube & JUNO paper is in preparation

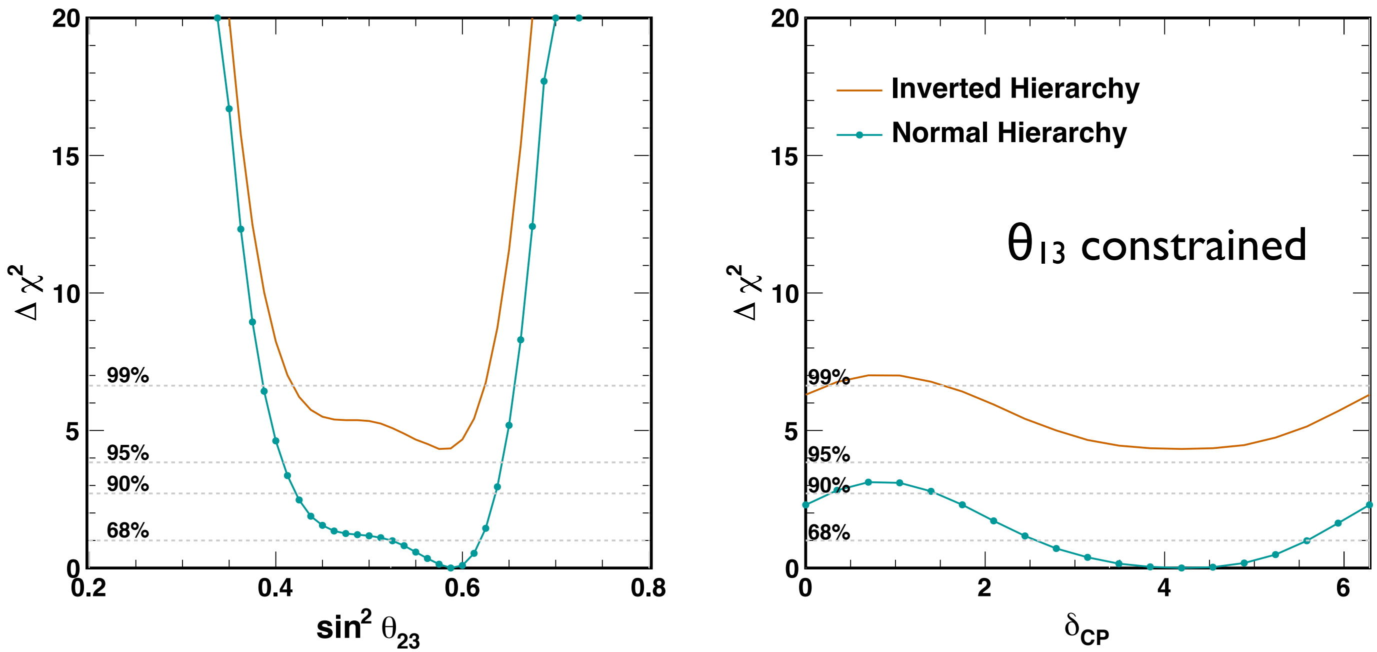
Mass ordering - atmospheric neutrinos



1710.09126

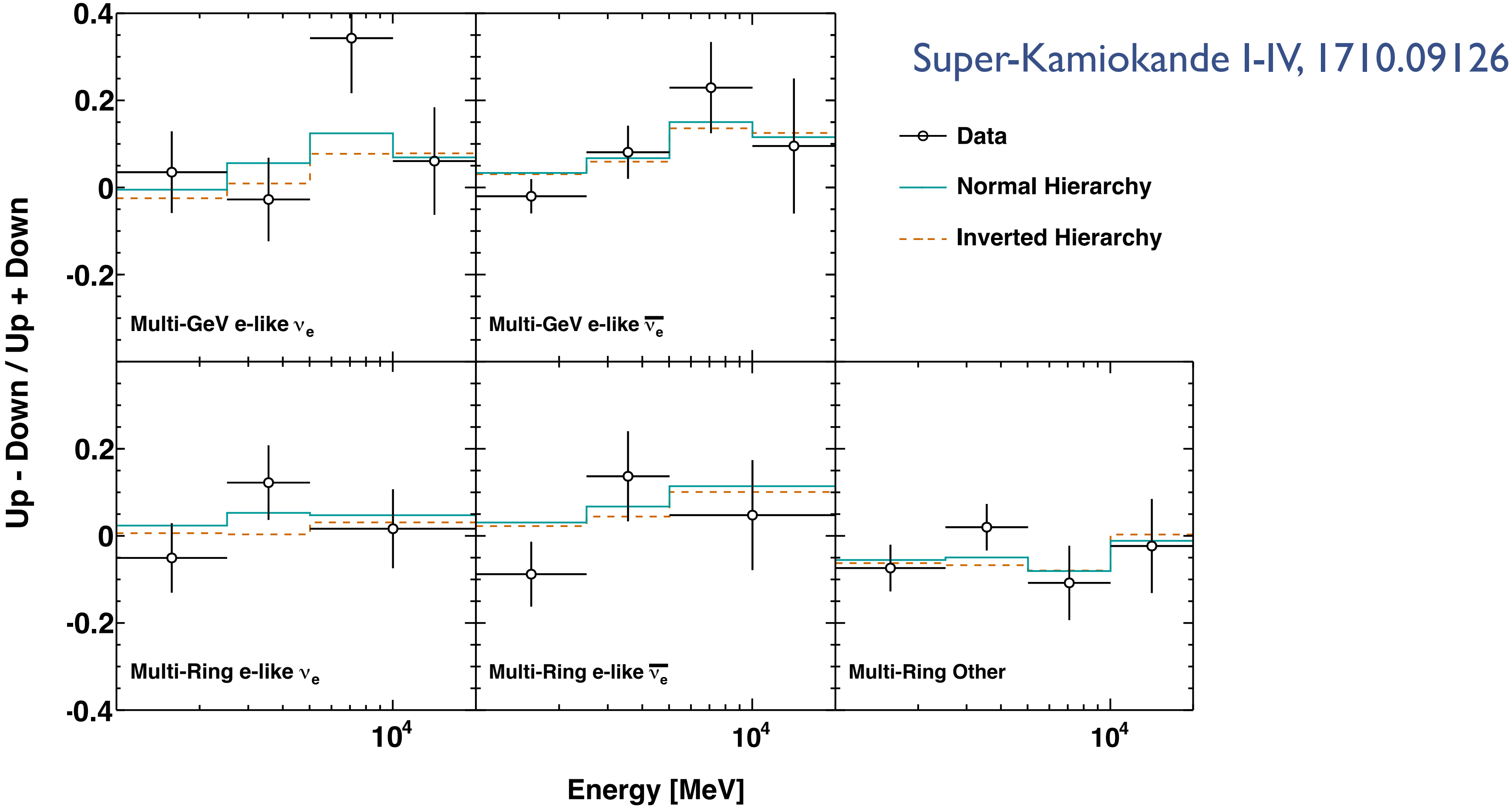
Mass ordering - atmospheric neutrinos

Super-Kamiokande I-IV, 1710.09126



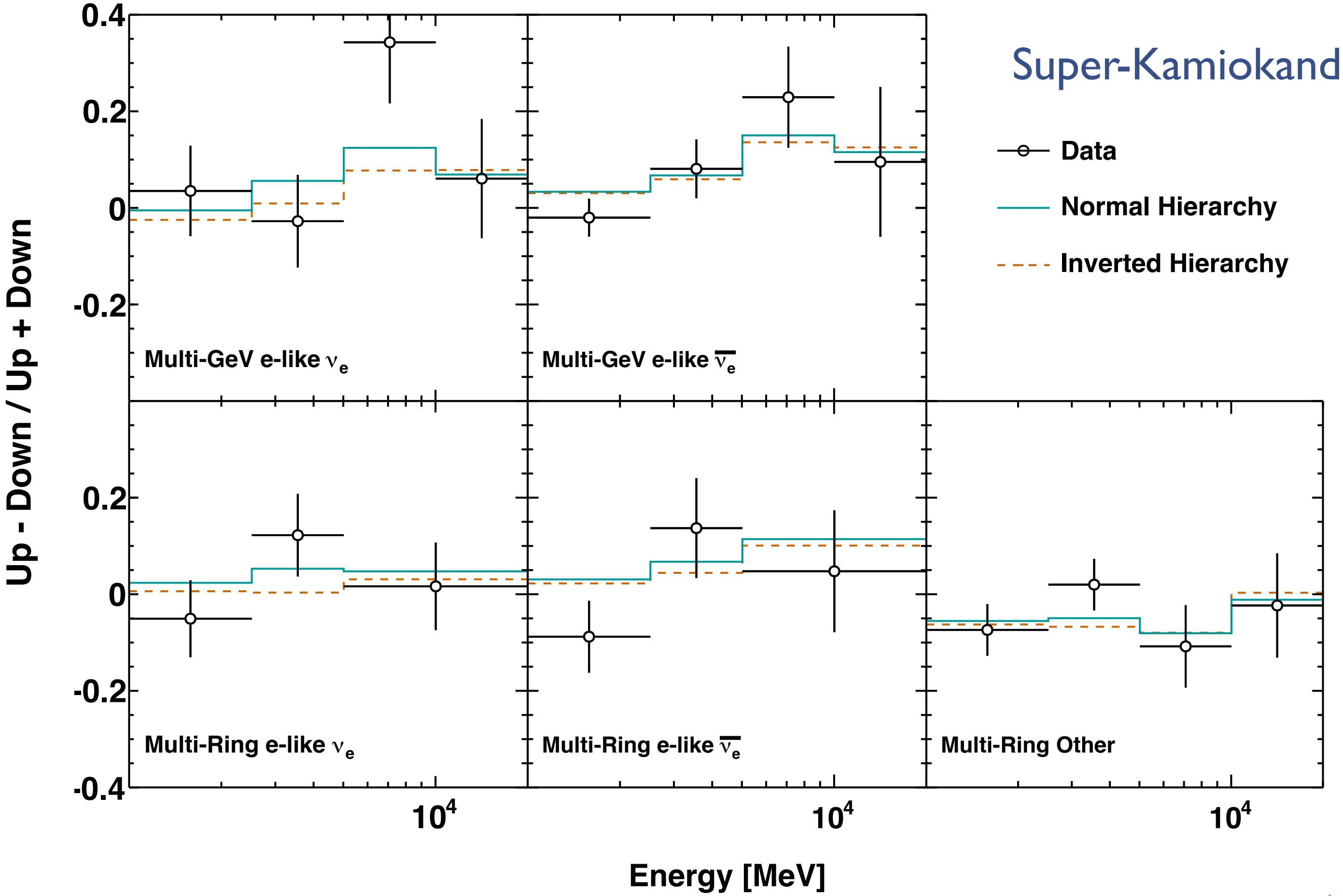
- prefers 2nd θ_{23} octant and $\pi < \delta < 2\pi$
- χ^2(IO) - χ^2(NO) = 4.3

Mass ordering - atmospheric neutrinos



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

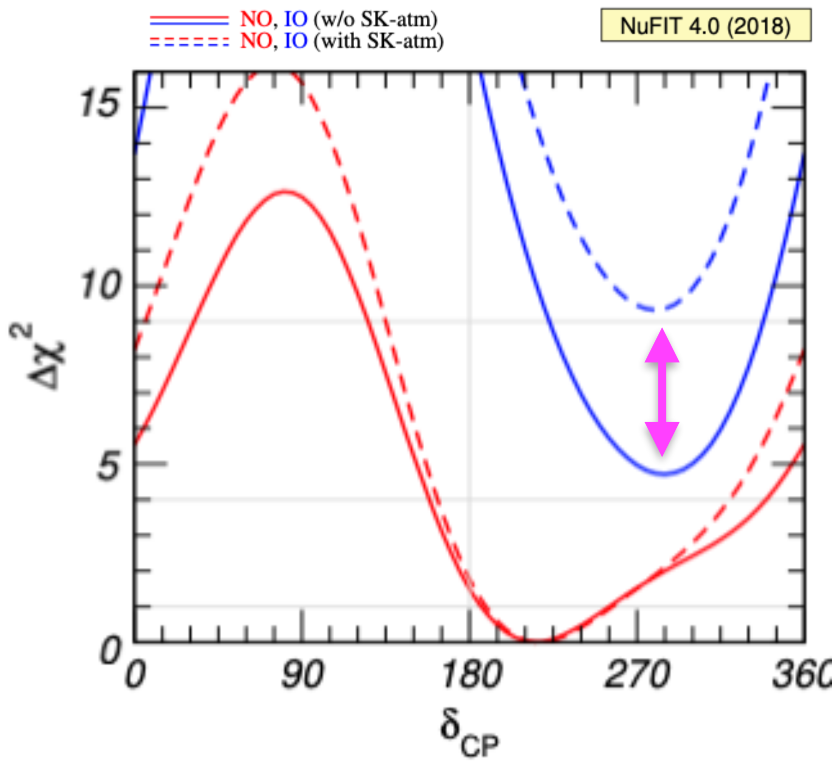
Mass ordering - atmospheric neutrinos



Where are 4.3 units in χ^2?

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

Mass ordering incl. atmospherics



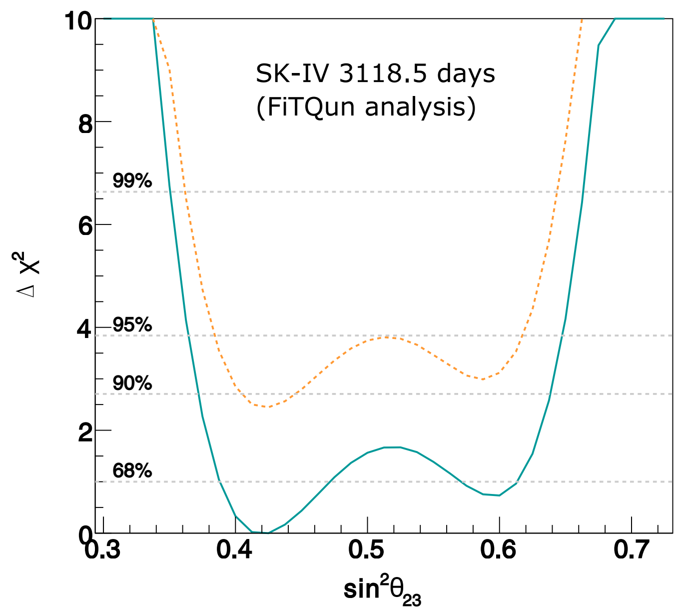
adding SuperK I-IV atm χ^2 table to the global fit → inverted ordering becomes disfavoured at 3σ

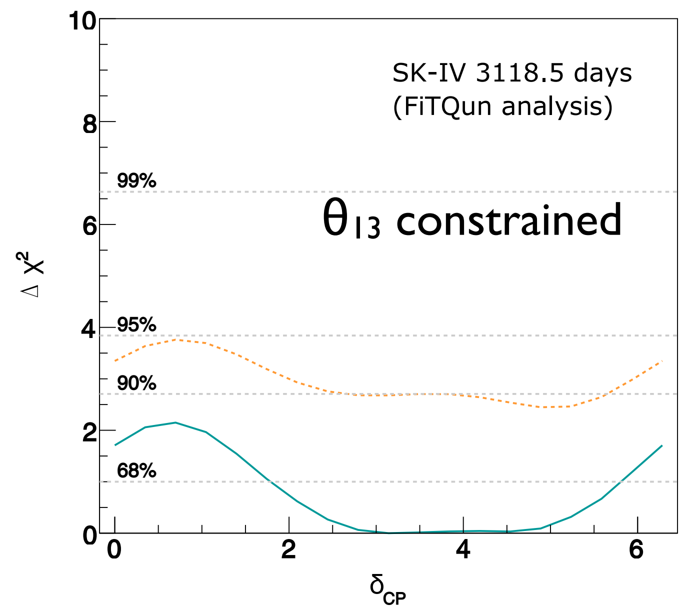
(contribution of IceCube to MO still very small)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\delta_{CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$

Mass ordering - atmospheric neutrinos

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

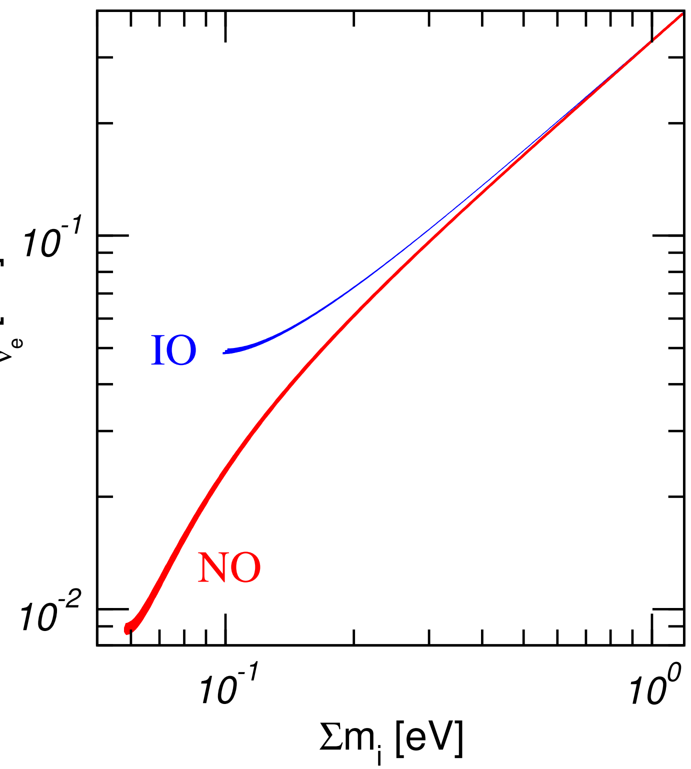


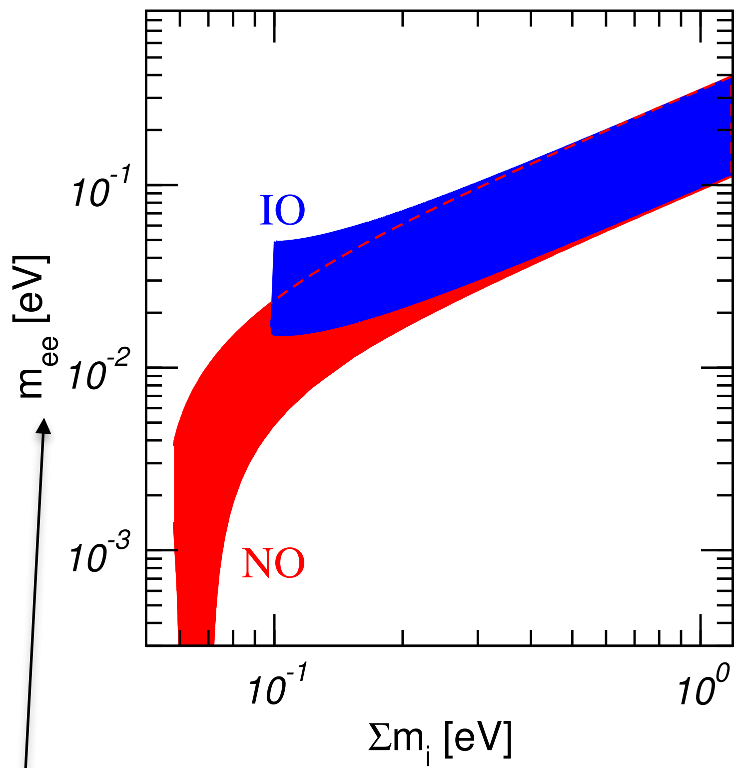


- χ^2(IO) - χ^2(NO) = 2.45 (compared to 4.3 from SK I-IV 2017)
- effective exposure 254 kt yr only 23% smaller (32% larger fiducial volume) (compared to 328 kt yr of SK I-IV 2017)

Absolute neutrino mass observables

NuFIT 4.0 (2018)





cosmology

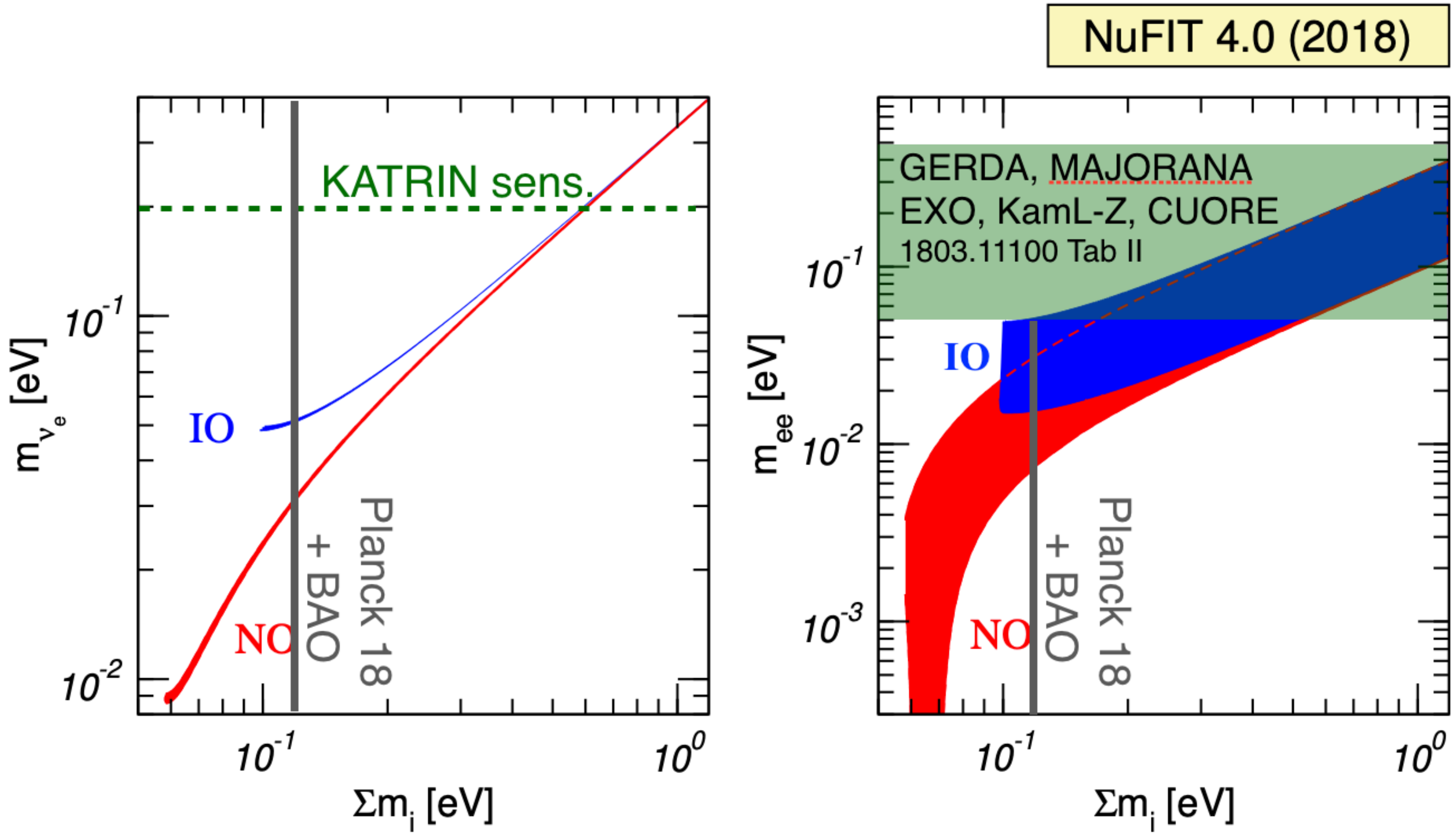
beta-decay endpoint

$m_\beta^2 = \sum_i |U_{ei}^2| m_i^2$

neutrinoless double-beta decay

$m_{ee} = |\sum_i U_{ei}^2 m_i|$

Absolute neutrino mass observables

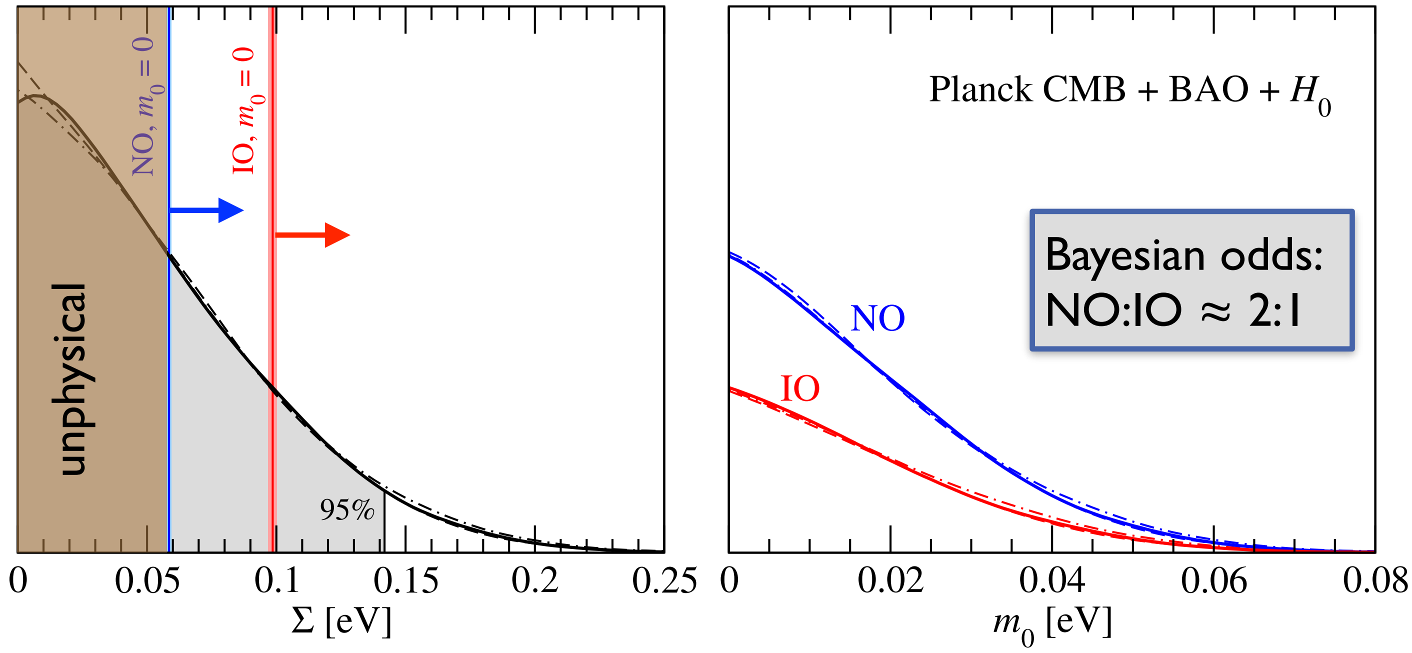


assumes standard 3-flavour & standard cosmology

Excluding inverted ordering with cosmology?

Hannestad, Schwetz, 1606.04691

minimal values:
$$\Sigma = \begin{cases} 58.5 \pm 0.48\,\text{meV} & \text{(NO)} \\ 98.6 \pm 0.85\,\text{meV} & \text{(IO)} \end{cases} \qquad (m_0 = 0)\,.$$



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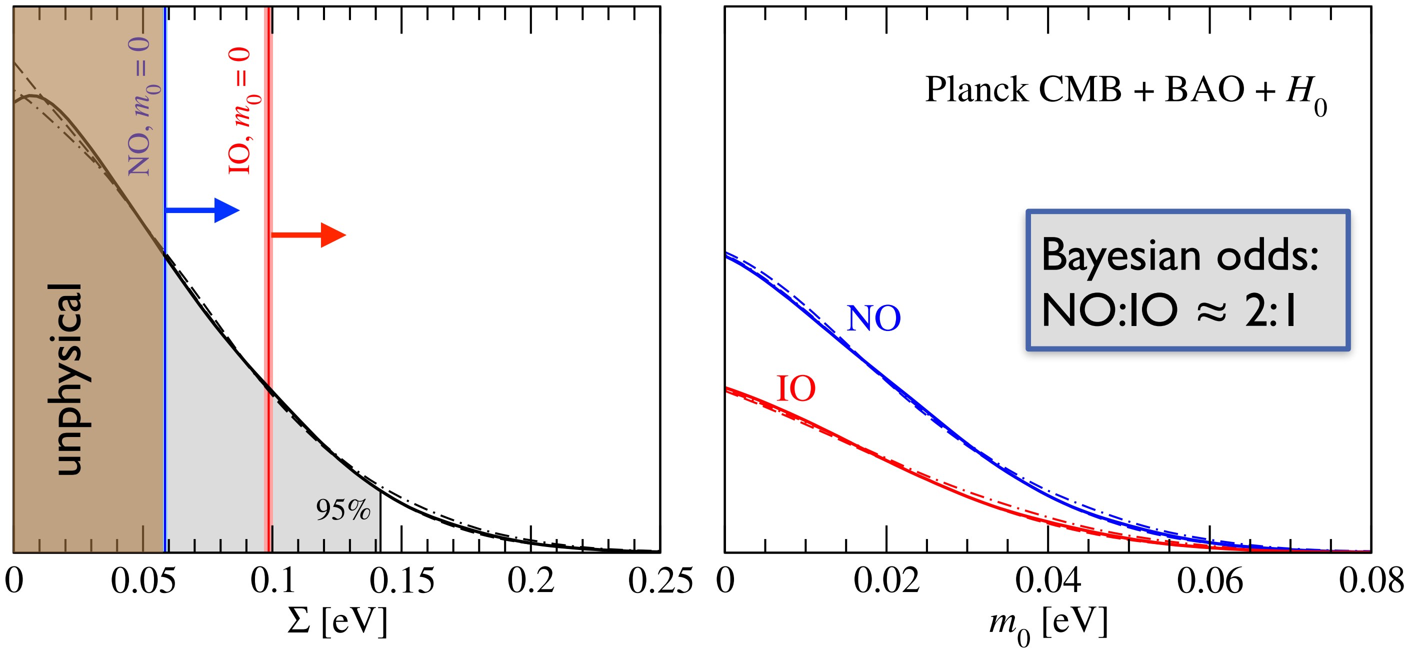


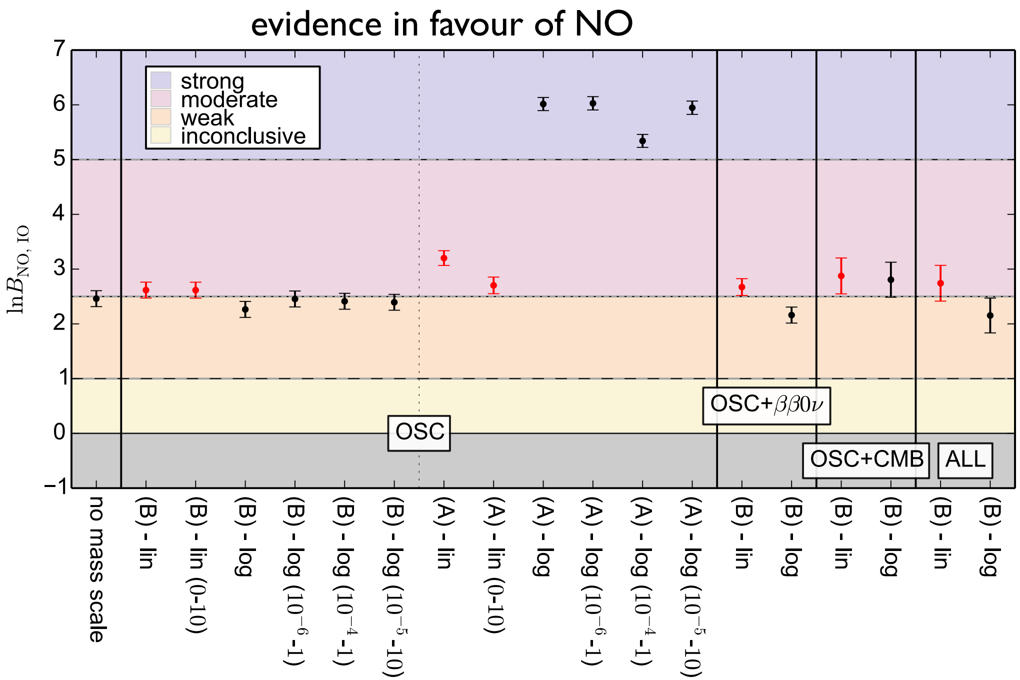
„Strong evidence“ for NO claimed in Simpson et al. 1703.03425

→ be aware of Bayesian priors [TS et al. 1703.04585]

Excluding inverted ordering with cosmology?

Model A			Model B		
Parameter	Prior	Range	Parameter	Prior	Range
m_1/eV	linear log	$0 - 1$ $10^{-5} - 1$	$m_{\mathrm{lightest}}/\mathrm{eV}$	linear log	$0 - 1$ $10^{-5} - 1$
m_2/eV	linear log	$0 - 1$ $10^{-5} - 1$	$\Delta m^2_{21}/\mathrm{eV}^2$	linear	$5 \times 10^{-5} - 10^{-4}$
m_3/eV	linear log	$0 - 1$ $10^{-5} - 1$	$\|\Delta m^2_{31}\|/\mathrm{eV}^2$	linear	$1.5 \times 10^{-3} - 3.5 \times 10^{-3}$

Archidiacono, de Salas, Gariazzo, Mena, Ternes, Tortola, 1801.04946



- assuming a log prior in the 3 masses prefers strongly NO (just from oscillation data!)

Excluding inverted ordering with cosmology?

Hannestad, Schwetz, 1606.04691

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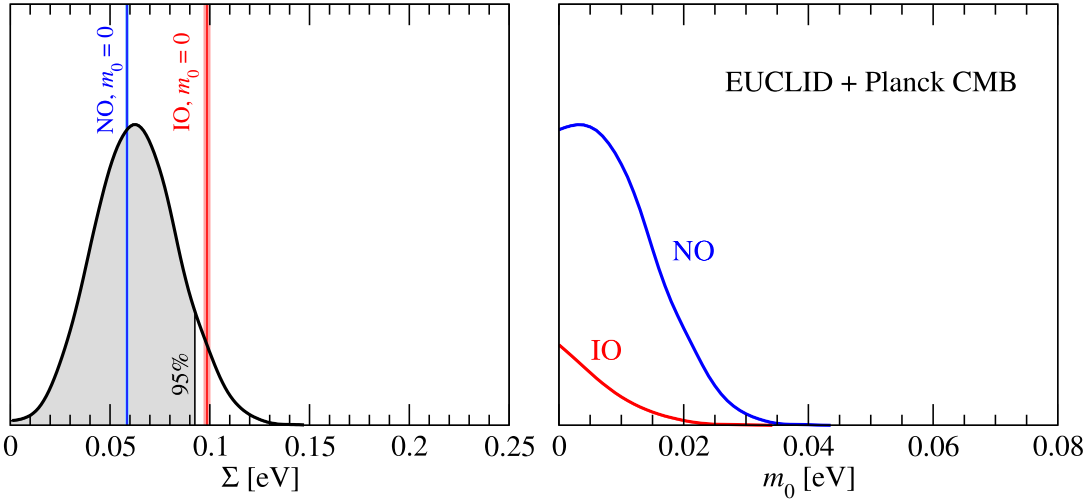
simulated future data:
2 yrs of EUCLID data, available ~2023-24



- 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 Sum = 0.06 eV)

Summary

- octant of θ_{23}:
  preference for second octant, bf at $\sin^2\theta_{23} = 0.58$
  $\sin^2\theta_{23} < 0.5$ disfavoured with $\Delta\chi^2 \approx 4.4$ (6.0) without (with) SK atm

- mass ordering:
  NO preferred by $\Delta\chi^2 = 4.7$ (9.3) without (with) SK atm
  SK significance goes down with „improved" analysis
  global fit (incl. IceCube & JUNO) may be the fastest track towards MO

- CP phase:
  CP conservation allowed at $\Delta\chi^2 = 1.8$, bf at $\delta = 217°$
  (slight tension between T2K and NOvA)

Summary

- octant of θ_{23}:
  preference for second octant, bf at $\sin^2\theta_{23} = 0.58$
  $\sin^2\theta_{23} < 0.5$ disfavoured with $\Delta\chi^2 \approx 4.4$ (6.0) without (with) SK atm

- mass ordering:
  NO preferred by $\Delta\chi^2 = 4.7$ (9.3) without (with) SK atm
  SK significance goes down with „improved" analysis
  global fit (incl. IceCube & JUNO) may be the fastest track towards MO

- CP phase:
  CP conservation allowed at $\Delta\chi^2 = 1.8$, bf at $\delta = 217°$
  (slight tension between T2K and NOvA)

Thank you for your attention!

supplementary slides

NuFit 4.0 (2018)

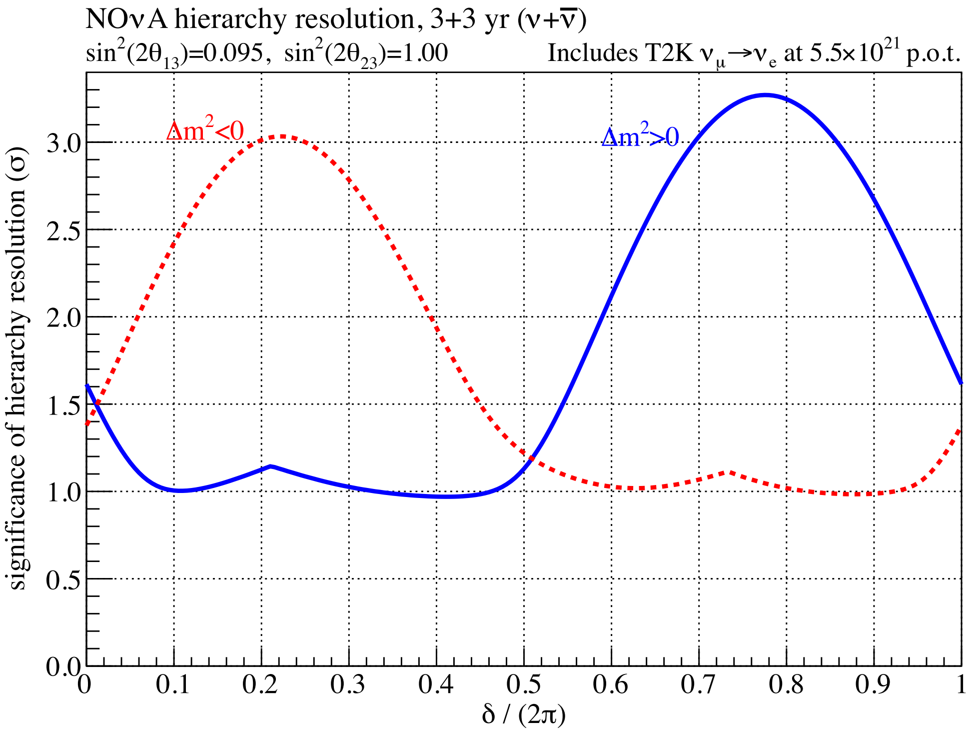
www.nu-fit.org

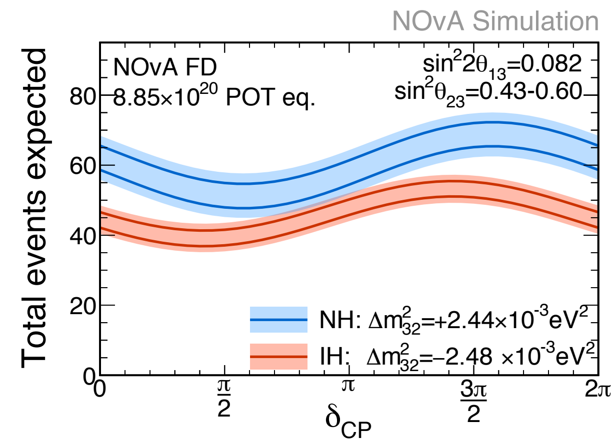
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
	$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

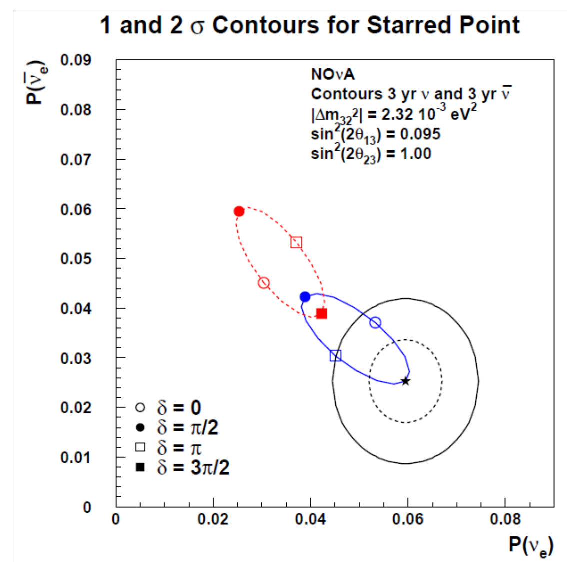
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$
	$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$	$0.582^{+0.015}_{-0.018}$	$0.433 \to 0.623$
	$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$	$49.7^{+0.9}_{-1.0}$	$41.2 \to 52.1$
	$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$	$0.02263^{+0.00065}_{-0.00066}$	$0.02067 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$	$8.65^{+0.12}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$	$-2.512^{+0.034}_{-0.031}$	$-2.606 \to -2.413$

MO sensitivity of existing experiments

- strong dependence on true ordering and δ_{CP}
- 3σ possible for the most favourable combinations



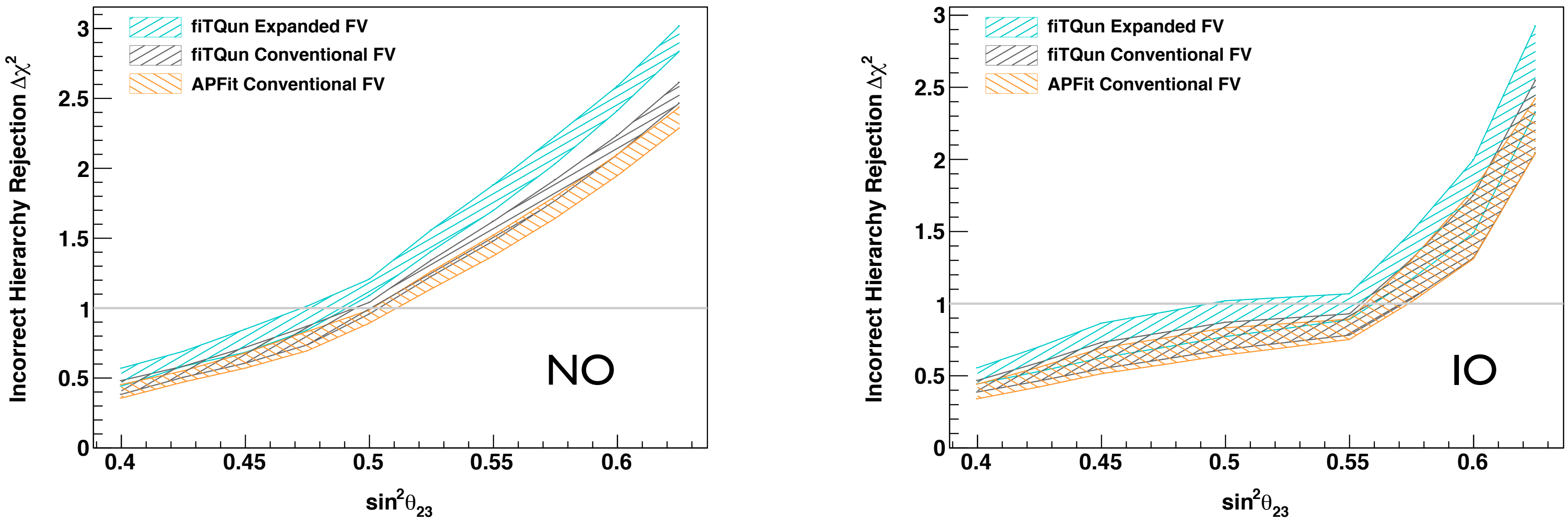




http://www-nova.fnal.gov/plots_and_figures/plots_and_figures.html

Mass ordering - atmospheric neutrinos

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



θ_{13} constrained — expected sensitivity