Neutrino oscillations: current status and future opportunities

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Outline

- Current status of the **standard three-neutrino** framework
  - ⇒ based on **de Salas et al, JHEP 02 (2021) 071[arXiv:2006.11237]**
  - ⇒ updated with the results presented in Neutrino 2020 Conference
  - ⇒ figures and $\chi 2$ tables publicly available at the website:

    https://globalfit.astroparticles.es/

    https://doi.org/10.5281/zenodo.4593330

    See also: Esteban et al. (NuFIT), Lisi et al.
  - ⇒ preliminary update using Super-K atmospheric $\chi 2$ tables
- Future prospects in neutrino oscillations:
  - ⇒ near future & next generation neutrino oscillation experiments
- Beyond the standard three-neutrino scenario:
  - ⇒ can BSM physics improve oscillation fits?

The three-flavour ν picture

neutrino mixing

$$U_{3\times3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

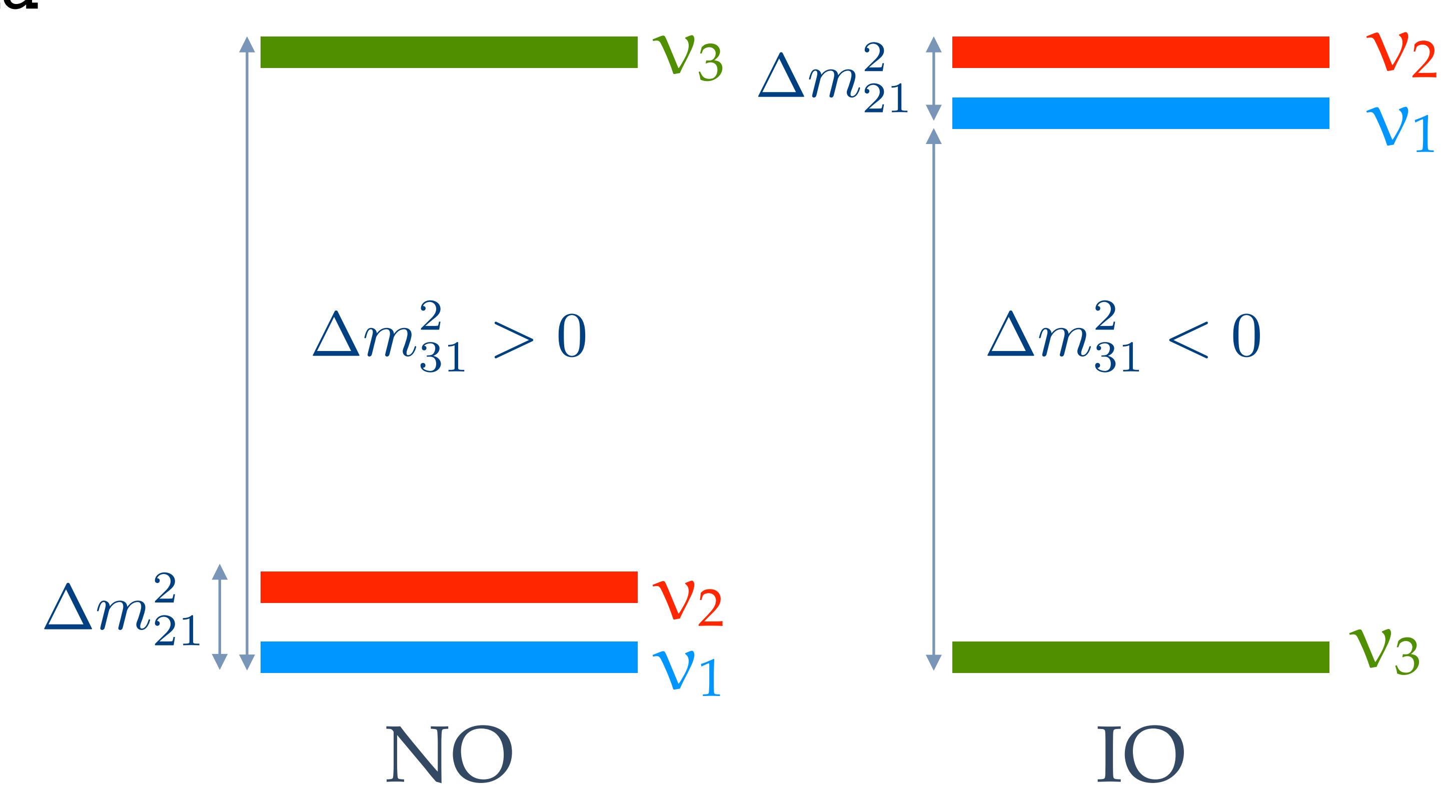
- ✓ 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- ✓ 3 CP phases: 1 Dirac + 2 Majorana
- ✓ 3 masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

$$\Delta m^2_{21}, \Delta m^2_{31}$$

neutrino mass spectrum



Three-neutrino mixing

- Currently, we have evidence for neutrino oscillations in atmospheric, solar, reactor and accelerator experiments

- Each type of experiment is sensitive to different mixing parameters:

$$U_{3\times 3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric + accelerator disapp	SBL reactor + accelerator app	solar + KamLAND
Δm^2_{31}	Δm^2_{31}	Δm^2_{21}

Experimental data

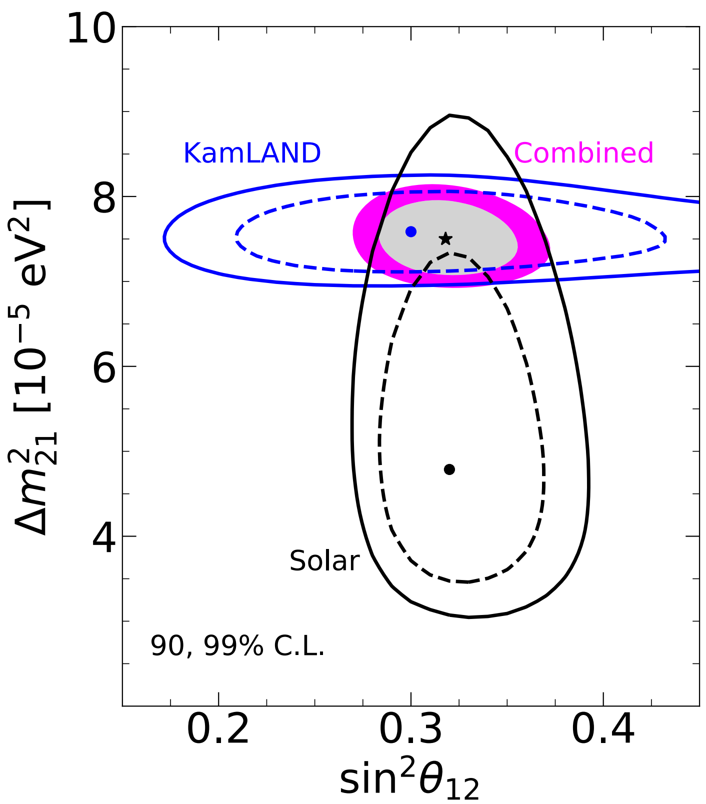
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]

solar sector

Cl, Ga, SK

SNO, Borexino

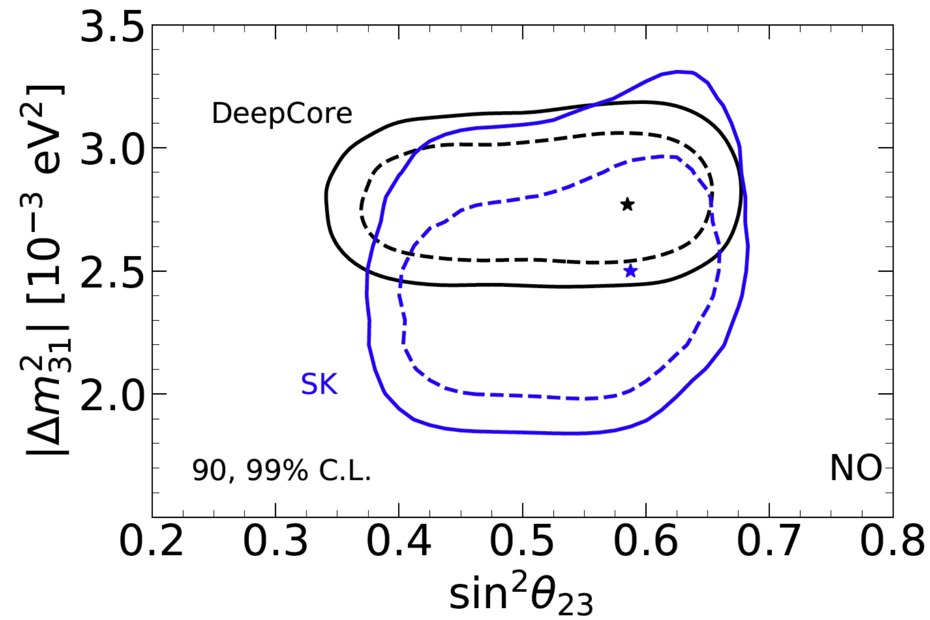
KamLAND



atmospheric results

Super-K

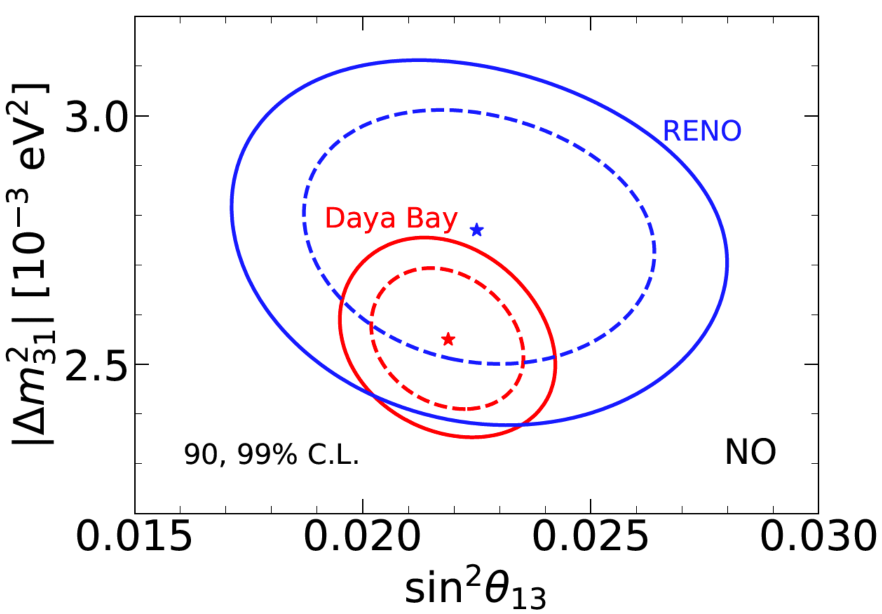
IC-DeepCore



SBL reactors

Daya Bay

RENO

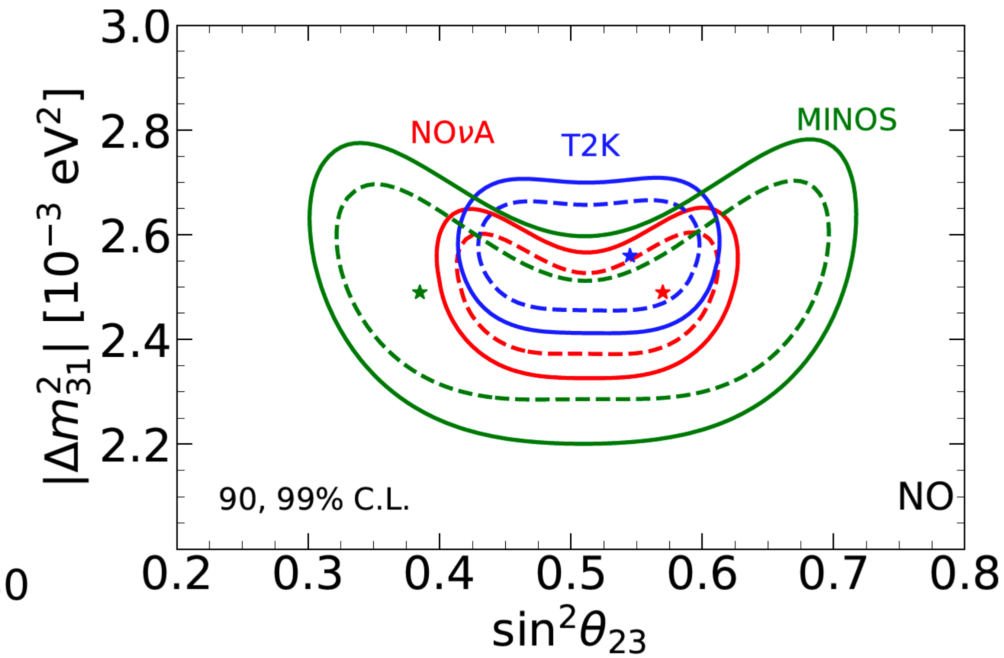


LBL experiments

MINOS

T2K

NOvA



Neutrino oscillation parameters

de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]

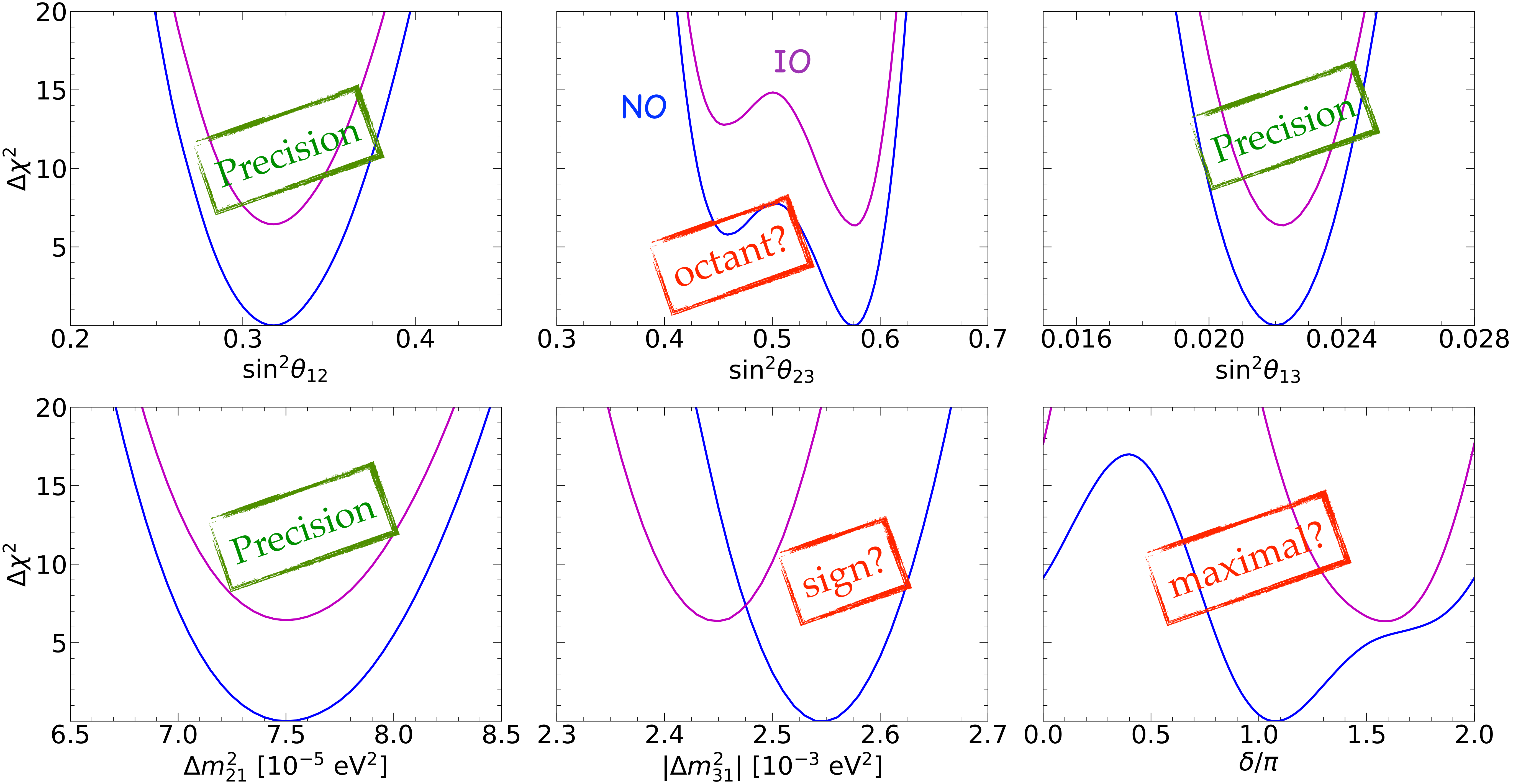
See also NuFIT and Bari group analysis

https://globalfit.astroparticles.es/

parameter	best fit $\pm 1\sigma$	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	6.94–8.14	2.7%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.47–2.63	1.1%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.37–2.53	
$\sin^2\theta_{12}$ $/10^{-1}$	3.18 ± 0.16	2.71–3.69	5.2%
$\sin^2\theta_{23}$ $/10^{-1}$ (NO)	5.74 ± 0.14	4.34–6.10	5.1%
$\sin^2\theta_{23}$ $/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	4.33–6.08	
$\sin^2\theta_{13}$ $/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.000–2.405	3.0%
$\sin^2\theta_{13}$ $/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.018–2.424	
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.71–1.99	20%
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.11–1.96	9.0%

Global fit to ν oscillation parameters

de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



Global fit to ν oscillation parameters

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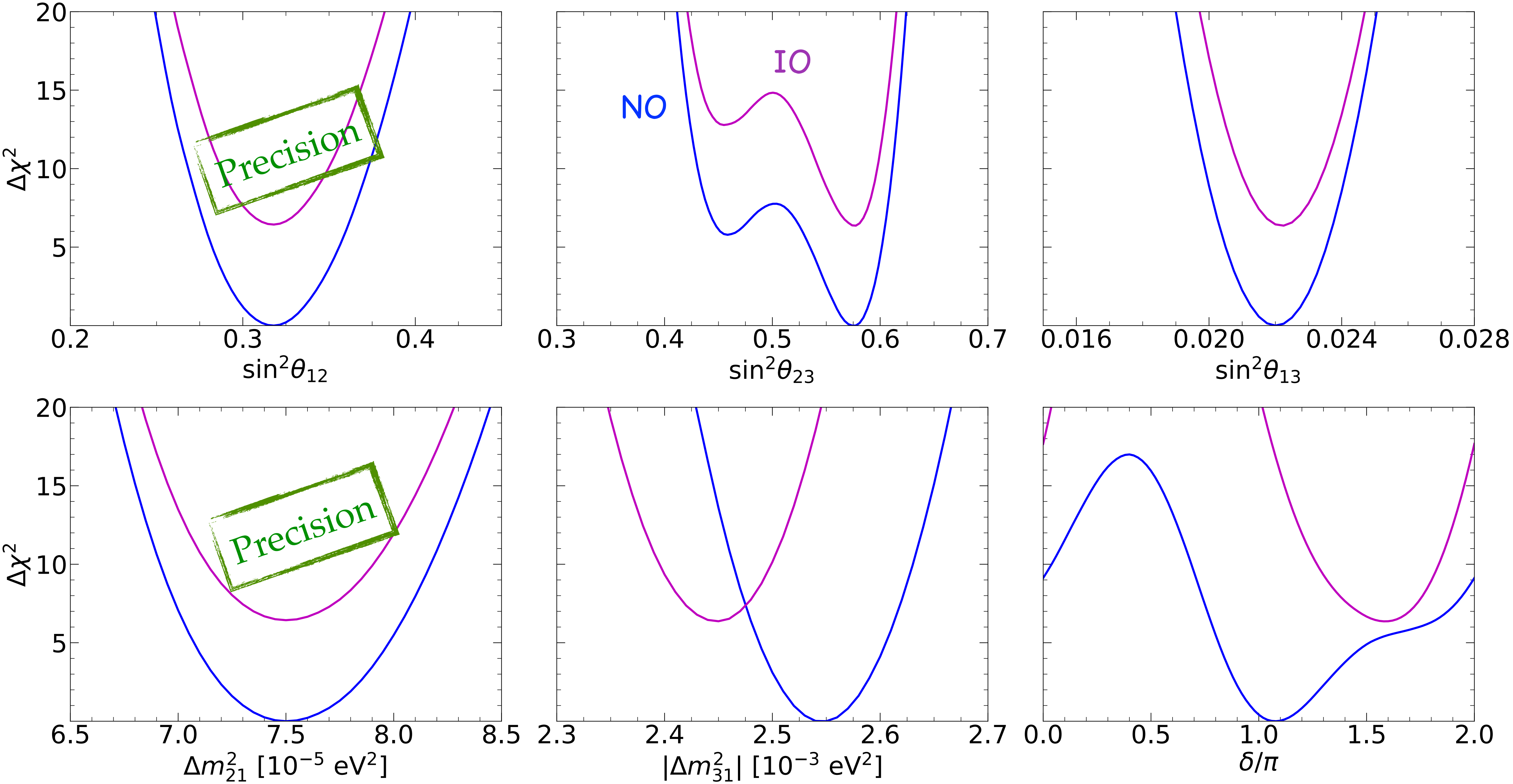
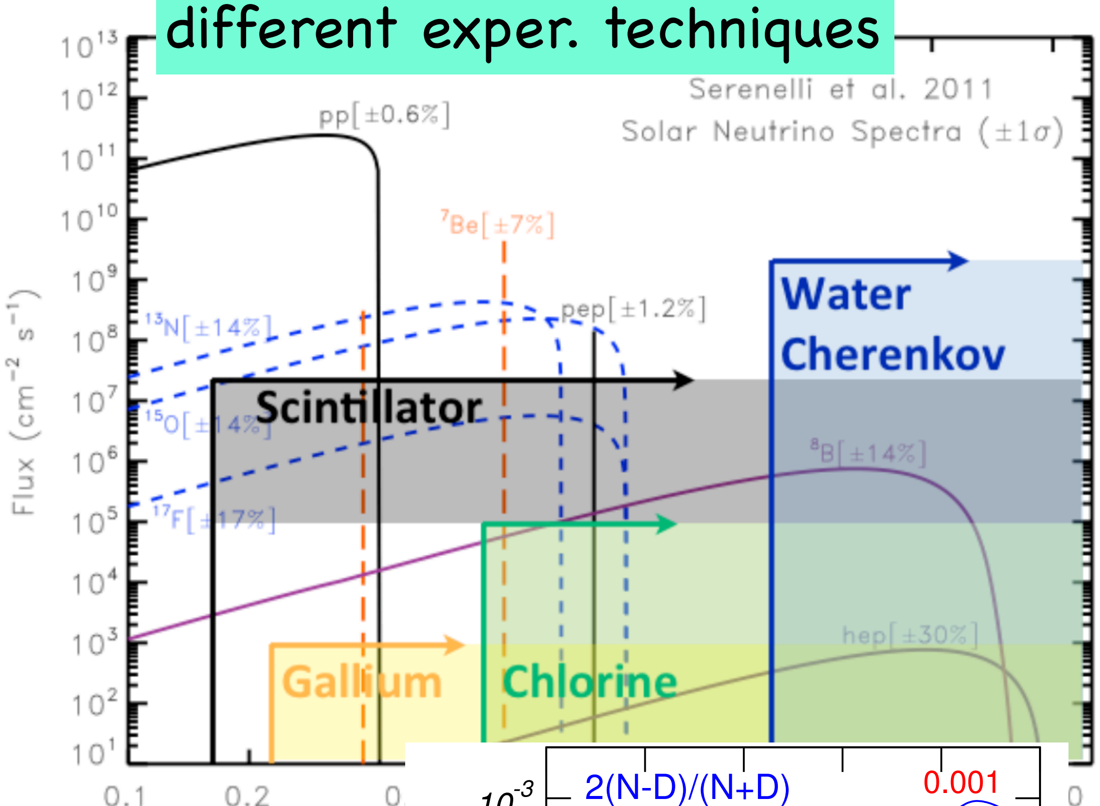


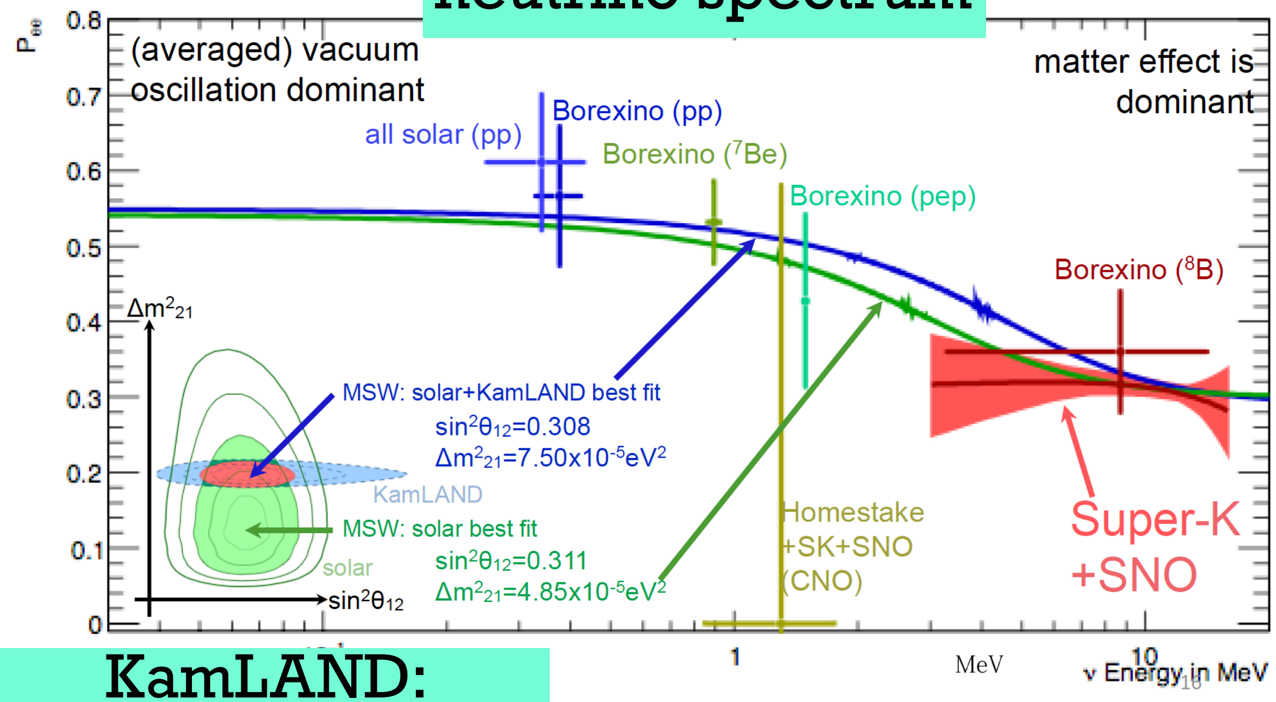
The solar sector

Solar experiments have measured neutrino disappearance for ~ 50 years

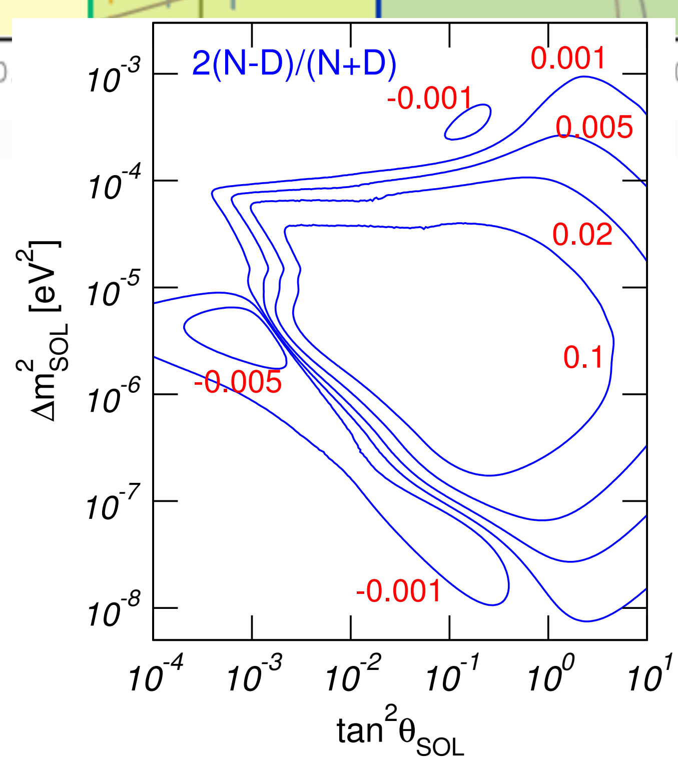
different exper. techniques



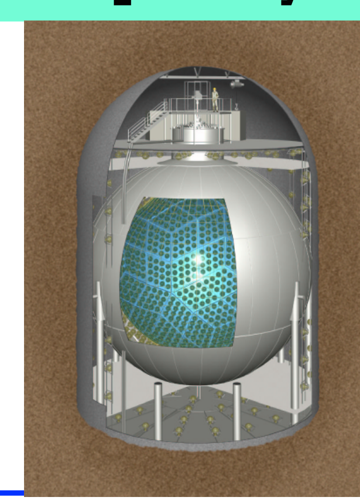
neutrino spectrum

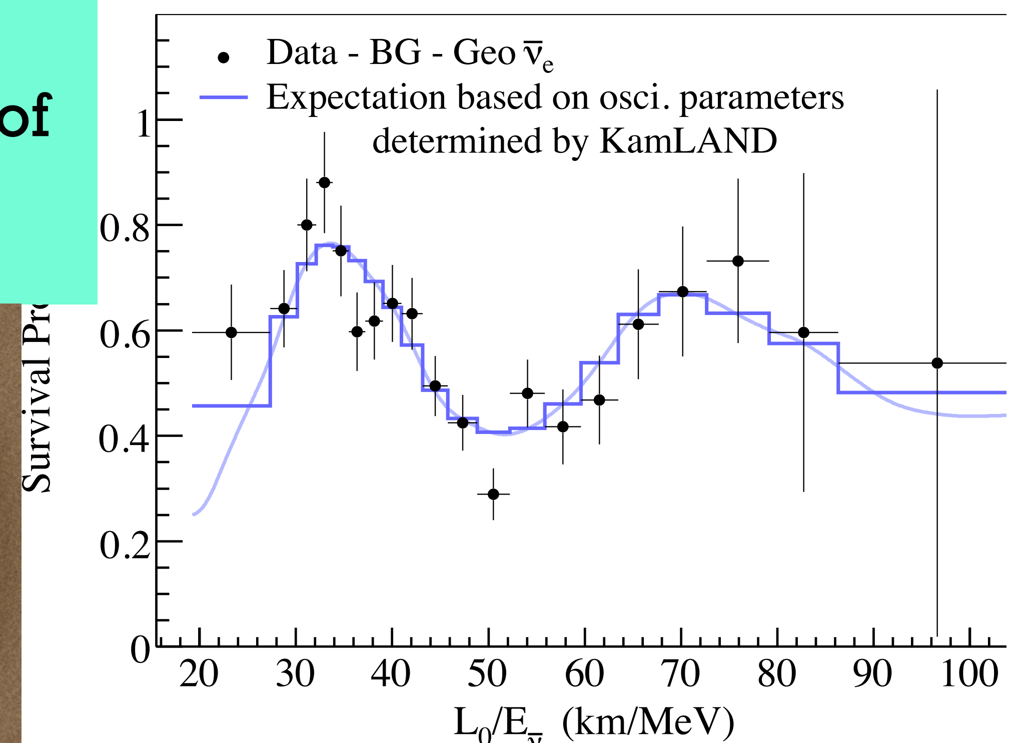


day/night asymmetry

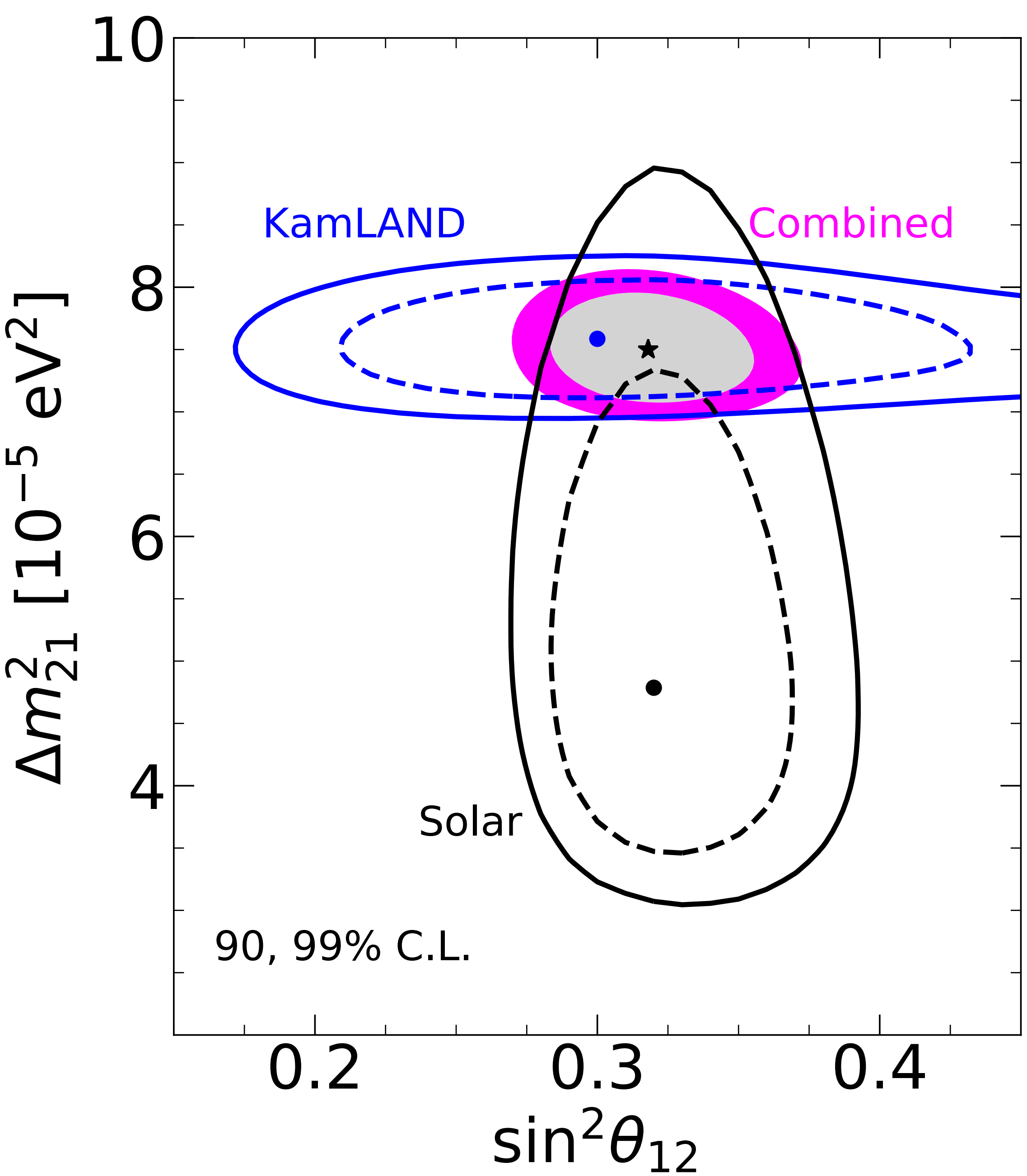


KamLAND: precise measurement of oscillation frequency



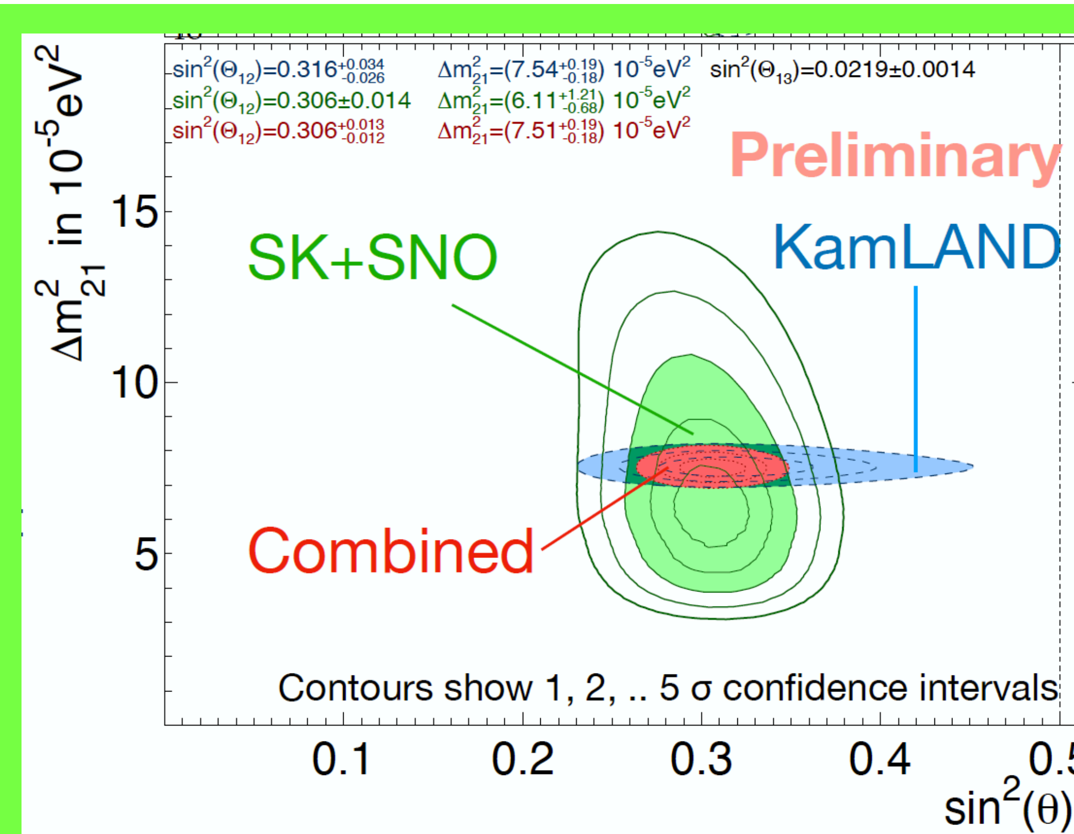


The solar sector



- θ_{12} measurement is dominated by solar neutrino data
- Δm^2_{21} is better measured by KamLAND.
- 2σ mismatch between the values of Δm^2_{21} measured by solar and KamLAND

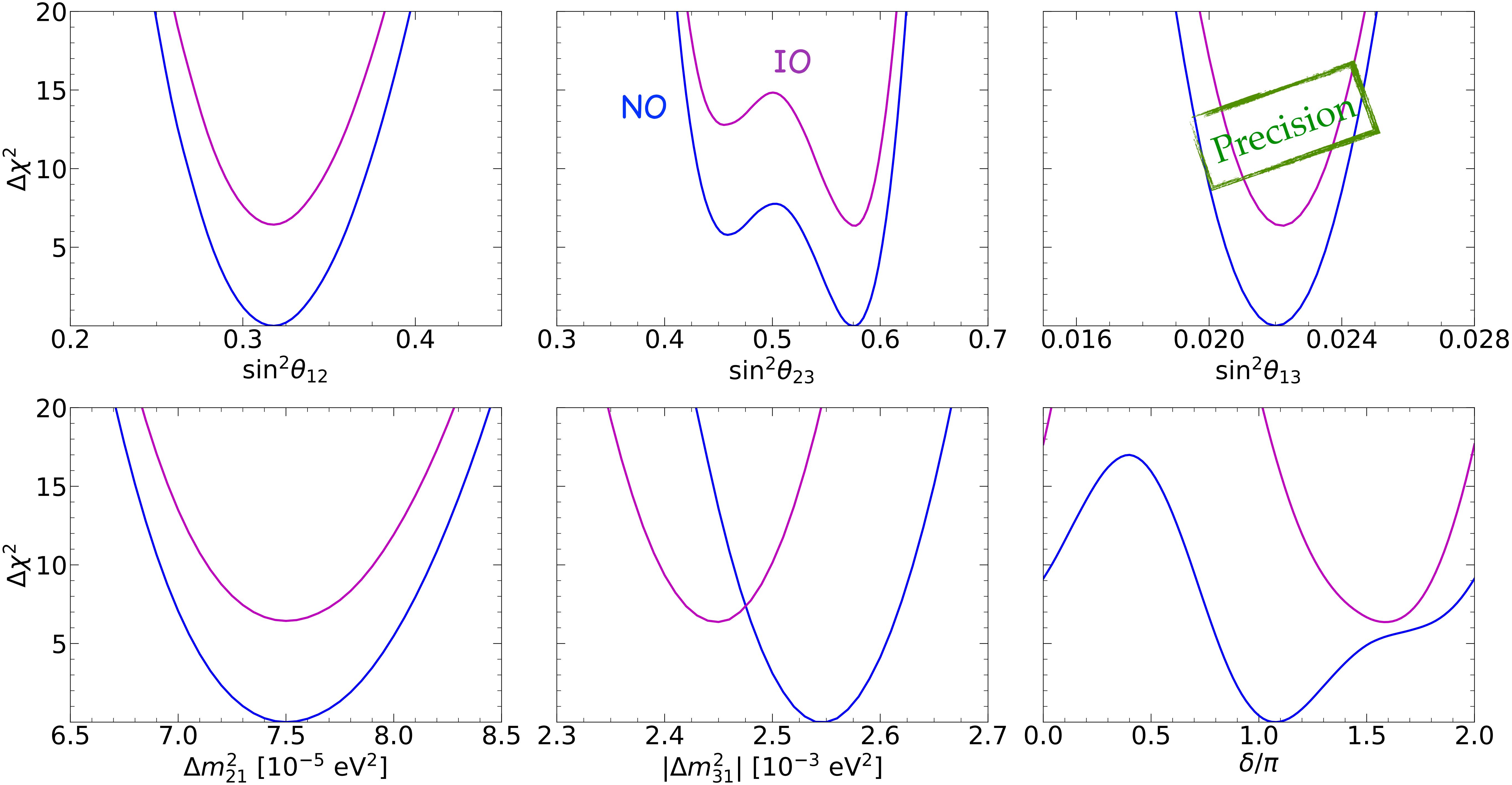
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



Y. Nakajima, Neutrino-2020

Global fit to ν oscillation parameters

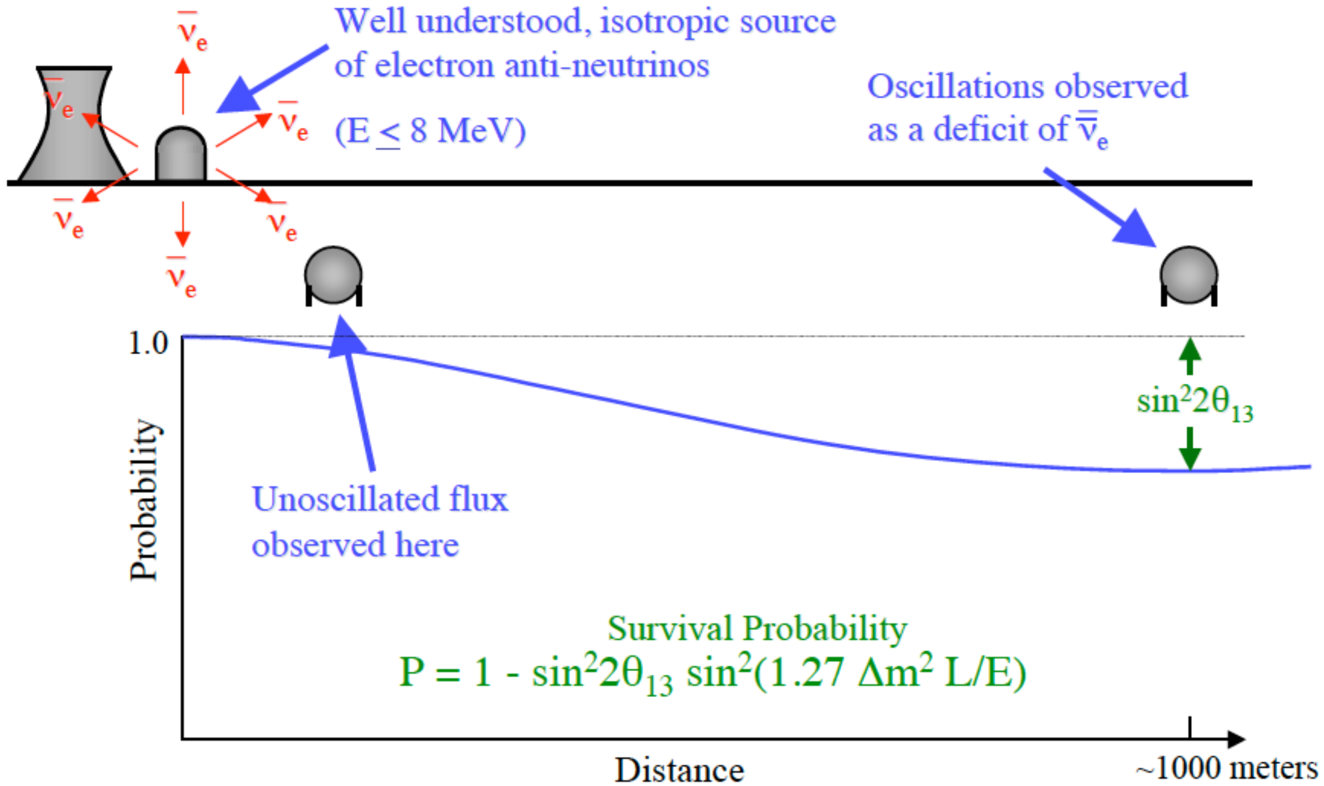
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



The reactor sector

New generation of SBL reactor experiments

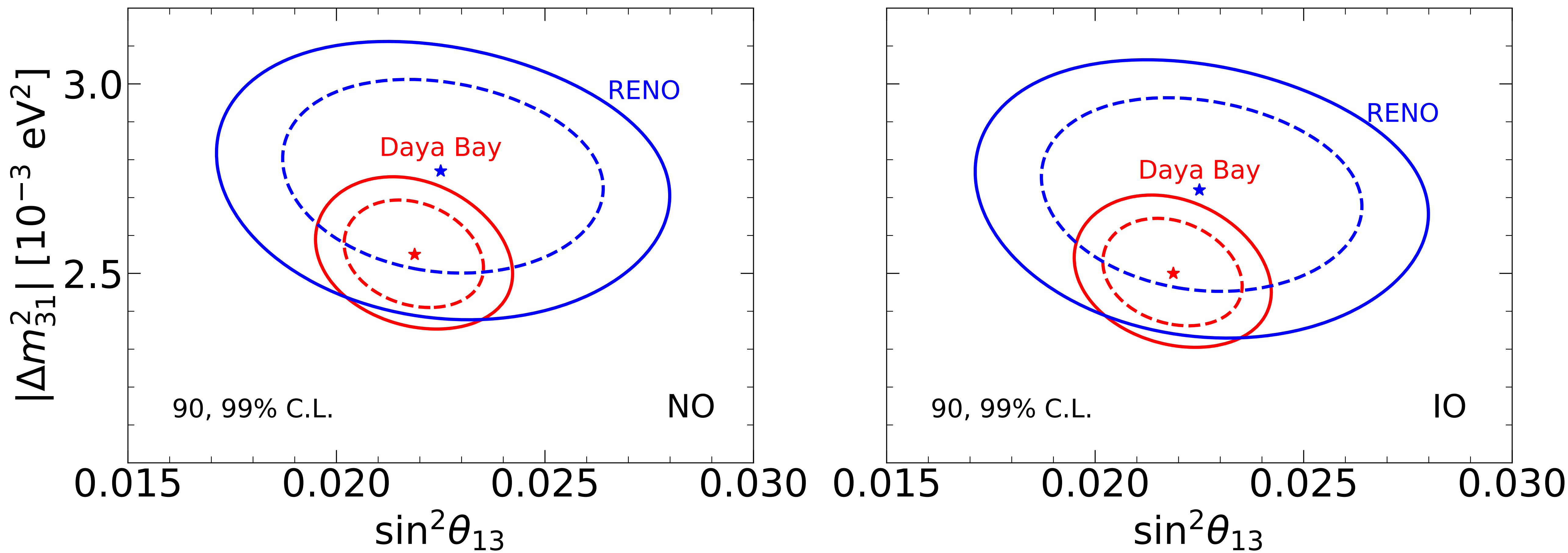
- more powerful reactors
- larger detector volume
- 2-8 detectors at 100 m – 1 km



6 cores + 4 ND + 4FD   2 cores + 1 ND + 1 FD   6 cores + 1 ND + 1 FD

The reactor sector

de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



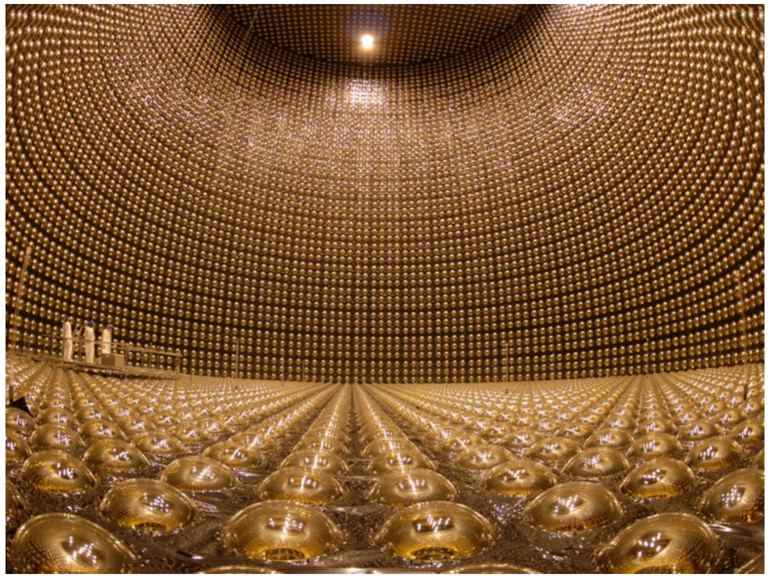
- Daya Bay: 1958-day data: $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$ (3.4%)
- RENO: 2900-day data: $\sin^2 2\theta_{13} = 0.0892 \pm 0.0063$ (7%)

Precision dominated by Daya Bay

The atmospheric sector

Atmospheric experiments

Super-Kamiokande



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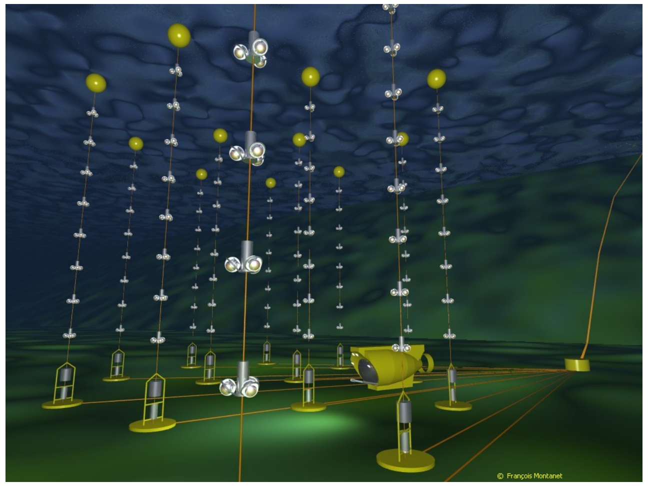
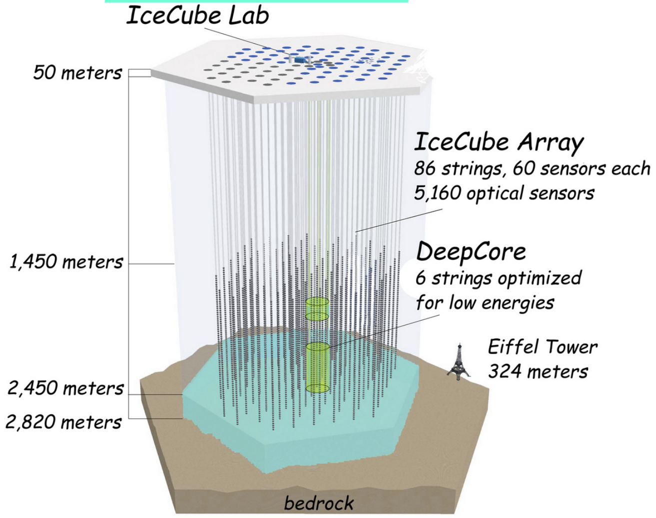
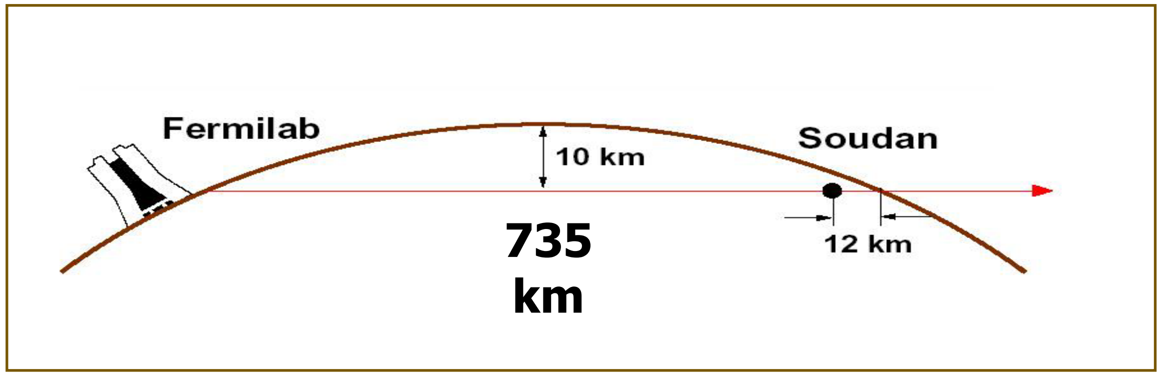


IceCube

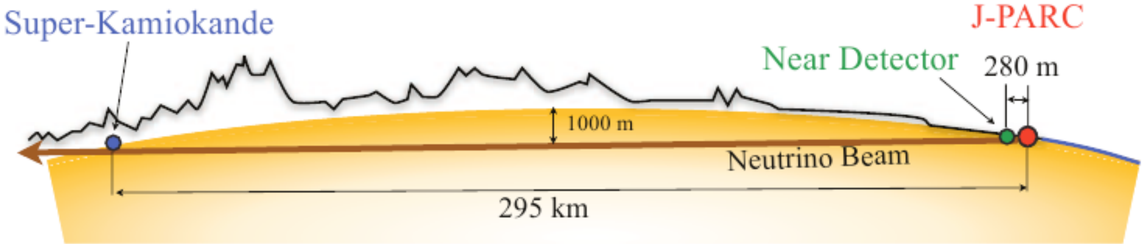


Accelerator long-baseline experiments

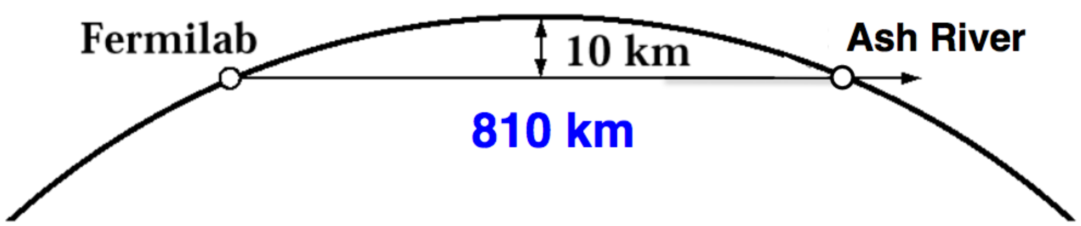
MINOS



T2K



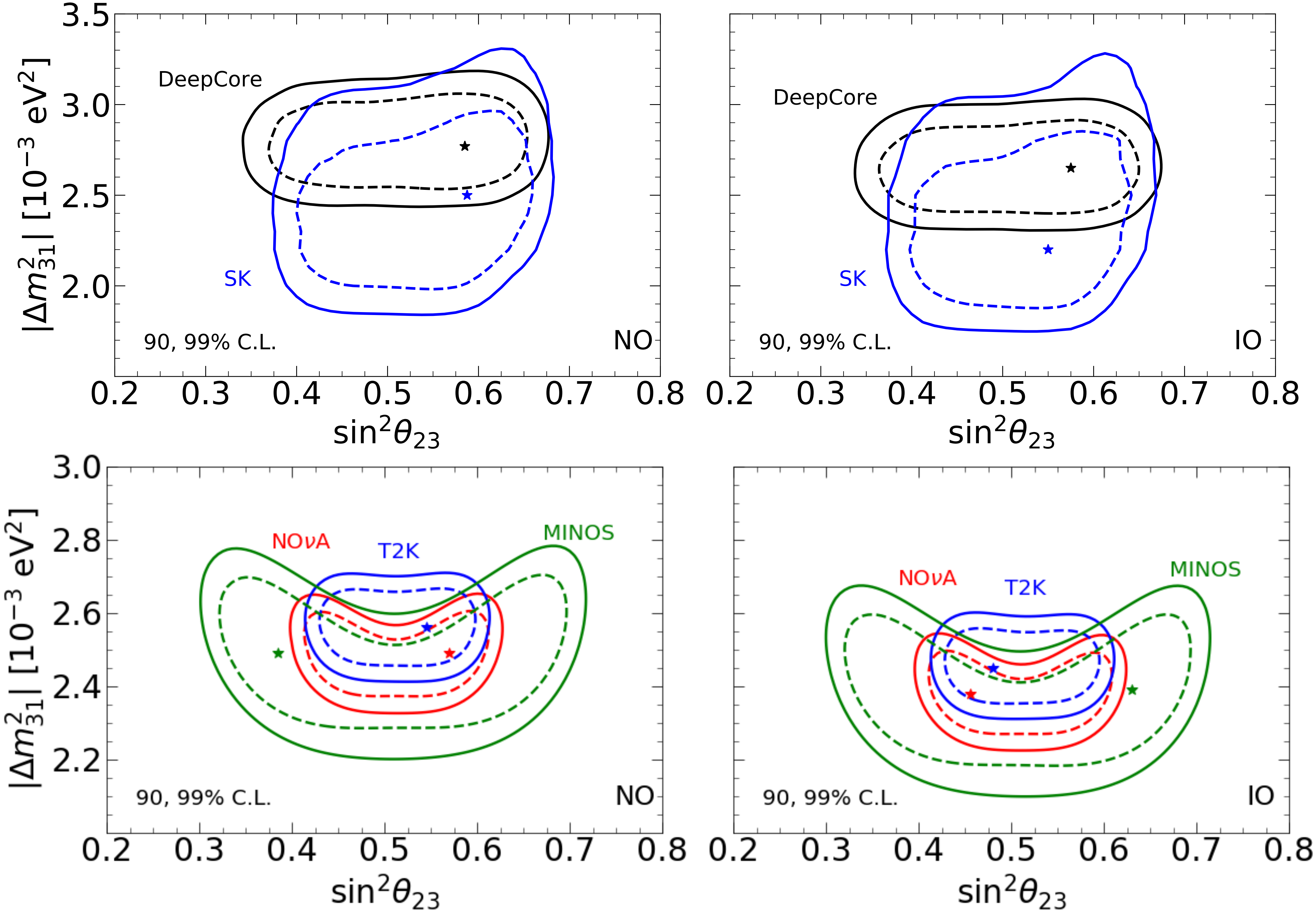
NOvA



→ consistent with atmospheric data

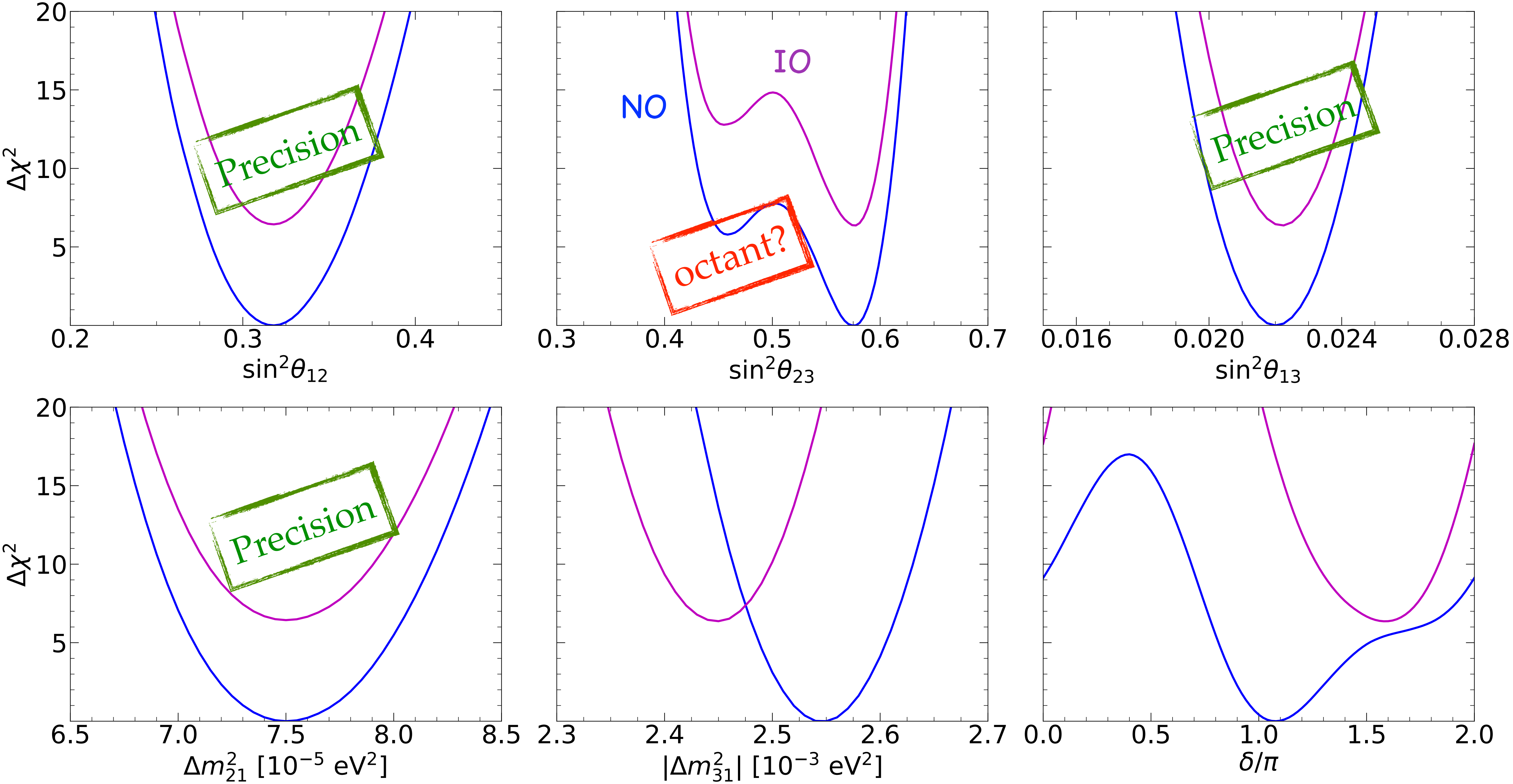
→ atm ν oscillations confirmed by lab exps

The atmospheric sector



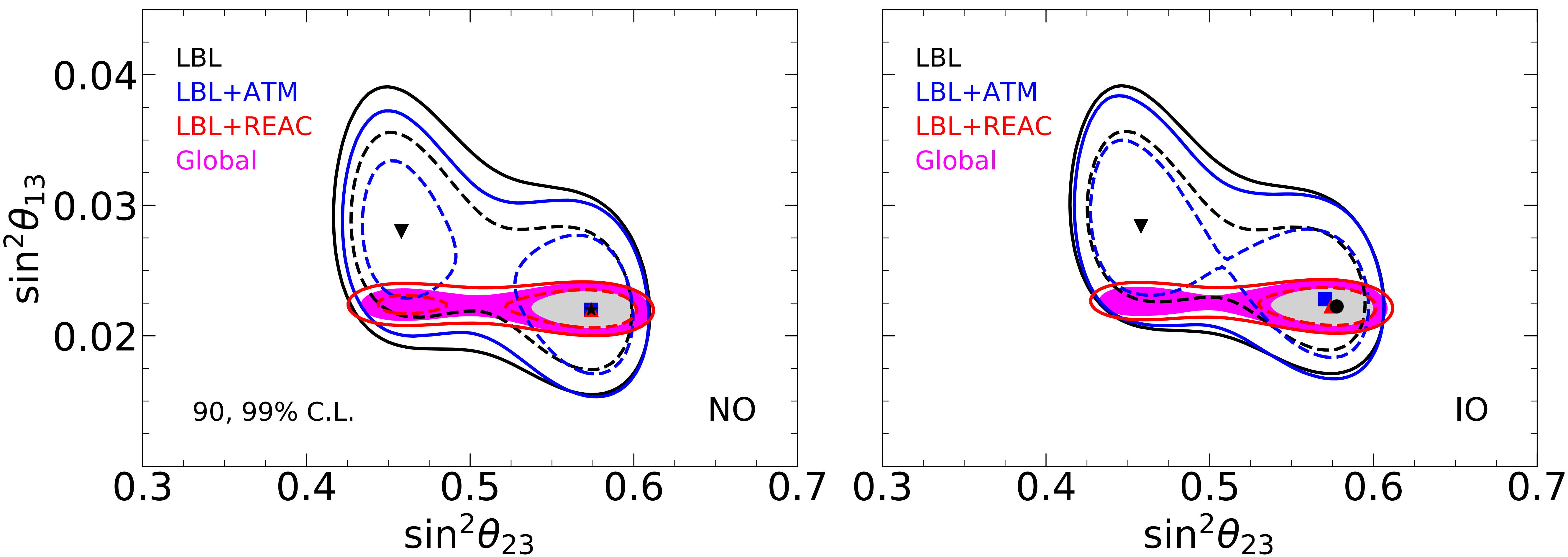
Global fit to ν oscillation parameters

de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



The octant of θ_{23}

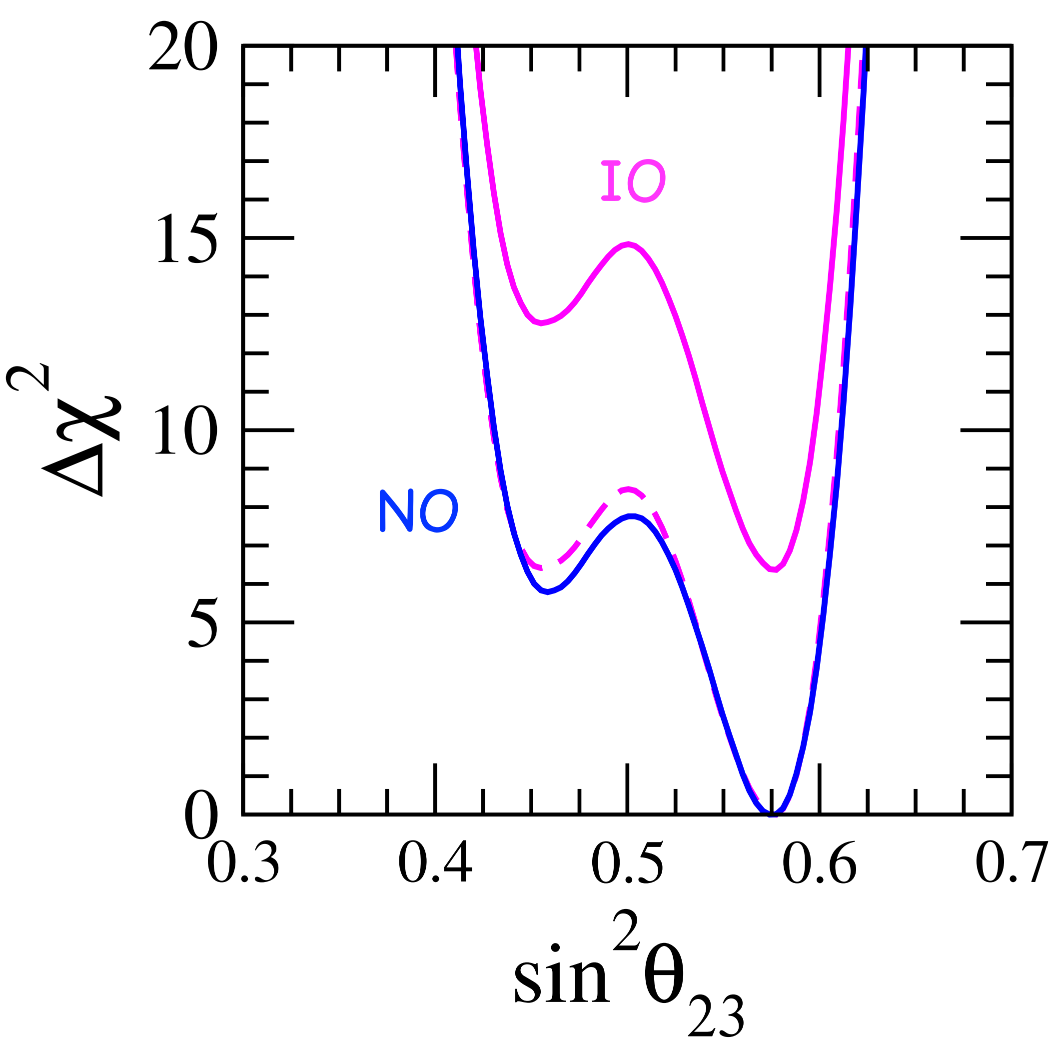
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



- The combination of LBL experiments prefers $\theta_{23} < 45°$ for both orderings
- The combination with atmospheric data shifts the preferred θ_{23} to the second octant
- The combination with SBL reactors also breaks the degeneracy in favor of 2nd octant

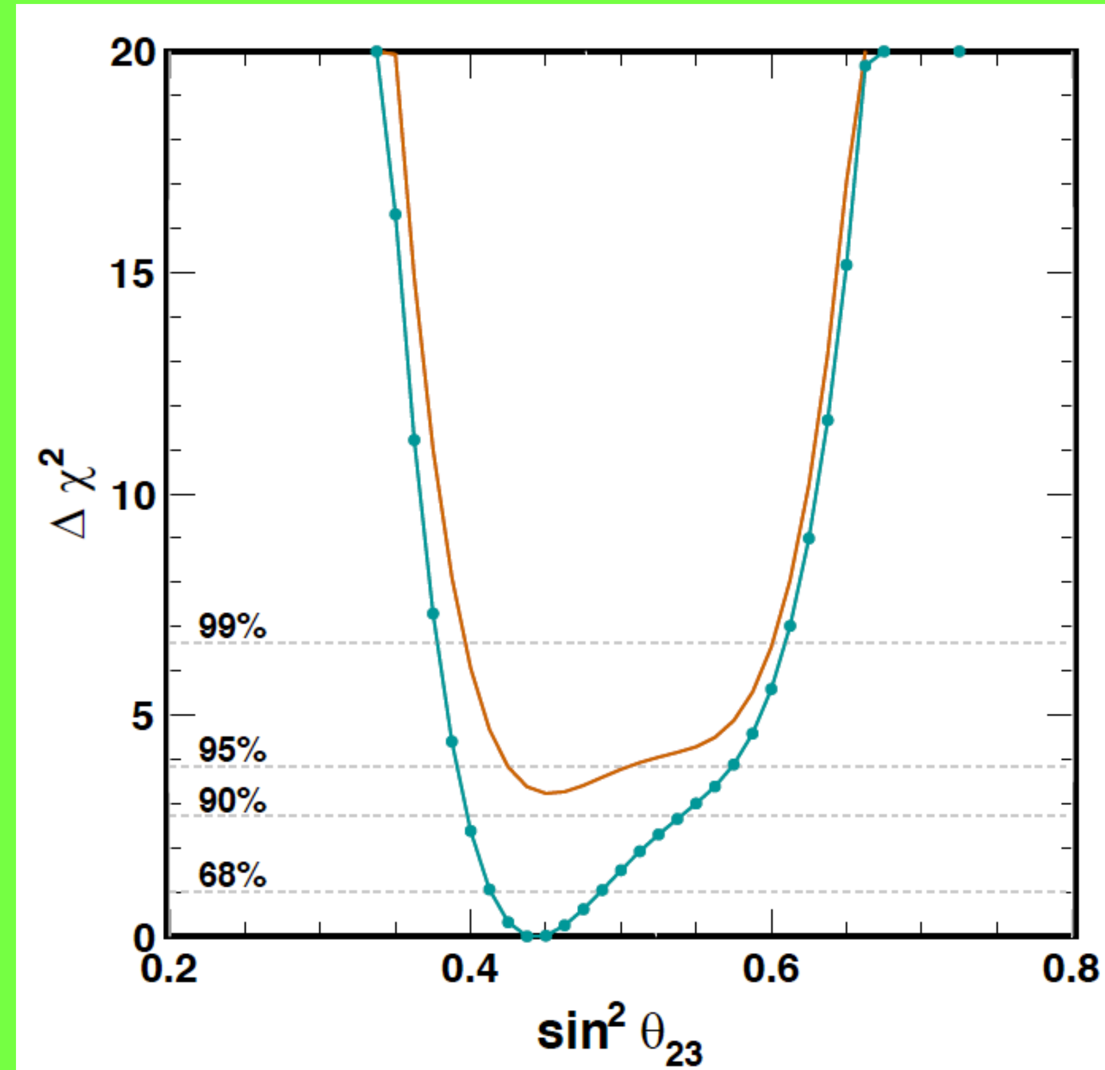
The octant of θ_{23}

de Salas et al, JHEP 02 (2021) 071



Values at the 1st octant disfavored with $\Delta\chi^2 \geq 5.8$ (6.4) for NO (IO)

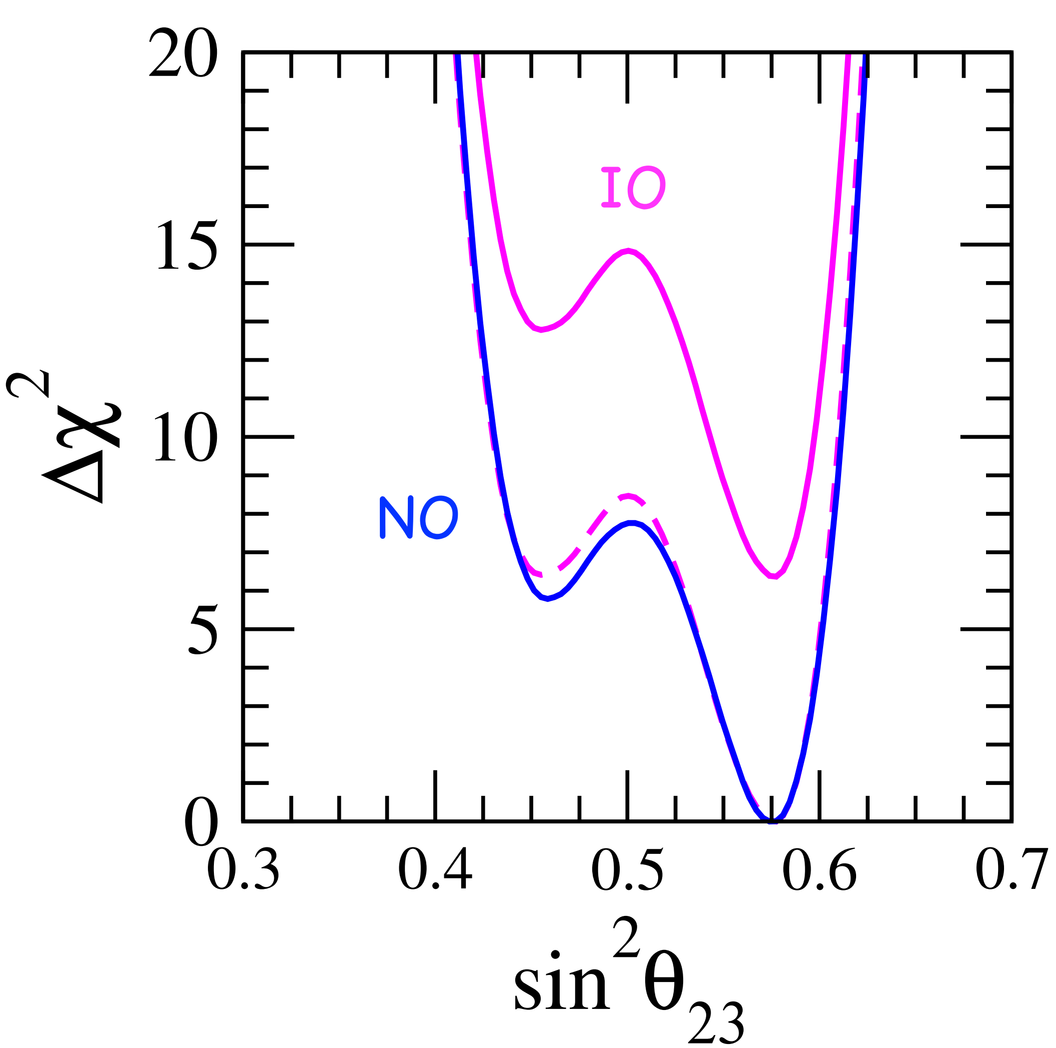
New Super-Kamiokande data



Y. Nakajima, Neutrino 2020

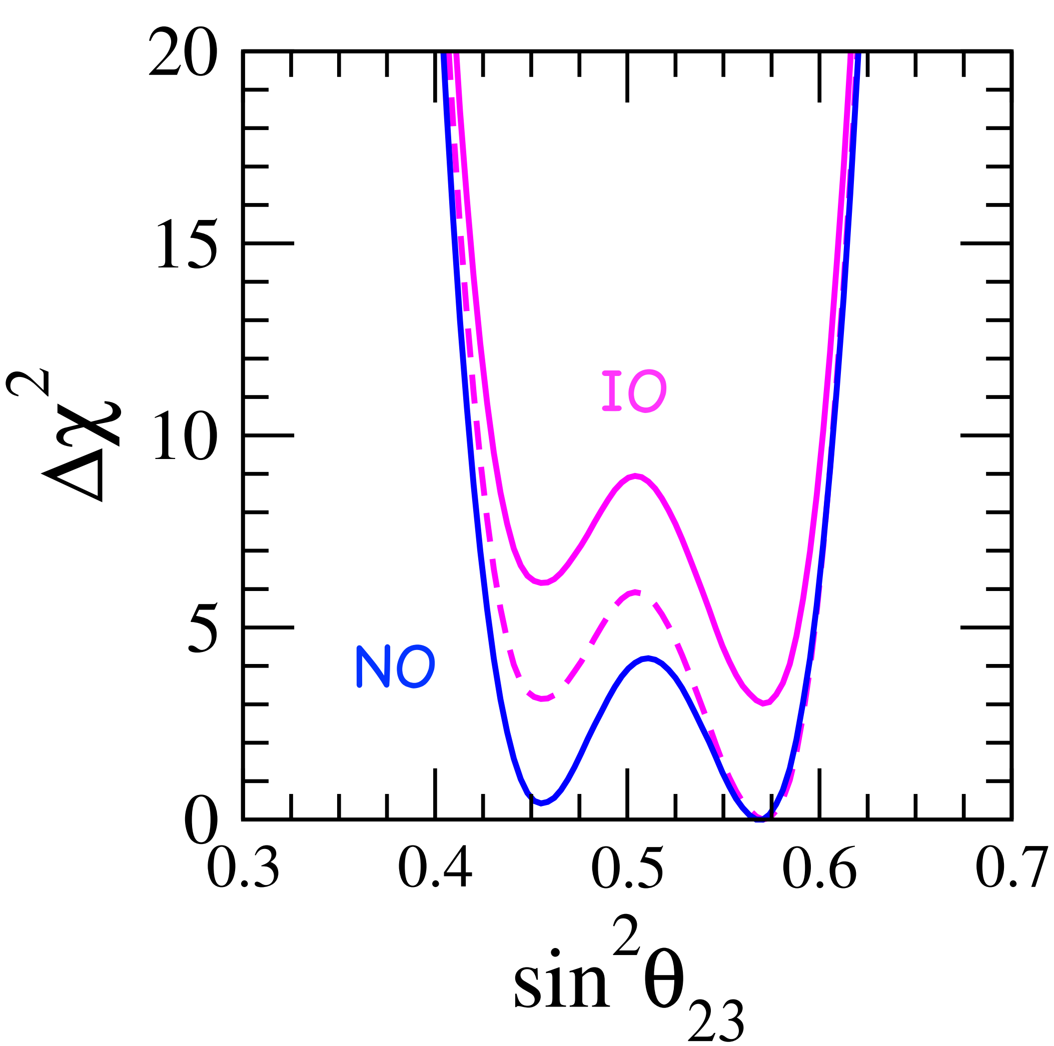
The octant of θ_{23}

de Salas et al, JHEP 02 (2021) 071



Values at the 1st octant disfavored with $\Delta\chi^2 \geq 5.8$ (6.4) for NO (IO)

de Salas et al, preliminary

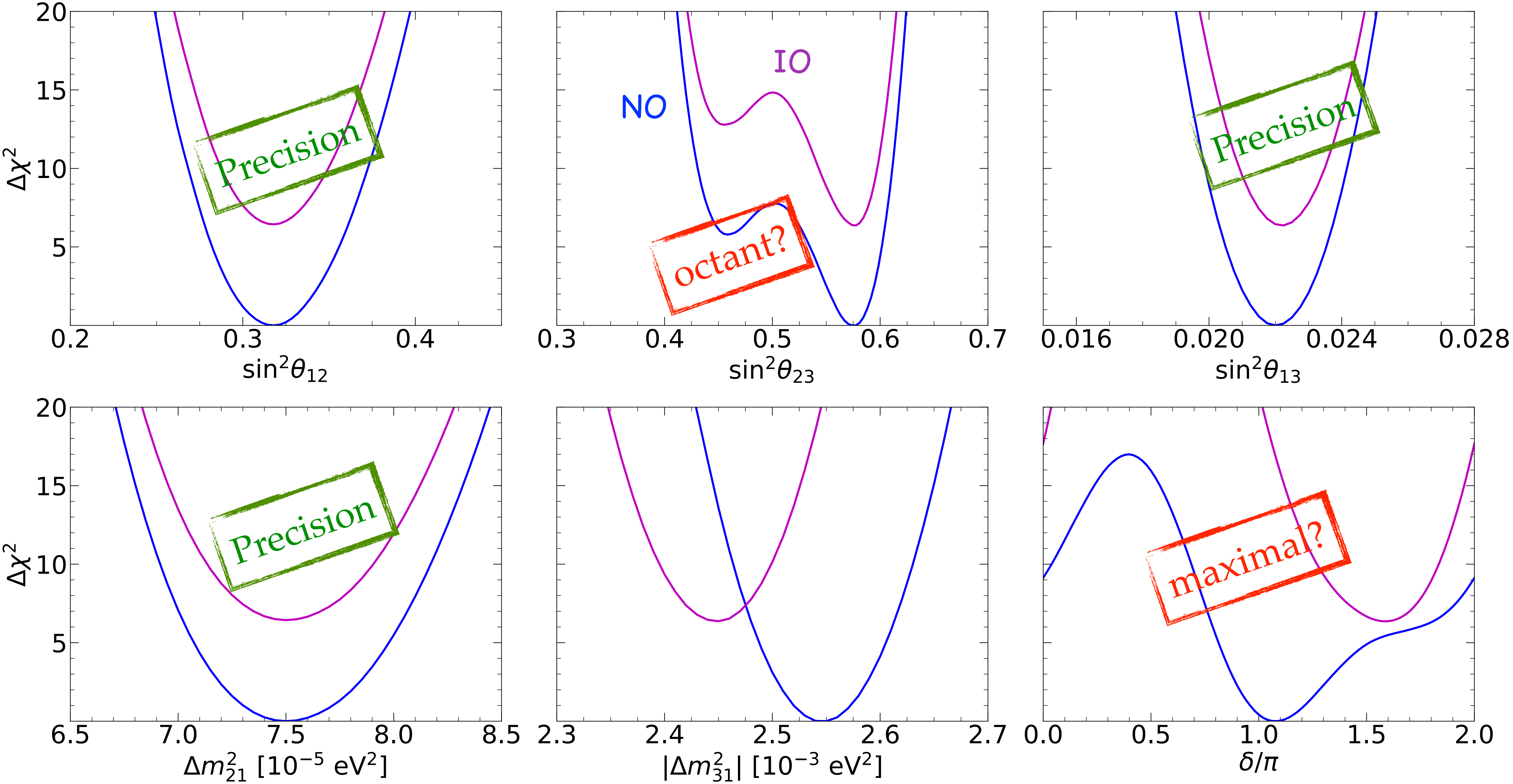


Values at the 1st octant disfavored with $\Delta\chi^2 \geq 0.4$ (3.1) for NO (IO)

→ degenerate solutions in NO

Global fit to ν oscillation parameters

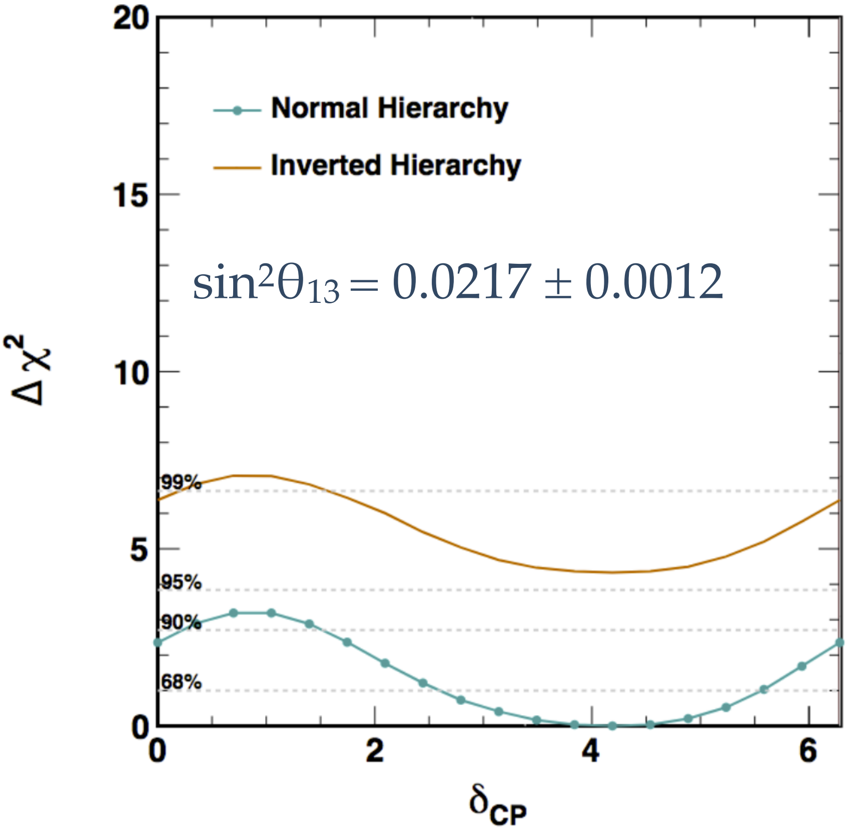
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



The CP phase

H. Tanaka, TAUP 2019

Super-Kamiokande (atm)



- δ_{BF} = 1.5π (1.2π) for NO (IO)
- preference driven by sub-GeV e-like samples

SK Collab. PRD97 (2018)

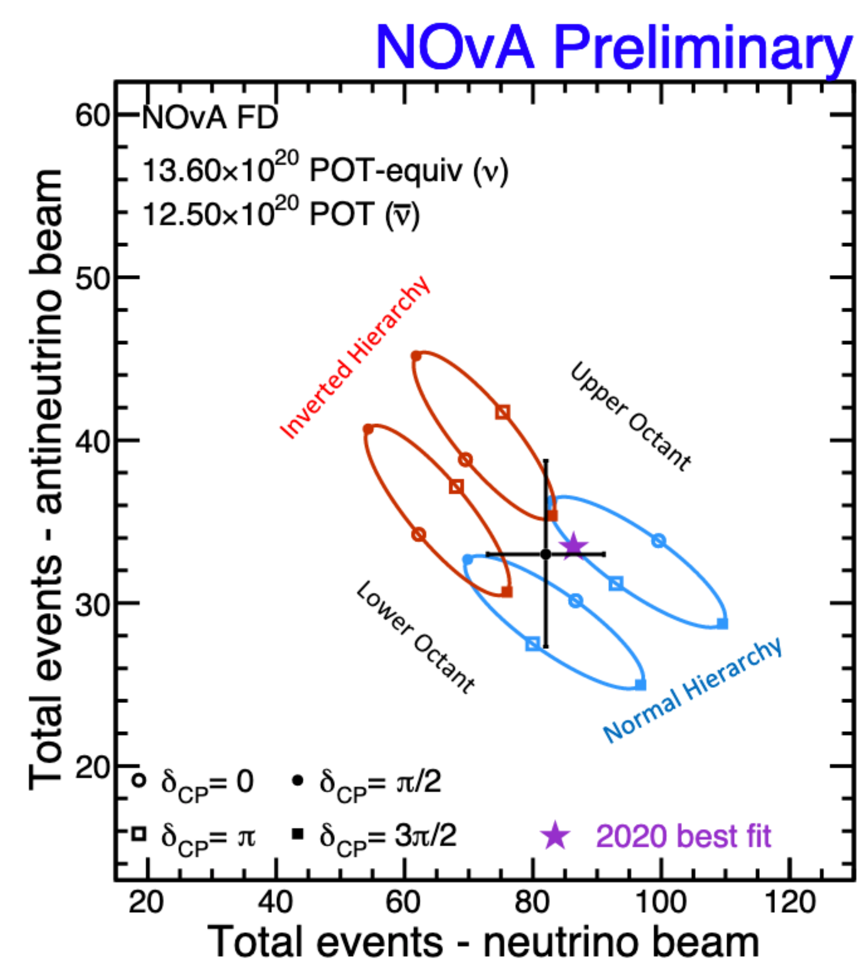
T2K

$\delta_{BF} \simeq 3\pi/2$ due to better agreement with observed ν_e and ν_e events

T2K (NO)		-π/2	0	+π/2	π	OBS
ν mode	1Re 0 d.e.	74.5	62.3	50.6	62.8	75
	1Re 1 d.e.	7.0	6.1	4.9	5.9	15
$\bar{\nu}$ mode	1Re 0 d.e.	17.1	19.6	21.7	19.3	15

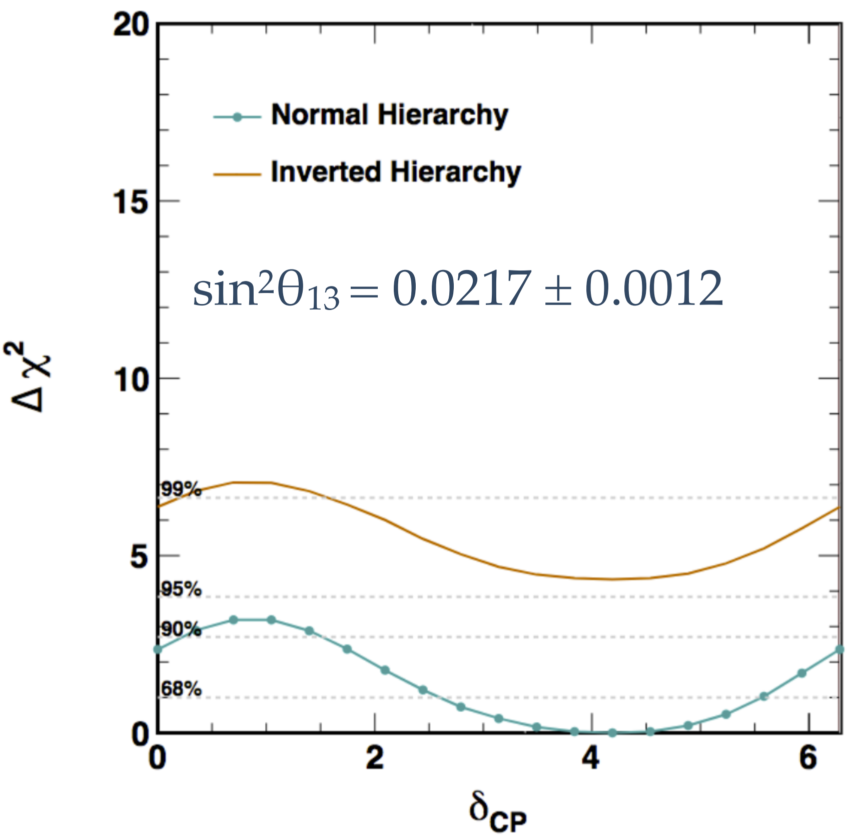
NOvA

P Vahle, TAUP 2021



The CP phase

Super-Kamiokande (atm)

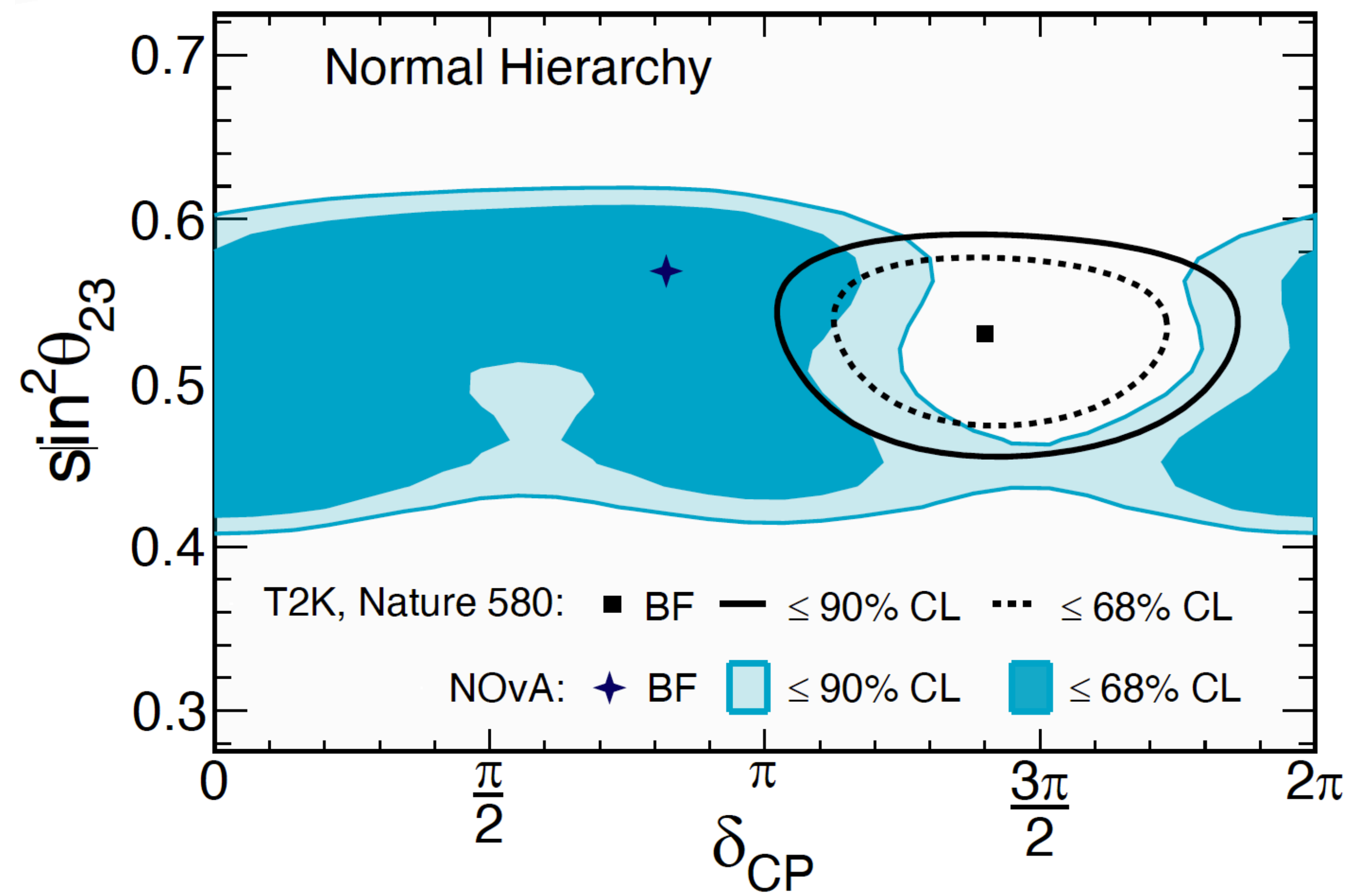


✦ $\delta_{BF} = 1.5\pi$ (1.2π) for NO (IO)

✦ preference driven by sub-GeV e-like samples

SK Collab. PRD97 (2018)

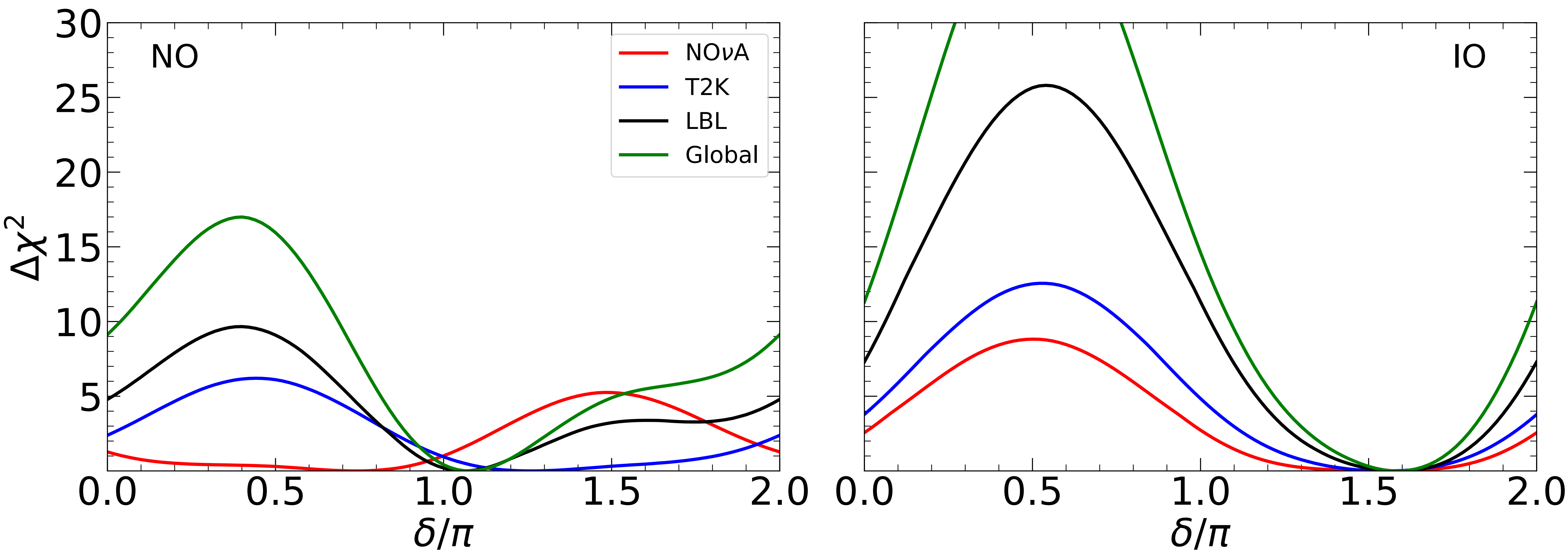
Strong tension between T2K and NOvA results for NO



A. Himmel, Neutrino 2020

The CP phase

de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



- NO: there is a tension between NOvA and T2K and SK atmospheric results

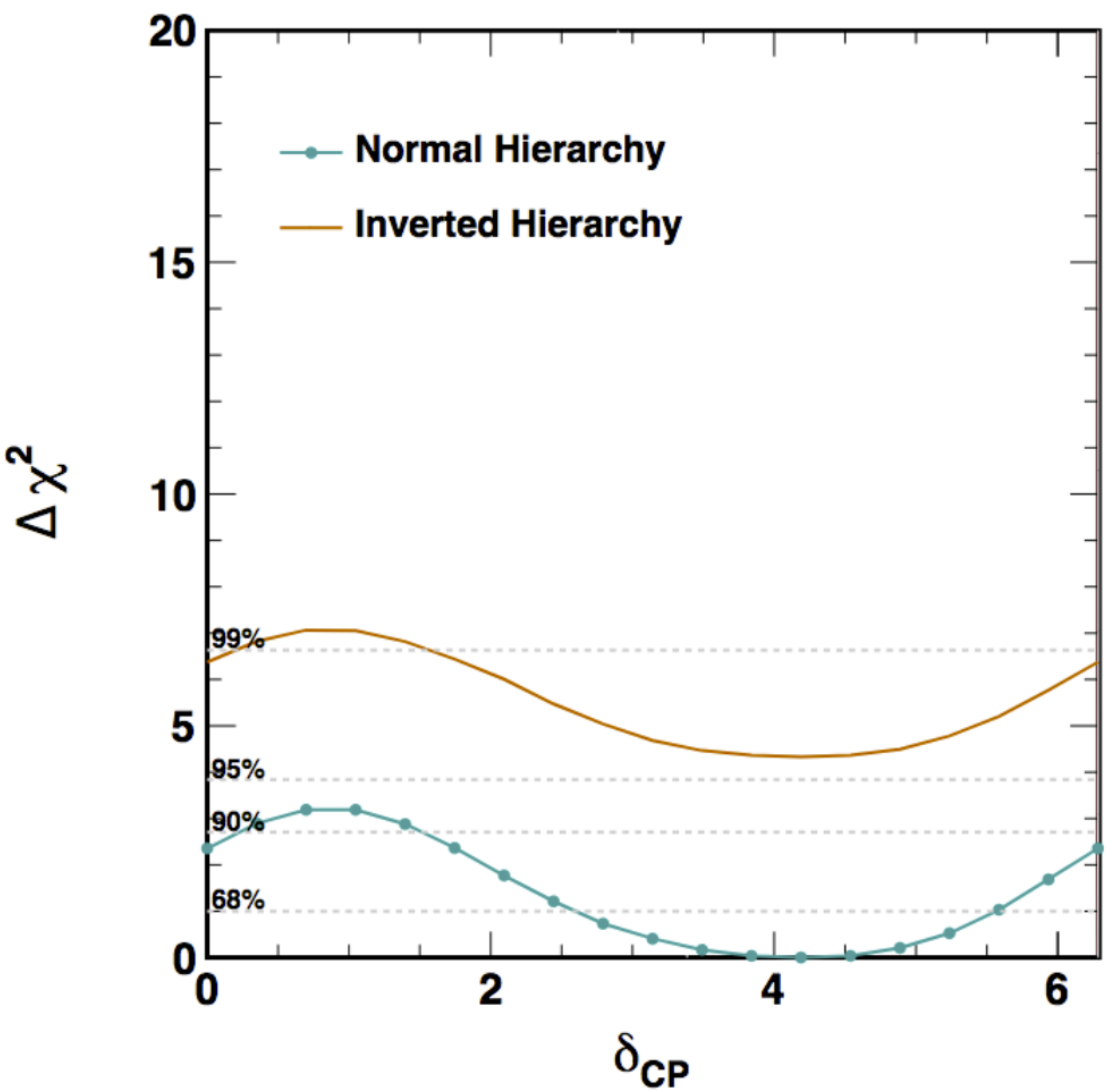
  δ_{BF} = 1.08π ; δ= π/2 (0) disfavored at 4.0σ (3.0σ); δ= 3π/2 with $\Delta\chi^2$ =4.9

- IO: all experiments prefer δ ≈ 3π/2

  δ_{BF} = 1.58π ; δ= π/2 (π) disfavored at 6.2σ (3.8σ);

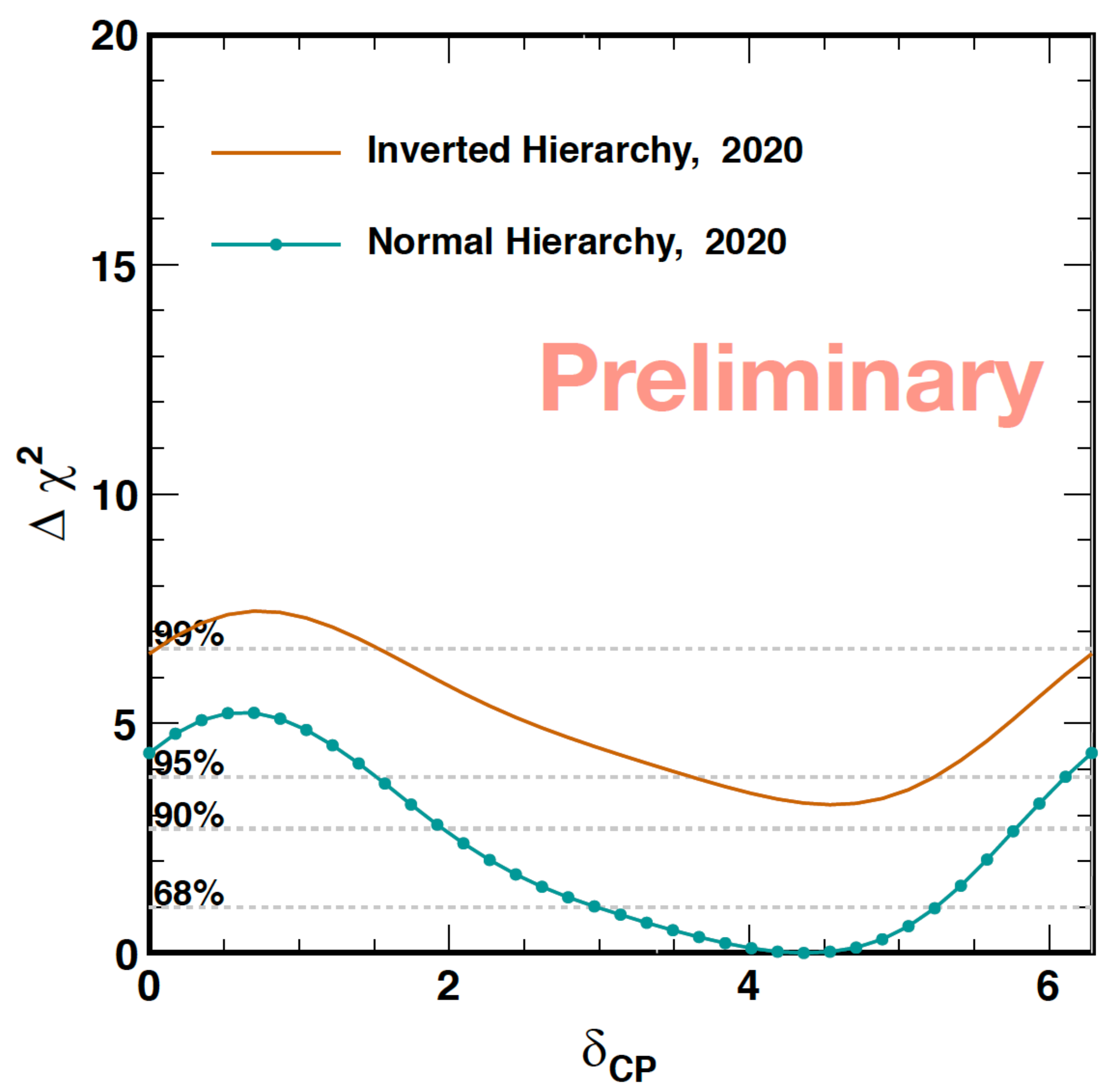
The CP phase

Super-Kamiokande (atm) 2018



SK Collab. PRD97 (2018)

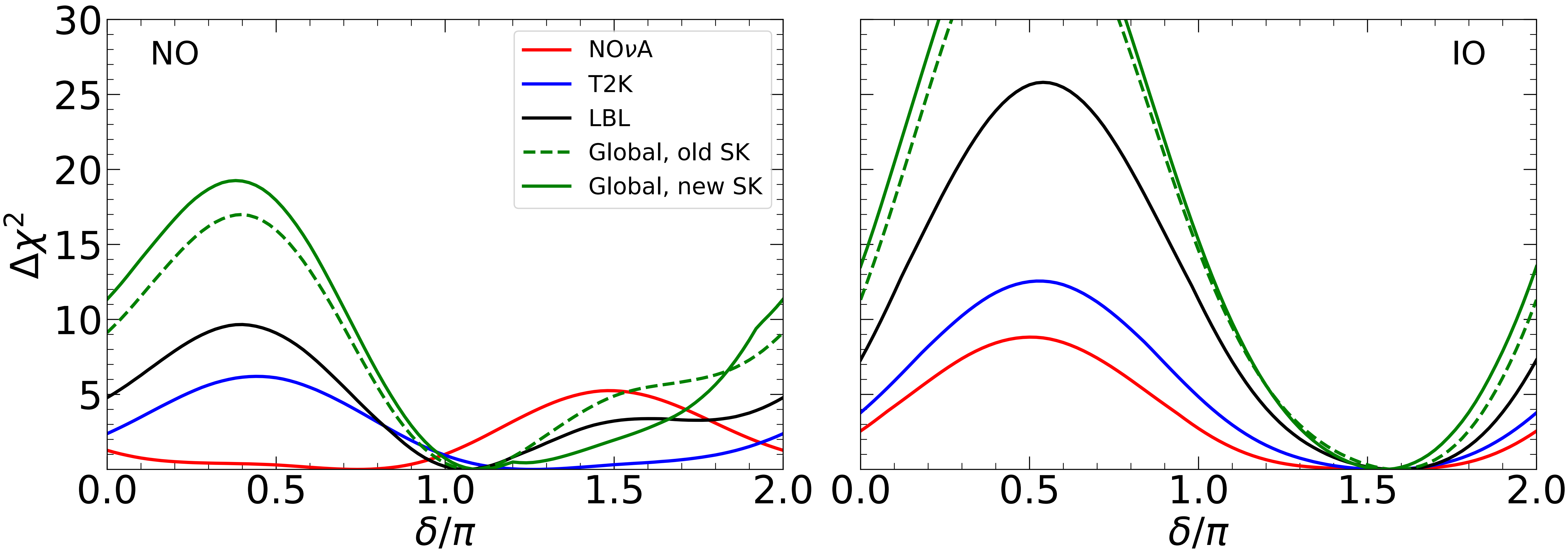
Super-Kamiokande (atm) 2020



Y. Nakajima, Neutrino 2020

The CP phase

de Salas et al, preliminary



- NO: there is a larger (smaller) rejection to δ= 0 and δ= π/2 (δ= 3π/2)

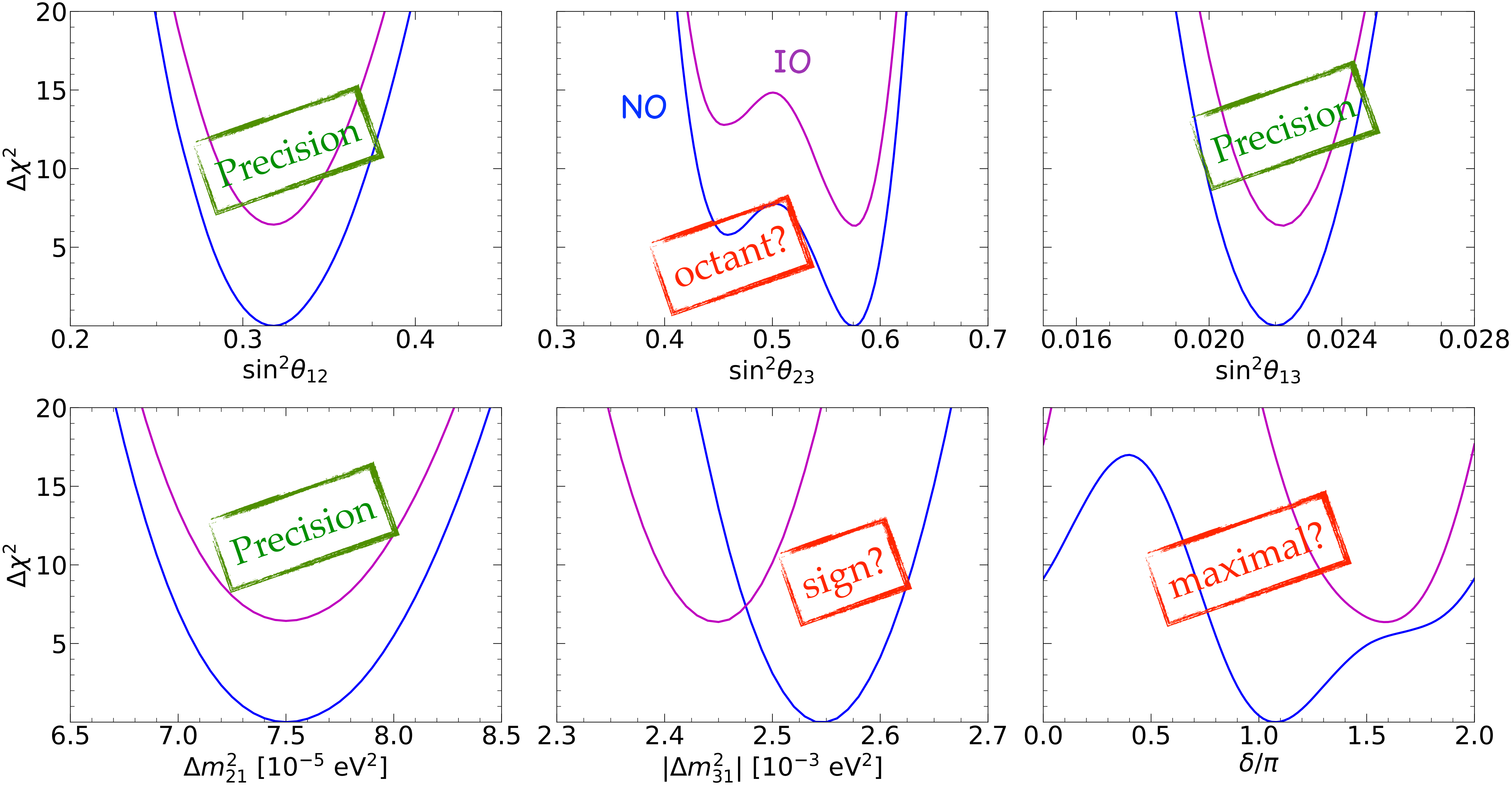
  $\delta_{BF} = 1.1\pi$; δ= π/2 (0) disfavored at 4.2σ (3.4σ); δ= 3π/2 with $\Delta\chi^2 = 2.0$

- IO: all experiments prefer δ ≈ 3π/2 (similar results)

  $\delta_{BF} = 1.54\pi$; δ= π/2 (π) disfavored at 6.4σ (3.9σ)

Global fit to ν oscillation parameters

de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



The mass ordering

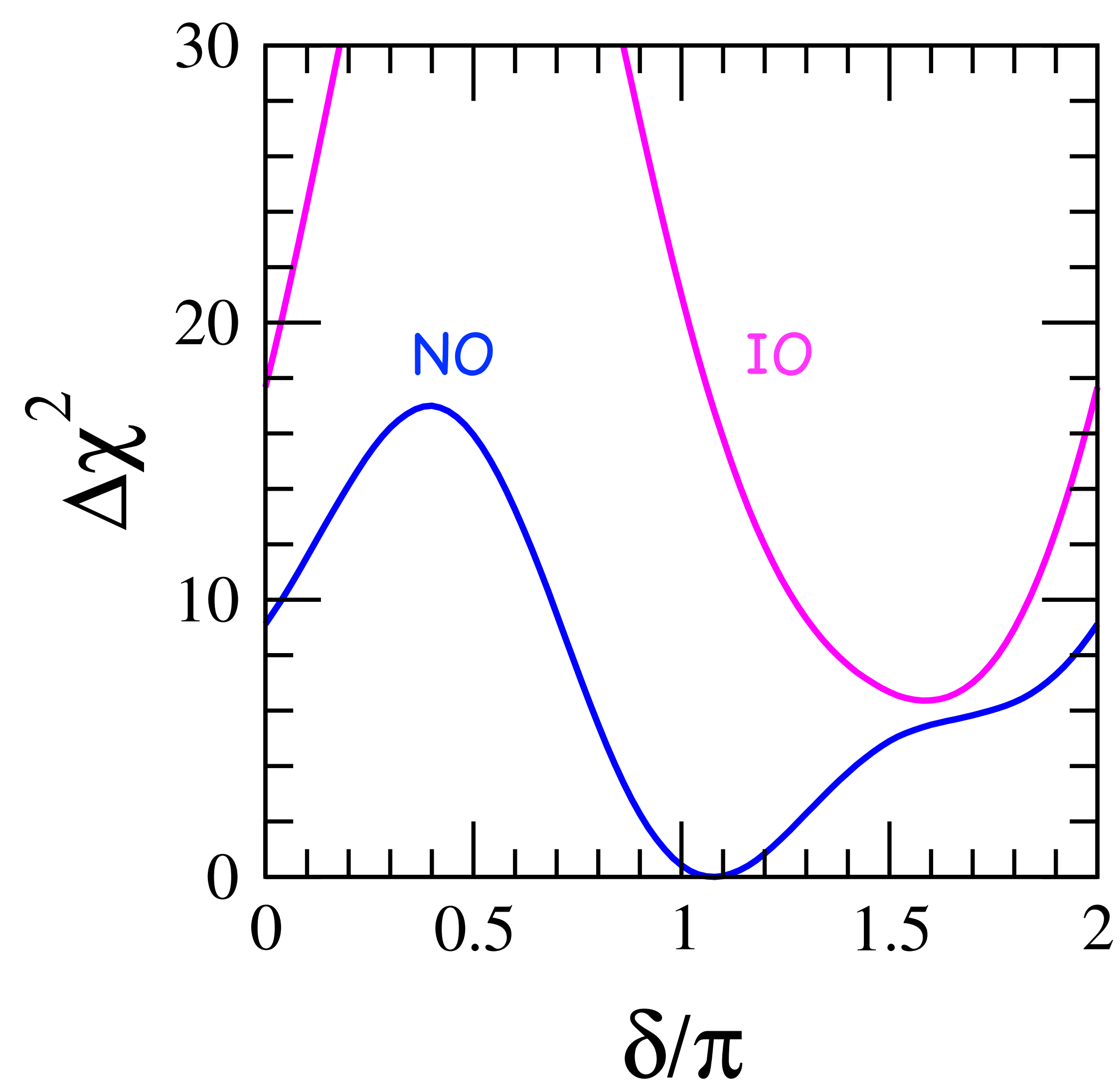
- T2K and NOvA separate analyses prefer NO with $\Delta\chi^2 \approx 0.4$

- T2K + NOvA combined prefer IO with $\Delta\chi^2 \approx 2.4$ (tension in δ for NO)

- LBL + REAC prefer NO with $\Delta\chi^2 \approx 1.4$ (tension in Δm^2_{31} measurement in IO)

- Atmos. sensitivity: Super-K ($\Delta\chi^2 \approx 3.5$) and DeepCore ($\Delta\chi^2 \approx 1.0$)

- Global fit: $\Delta\chi^2 = 6.4 \rightarrow$ 2.5σ preference for NO



de Salas et al, JHEP 02 (2021) 071

Other inputs for mass ordering?

Experimental sensitivity to neutrino masses:

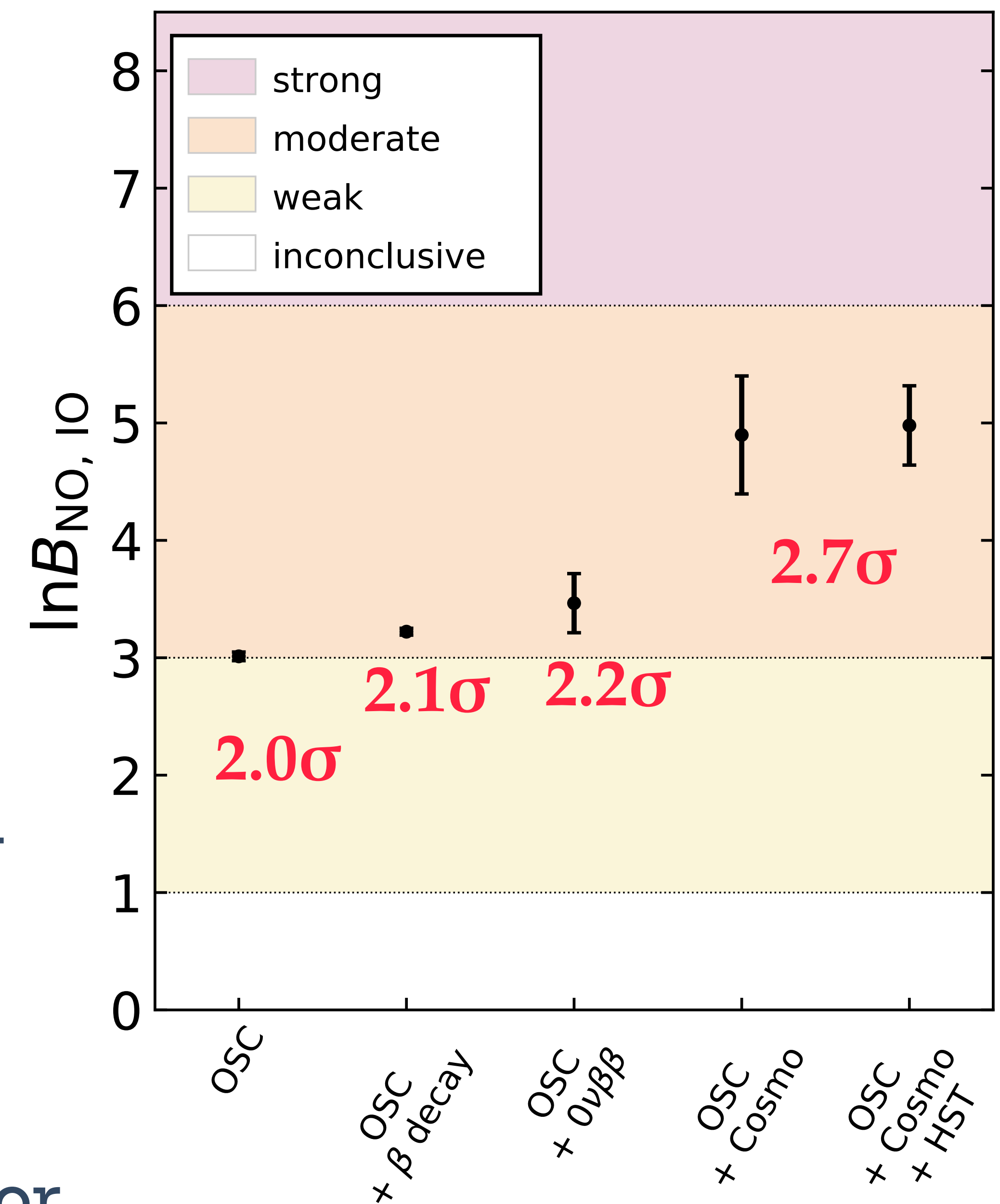
- ✦ ν-oscillations: Δm^2_{ij}
- ✦ β-decay: $m_\beta = f(m_i,\theta_{ij})$
- ✦ 0νββ: $m_{\beta\beta} = f(m_i,\theta_{ij},\phi_i)$
- ✦ cosmology: Σm_i

Results from the combined bayesian analysis:

⇒ weak/moderate preference for NO driven by oscillation data (2.0σ)

⇒ β-decay and 0νββ have little impact on MO.

⇒ cosmological data enhances the preference for NO from 2.0σ to 2.7σ



de Salas et al, JHEP 02 (2021) 071

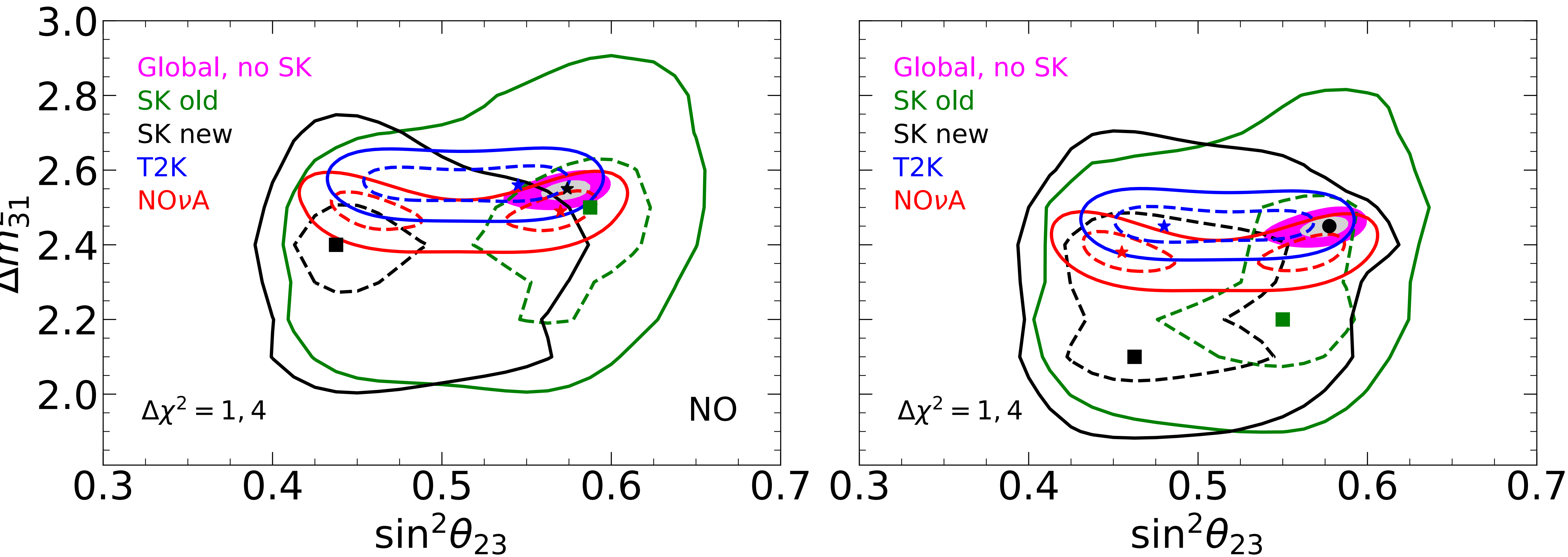
The mass ordering (preliminary)

✦ New Super-K atmospheric analysis (preliminary) **Y. Nakajima, Neutrino-2020**

✦ Preliminary Super-K analysis shows weaker preference for NO

⇒ $\Delta\chi^2$ =3.5 (previous SK analysis) → $\Delta\chi^2$ = 2.9

✦ Super-K results for atm parameters are in more tension with LBL for NO



de Salas et al, preliminary

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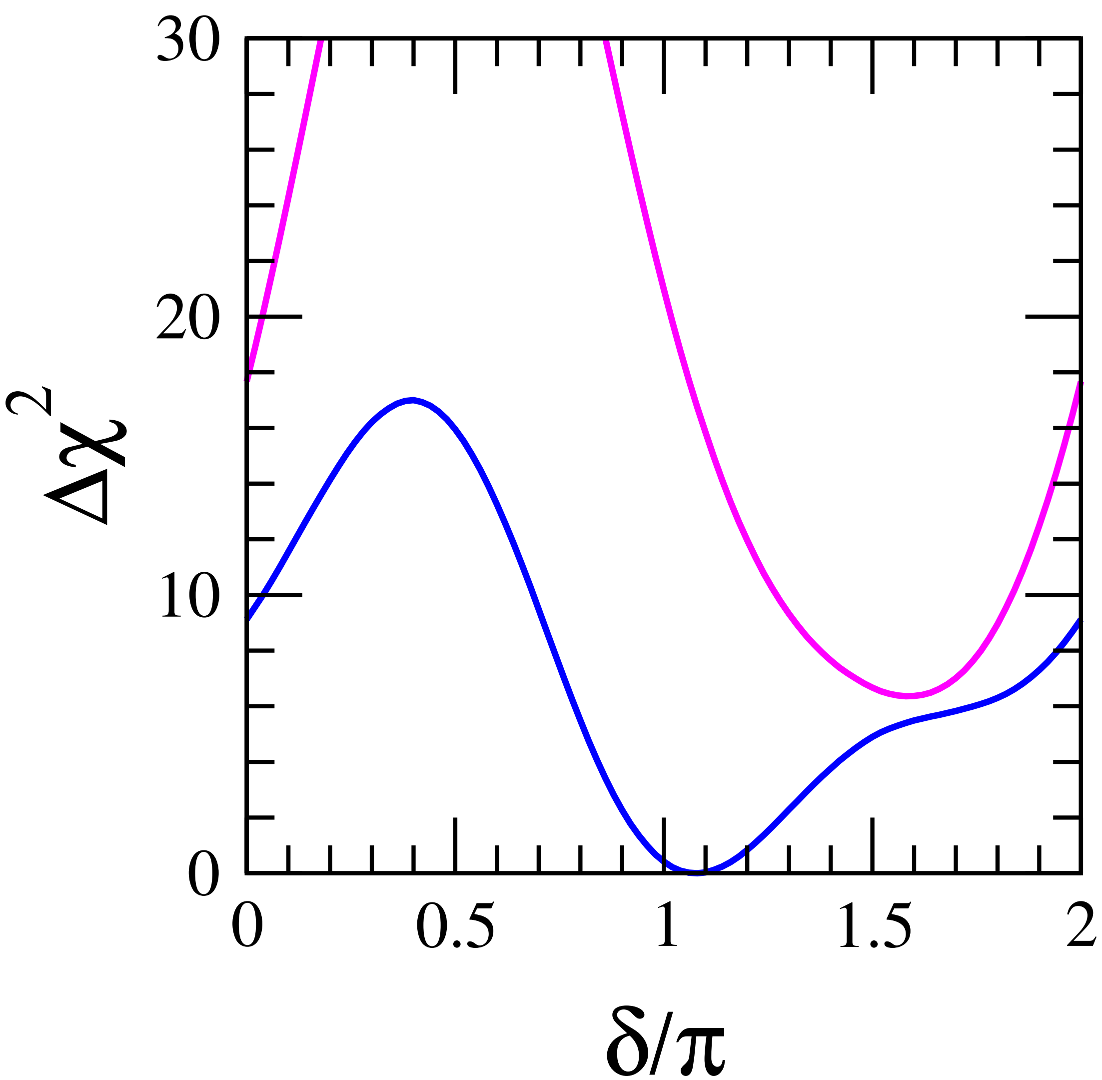
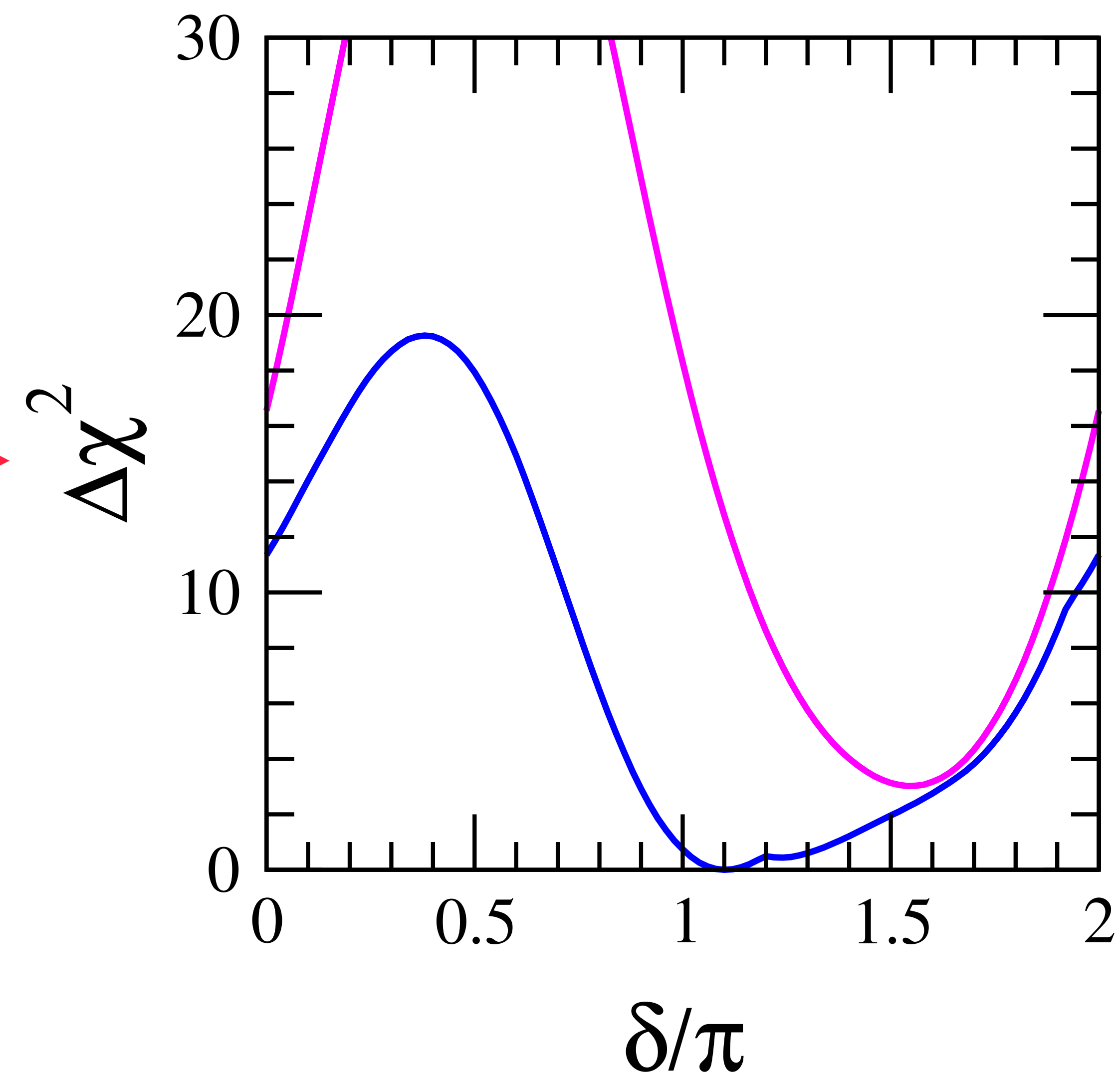
✦ New Super-K atmospheric analysis (preliminary) **Y. Nakajima, Neutrino-2020**

de Salas et al, JHEP 02 (2021) 071



de Salas et al, preliminary

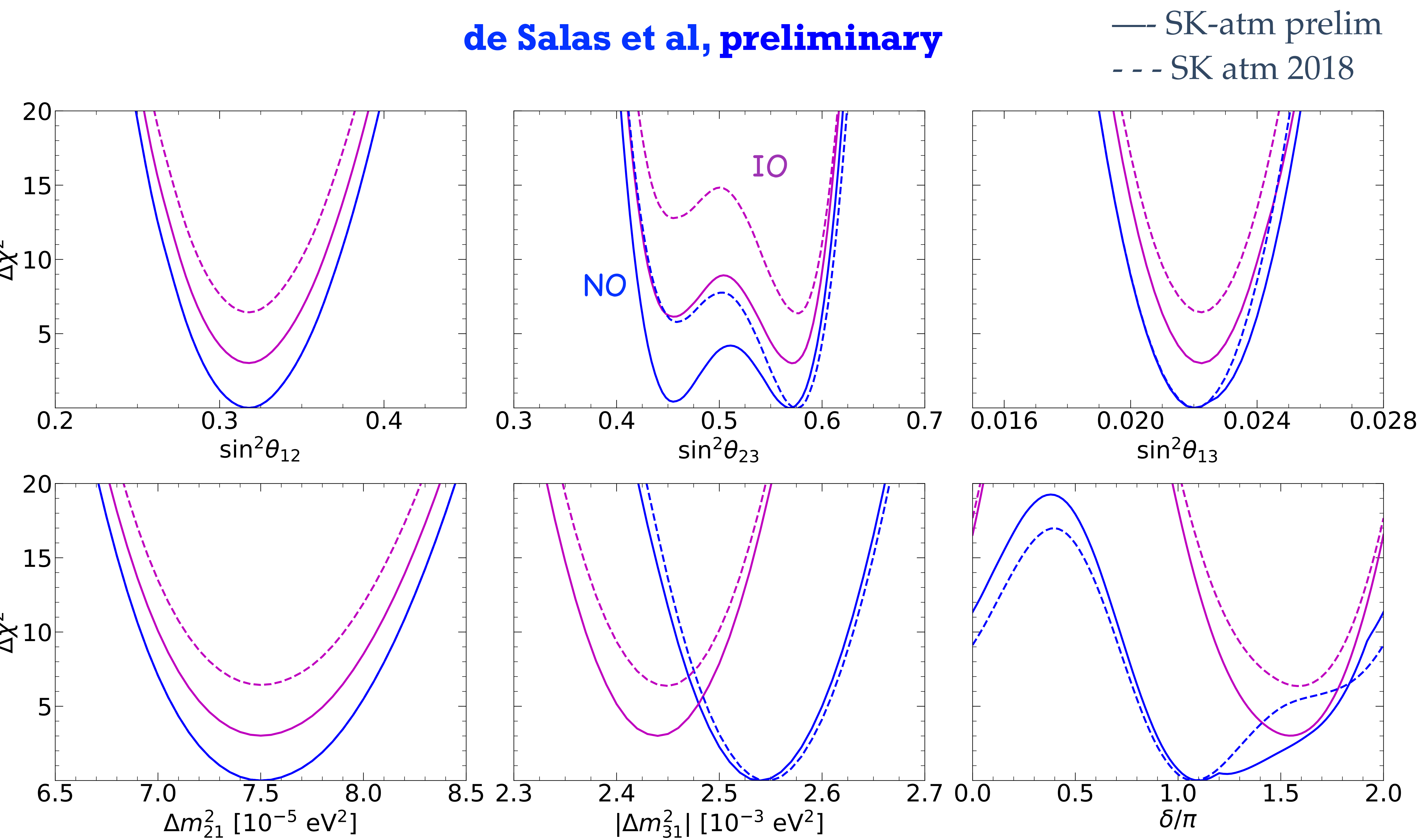


✦ $\Delta\chi 2$ =6.4 → 2.5σ preference for NO

✦ $\Delta\chi^2$ =3.0 → 1.7σ preference for NO

Global fit to ν oscillation parameters

de Salas et al, preliminary

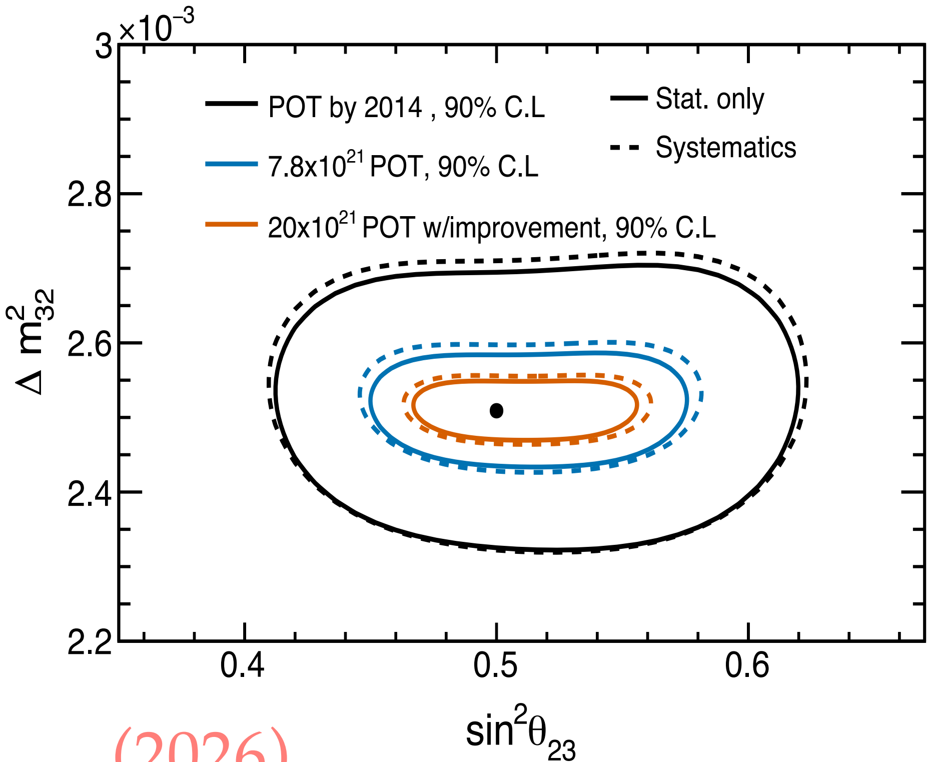


Future prospects in neutrino oscillations

Prospects for precision

T2K

Abe et al, 1609.04111

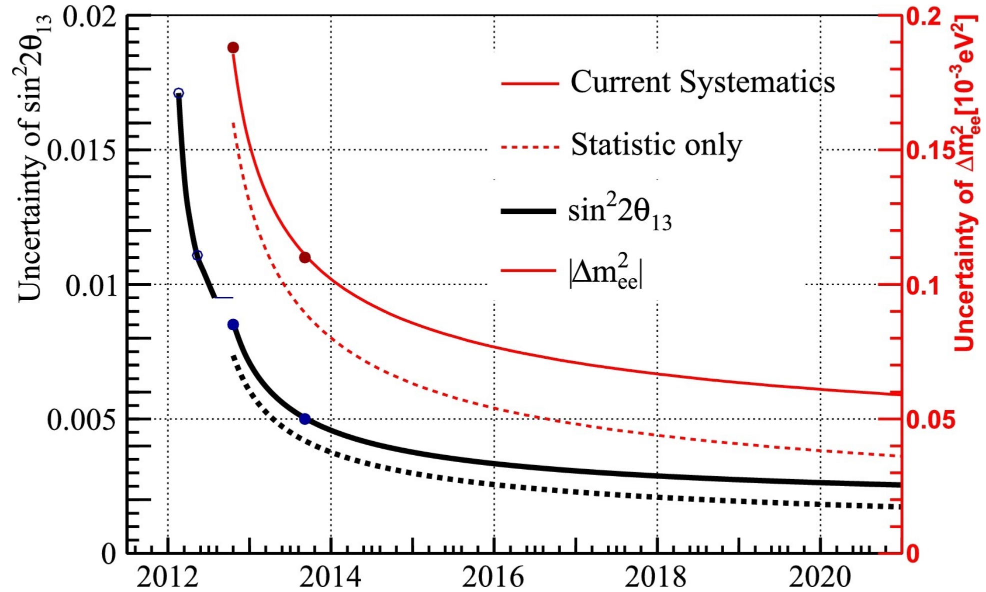


(2026)

~1% precision on Δm^2_{32}

~1-3% precision on $\sin^2\theta_{23}$

DayaBay

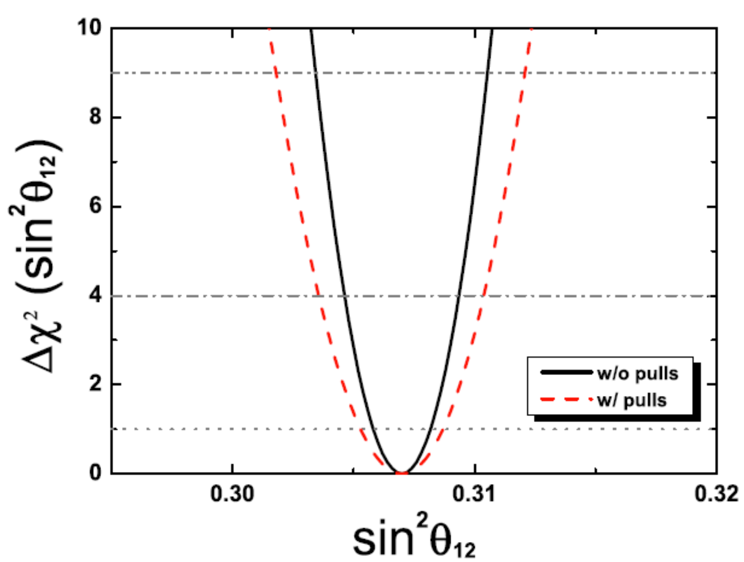


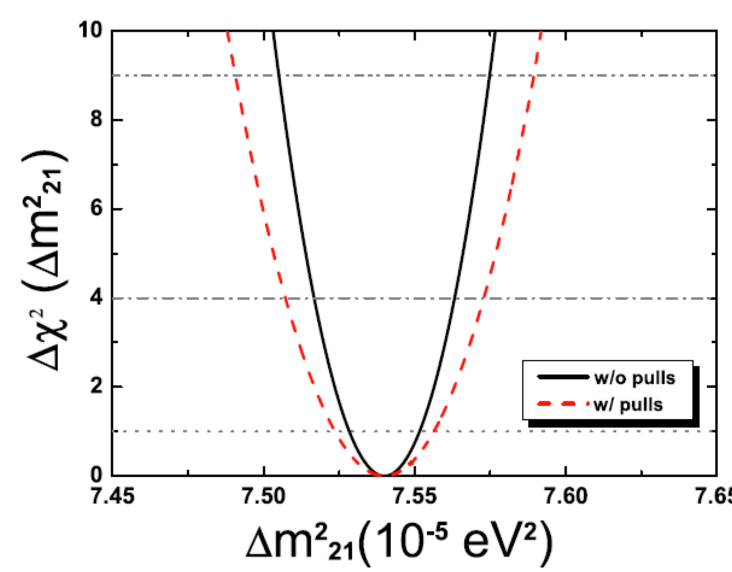
Cao and Luk, 1605.01502

< 3% precision in $\sin^2 2\theta_{13}$ and Δm^2_{ee}

2.7% in $\sin^2 2\theta_{13}$
[Z, Yu, TAUP'21]

JUNO (6 years)



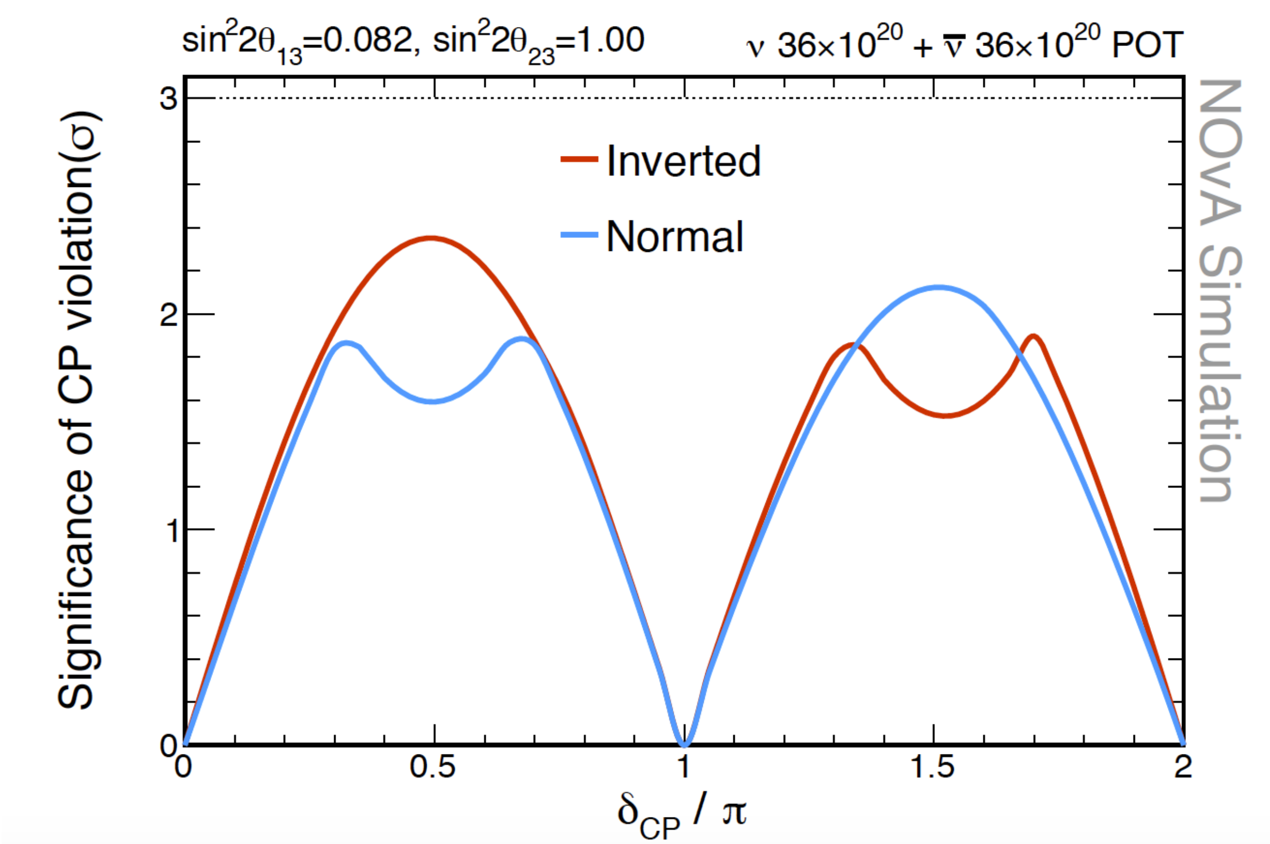


~0.7% precision on $\sin^2\theta_{12}$ ~0.6% precision on Δm^2_{21}

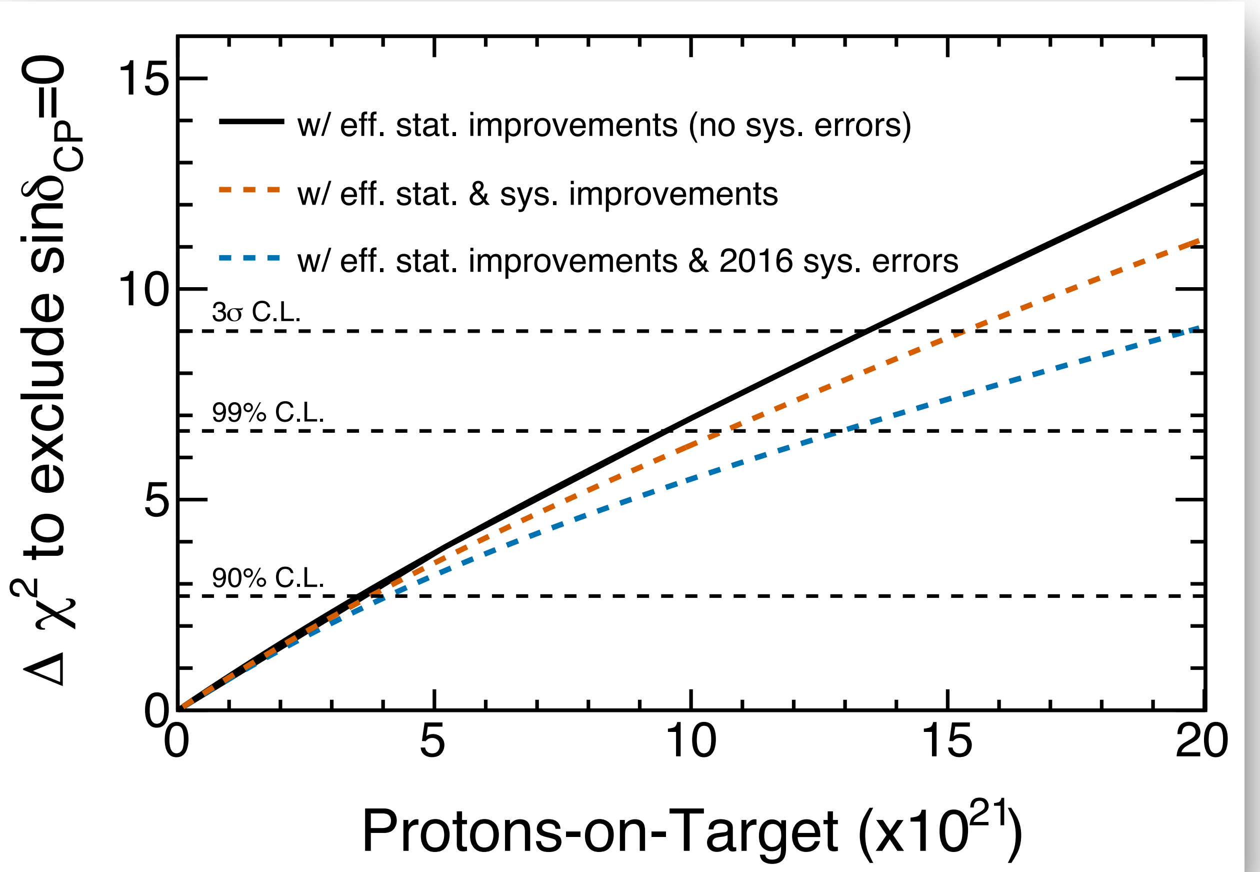
An et al, 1507.05613

Prospects for CP violation

NOvA **M. Sánchez, Neutrino'18**
P. Vahle, TAUP'21



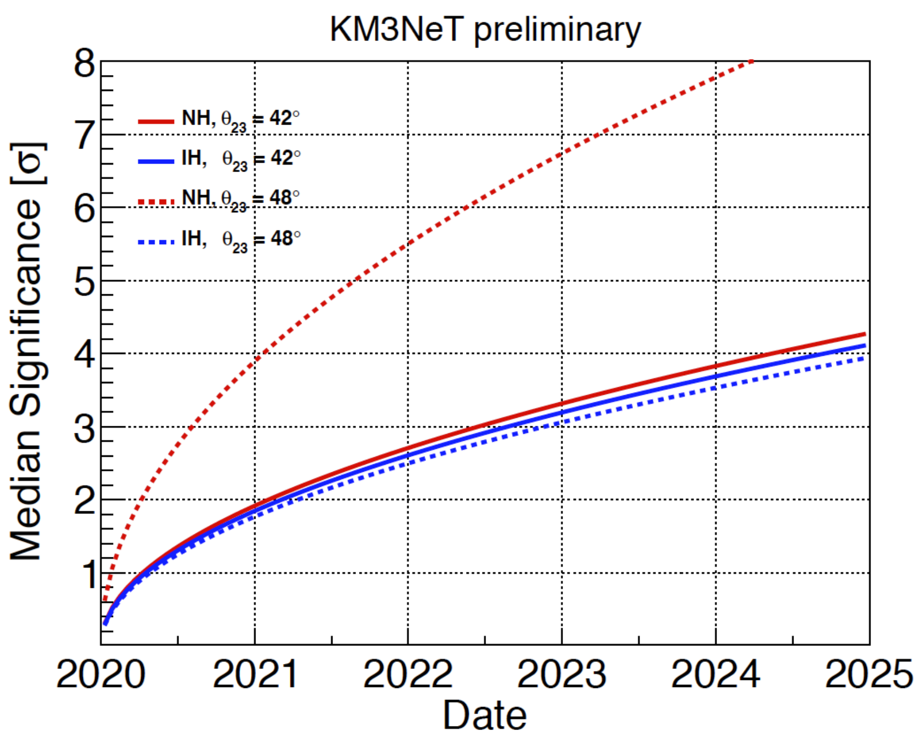
T2K **Abe et al, 1609.04111**



- by 2026 (60-70 x 10^{20} POT): ~ 2σ sensitivity on CP violation at max CP violation (π/2 & 3π/2)
- by 2026 (20×10^{21} POT): > 3σ sensitivity on CP violation

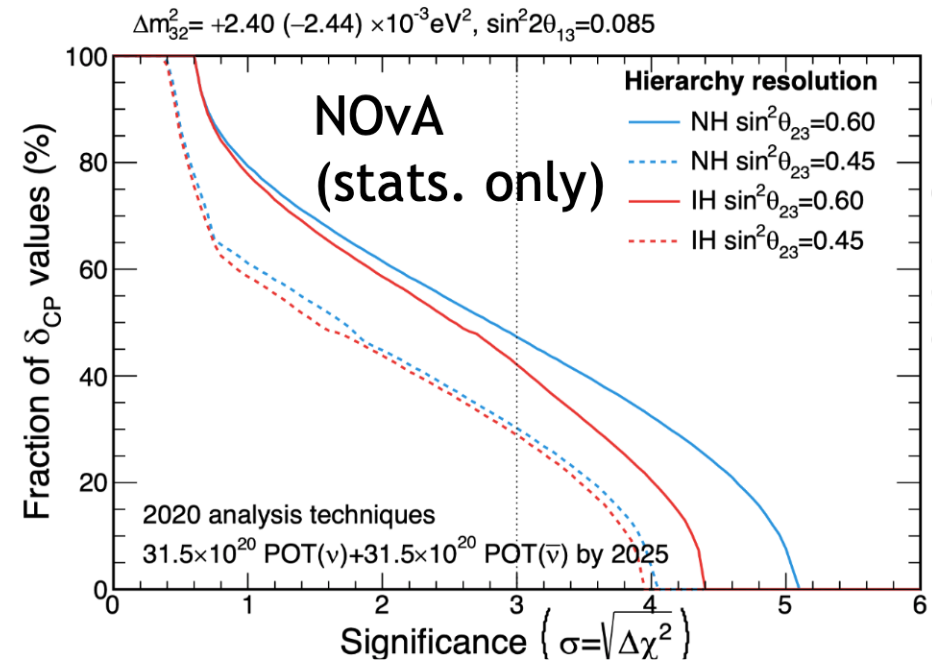
Prospects for mass ordering

ORCA — **Adrian-Martinez et al, 1601.07459**



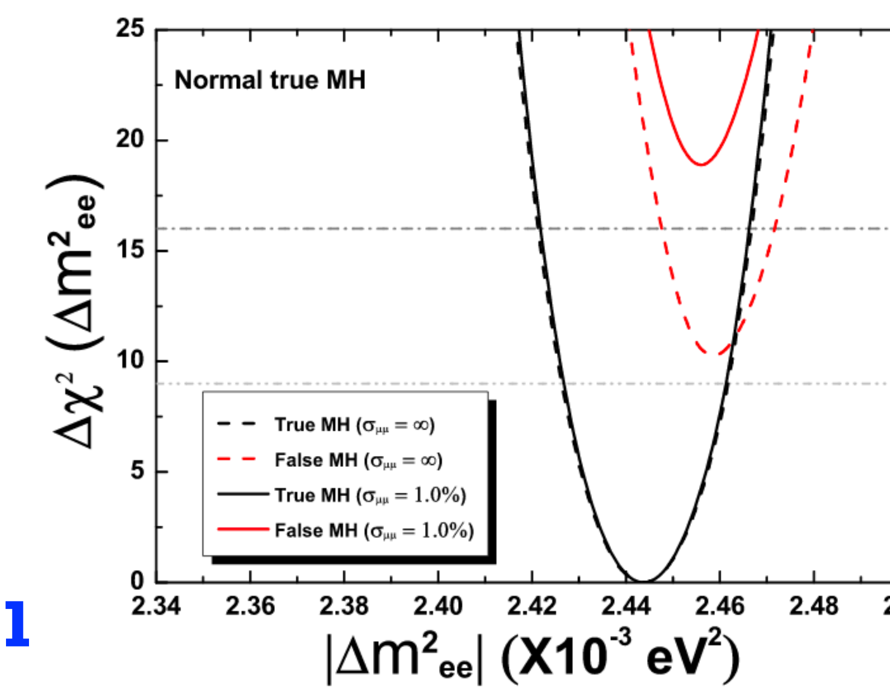
- 2023: 3σ determination of MO

NOvA — **P. Vahle, TAUP'21**



- 2026: 3σ sensitivity for 30-50% of δ

JUNO

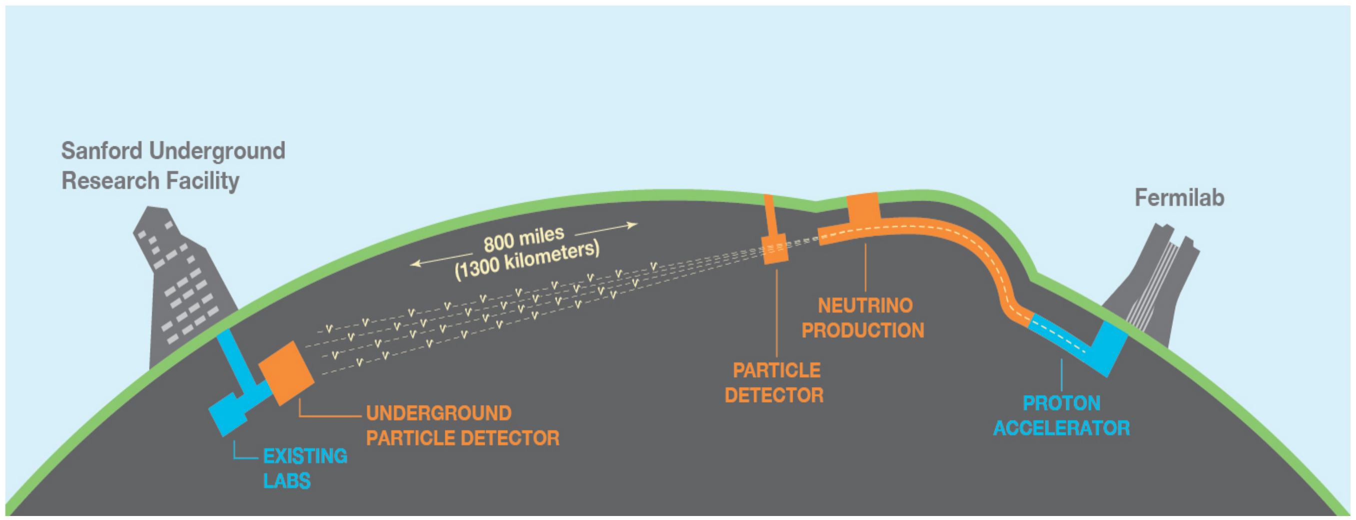


⇒ 3σ sensitivity on mass ordering after 6 years

An et al, J. Phys. G 43 (2016) 030401

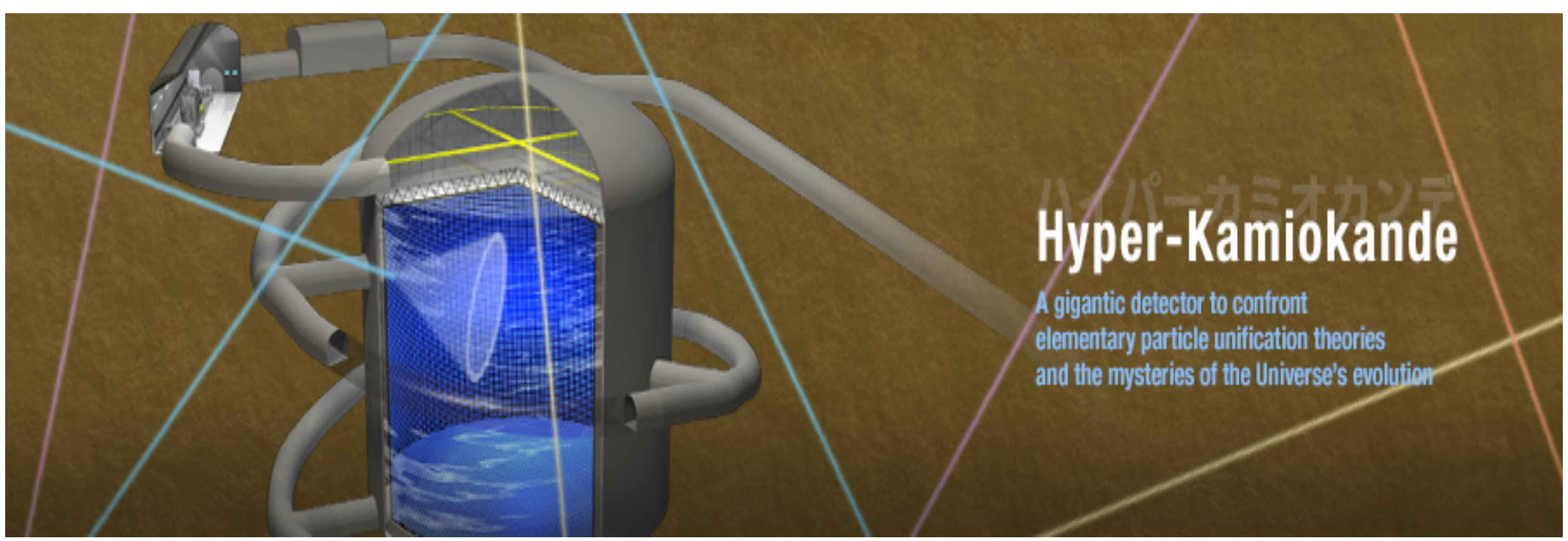
Next generation of ν experiments

DUNE



- 1.2 MW wide-band beam from FNAL to SURF (1300km)
- 4x10 kt Liquid Argon TPCs
- capability to probe 2nd oscillation max
- great sensitivity to mass ordering

Hyper-Kamiokande

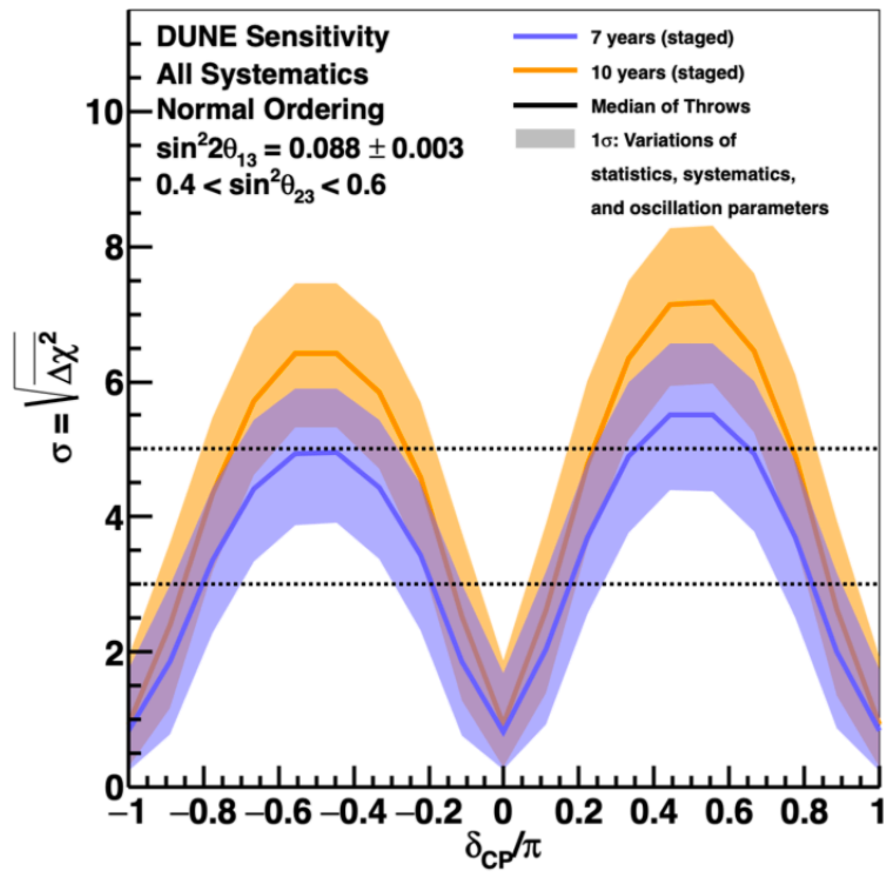


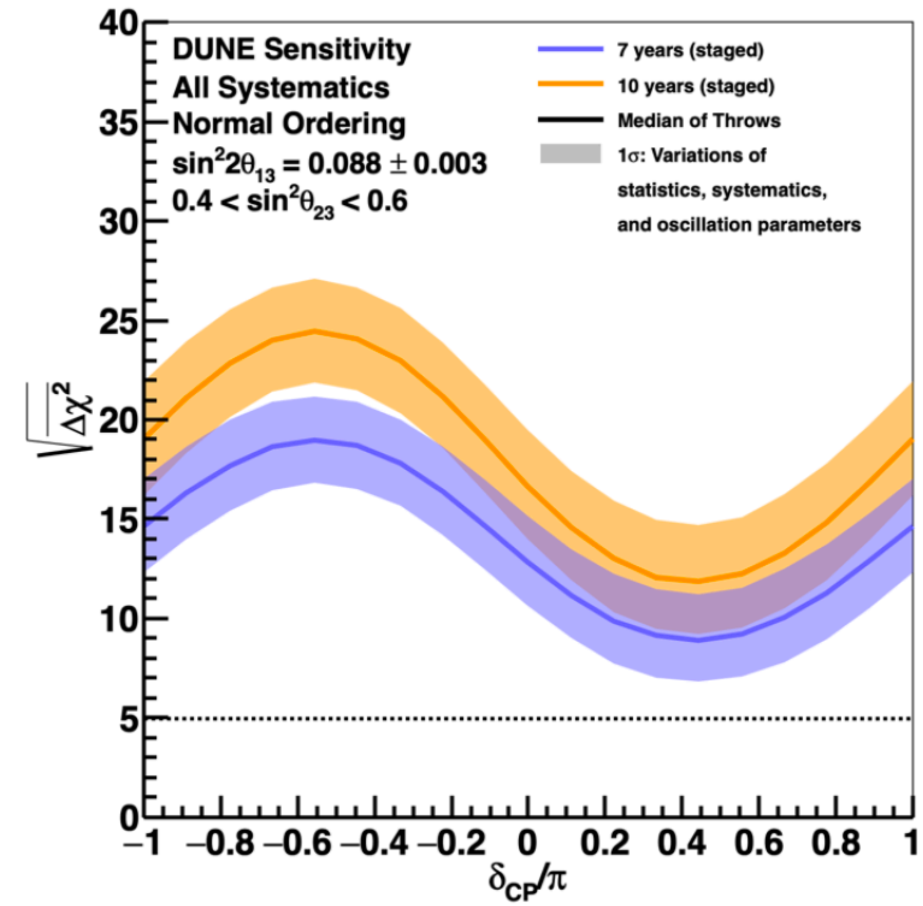
- 188 kton water Cerenkov
- T2HK: great sensitivity to δ_{CP}
- T2HKK (1100km) will have similar sensitivities as DUNE

Next generation of ν experiments

DUNE

DUNE Collaboration

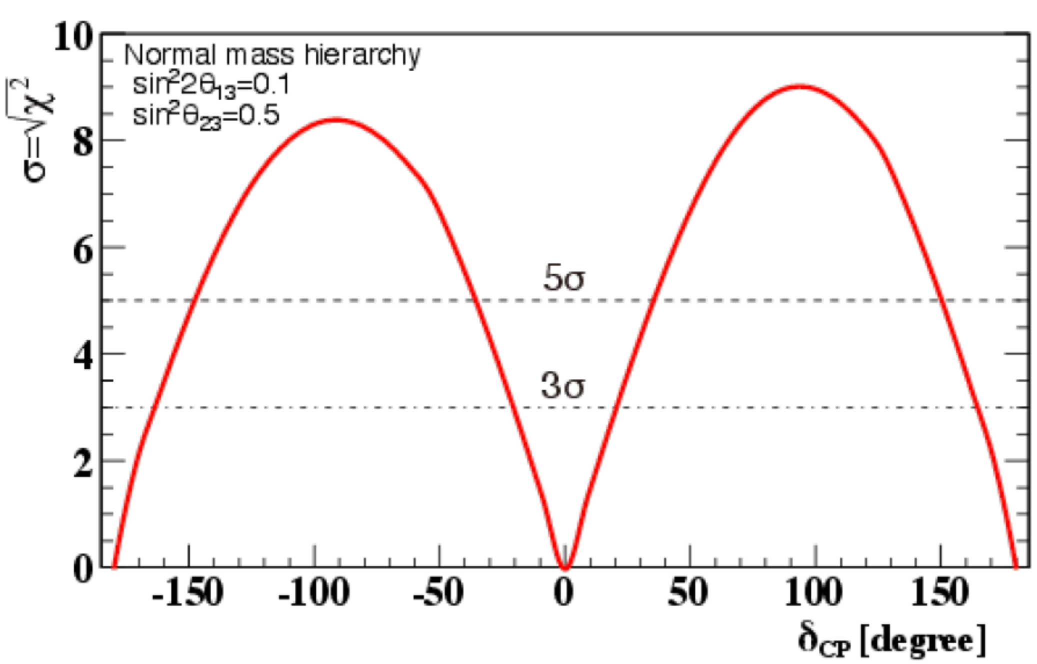


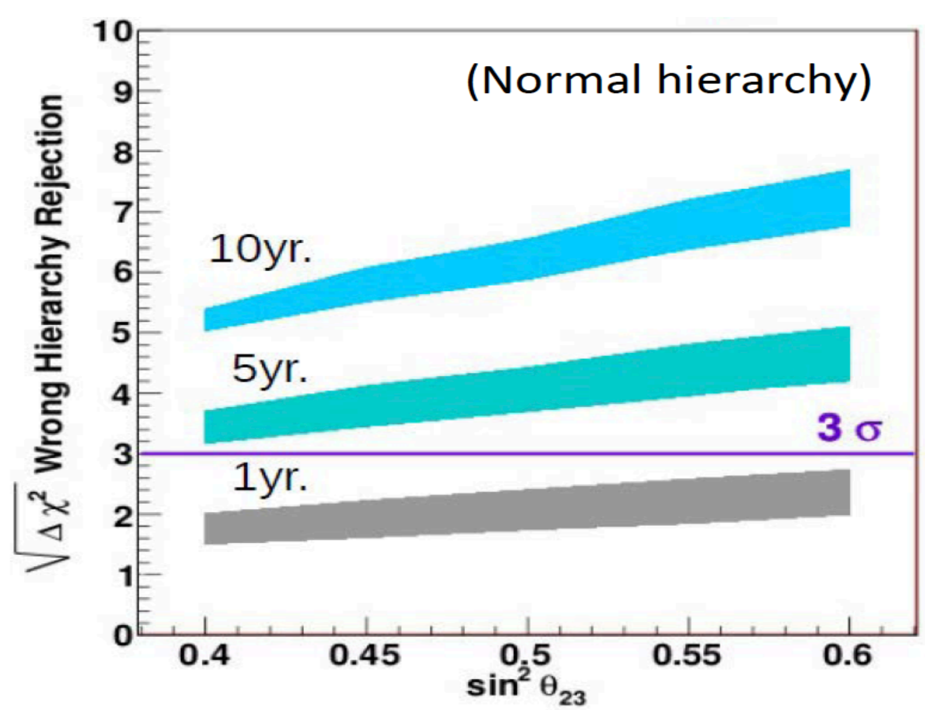


Hyper-K

Y. Koshio, 2018

(10 yr data)





Beyond the standard three-neutrino scenario

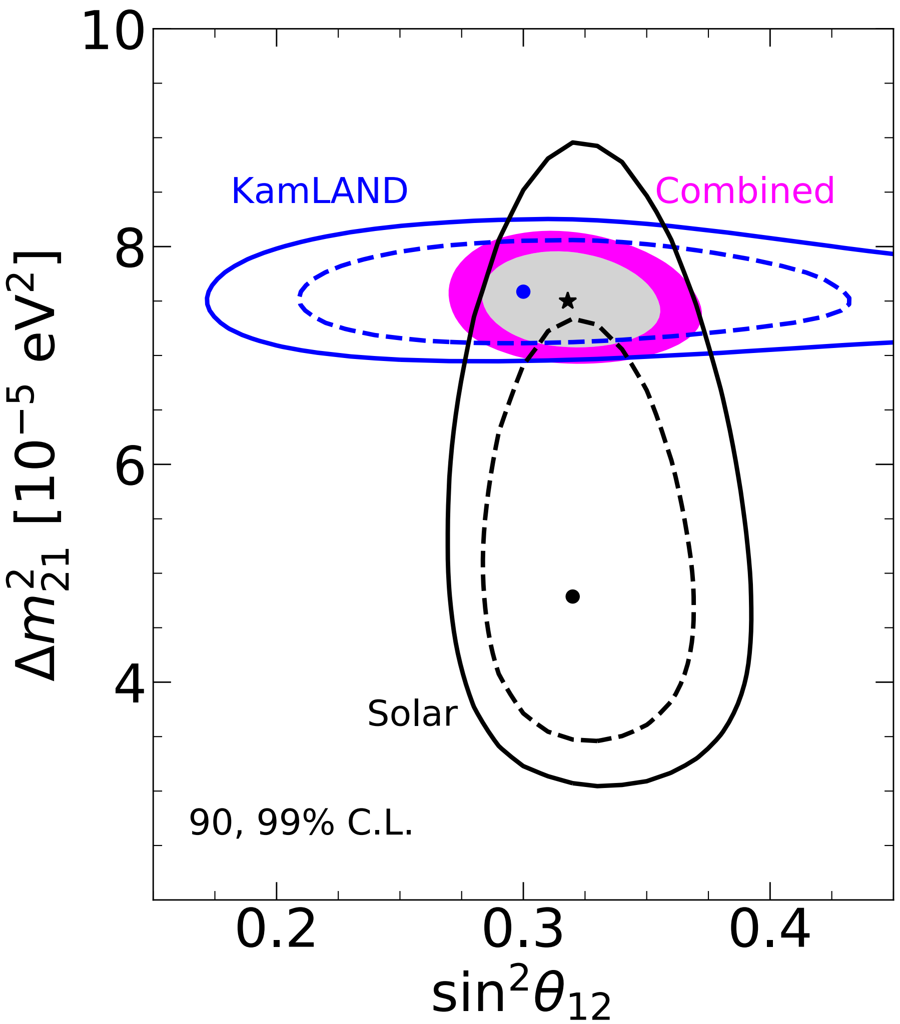
Beyond the 3-neutrino scenario

- Neutrino results suggest the presence of **physics BSM** to explain:
  - ✓ light neutrino masses (mass generation mechanism)
  - ✓ large neutrino mixing compared to quark sector (flavour problem)
  - ✓ short-distance anomalies (LSND, reactor and Ga anomalies)
- Many different **BSM scenarios** analyzed in the literature:
  - ✓ neutrino non-standard interactions (NSI) with matter
  - ✓ exotic neutrino electromagnetic properties
  - ✓ presence of light sterile neutrinos
  - ✓ mixing with heavy sterile neutrinos: non-unitary neutrino mixing

⇒ the presence of new physics may affect our current description of 3-nu oscillations as well as the future measurements

Can they also help reducing the current tensions?

The solar-KamLAND Δm^2_{21} tension



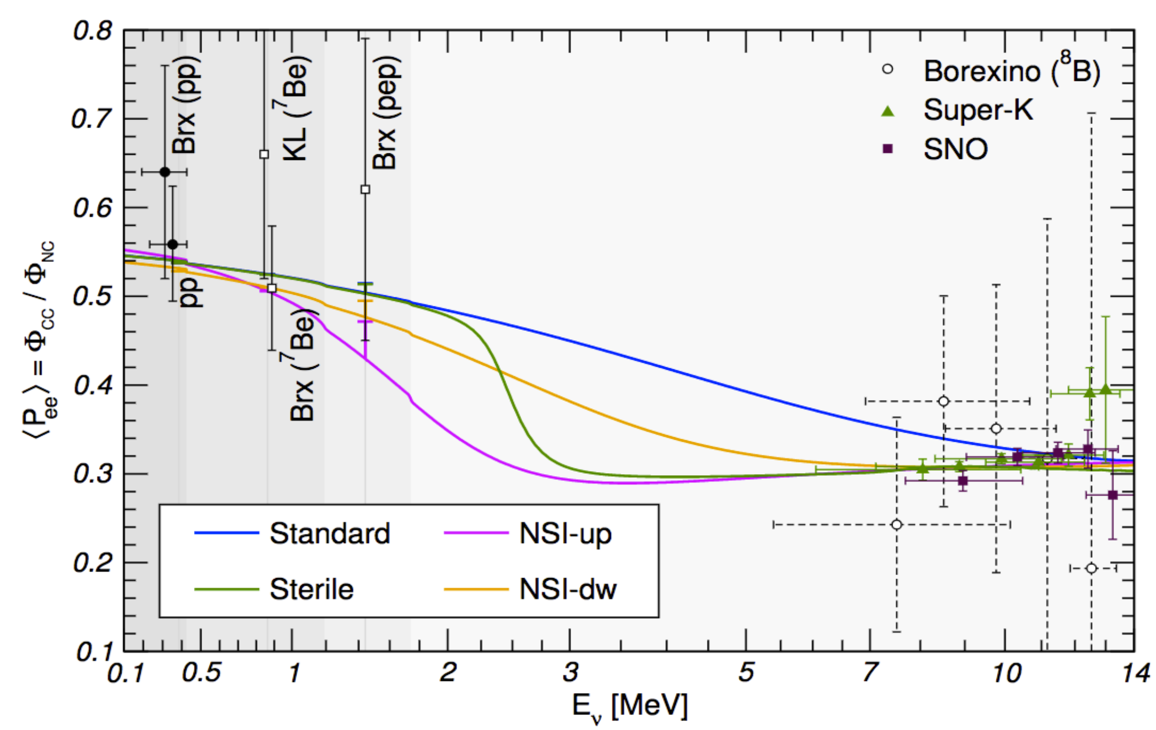
⇒ 2σ tension between preferred value of Δm^2_{21} from KamLAND and solar data

⇒ Δm^2_{21} preferred by KamLAND predicts steep upturn and smaller D/N asymmetry

✦ NSI (ε ~0.3) can reconcile both results:

⇒ flatter spectrum at intermediate E-region

⇒ larger D/N asymmetries can be expected

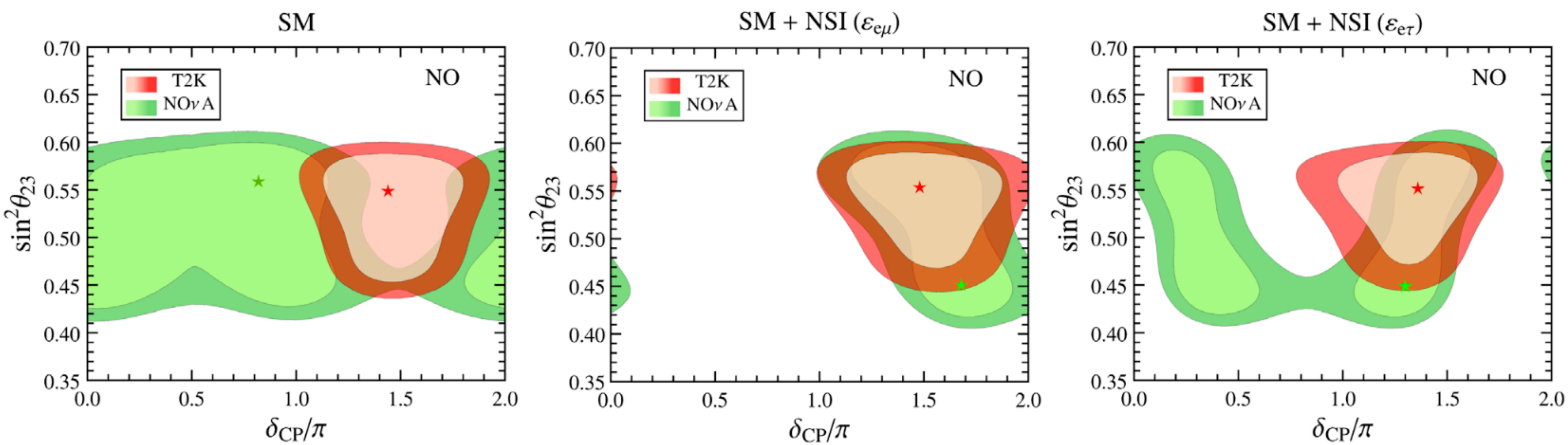


Escrihuela et al, PRD80 (2009); Coloma et al, PRD96 (2017) Maltoni & Smirnov, EPJ 2015

The T2K-NOvA δ_{CP} tension

✦ NSI may include new sources of CP violation besides δ_{CP}: $\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}| \exp(i\phi_{\alpha\beta})$

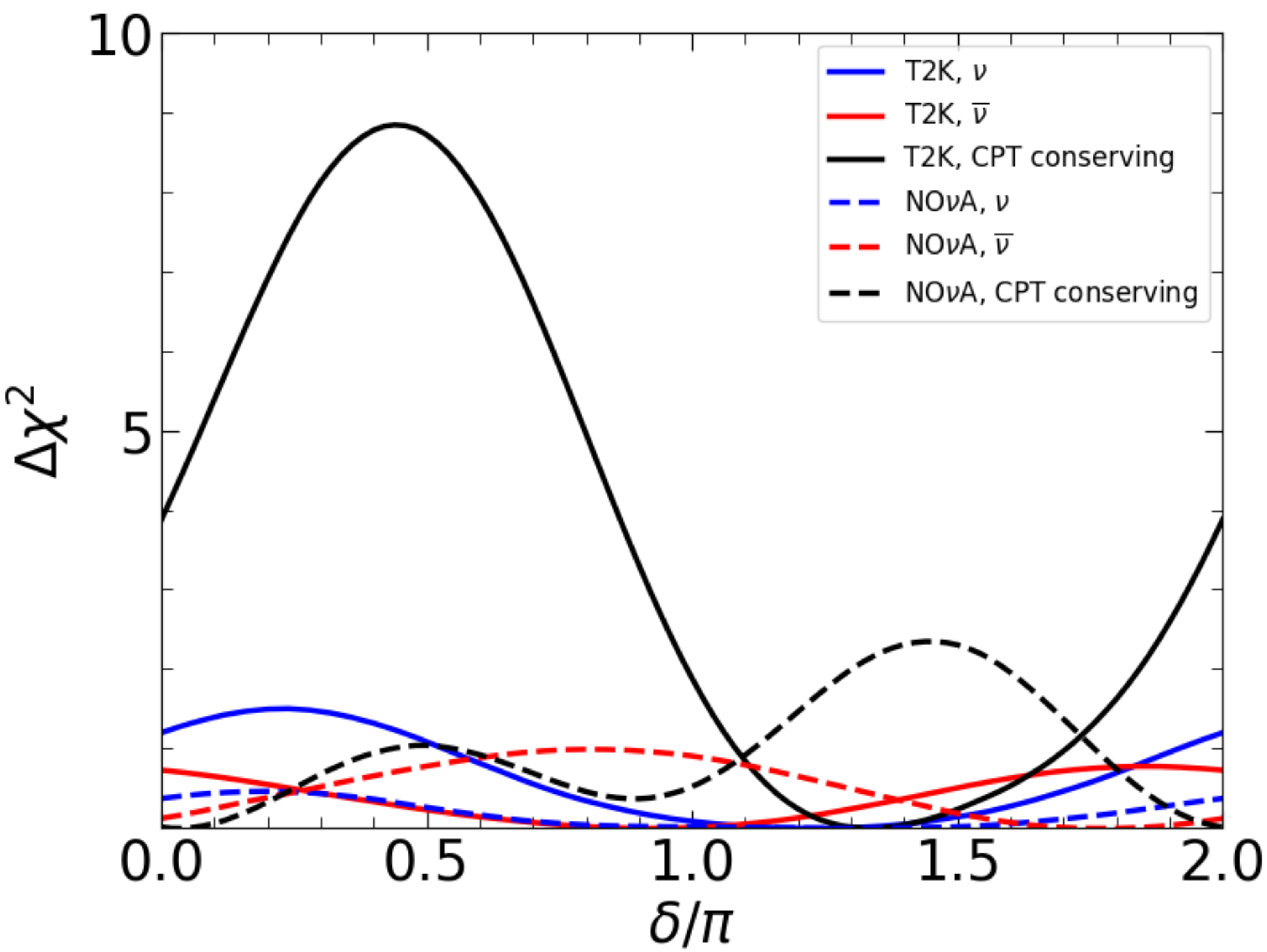
✦ CP-violating NSI with a new complex phase $\phi_{e\mu}$ or $\phi_{e\tau}$ close to maximal with NSI couplings $\varepsilon_{e\mu}$ or $\varepsilon_{e\tau}$ of the order of 0.2 may reconcile T2K and NOvA results.



Chatterjee and Palazzo, PRL 2021 **Denton et al, PRL 2021**

The T2K-NOvA δ_{CP} tension

CPT-violating analysis of T2K and NOvA (normal ordering)



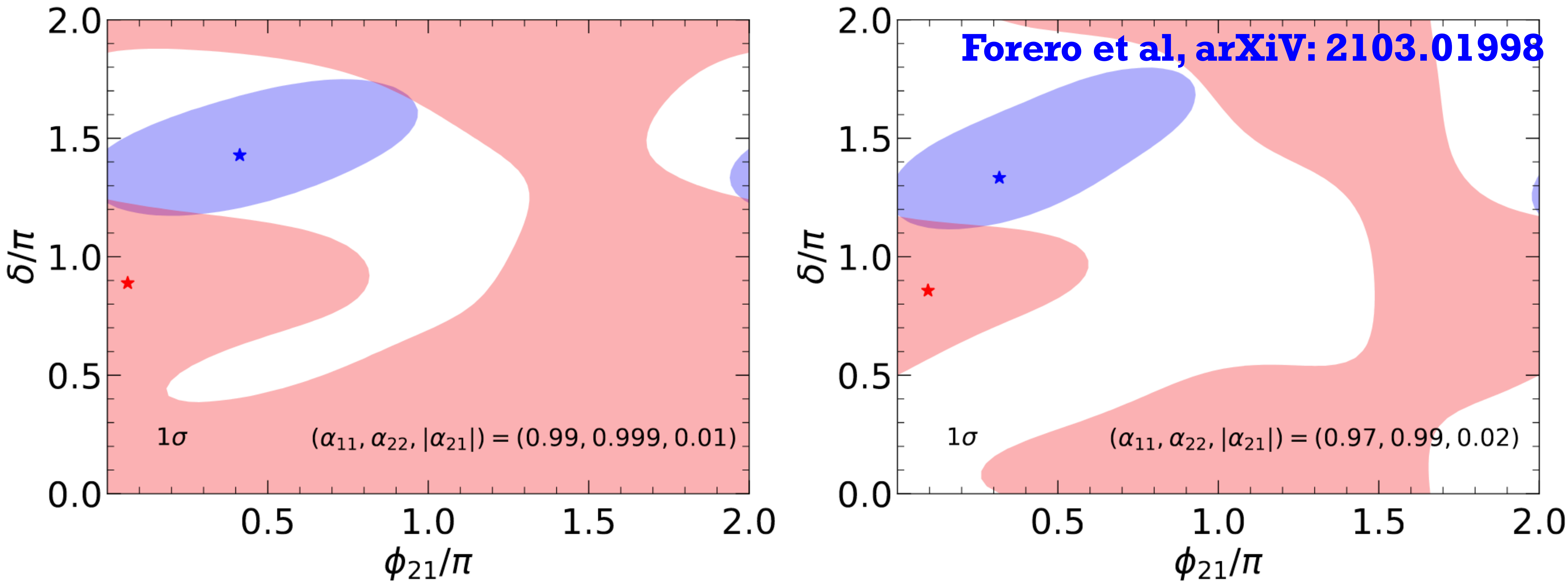
- the tension appears only in the $\bar{\nu}$ channel, with less sensitivity
- all values of δ and $\bar{\delta}$ remain allowed at $\sim 1\sigma$
- $\theta_{13} \neq \bar{\theta}_{13}$ can account for different behavior in neutrino and antineutrino channels

$\Rightarrow$ very poor sensitivity on CP violation compared to CPT-conserving scenario

Barenboim, Ternes, MT, JHEP2020

The T2K-NOvA δ_{CP} tension

Non-unitary mixing analysis of T2K and NOvA (normal ordering)



- NU includes additional sources of CP violation.
- No significant deviation from unitary mixing is found: updated bounds with LBL and SBL ⇒MINOS improves current neutrino limits!

⇒ The tension is not alleviated in the context of NU neutrino mixing

Summary

✦ Current status of three-neutrino oscillation parameters:

- ✓ very precise and robust determinations for most of them (1.3-10%)
- ✓ preference for $\theta_{23} > 45°$, 1st octant value disfavoured with $\Delta\chi^2 \geq 5.8$ (6.4)
- ✓ $\delta_{BF} = 1.08\pi$ (1.58π) for NO (IO) ; $\delta = \pi/2$ disfavored at 4.0σ (6.2σ)
- ✓ 2.5σ hint for normal ordering from atmospheric, LBL and reactor data

✦ Preliminary Super-K atmospheric data may change some results:

- ✓ degenerate octant solutions for θ_{23} : $\Delta\chi^2$ (1st octant) = 0.4 (3.1) for NO (IO)
- ✓ similar results for CP-violation, with $\delta=\pi/2$ disfavored at 4.2σ (6.4σ)
- ✓ preference for normal ordering reduced to 1.7σ

✦ By 2025/2026:

- ✓ oscillation parameters will be measured with 0.6-3% precision
- ✓ θ_{23} octant can be resolved at more than 3σ (for some values)
- ✓ $2\text{-}3\sigma$ sensitivity to CP violation at NOvA and T2K
- ✓ 3σ sensitivity to MO from reactor, accelerator and nu-telescopes

⇒ sensitivities above 3σ from a single experiment: DUNE, Hyper-Kamiokande

✦ New physics BSM may affect the current description of neutrino oscillations relaxing tensions or worsening the precision of measurements.