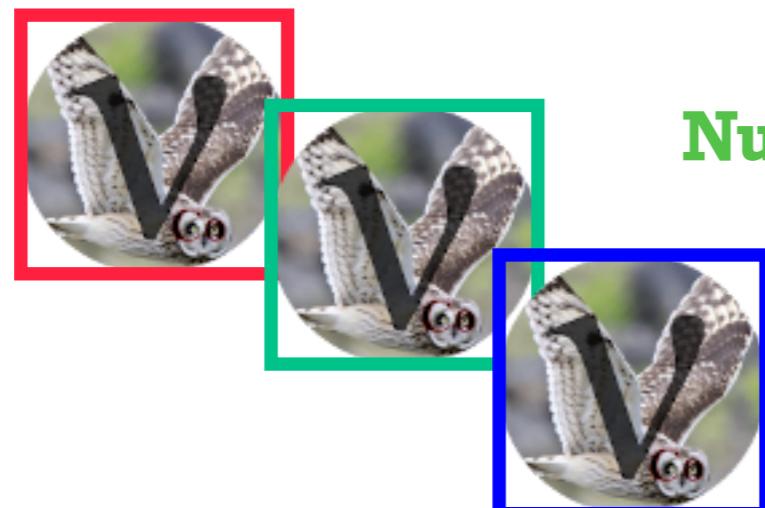


# A global overview of the three-neutrino oscillation picture

Mariam Tórtola  
IFIC, CSIC/Universitat de València



NuCo 2021: Neutrinos en Colombia  
30 Julio, 2021

# 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

## ♦ Beyond the standard three-neutrino scenario:

- ⇒ can BSM physics improve oscillation fits?

# The three-flavour $\nu$ picture

## neutrino mixing

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

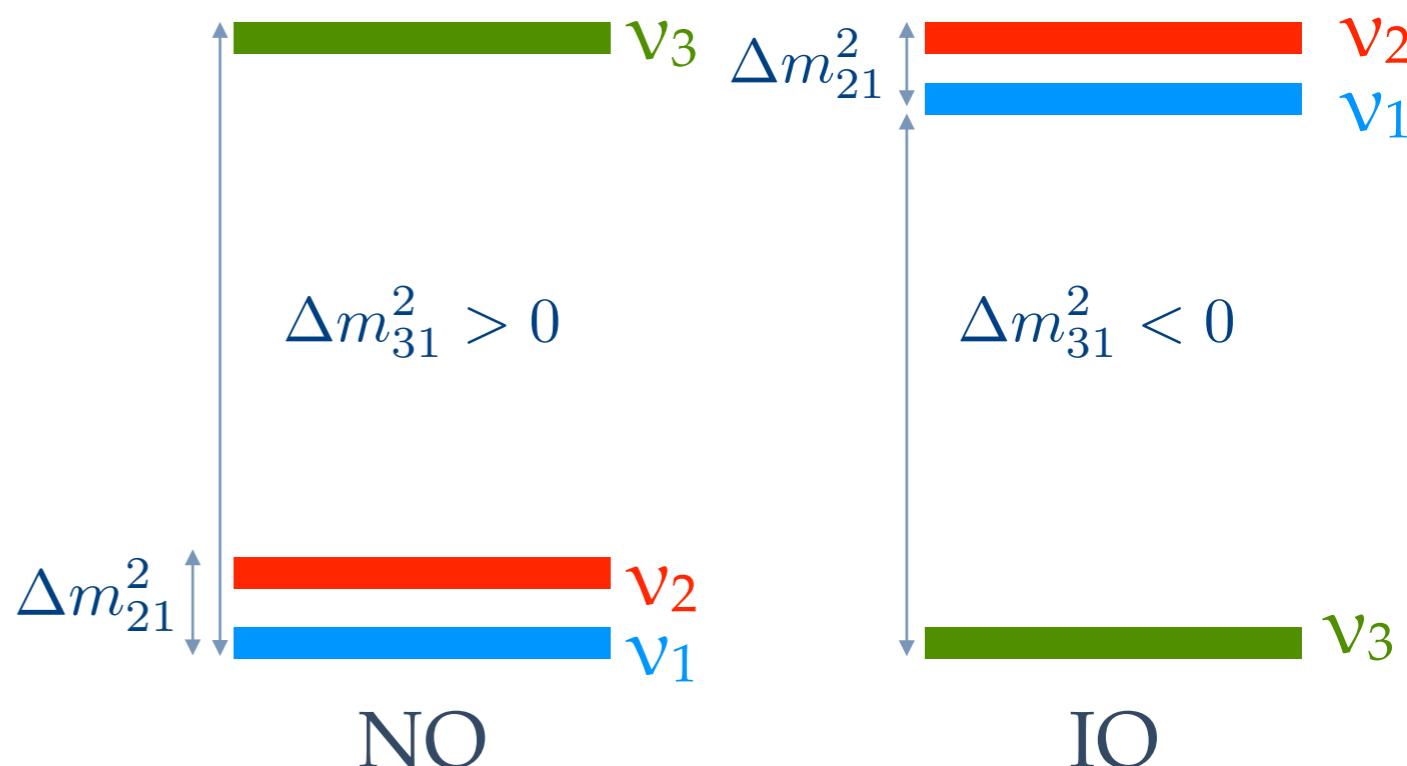
- ✓ 3 mixing angles:  $\theta_{12}, \theta_{23}, \theta_{13}$
- ✓ 3 CP phases: 1 Dirac + 2 Majorana
- ✓ 3 masses:  $m_1, m_2, m_3$

⇒ absolute neutrino mass:  $m_0$

⇒ two mass splittings:

$$\Delta m_{21}^2, \Delta m_{31}^2$$

## 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

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

# Experimental data

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

solar  
sector

Cl, Ga, SK

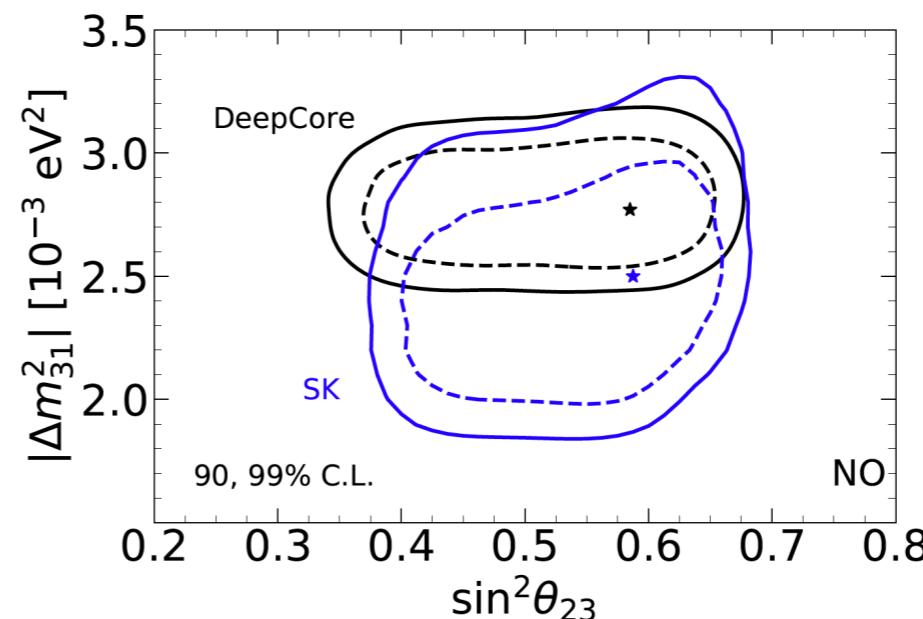
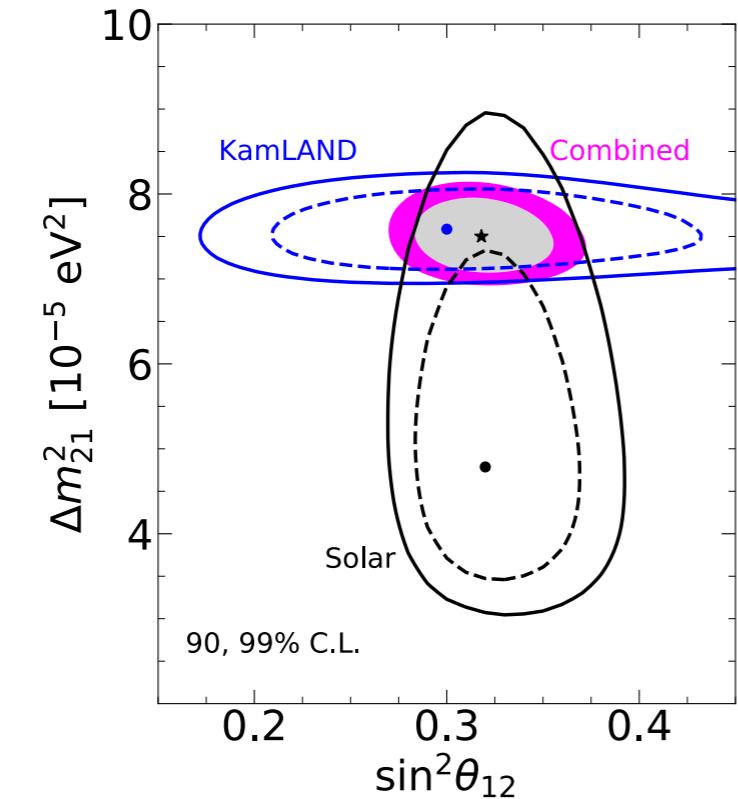
SNO, Borexino

KamLAND

SBL  
reactors

Daya Bay

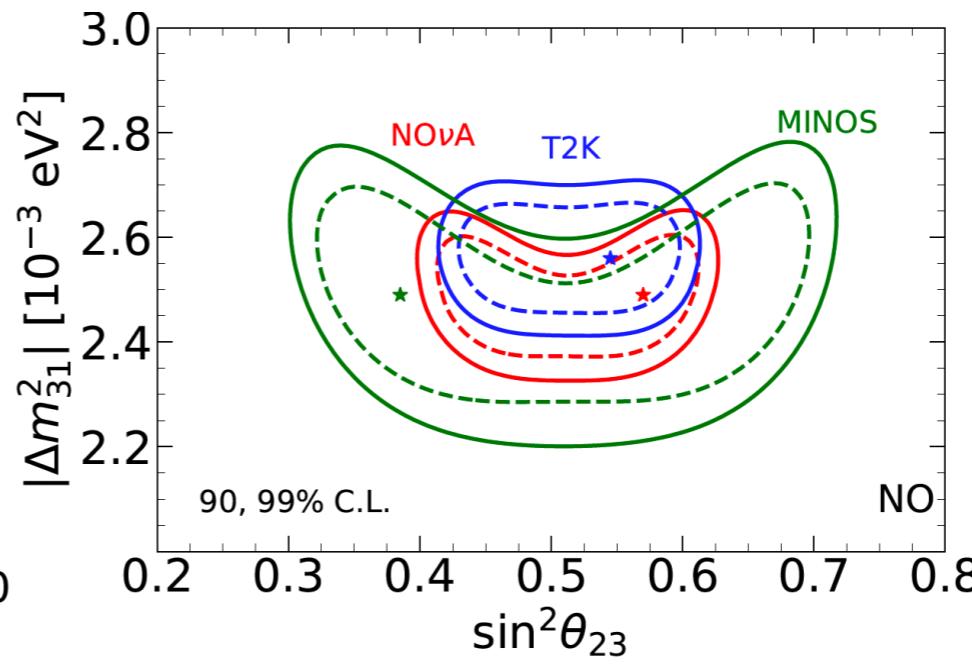
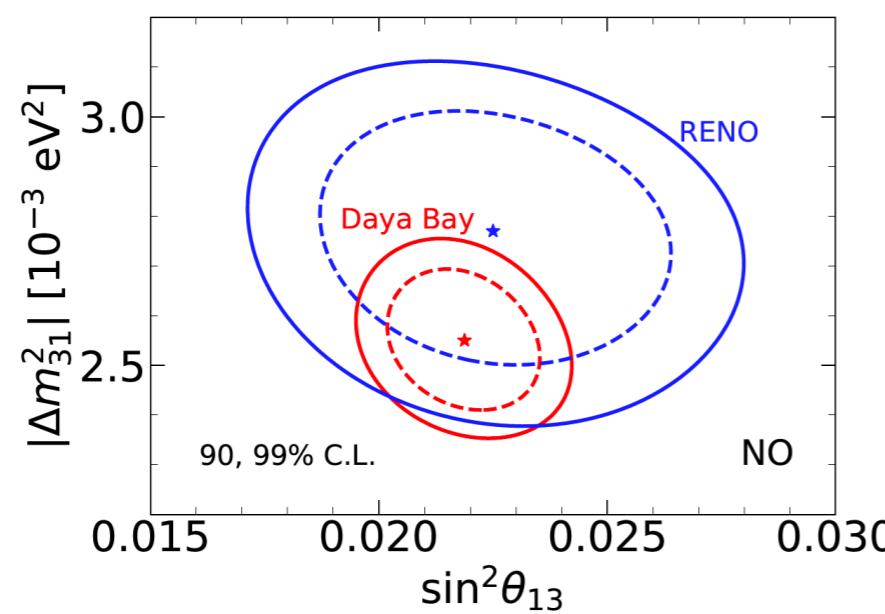
RENO



atmospheric  
results

Super-K

IC-DeepCore



LBL  
experiments

MINOS

T2K

NOvA

# Neutrino oscillation parameters

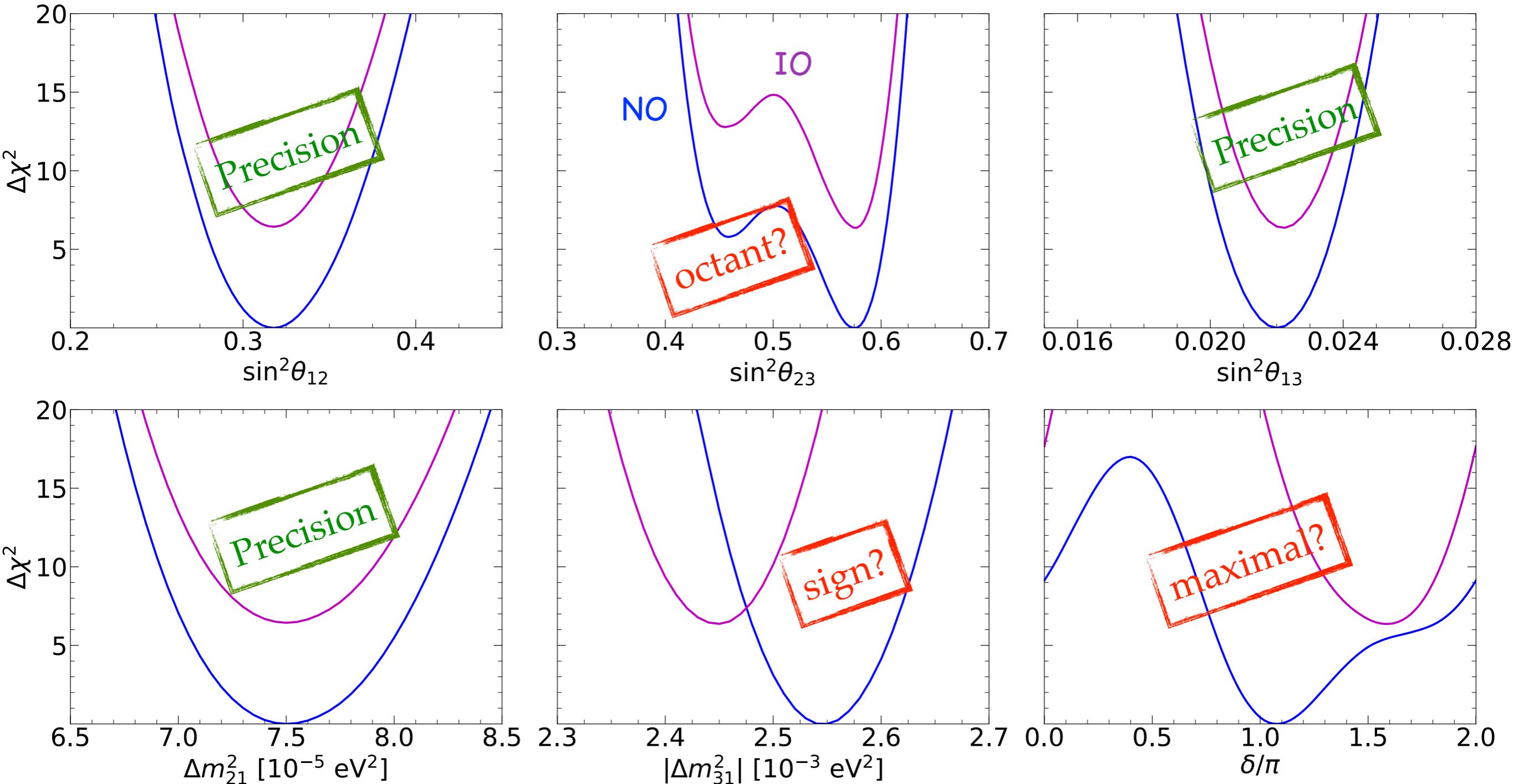
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]

See also  
NuFIT and  
Bari group  
analysis

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

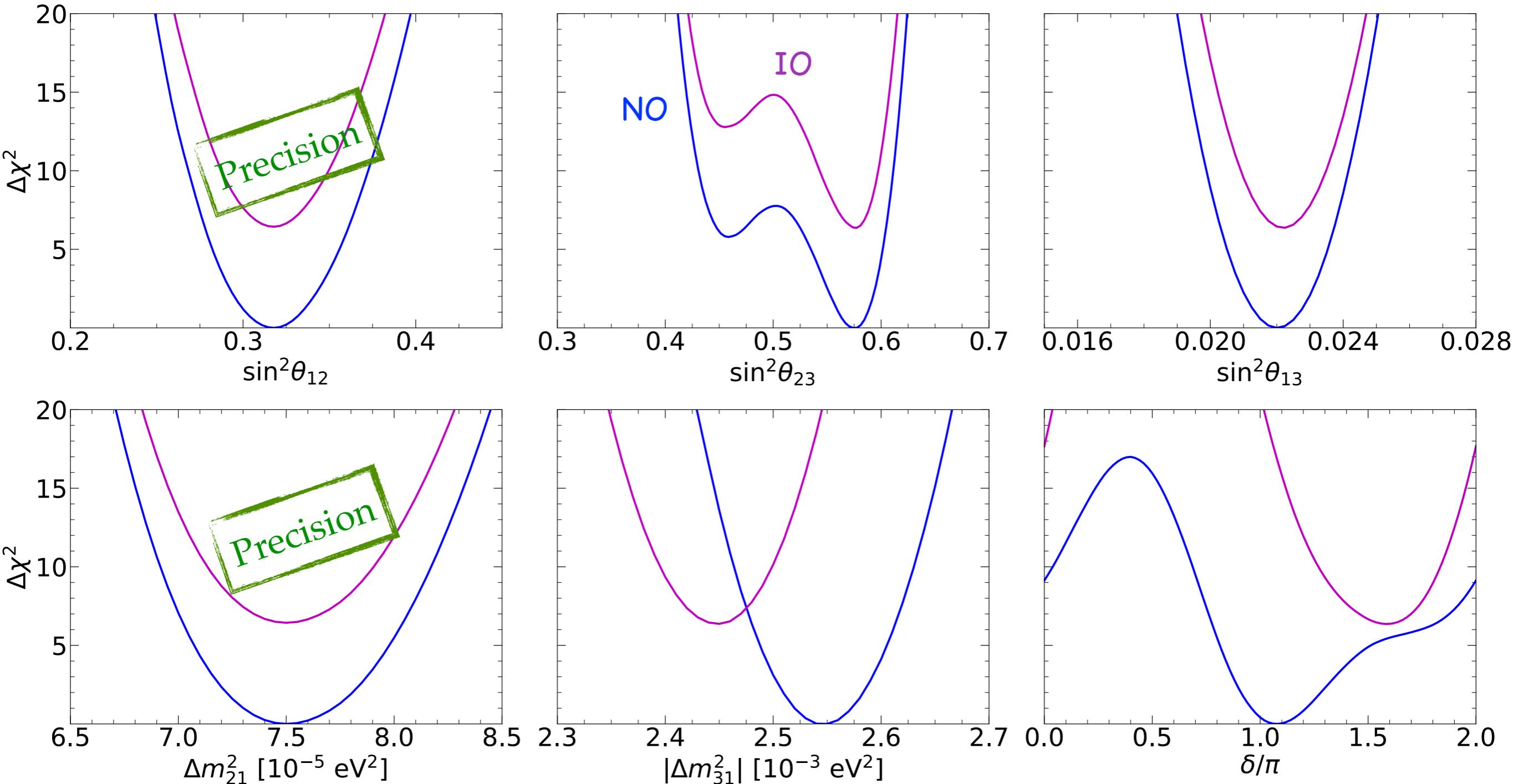
# Global fit to ν oscillation parameters

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



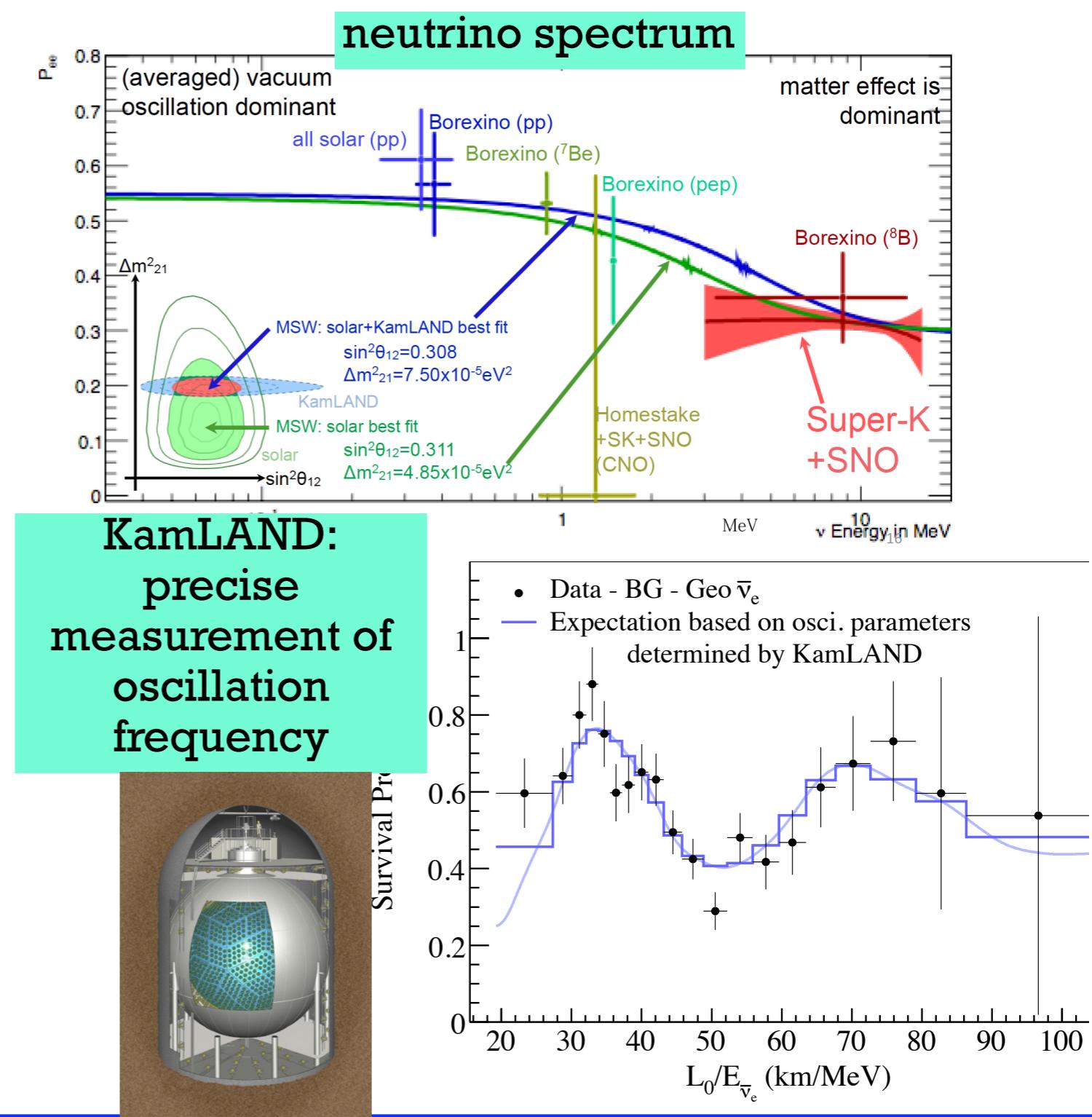
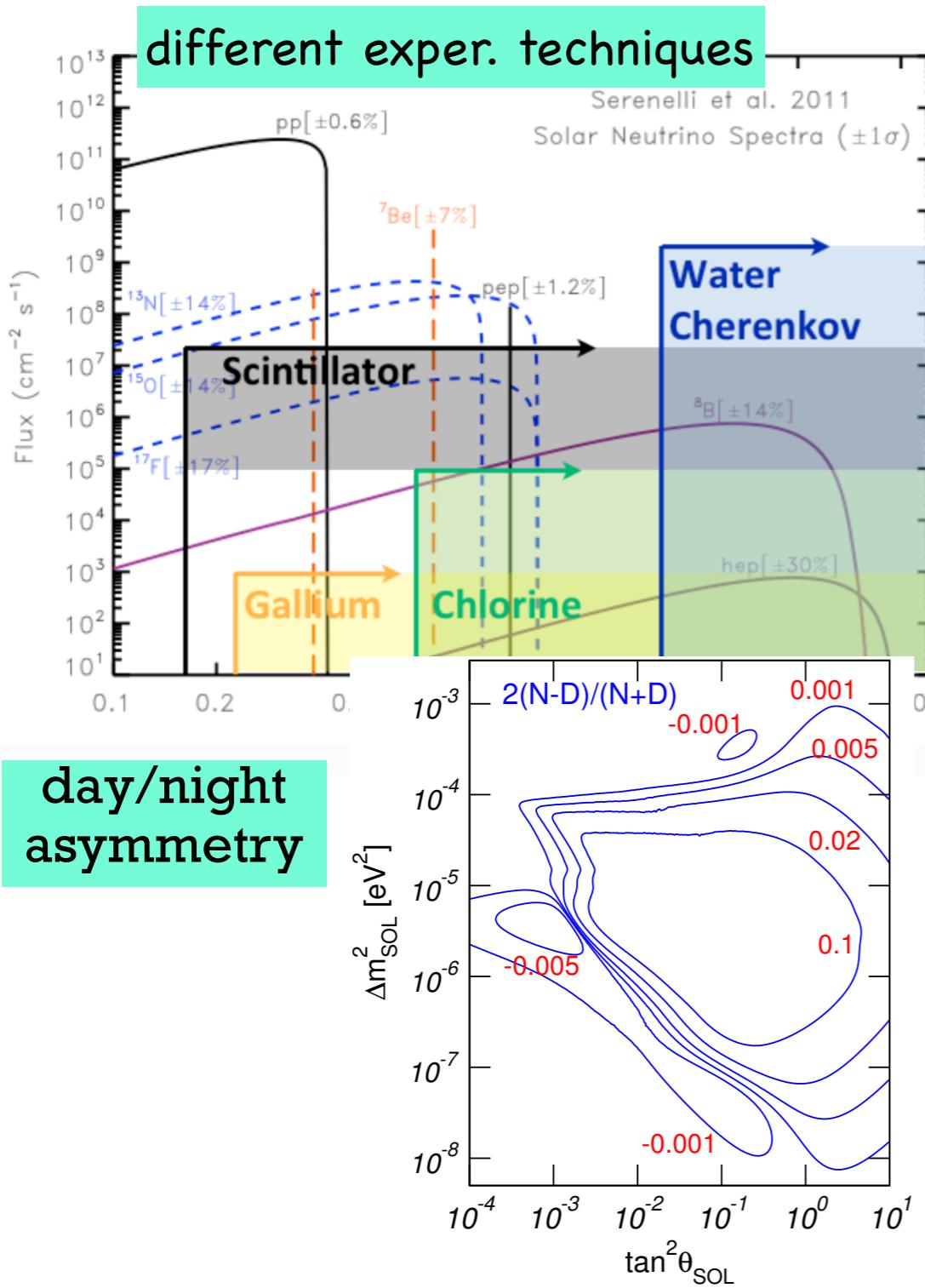
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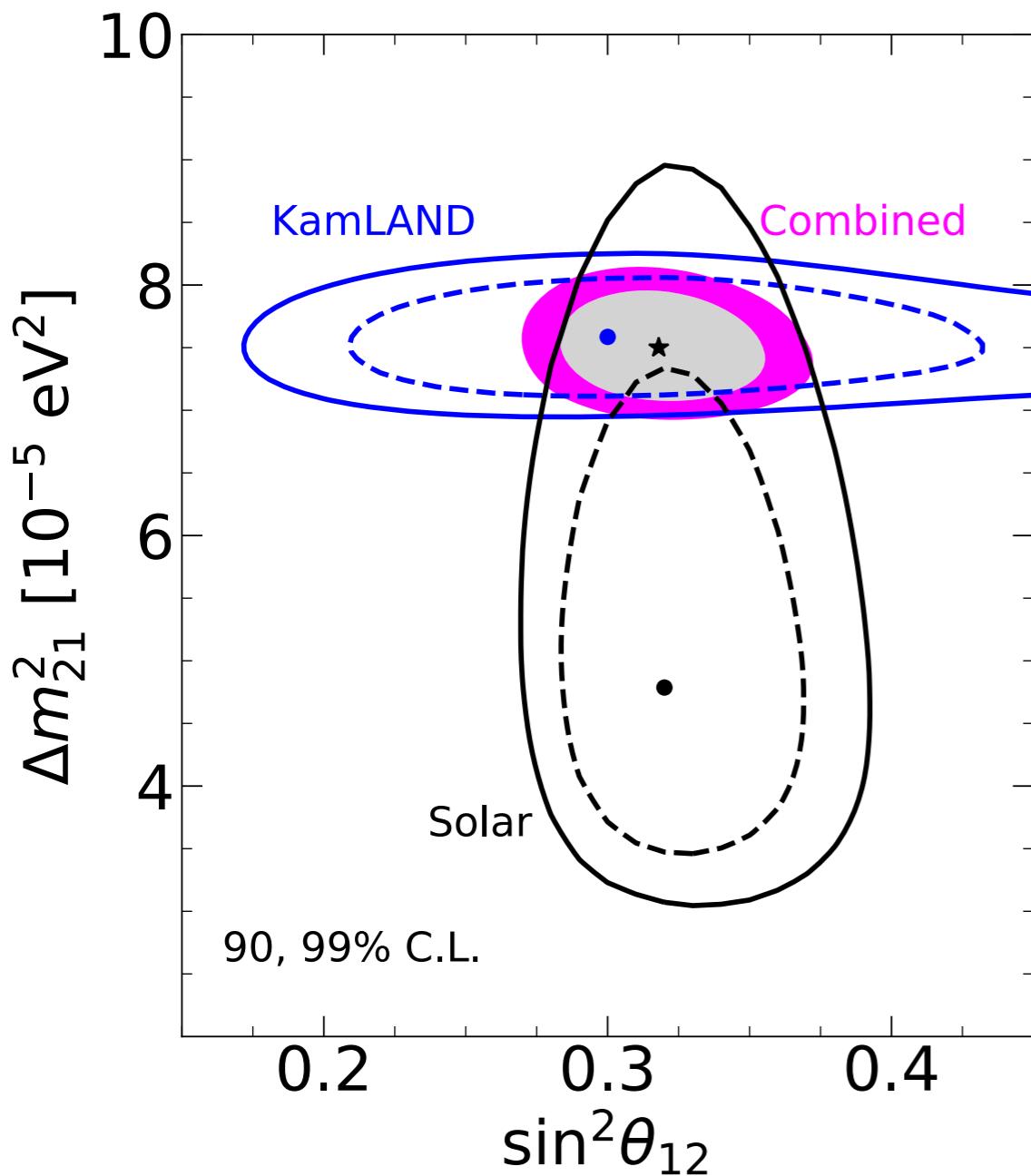


# The solar sector

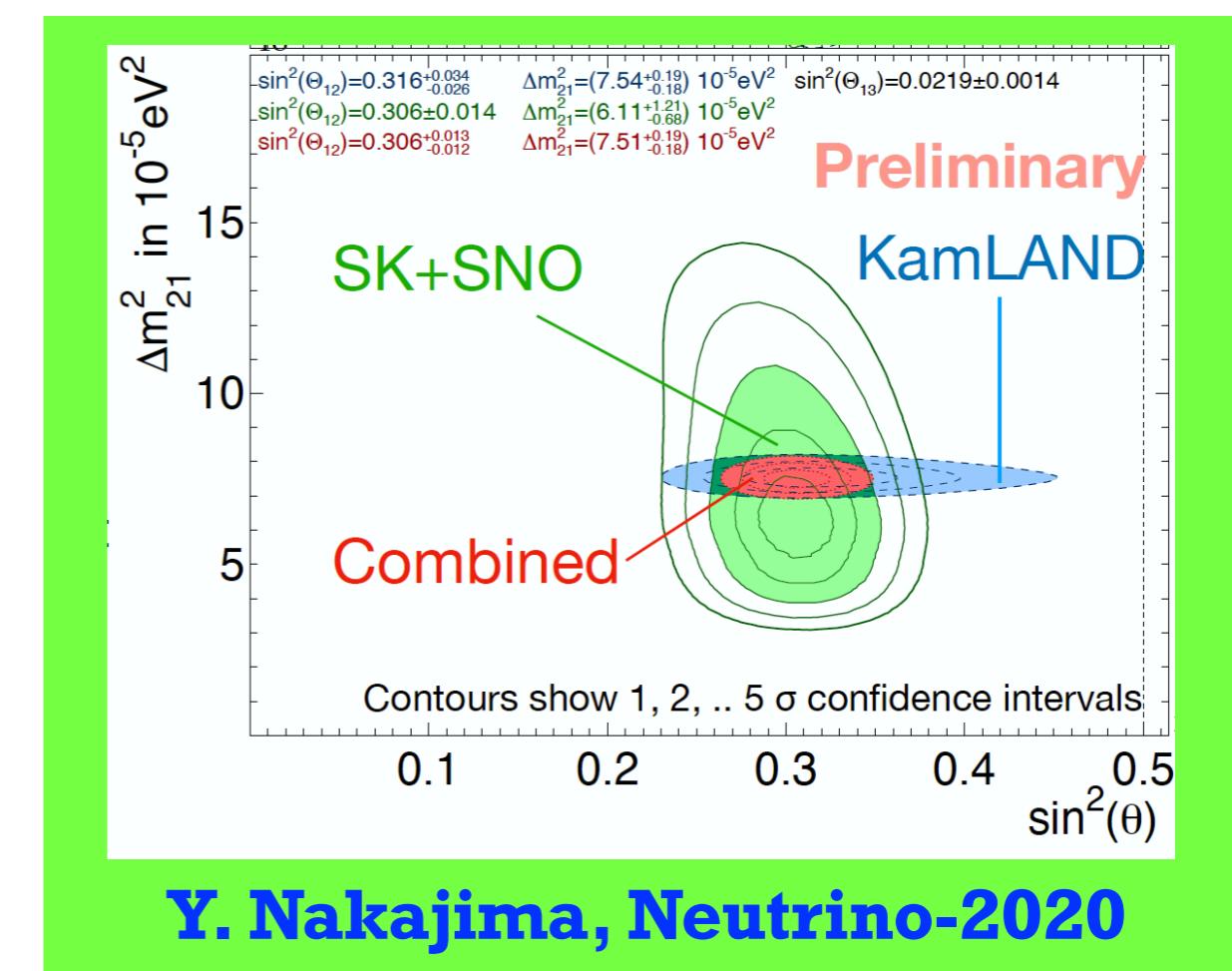
Solar experiments have measured neutrino disappearance for  $\sim 50$  years



# The solar sector



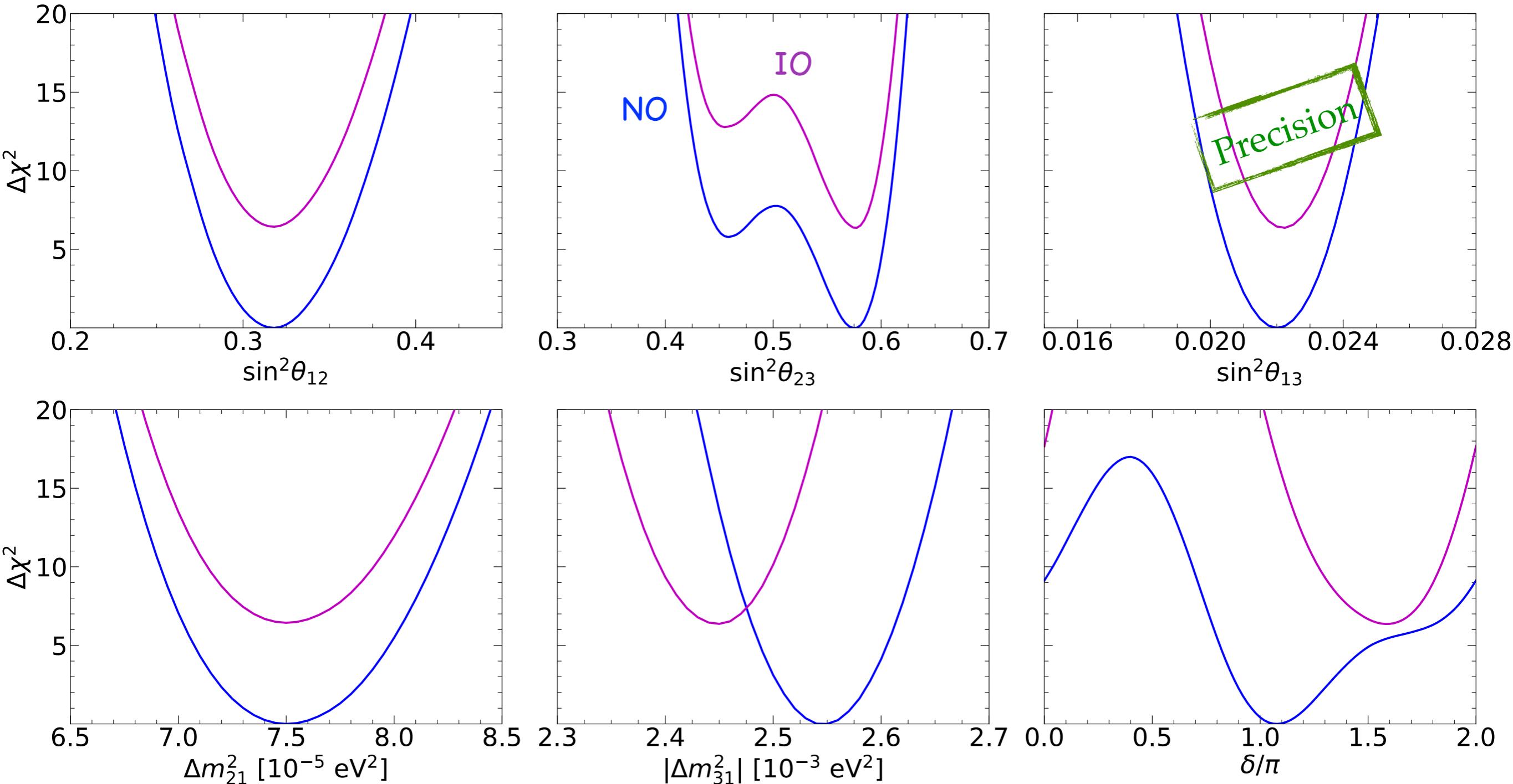
- ◆  $\theta_{12}$  measurement is dominated by solar neutrino data
- ◆  $\Delta m^2_{21}$  is better measured by KamLAND.
- ◆ **2 $\sigma$  mismatch** between the values of  $\Delta m^2_{21}$  measured by solar and KamLAND



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

# Global fit to ν oscillation parameters

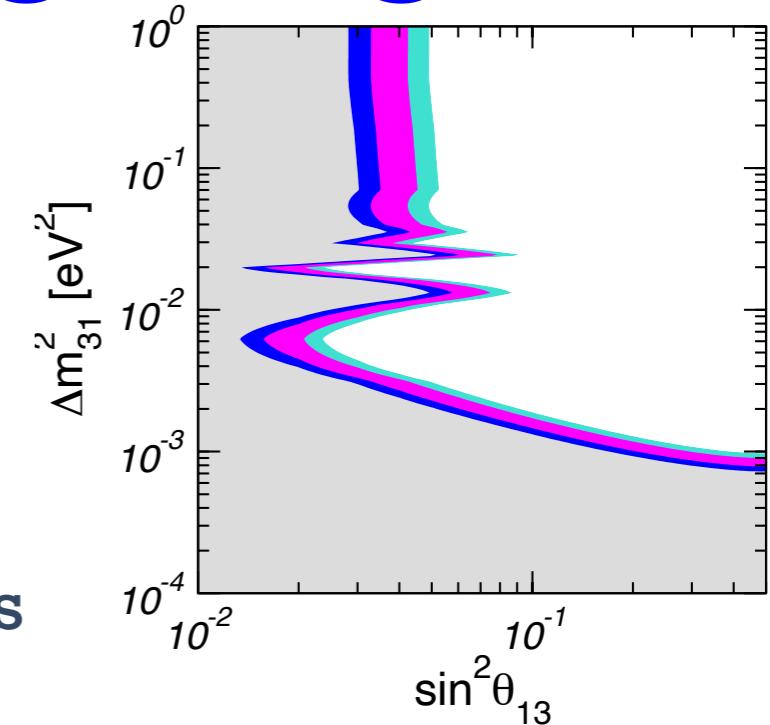
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



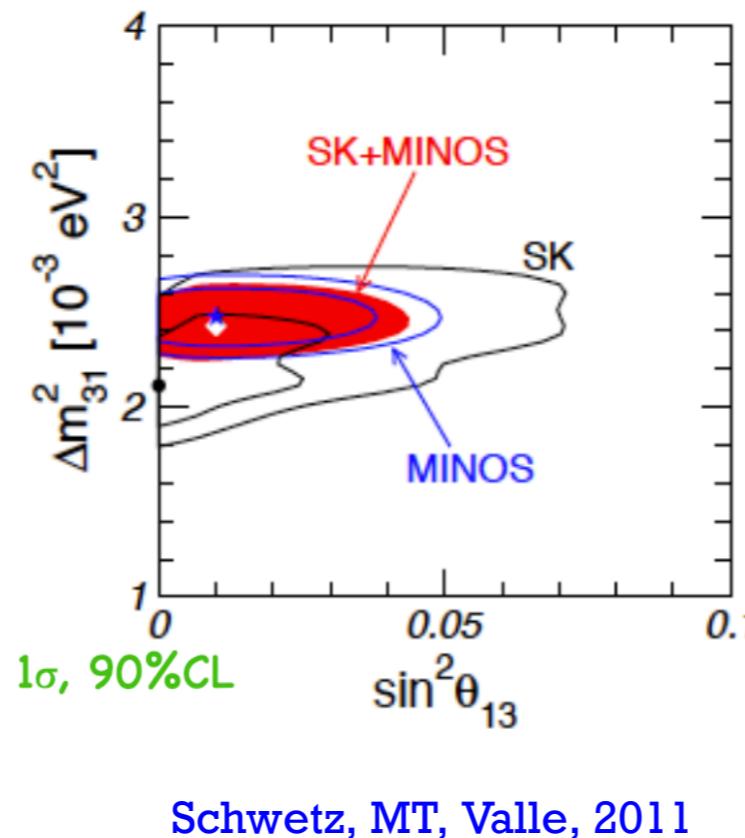
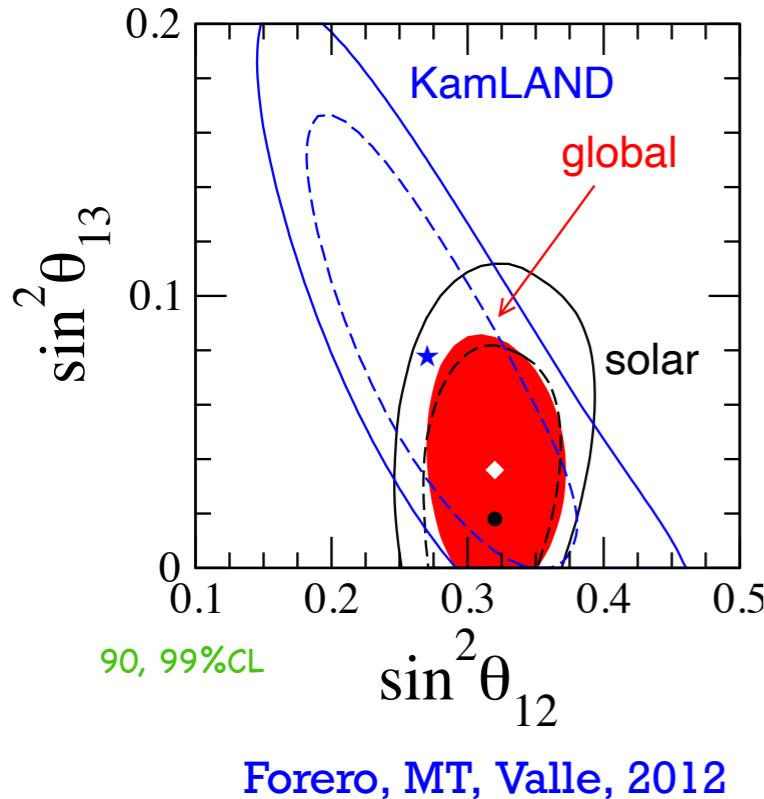
# The reactor mixing angle

- ◆ Searches for  $\theta_{13}$  at reactor experiments (CHOOZ, Palo Verde)

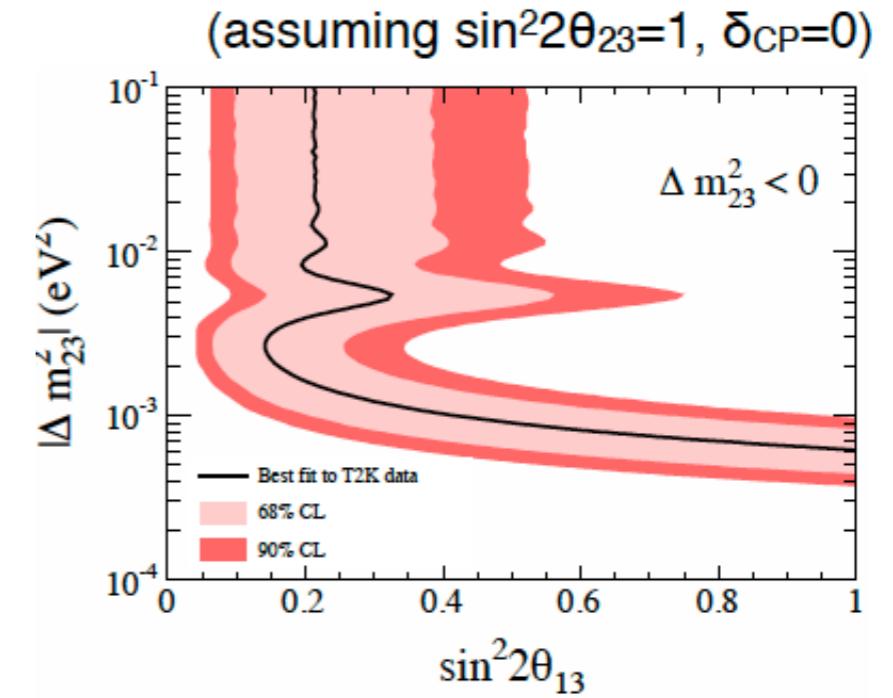
For  $\Delta m_{31}^2 = 2.5 \cdot 10^{-3} \text{ eV}^2$   
 $\Rightarrow \sin^2 \theta_{13} < 0.039$  (90%CL)



- ◆ Hints on  $\theta_{13} \neq 0$  from tensions in combined analyses



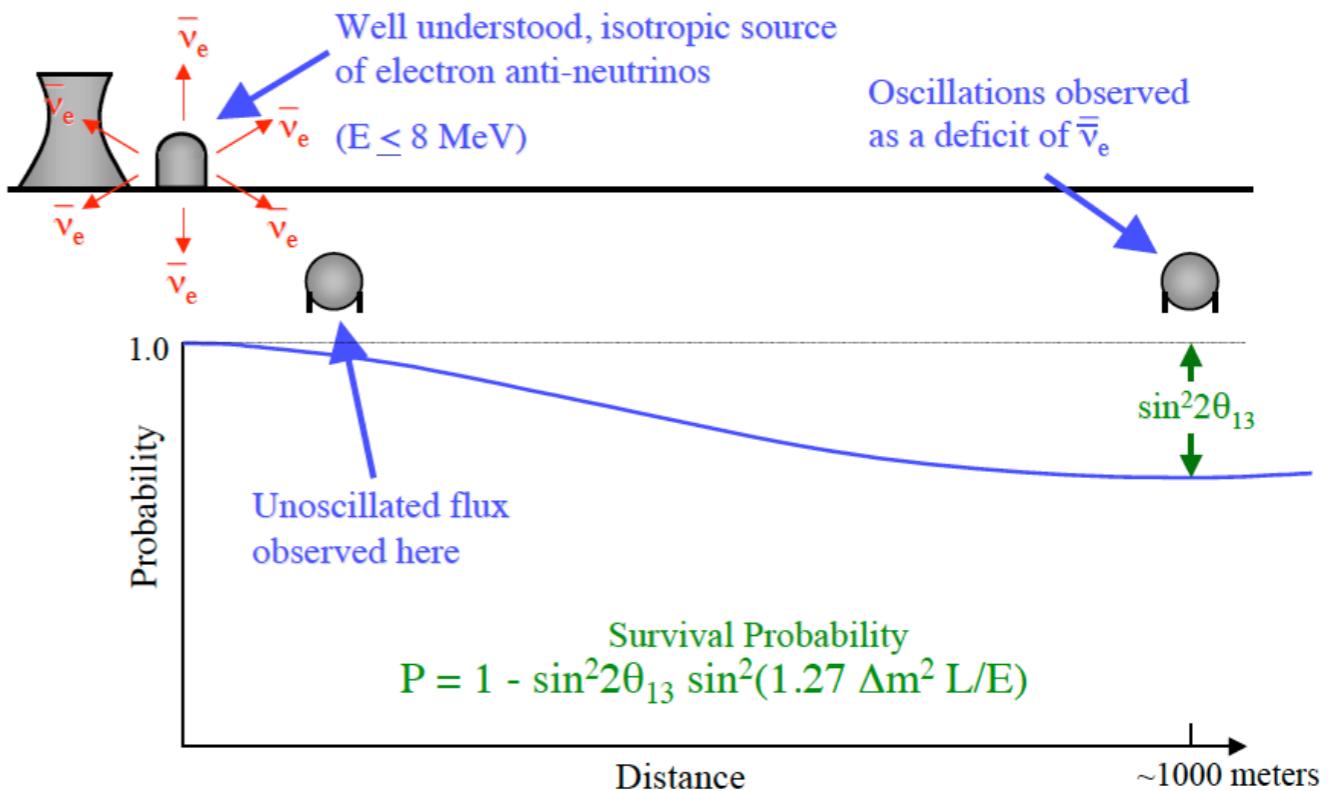
- ◆ First evidence for  $\nu_e$  app in T2K



# The reactor sector

## New generation of SBL reactor experiments

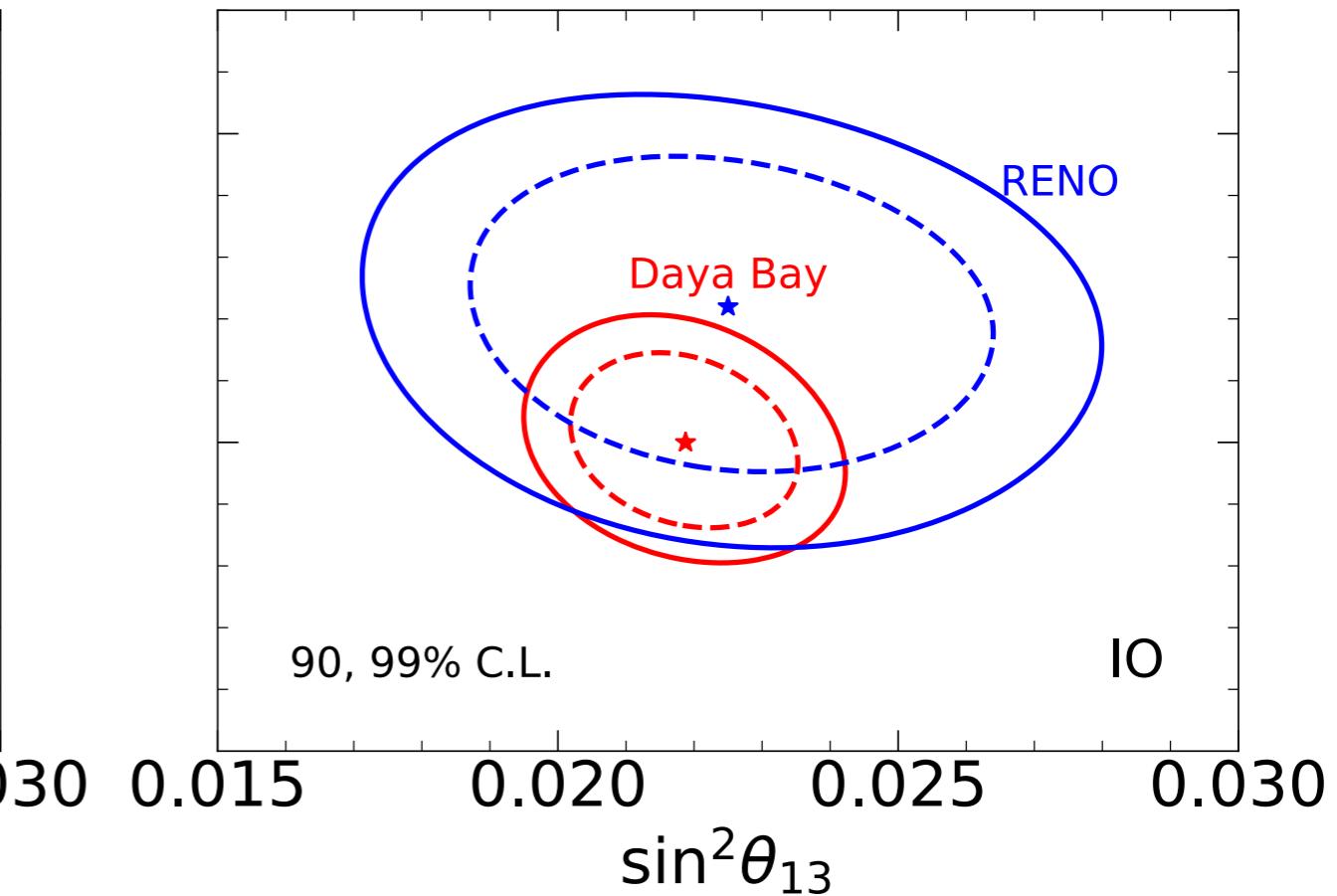
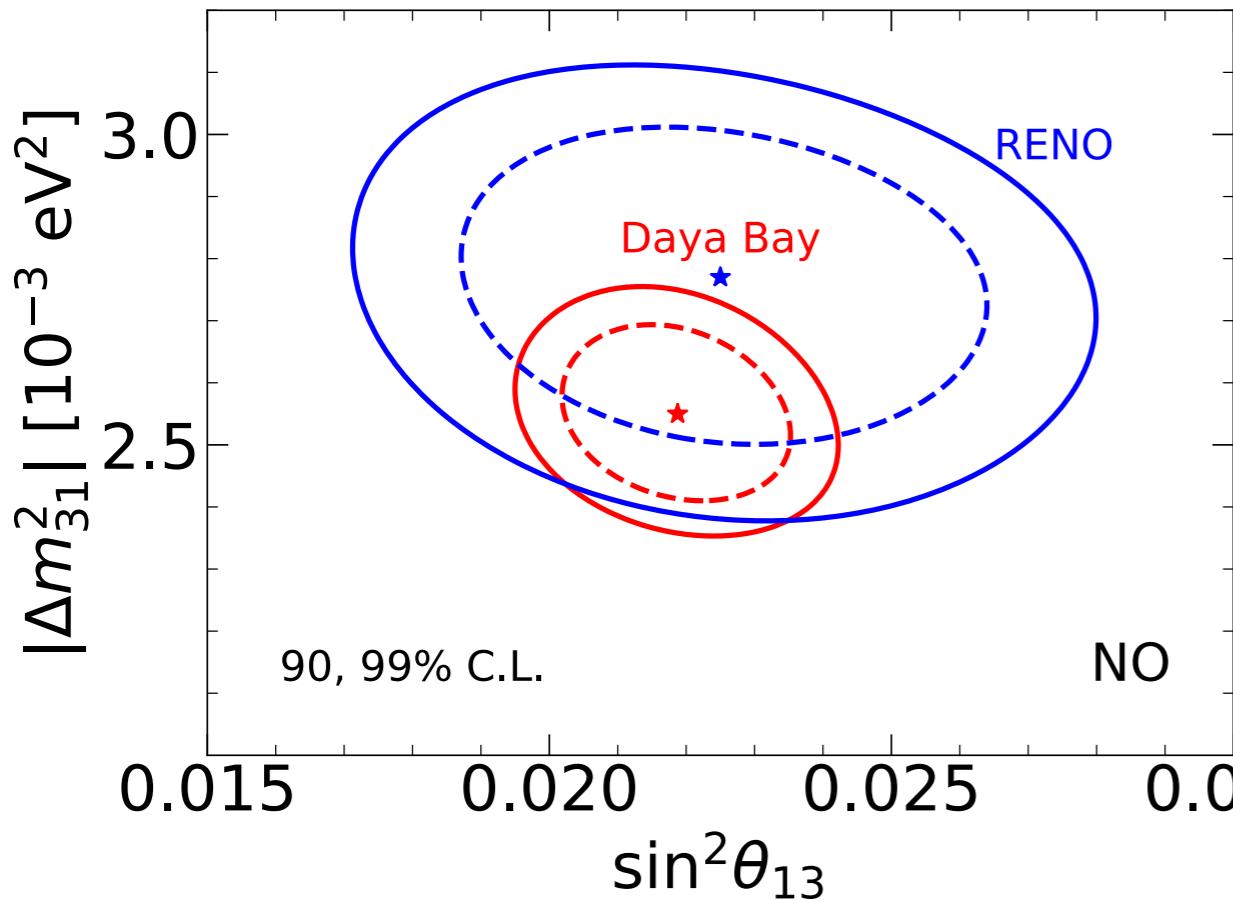
- ◆ more powerful reactors
- ◆ larger detector volume
- ◆ 2-8 detectors at 100 m – 1 km



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]



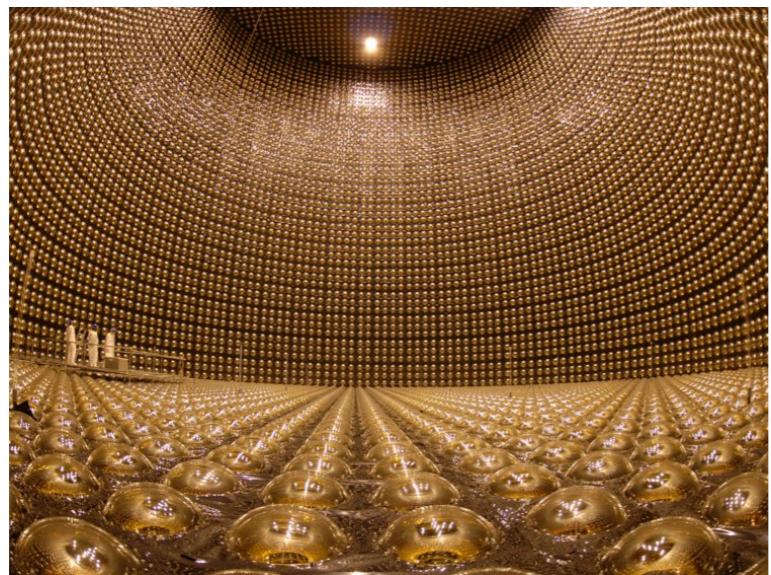
- ◆ Daya Bay: 1958-day data:  $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$  (3.4%)
- ◆ RENO: 2900-day data:  $\sin^2 2\theta_{13} = 0.0892 \pm 0.0063$  (7%)

Precision dominated by Daya Bay

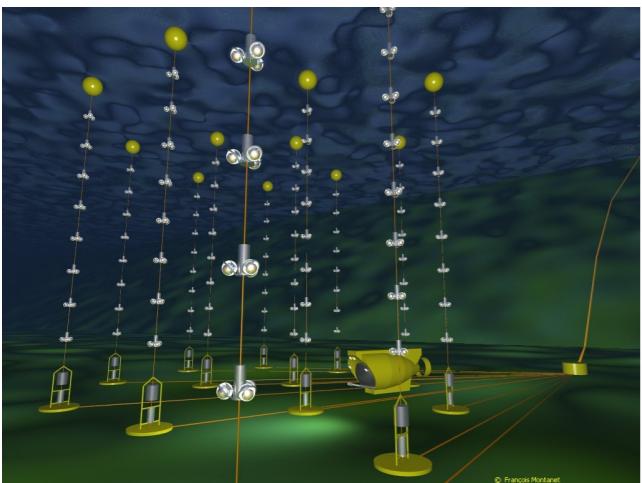
# The atmospheric sector

## Atmospheric experiments

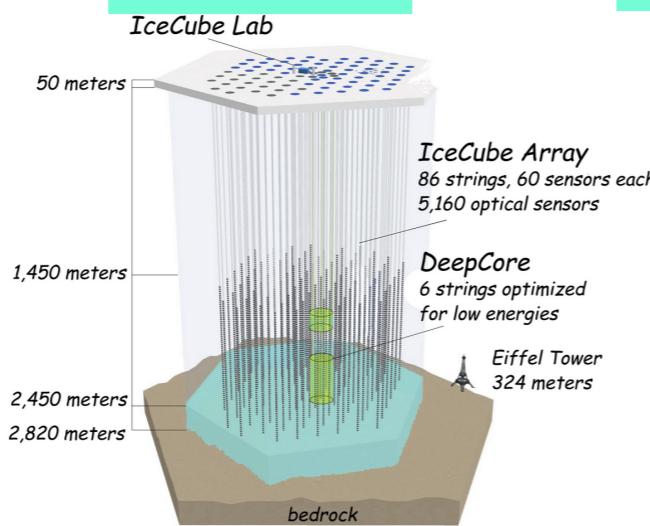
Super-Kamiokande



ANTARES

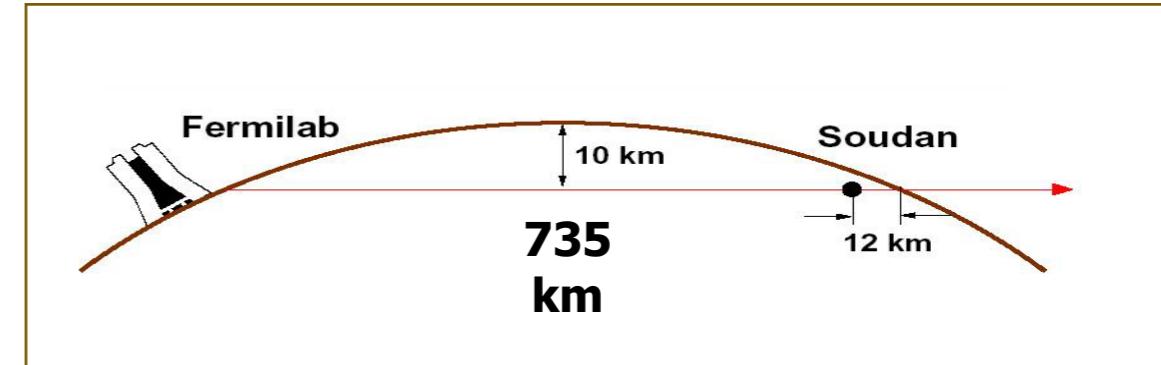


IceCube

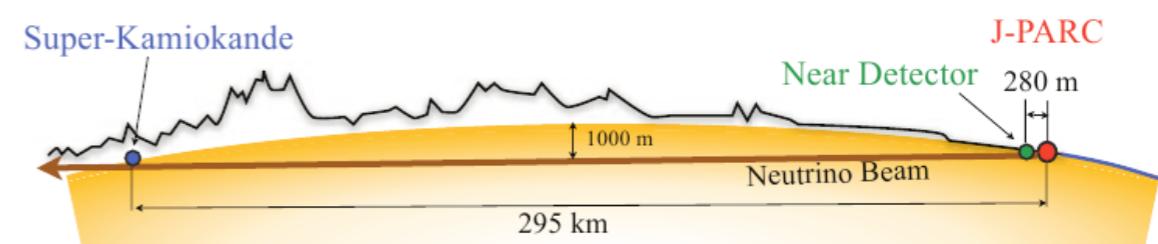


## Accelerator long-baseline experiments

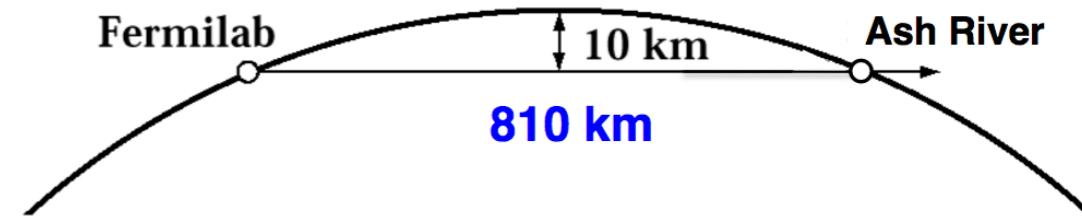
MINOS



T2K

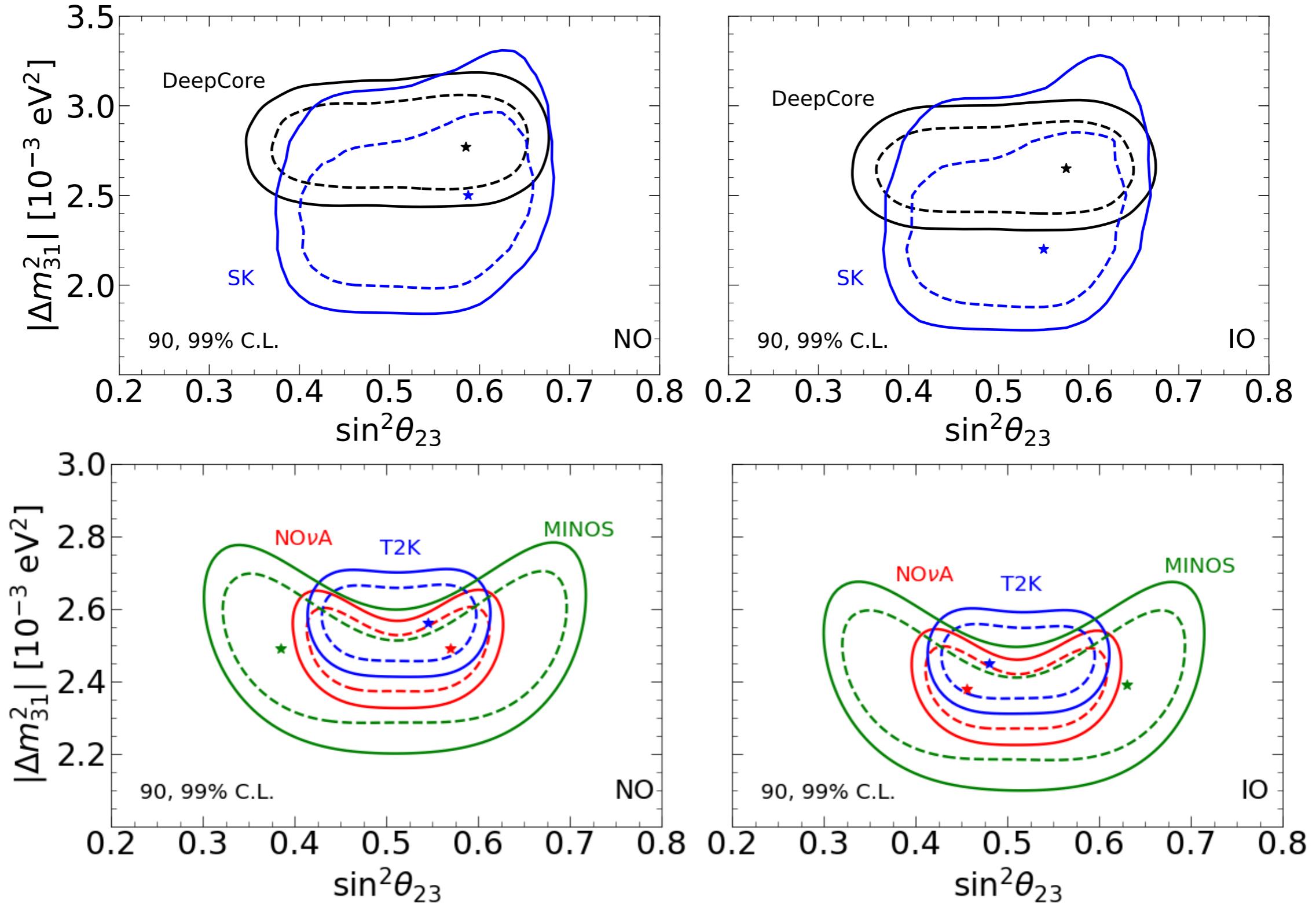


NOvA



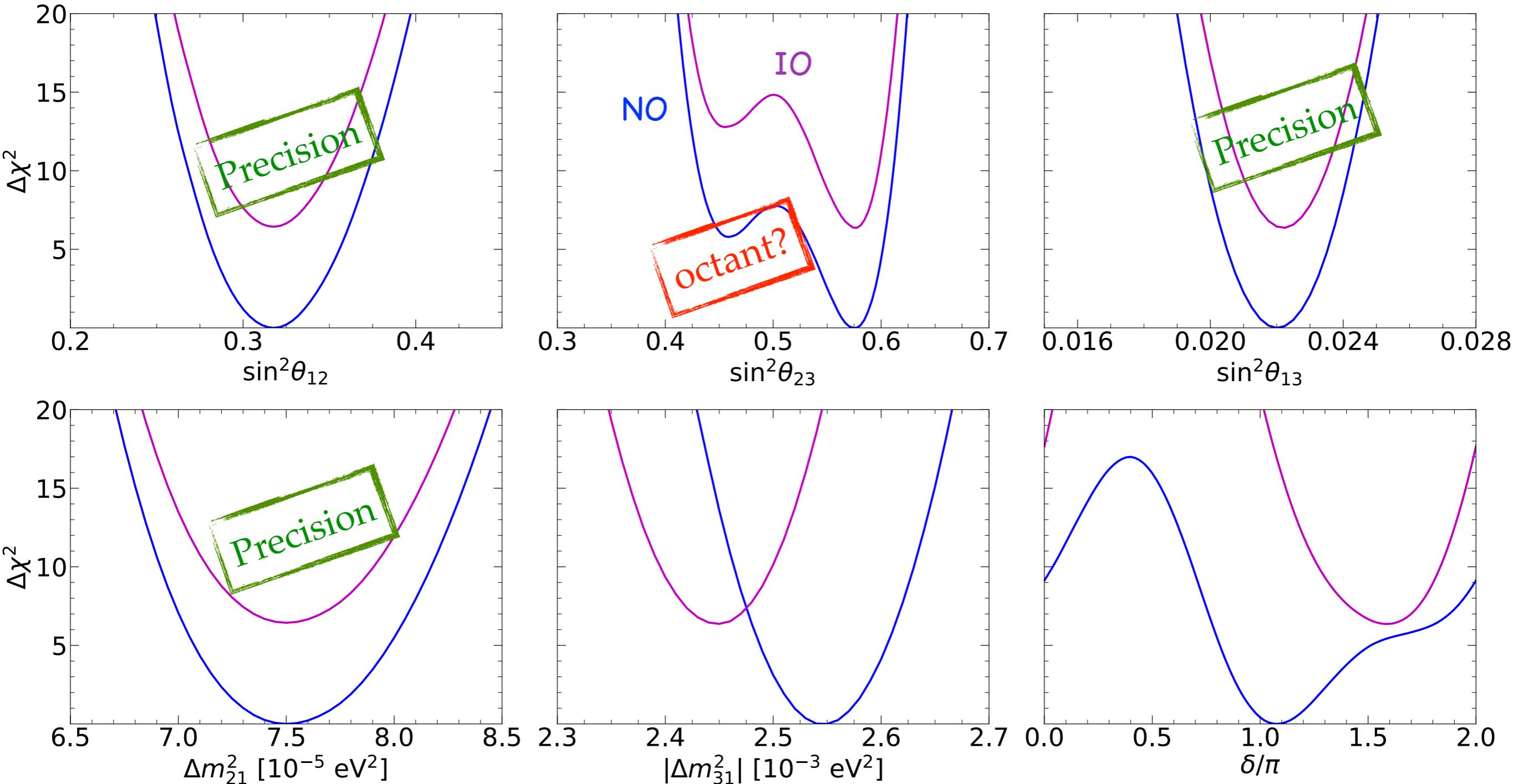
- consistent with atmospheric data
- atm  $\nu$  oscillations confirmed by lab exps

# The atmospheric sector



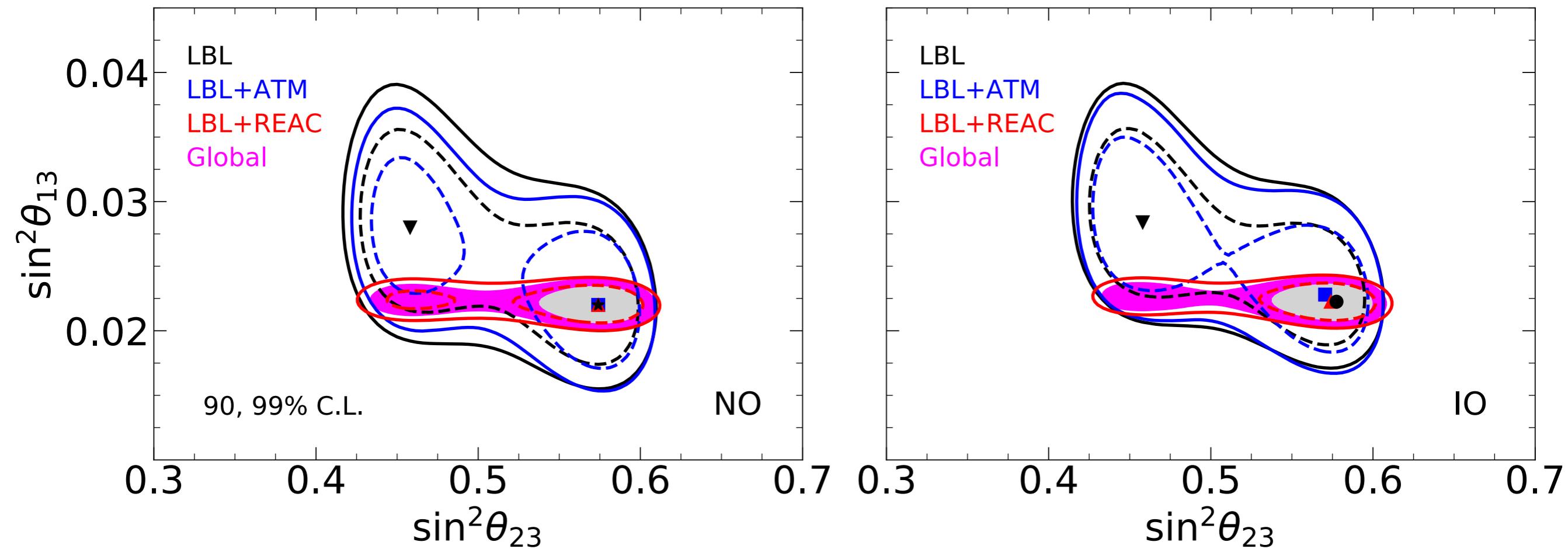
# Global fit to ν oscillation parameters

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



# The octant of $\theta_{23}$

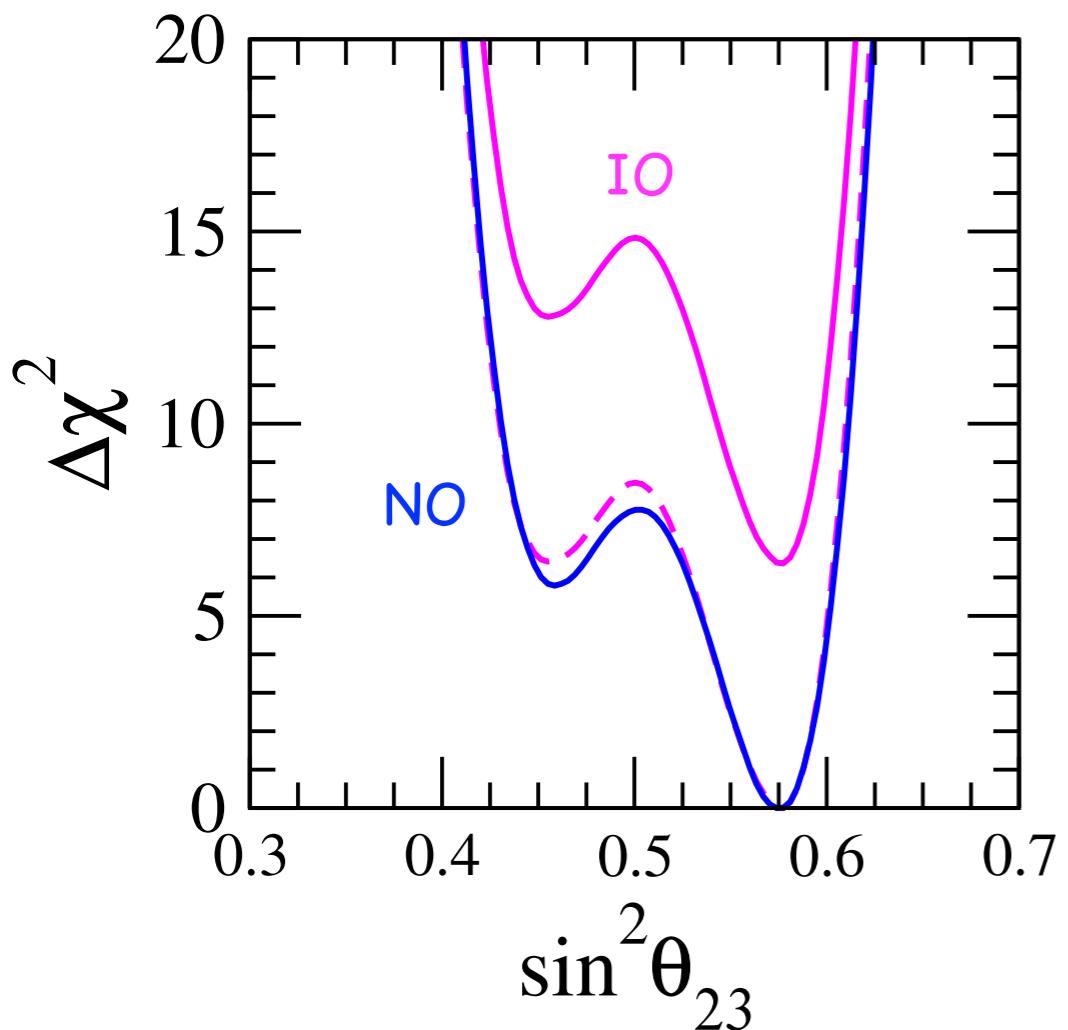
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



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

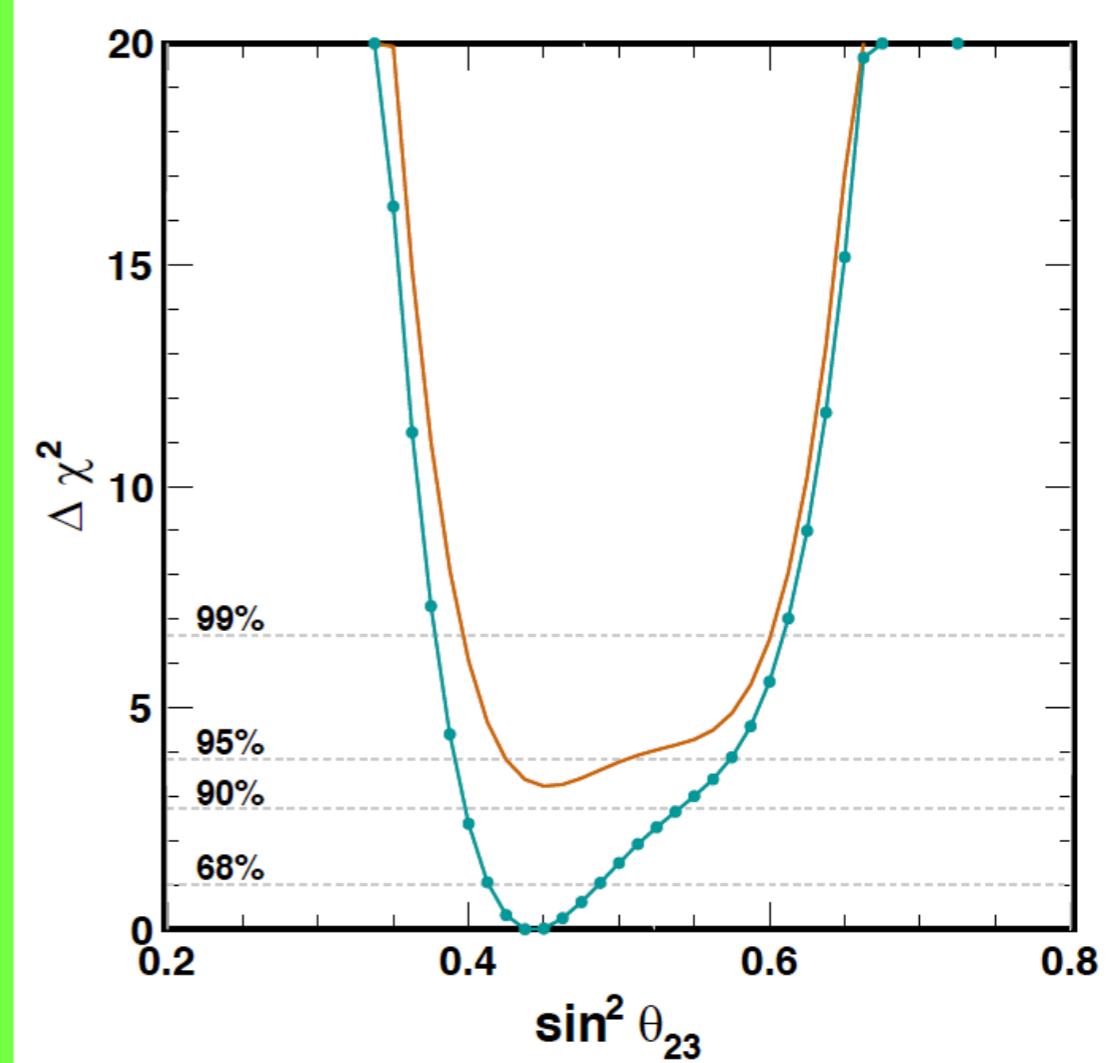
# The octant of $\theta_{23}$

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

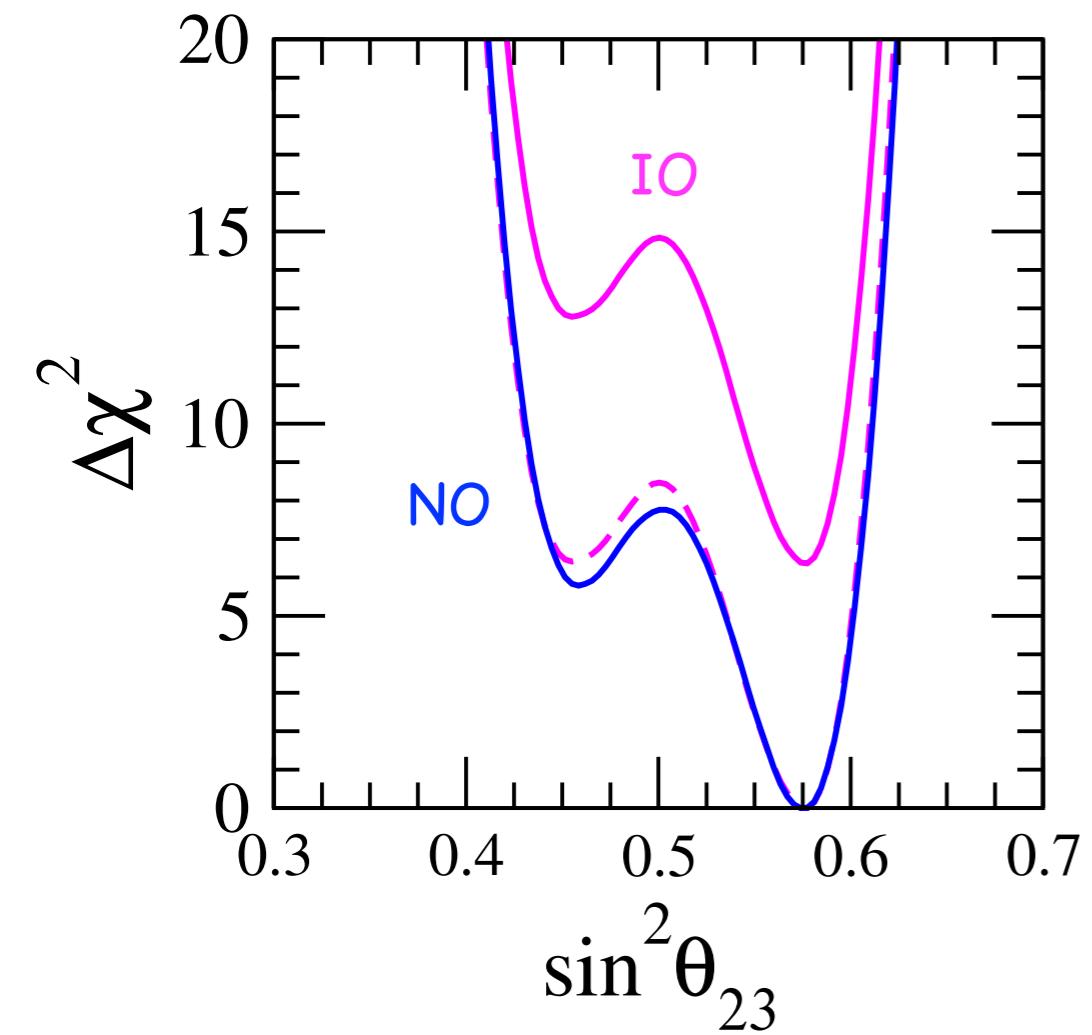


Y. Nakajima, Neutrino 2020

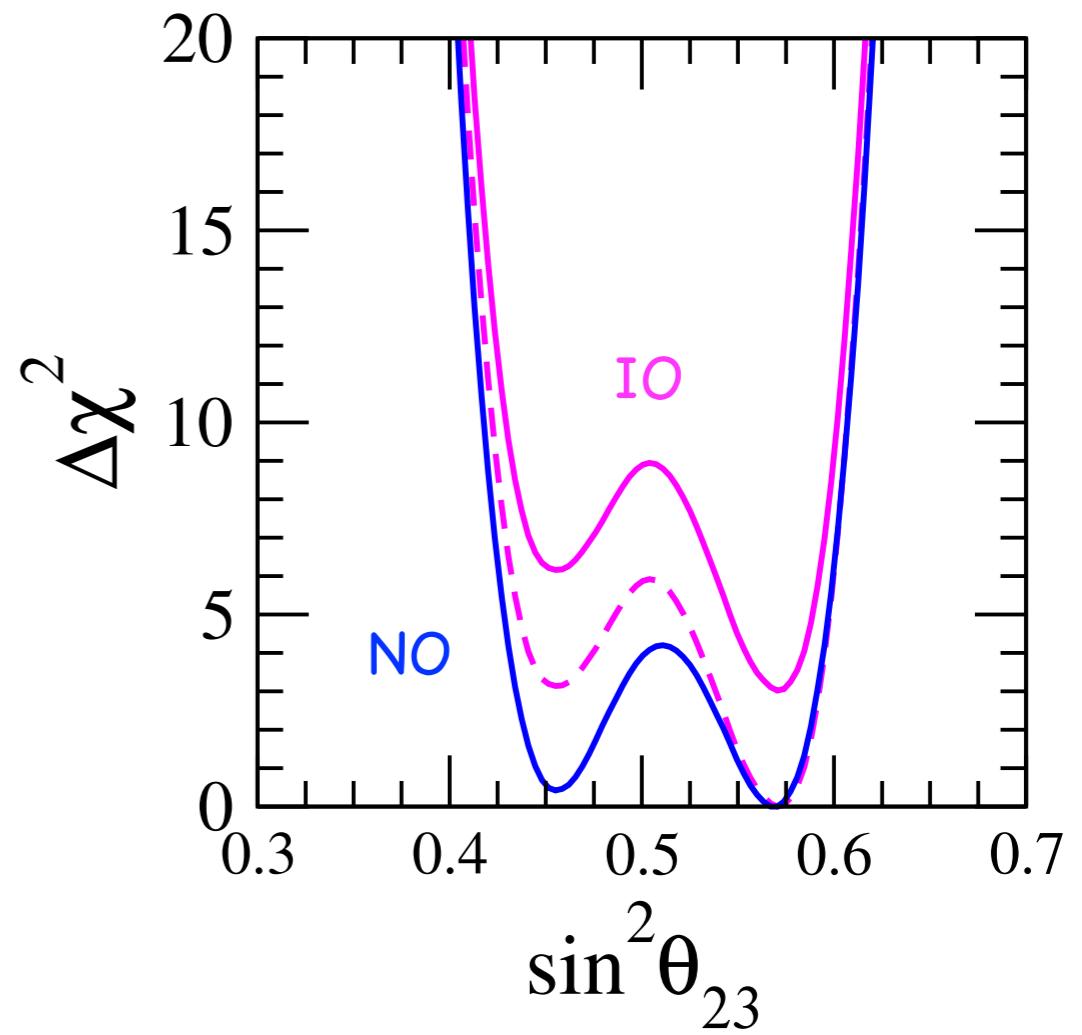
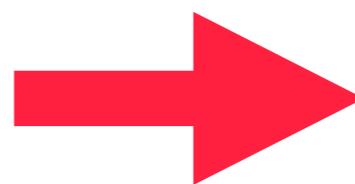
# The octant of $\theta_{23}$

de Salas et al, JHEP 02 (2021) 071

de Salas et al, preliminary



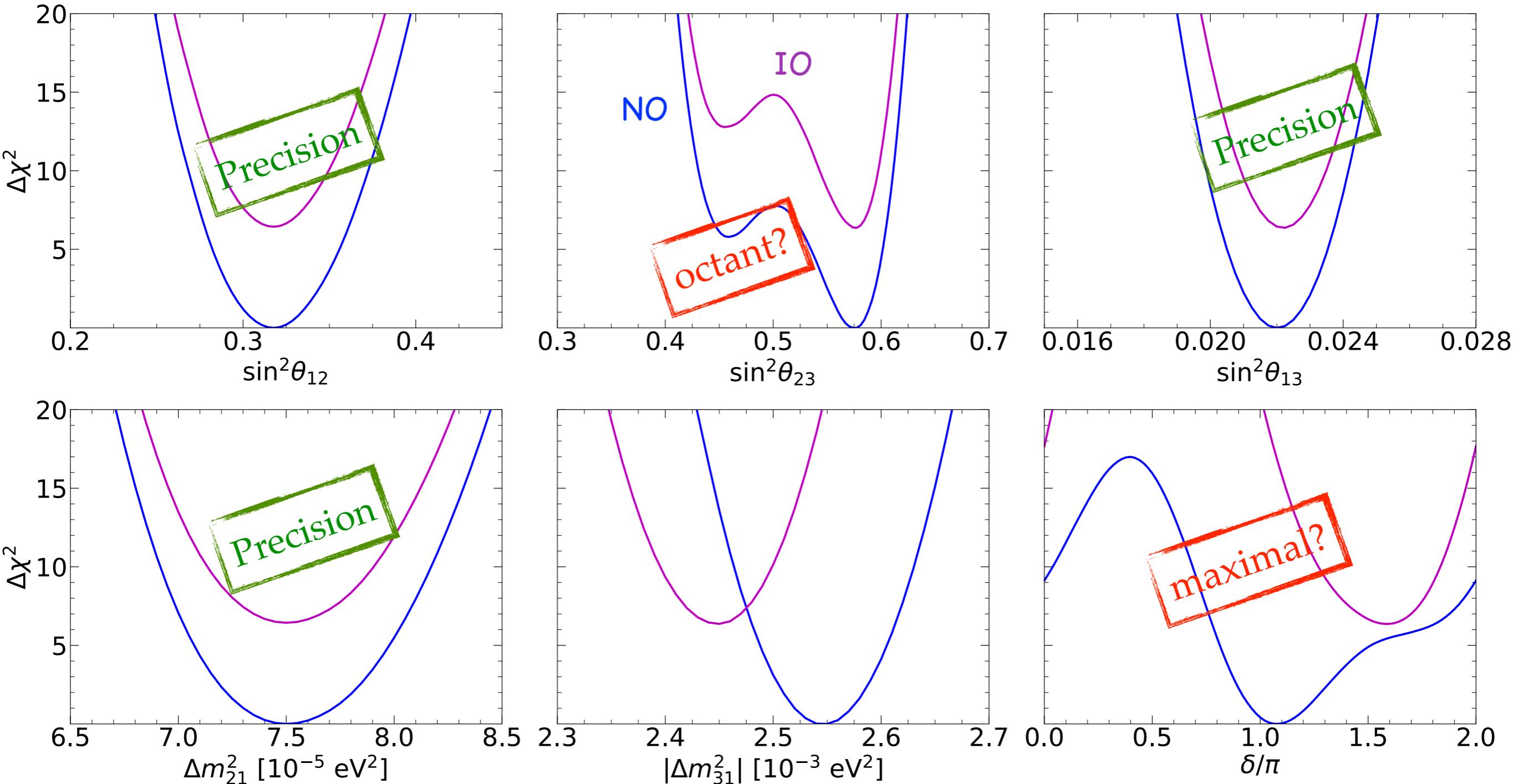
Values at the 1st octant disfavored  
with  $\Delta\chi^2 \geq 5.8$  (6.4) for NO (IO)



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

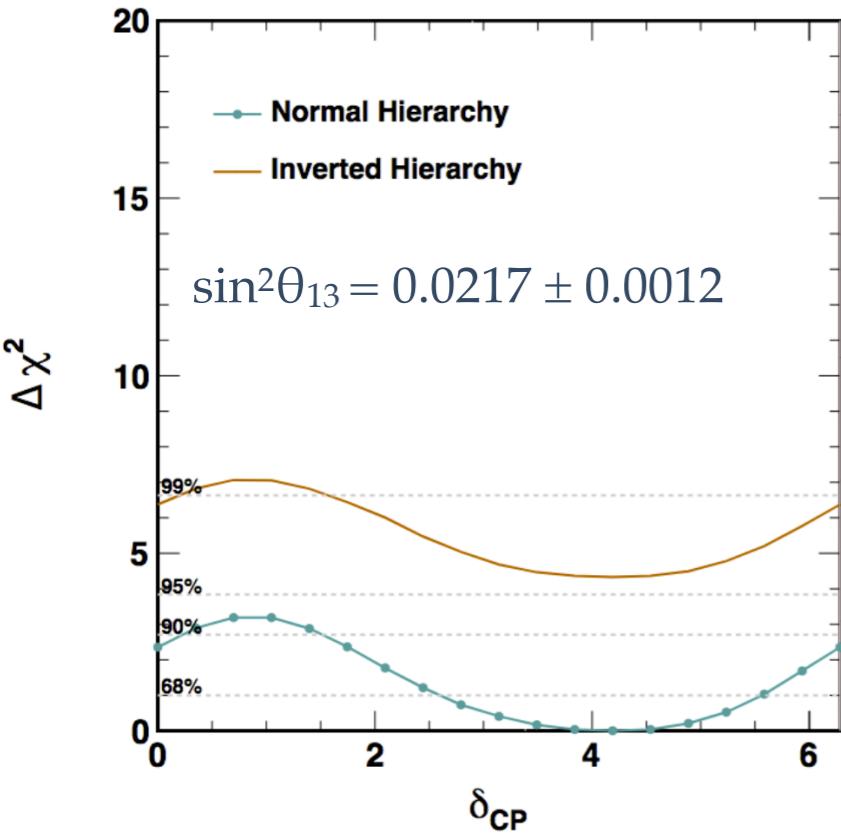
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



# The CP phase

H. Tanaka, TAUP 2019

Super-Kamiokande (atm)



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

◆ preference driven by sub-GeV e-like samples

SK Collab. PRD97 (2018)

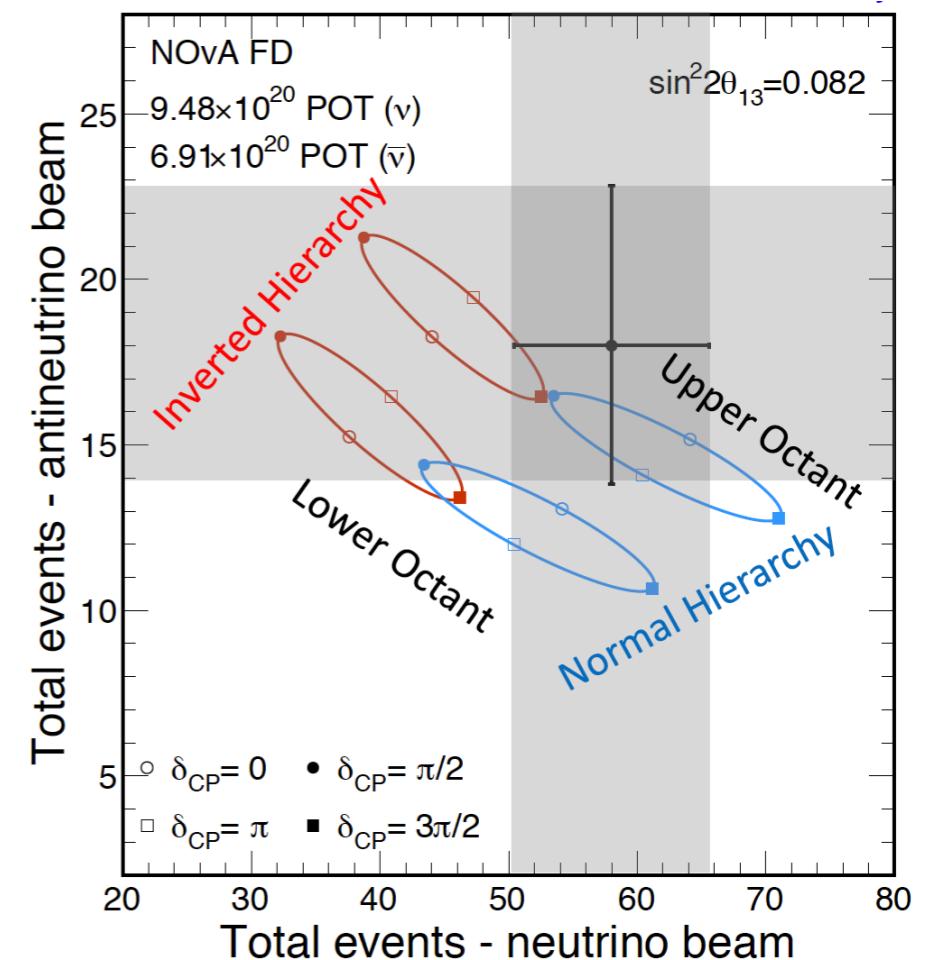
T2K

$\delta_{BF} \approx 3\pi/2$  due to better agreement with observed  $\nu_e$  and  $\bar{\nu}_e$  events

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

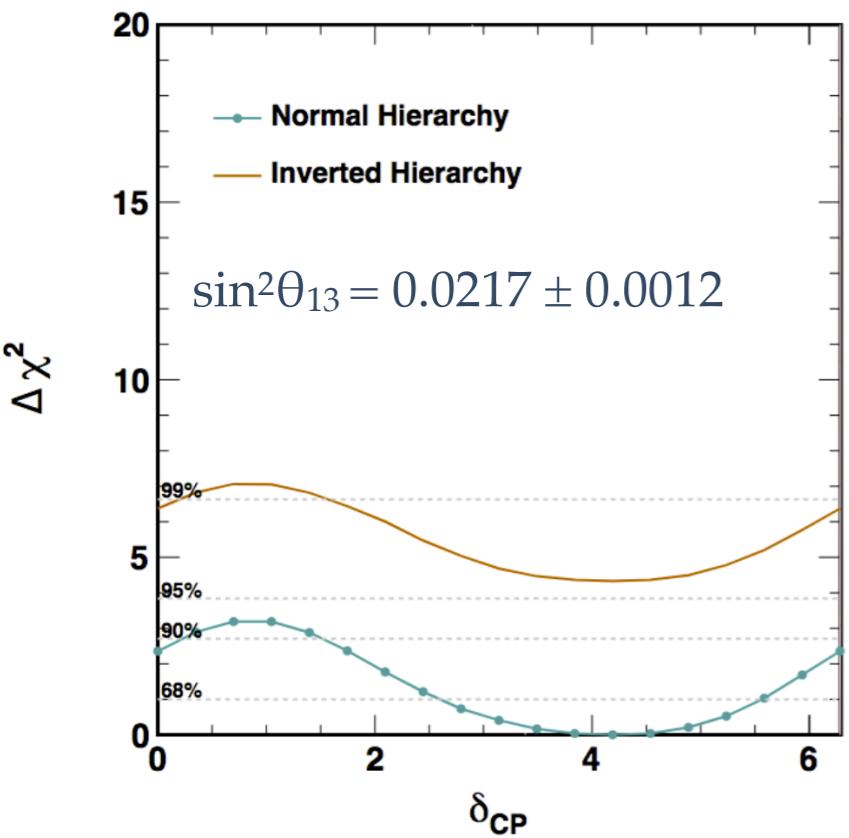
NOvA

A. Himmel,  
Fermilab 2018



# The CP phase

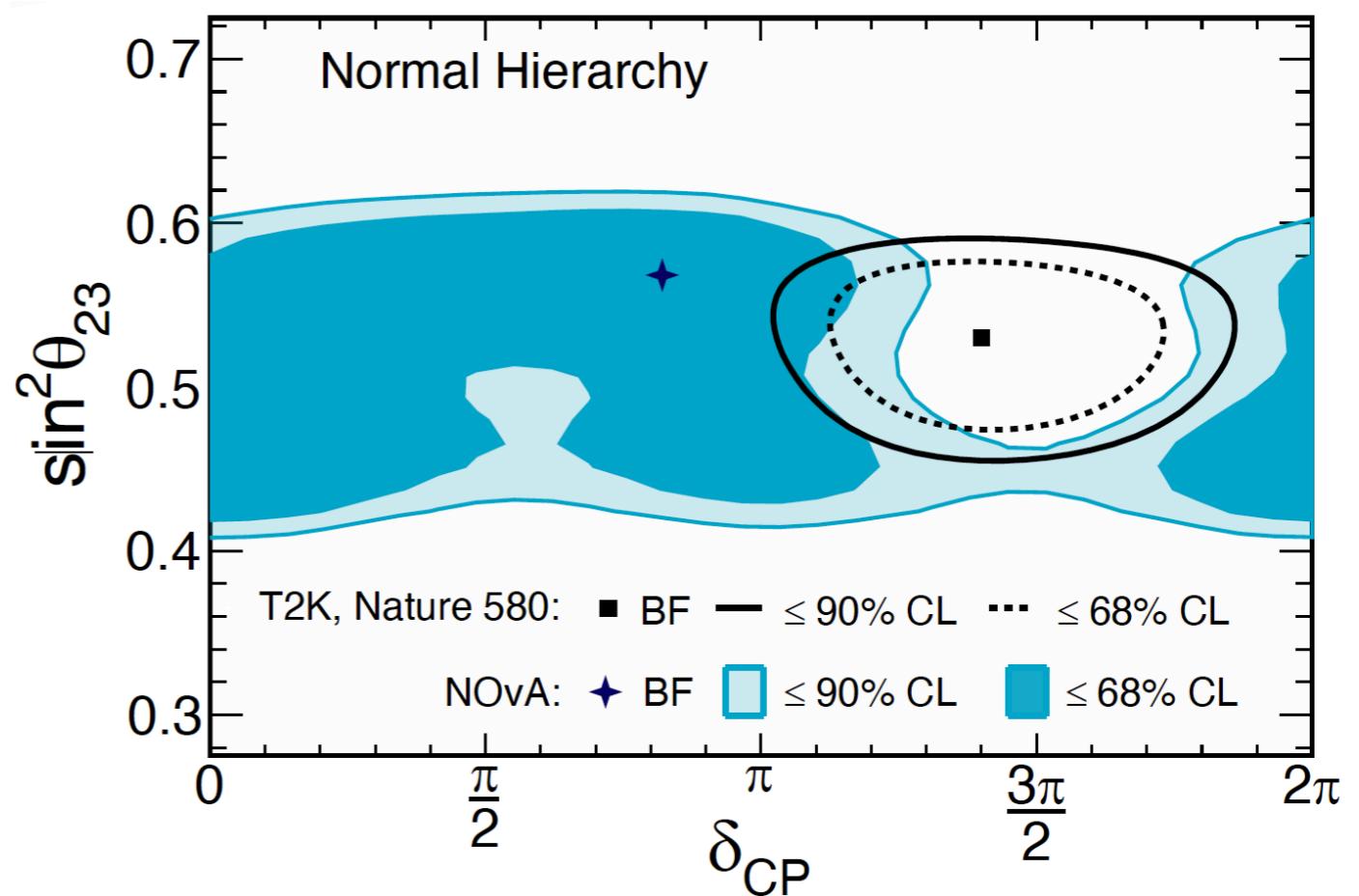
Super-Kamiokande (atm)



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- ◆ preference driven by sub-GeV e-like samples

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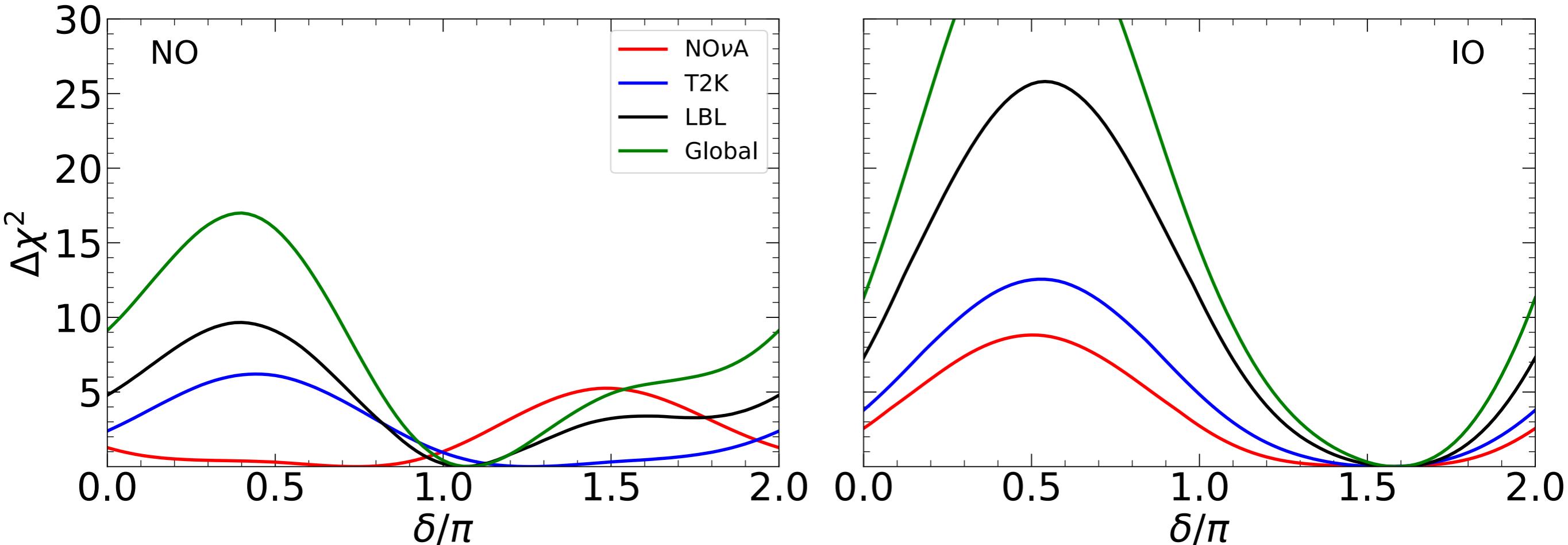
Strong tension between T2K and NOvA results for NO



A. Himmel, Neutrino 2020

# The CP phase

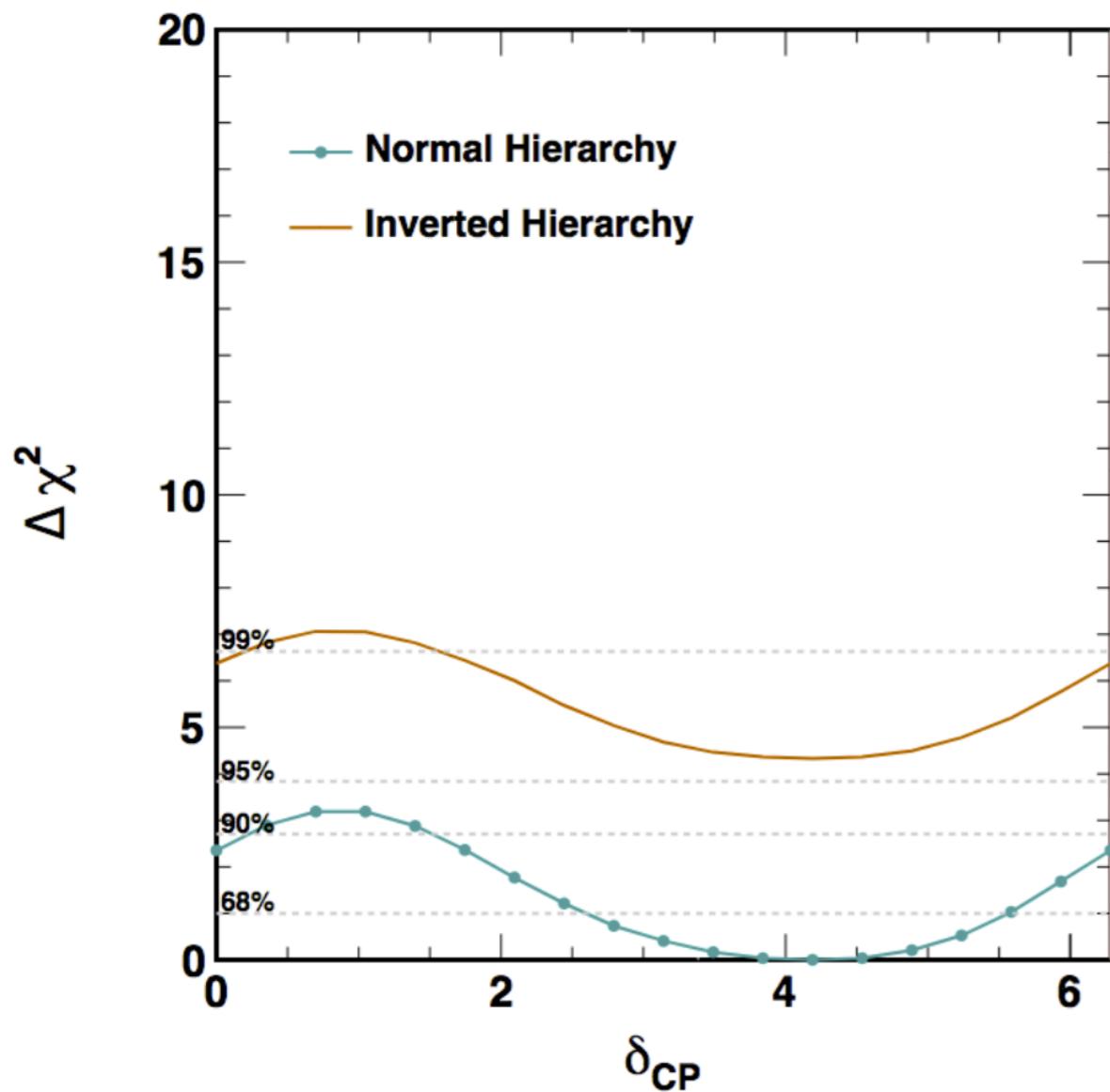
de Salas et al, JHEP 02 (2021) 071 [arXiv:2006.11237]



- ♦ NO: there is a tension between NOvA and T2K and SK atmospheric results  
 $\delta_{BF} = 1.08\pi$ ;  $\delta = \pi/2$  (0) disfavored at  $4.0\sigma$  ( $3.0\sigma$ );  $\delta = 3\pi/2$  with  $\Delta\chi^2 = 4.9$
- ♦ IO: all experiments prefer  $\delta \approx 3\pi/2$   
 $\delta_{BF} = 1.58\pi$ ;  $\delta = \pi/2$  ( $\pi$ ) disfavored at  $6.2\sigma$  ( $3.8\sigma$ );

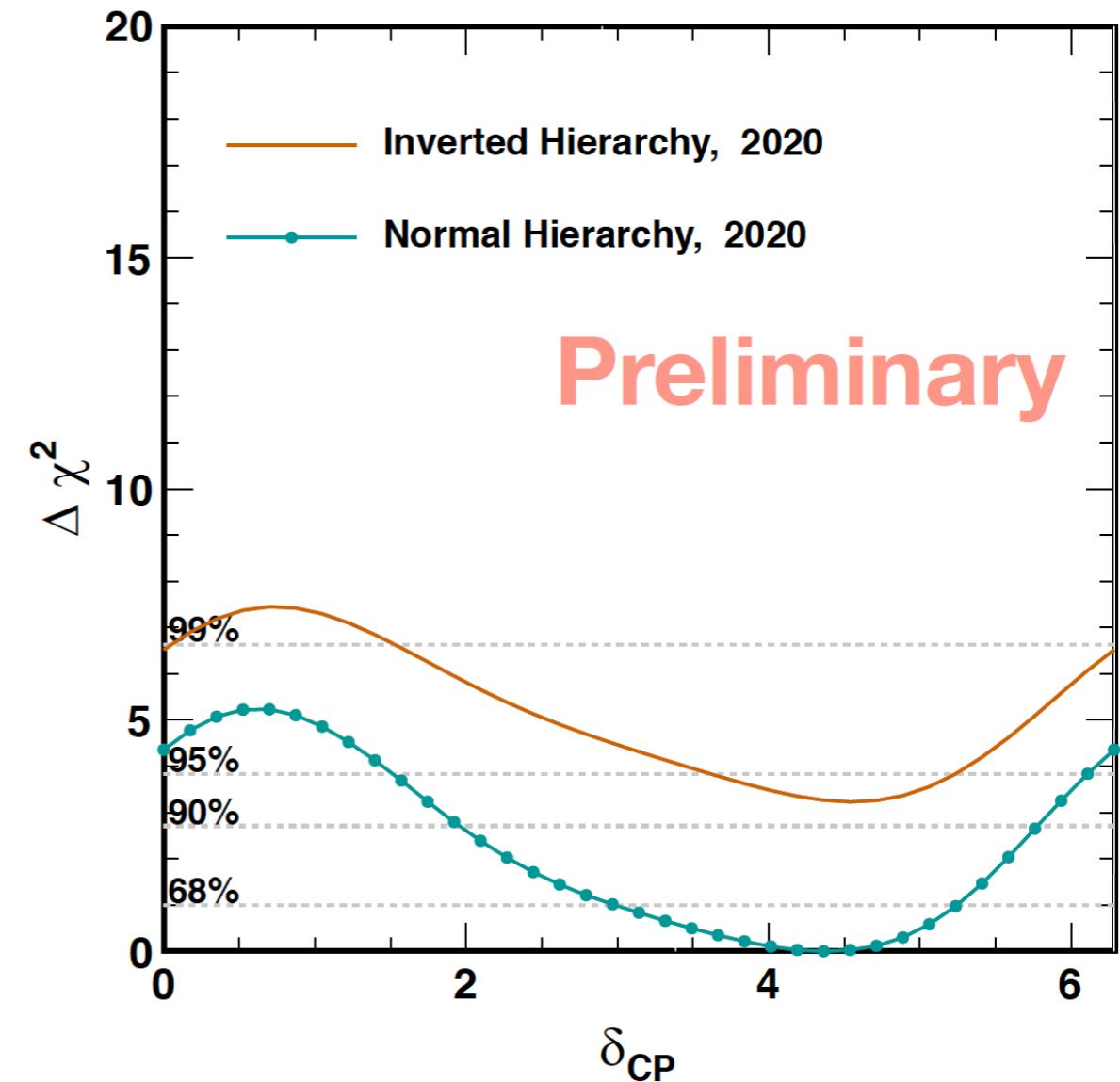
# The CP phase

Super-Kamiokande (atm) 2018



SK Collab. PRD97 (2018)

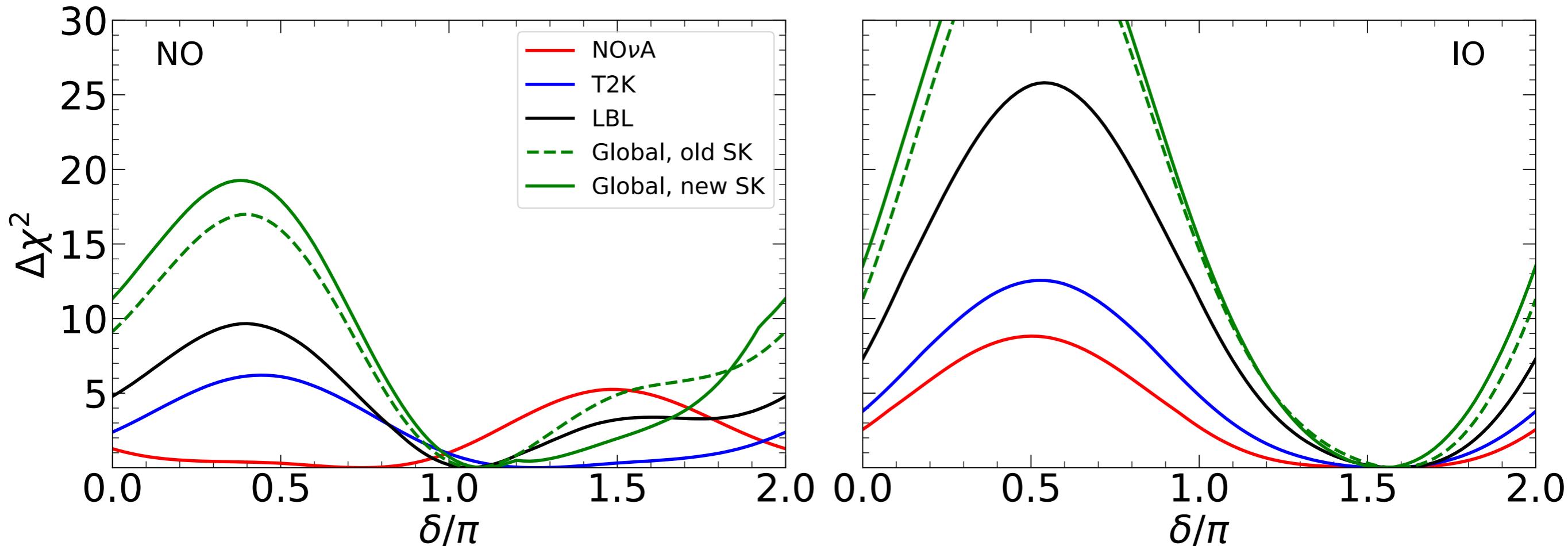
Super-Kamiokande (atm) 2020



Y. Nakajima, Neutrino 2020

# The CP phase

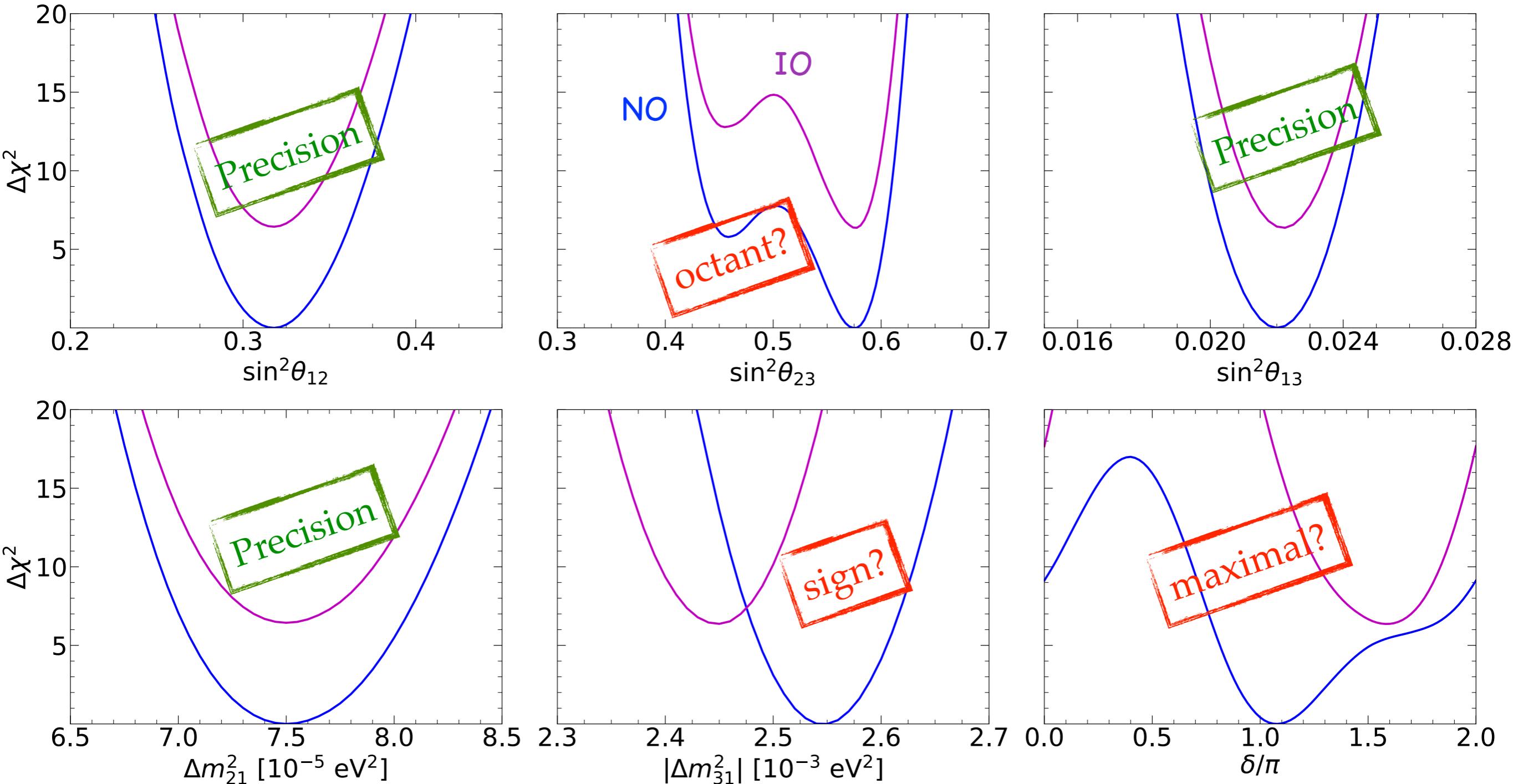
de Salas et al, preliminary



- ♦ NO: there is a larger (smaller) rejection to  $\delta=0$  and  $\delta=\pi/2$  ( $\delta=3\pi/2$ )  
 $\delta_{BF} = 1.1\pi$ ;  $\delta=\pi/2$  (0) disfavored at  $4.2\sigma$  ( $3.4\sigma$ );  $\delta=3\pi/2$  with  $\Delta\chi^2=2.0$
- ♦ IO: all experiments prefer  $\delta \approx 3\pi/2$  (similar results)  
 $\delta_{BF} = 1.54\pi$ ;  $\delta=\pi/2$  ( $\pi$ ) disfavored at  $6.4\sigma$  ( $3.9\sigma$ )

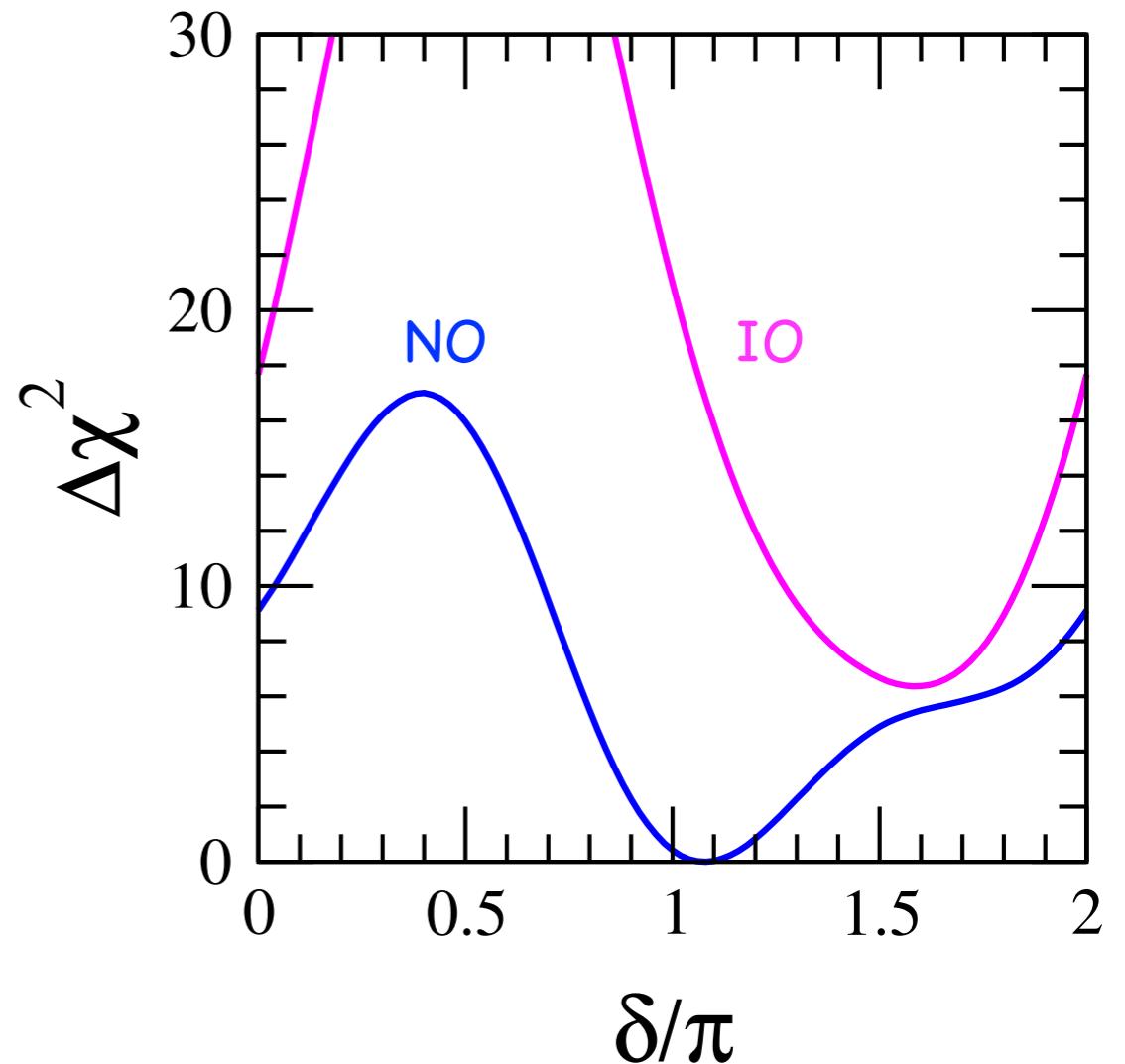
# Global fit to ν oscillation parameters

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



# The mass ordering

- ◆ T2K and NOvA separate analysis prefers NO with  $\Delta\chi^2 \approx 0.4$
- ◆ T2K + NOvA combined prefer IO with  $\Delta\chi^2 \approx 2.4$  (tension in  $\delta$  for NO)
- ◆ LBL + REAC prefer NO with  $\Delta\chi^2 \approx 1.4$  (tension in  $\Delta m^2_{31}$  measurement in IO)
- ◆ Atmos. sensitivity: Super-K ( $\Delta\chi^2 \approx 3.5$ ) and DeepCore ( $\Delta\chi^2 \approx 1.0$ )
- ◆ Global fit:  $\Delta\chi^2 = 6.4 \rightarrow 2.5\sigma$  preference for NO



de Salas et al, JHEP 02 (2021) 071

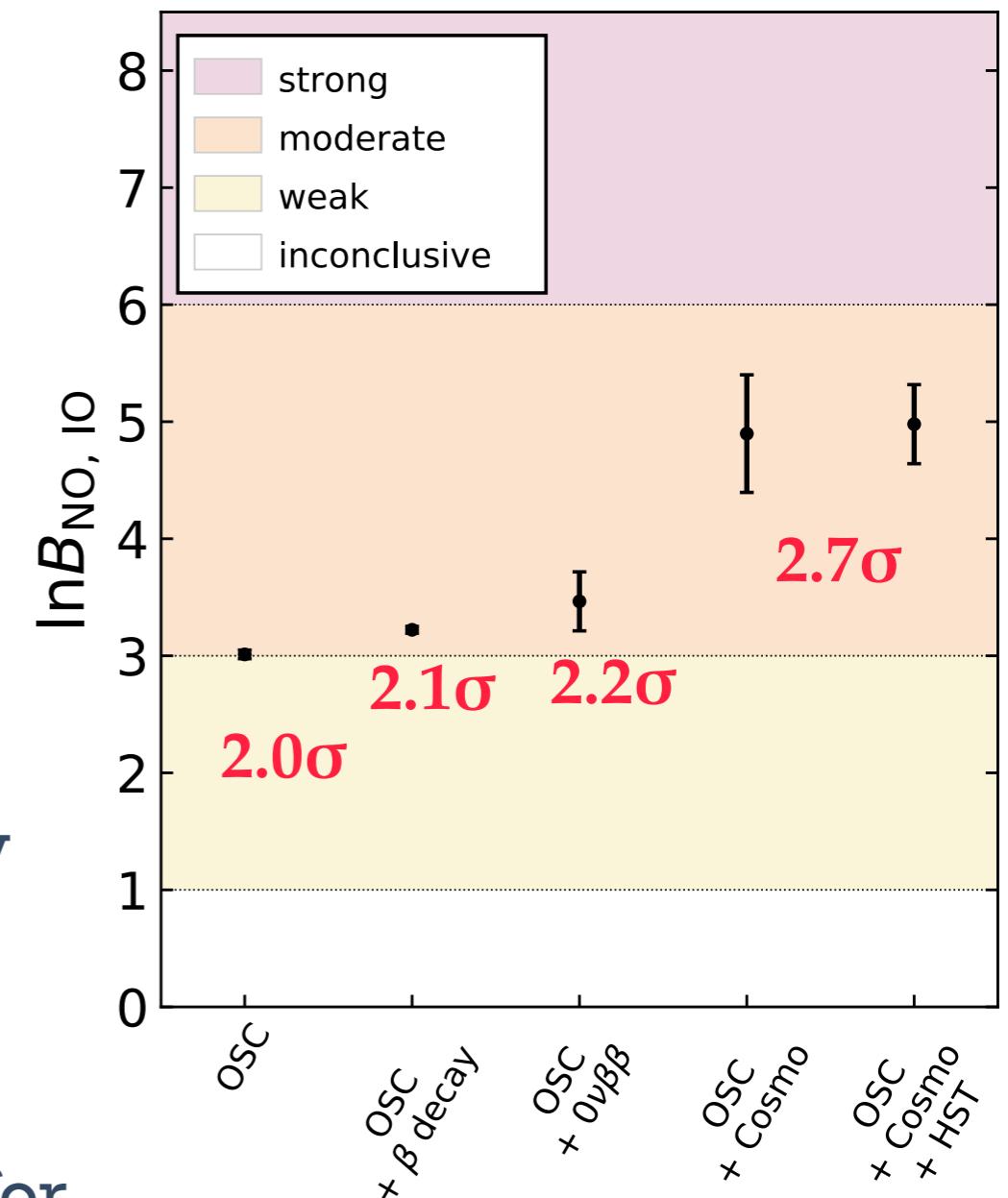
# Other inputs for mass ordering?

## Experimental sensitivity to neutrino masses:

- ◆ ν-oscillations:  $\Delta m_{ij}^2$
- ◆ β-decay:  $m_\beta = f(m_i, \theta_{ij})$
- ◆ 0νββ:  $m_{\beta\beta} = f(m_i, \theta_{ij}, \phi_i)$
- ◆ cosmology:  $\sum m_i$

## Results from the combined bayesian analysis:

- ⇒ weak/moderate preference for NO driven by oscillation data ( $2.0\sigma$ )
- ⇒ β-decay and 0νββ have little impact on MO.
- ⇒ cosmological data enhances the preference for NO from  $2.0\sigma$  to  $2.7\sigma$



de Salas et al, JHEP 02 (2021) 071

# The mass ordering (preliminary)

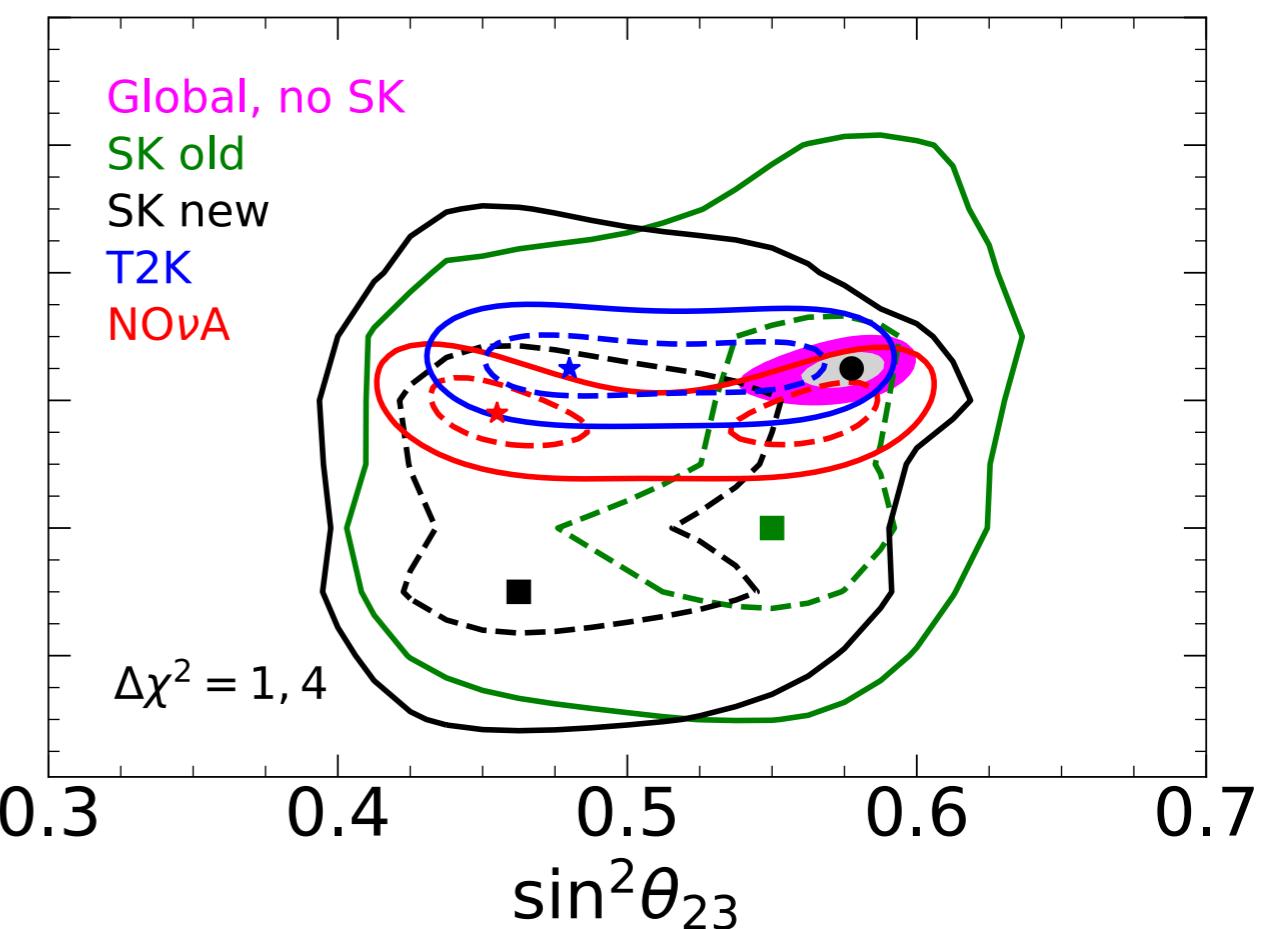
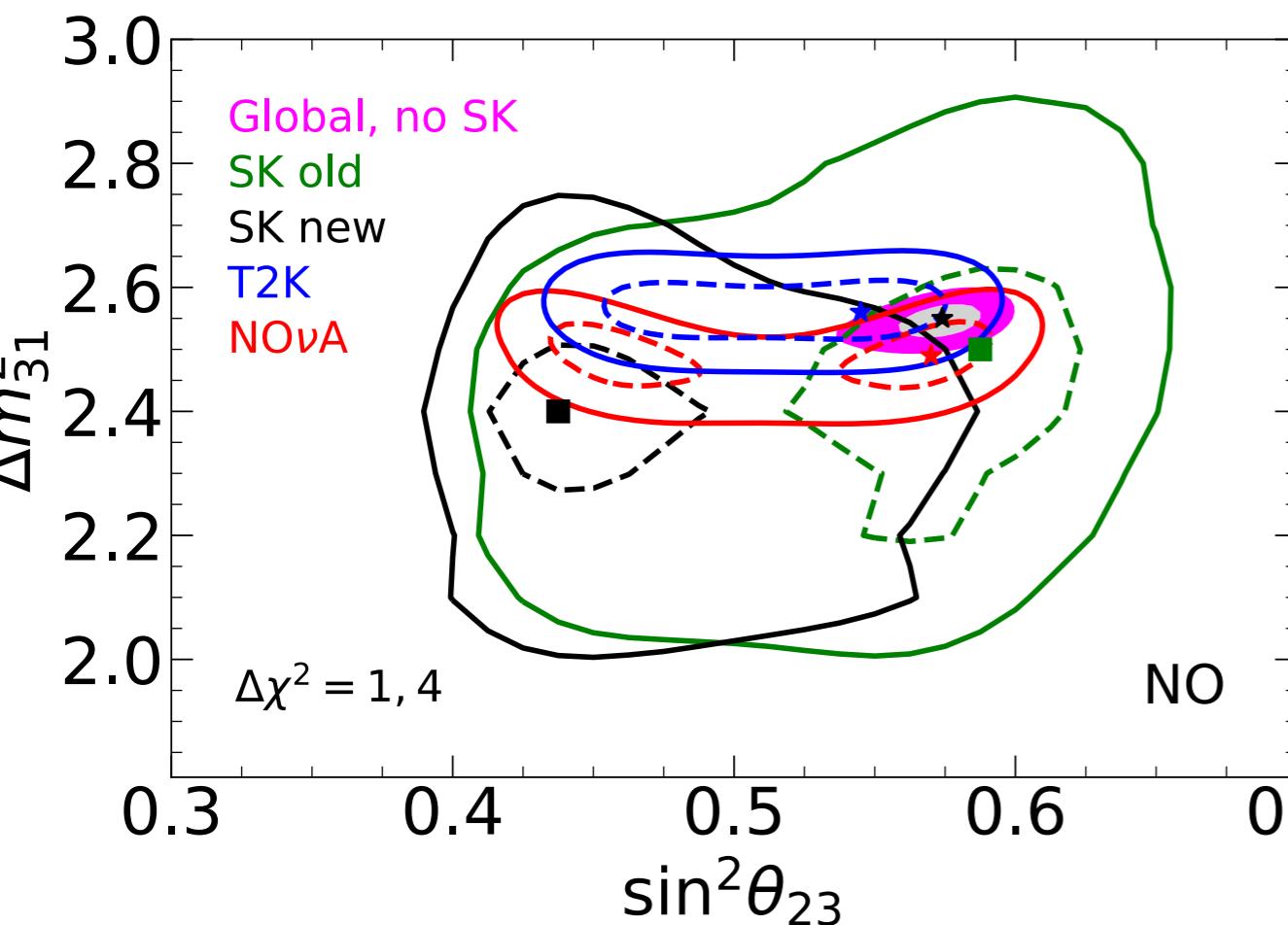
◆ New Super-K atmospheric analysis (preliminary)

**Y. Nakajima, Neutrino-2020**

◆ Preliminary Super-K analysis shows weaker preference for NO

$$\Rightarrow \Delta\chi^2 = 3.5 \text{ (previous SK analysis)} \rightarrow \Delta\chi^2 = 2.9$$

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



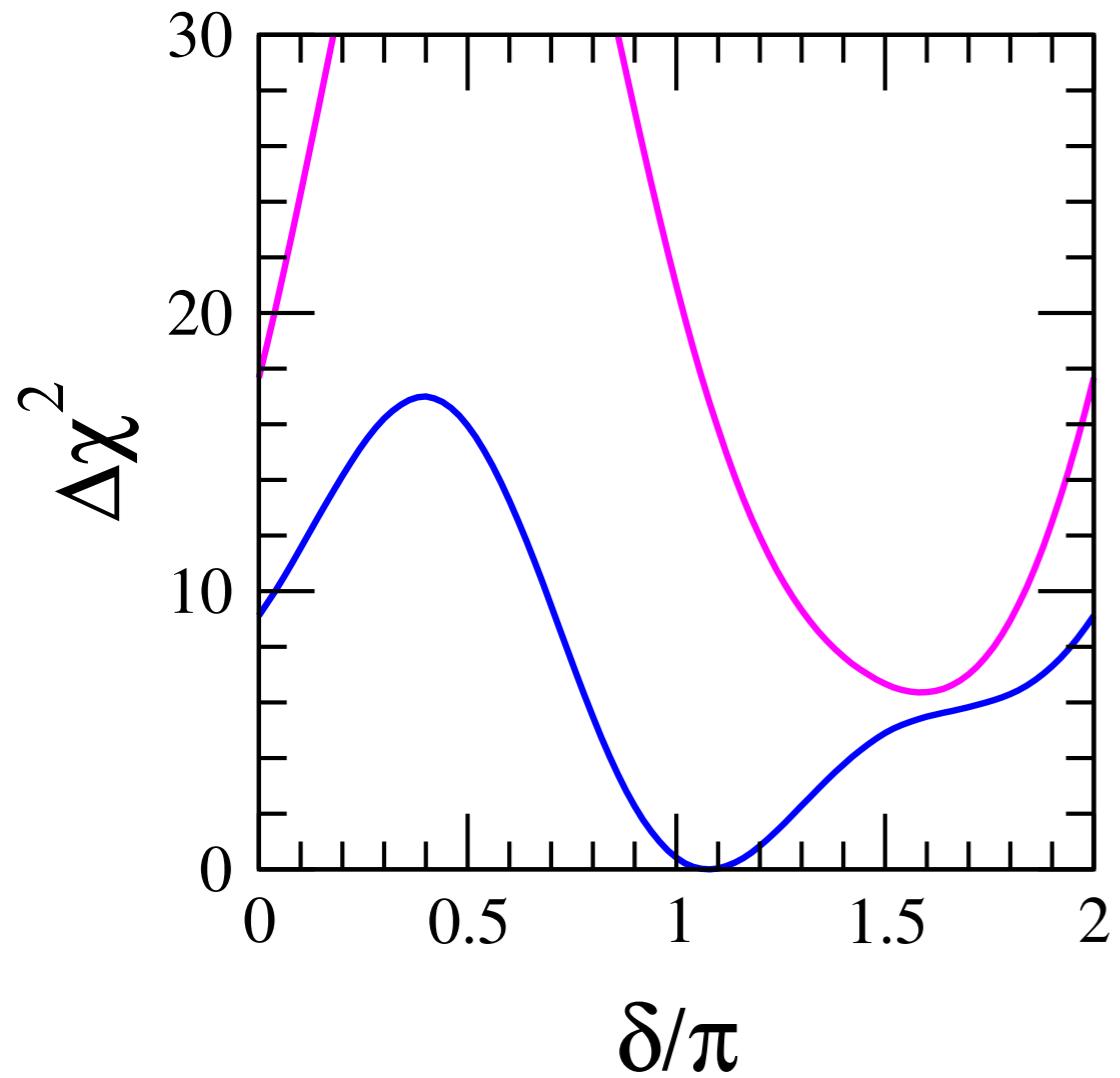
**de Salas et al, preliminary**

# The mass ordering (preliminary)

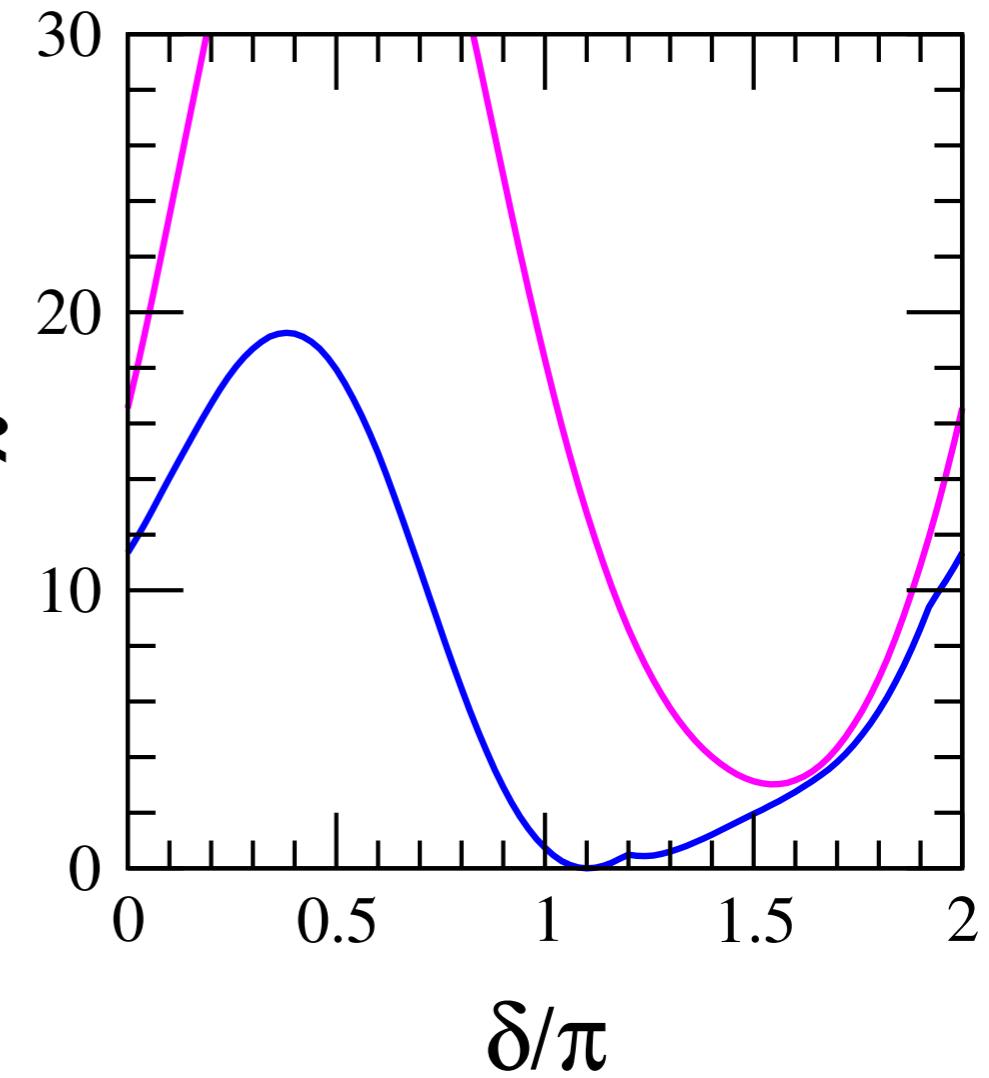
♦ New Super-K atmospheric analysis (preliminary)

Y. Nakajima, Neutrino-2020

de Salas et al, JHEP 02 (2021) 071



de Salas et al, preliminary



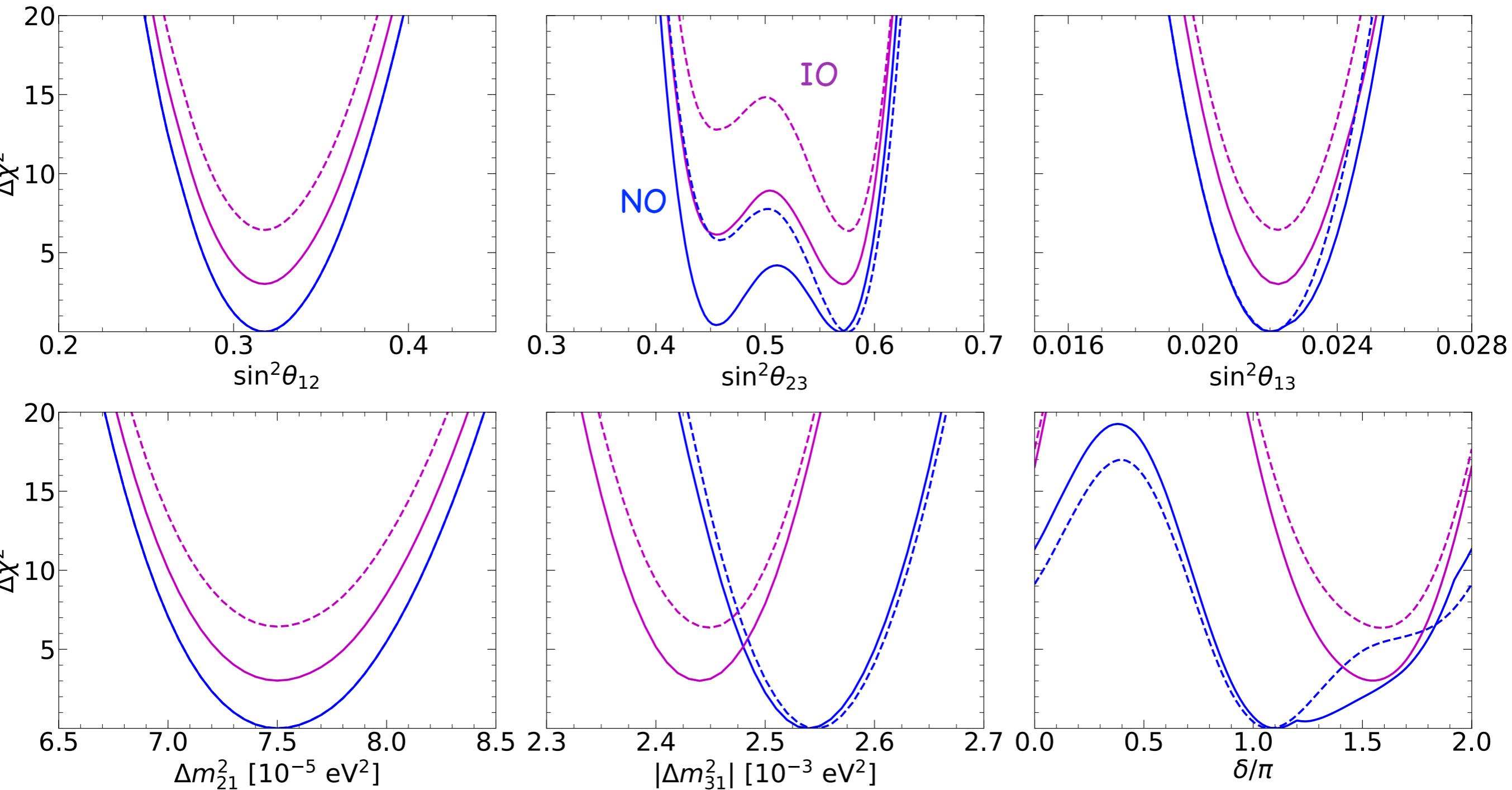
♦  $\Delta\chi^2 = 6.4 \rightarrow 2.5\sigma$  preference for NO

♦  $\Delta\chi^2 = 3.0 \rightarrow 1.7\sigma$  preference for NO

# Global fit to ν oscillation parameters

de Salas et al, preliminary

— SK-atm prelim  
- - - SK atm 2018



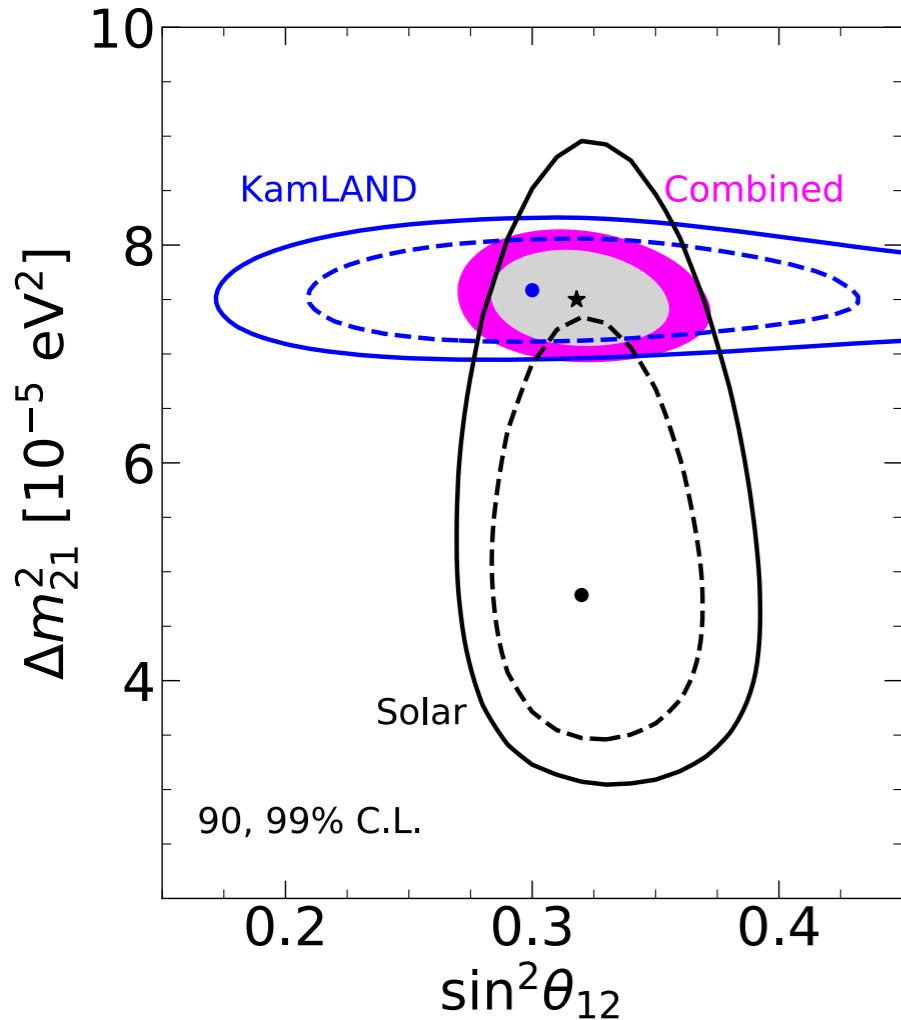
# Beyond the 3-neutrino scenario

- ♦ 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

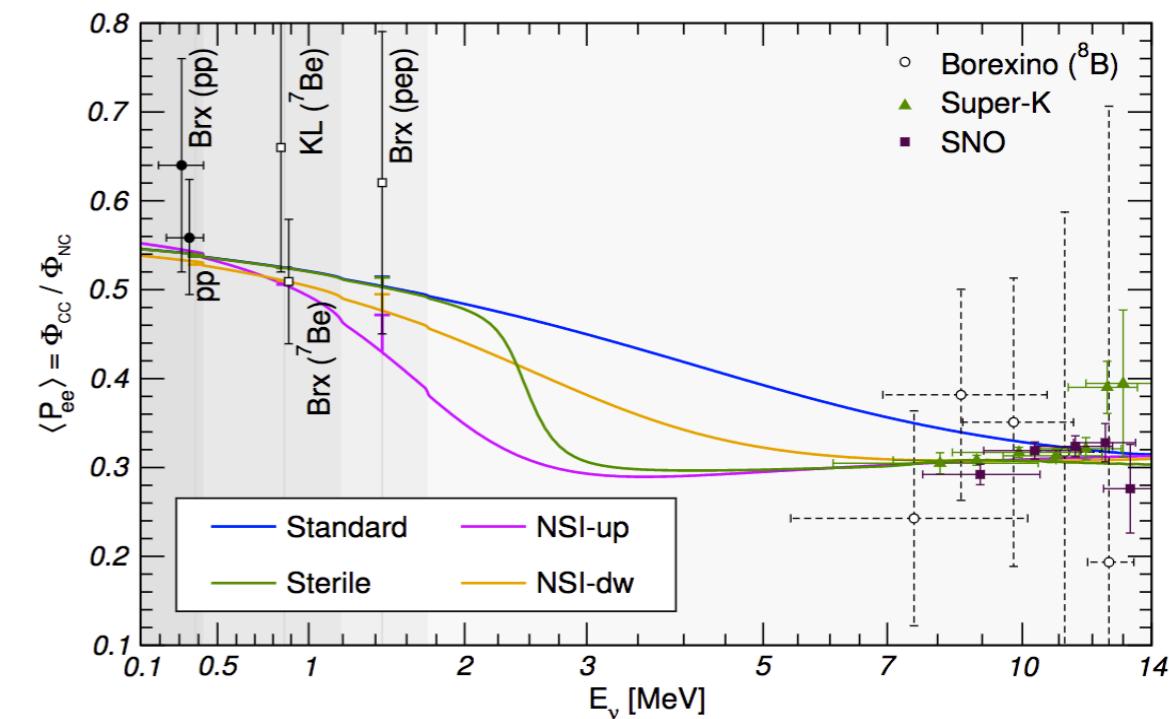
Can they also help reducing the current tensions?

# The solar-KamLAND $\Delta m^2_{21}$ tension



⇒ 2 $\sigma$  tension between preferred value of  $\Delta m^2_{21}$  from KamLAND and solar data  
⇒  $\Delta m^2_{21}$  preferred by KamLAND predicts steep upturn and smaller D/N asymmetry

- ♦ NSI ( $\varepsilon \sim 0.3$ ) can reconcile both results:
- ⇒ flatter spectrum at intermediate E-region
- ⇒ larger D/N asymmetries can be expected

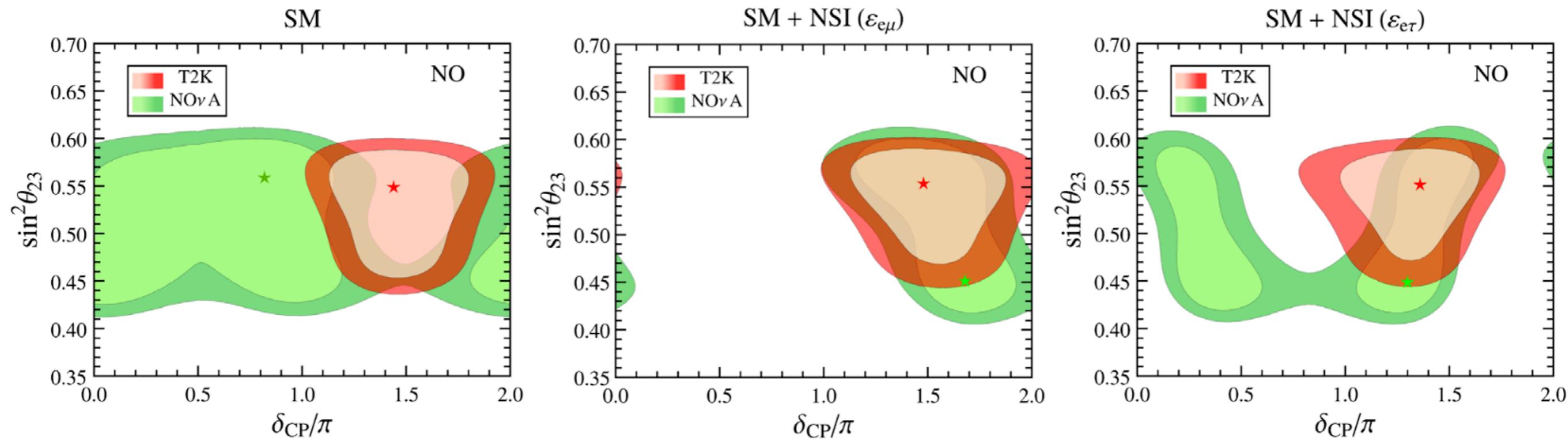


Escrihuela et al, PRD80 (2009); Coloma et al, PRD96 (2017)

Maltoni & Smirnov, EPJ 2015

# The T2K-NO $\nu$ A $\delta_{\text{CP}}$ tension

- ♦ NSI may include new sources of CP violation besides  $\delta_{\text{CP}}$ :  $\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}| \exp(i\phi_{\alpha\beta})$
- ♦ 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 NO $\nu$ A results.

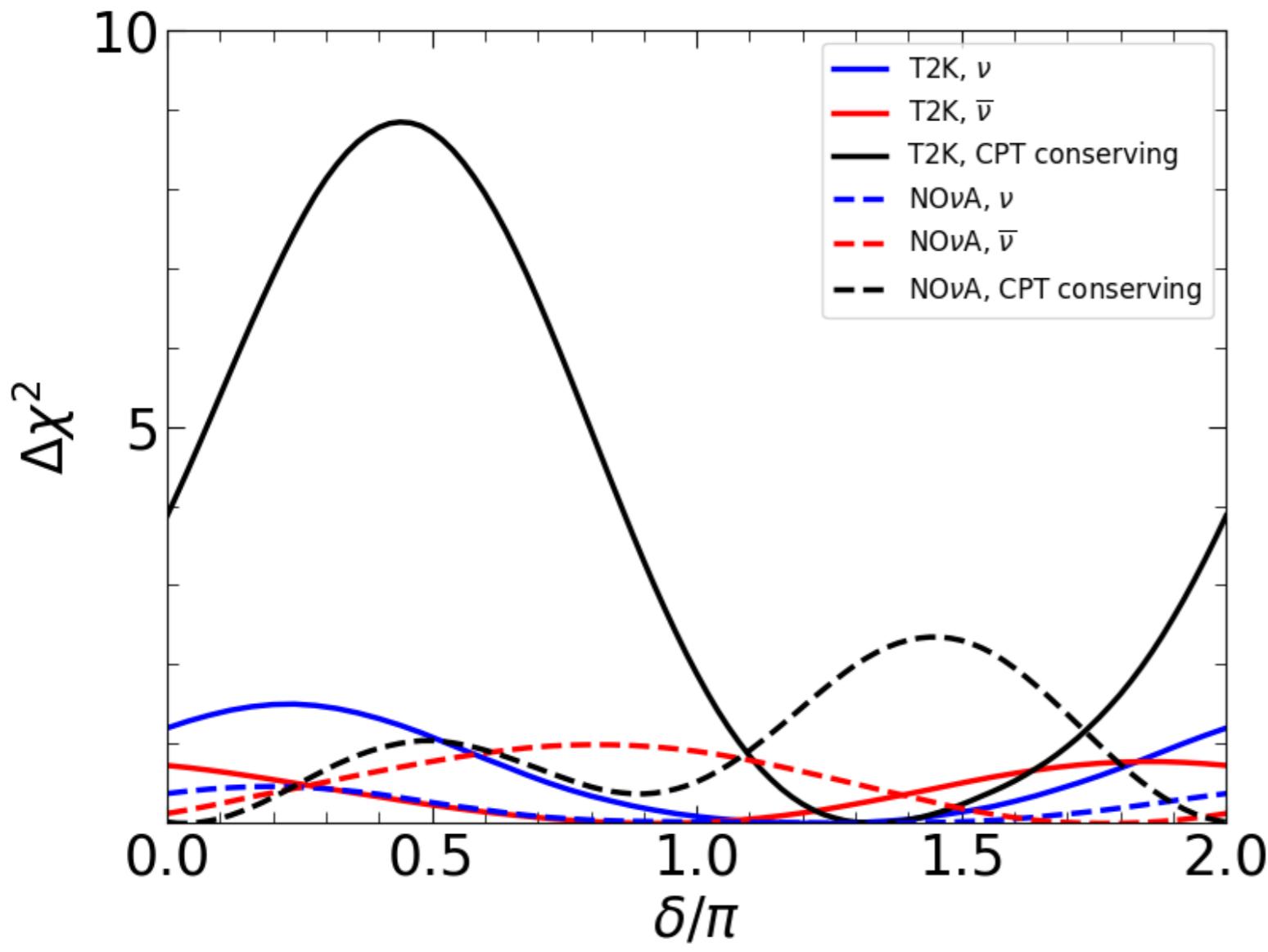


**Chatterjee and Palazzo, PRL 2021**

**Denton et al, PRL 2021**

# The T2K-NOvA $\delta_{\text{CP}}$ tension

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

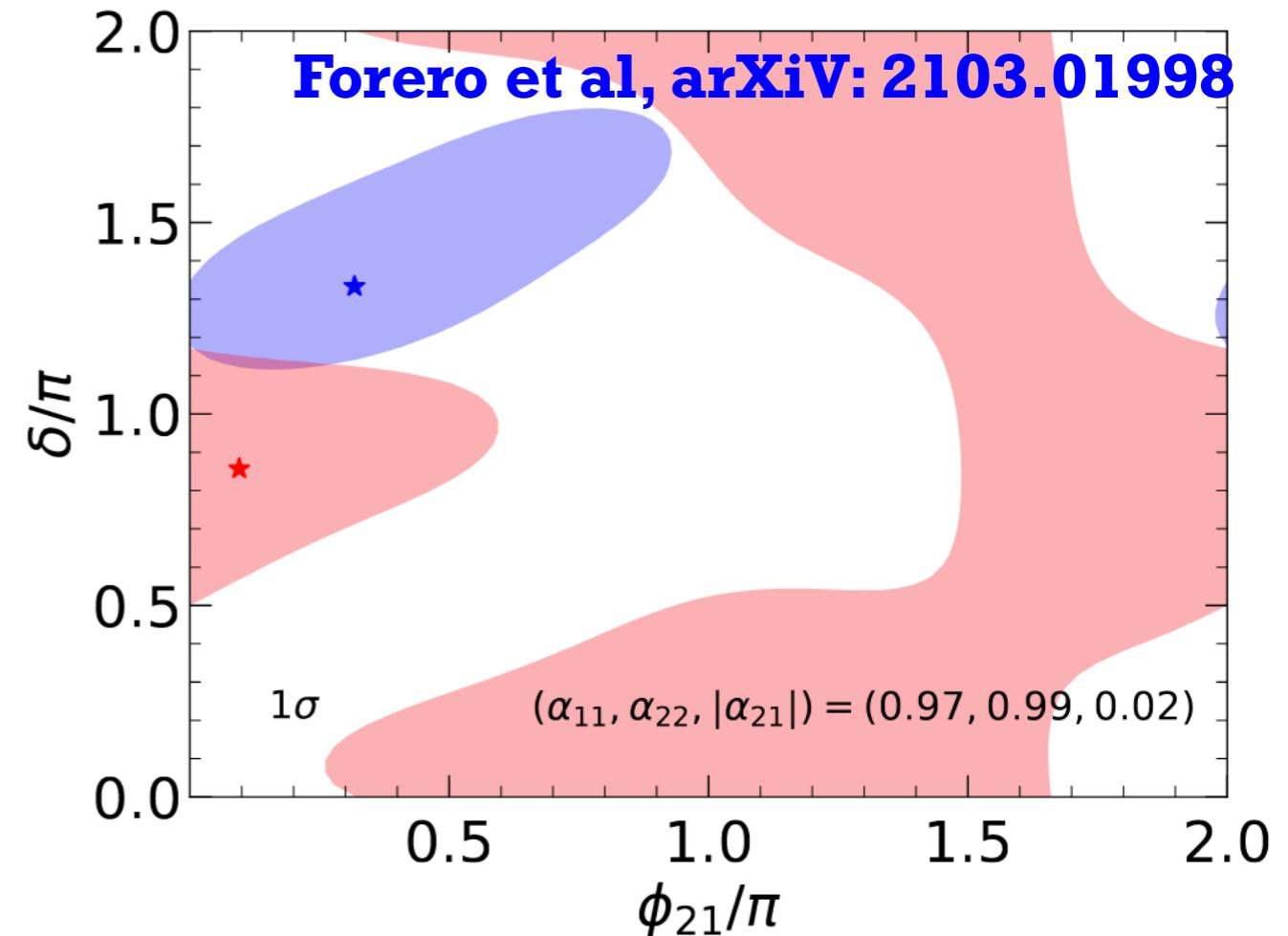
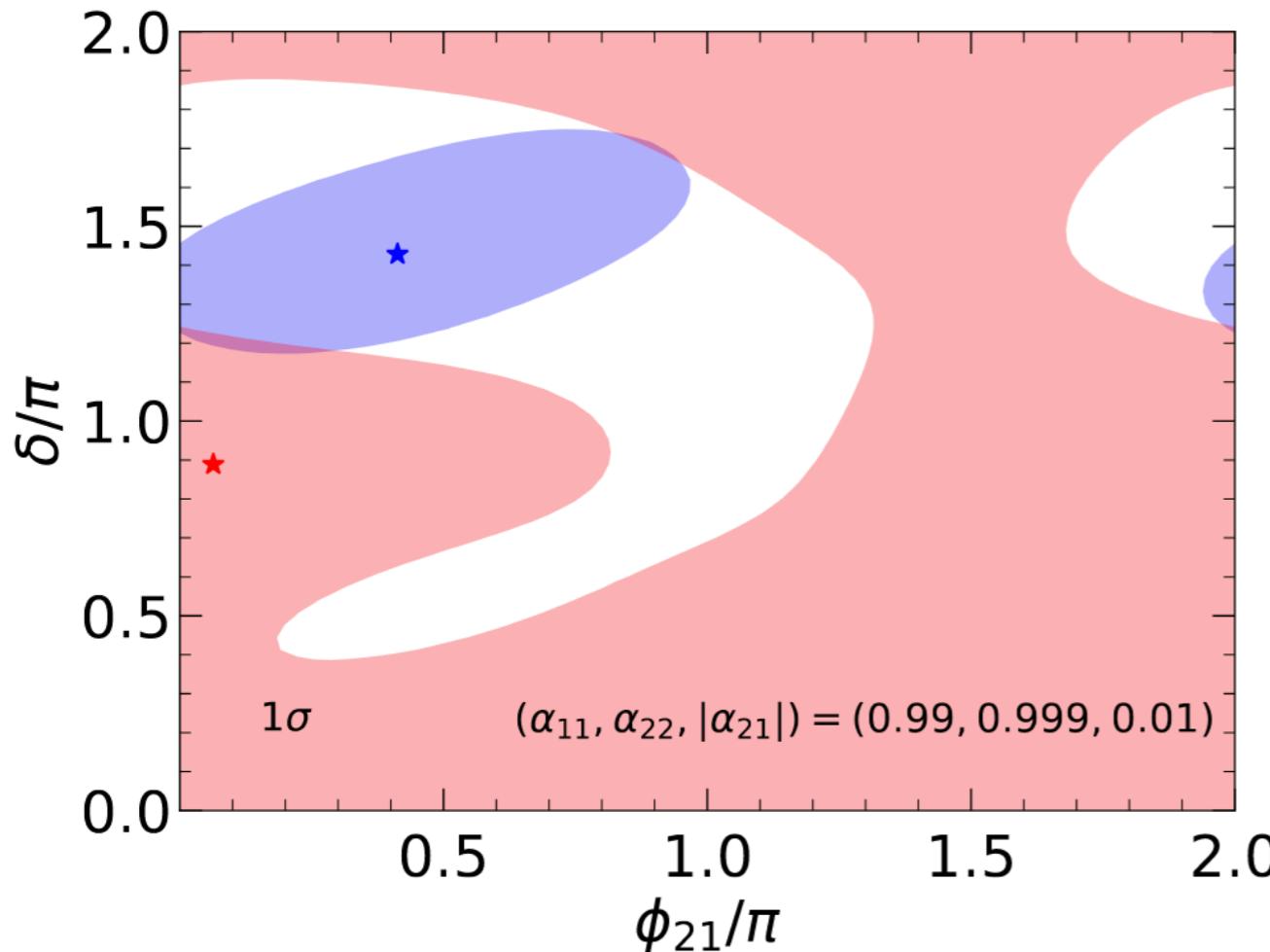


- ♦ the **tension** appears only in the  $\bar{\nu}$  channel, with less sensitivity
- ♦ all values of  $\delta$  and  $\bar{\delta}$  remain allowed at  $\sim 1\sigma$
- ♦  $\theta_{13} \neq \bar{\theta}_{13}$  can account for different behavior in neutrino and antineutrino channels
- very poor sensitivity on CP violation compared to CPT-conserving scenario

Barenboim, Ternes, MT, JHEP2020

# The T2K-NOvA $\delta_{\text{CP}}$ 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  $\Rightarrow$  **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  $\theta_{23} > 45^\circ$ , 1st octant value disfavoured with  $\Delta\chi^2 \geq 5.8$  (6.4)
  - ✓  $\delta_{BF} = 1.08\pi$  ( $1.58\pi$ ) for NO (IO) ;  $\delta = \pi/2$  disfavored at  $4.0\sigma$  ( $6.2\sigma$ )
  - ✓ 2.5 $\sigma$  hint for **normal ordering** from atmospheric, LBL and reactor data
- ♦ Preliminary Super-K atmospheric data may change some results:
  - ✓ **degenerate octant** solutions for  $\theta_{23}$  :  $\Delta\chi^2$  (1st octant) = 0.4 (3.1) for NO (IO)
  - ✓ similar results for **CP-violation**, with  $\delta=\pi/2$  disfavored at  $4.2\sigma$  ( $6.4\sigma$ )
  - ✓ Reduced **preference for normal ordering** to 1.7 $\sigma$
- ♦ The presence of **new physics BSM** may affect the current description of neutrino oscillations relaxing tensions or worsening the precision of measurements.