The global three-neutrino picture before DUNE

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ASTROPARTICLES
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EXCELENCIA SEVERO OCHOA

Current status (pre-Neutrino 2018 Conference)

- Based on **deSalas et al, 1708.01186 (May2018)** [https://globalfit.astroparticles.es/]
- Restricted to **standard three-neutrino** framework

⇒ **Four-neutrino scenario**: Friday sessions, Poster by S. Gariazzo

⇒ **Robustness against physics beyond the SM**: Talk by D. Marfatia

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Near-future prospects (Before DUNE)

- Main **unknowns** in three-neutrino oscillation scenario:

⇒ maximality/octant of θ_{23} **T2K, NOνA, Super-K**

⇒ leptonic CP violation **JUNO, RENO-50**

⇒ neutrino mass ordering **ORCA, PINGU**

…

The three-flavour picture: notation

neutrino mixing

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

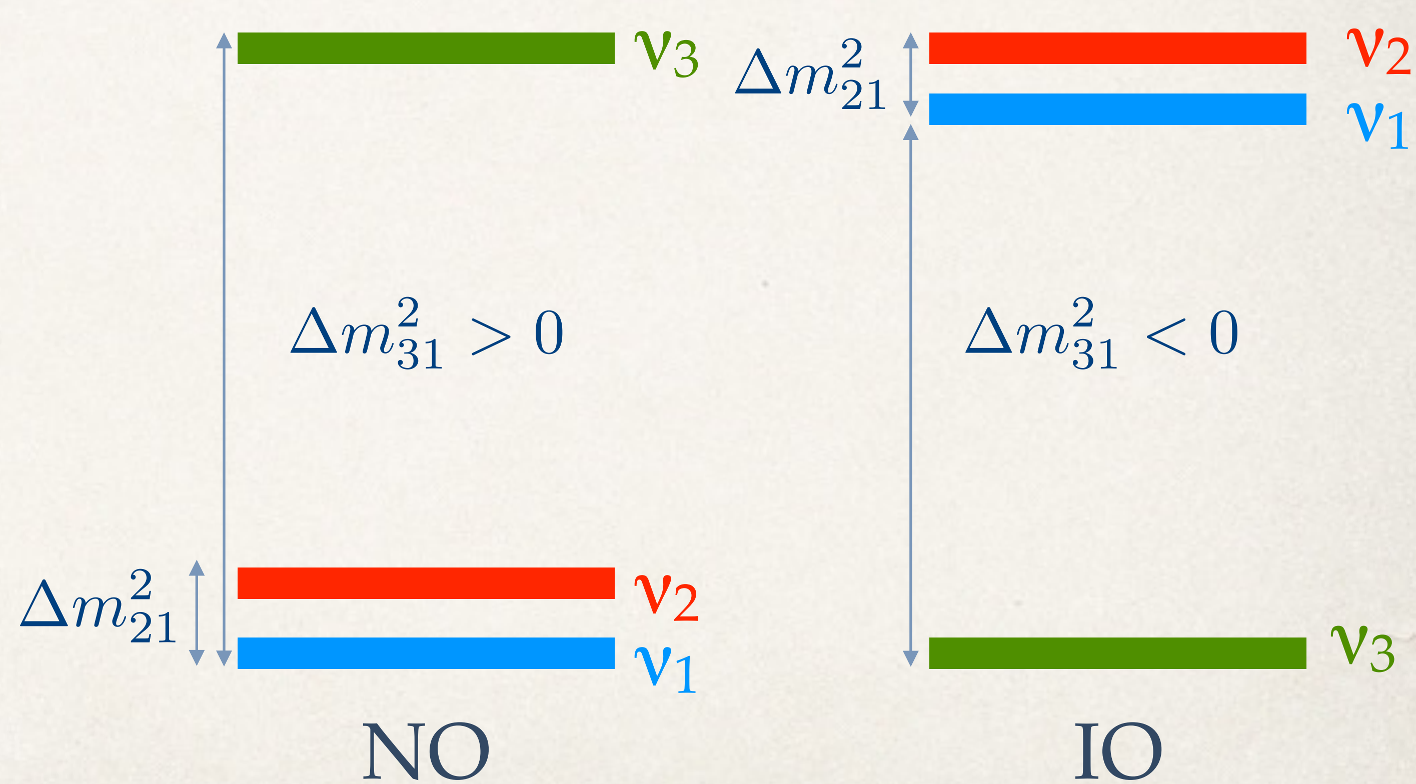
- three mixing angles: θ_{12}, θ_{23}, θ_{13}
- three CP phases: 1 Dirac + 2 Majorana
- three masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

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

neutrino mass spectrum



$$|\Delta m^2_{31}|_{\mathrm{NO}} > |\Delta m^2_{31}|_{\mathrm{IO}}$$

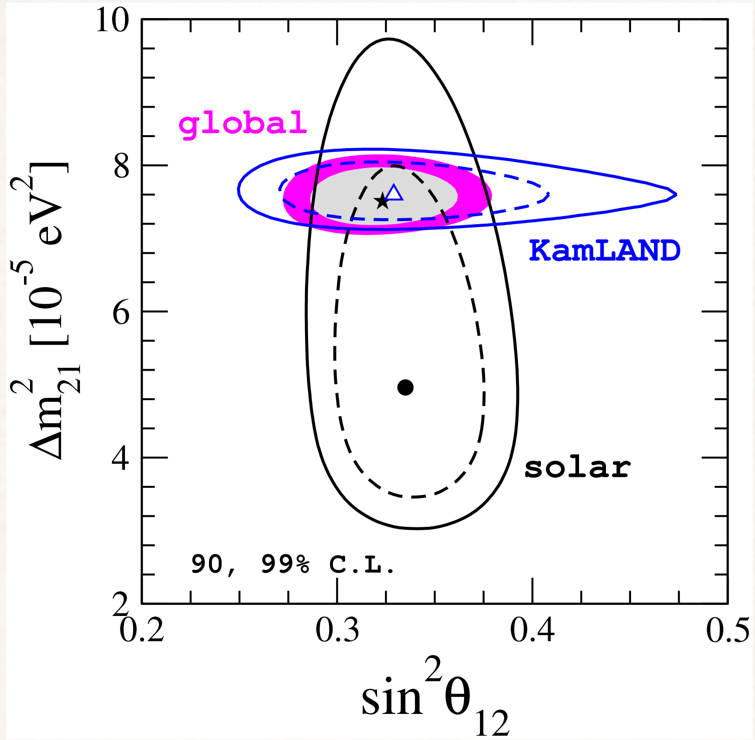
Experimental data (pre-Nu2018)

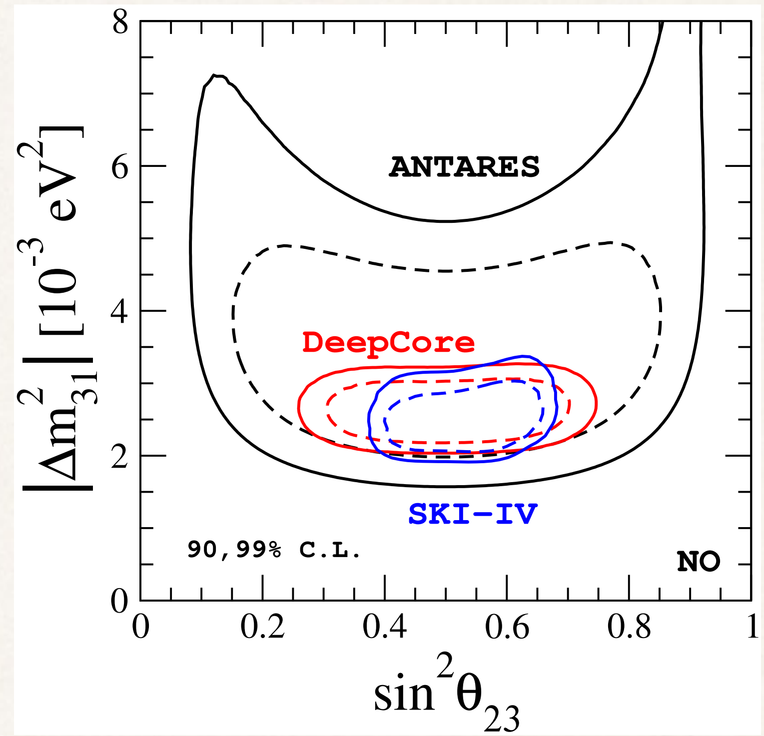
solar sector

Cl, Ga, SK

SNO, Borexino

KamLAND





atmospheric results

SK (official χ^2 maps)

IceCube-DeepCore

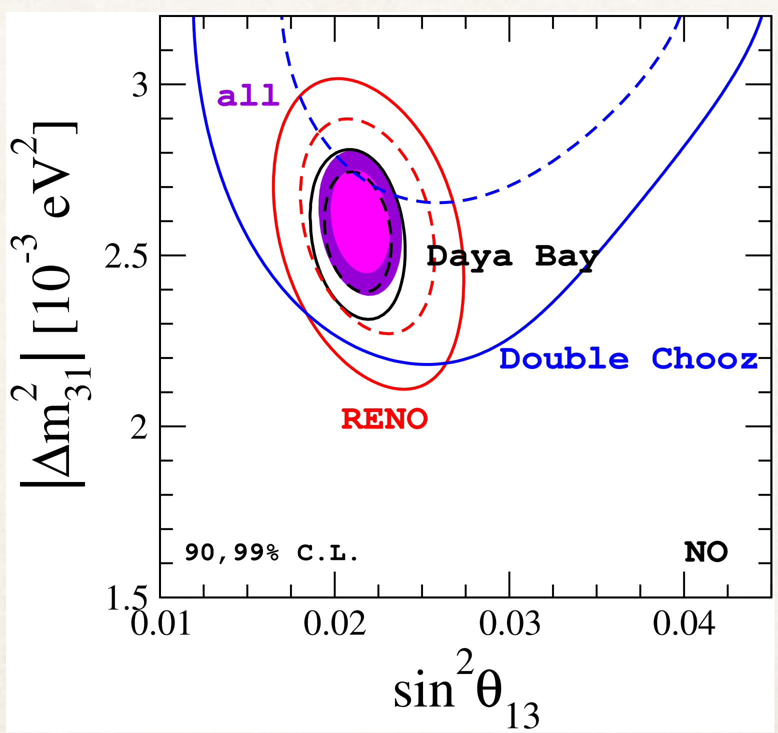
ANTARES

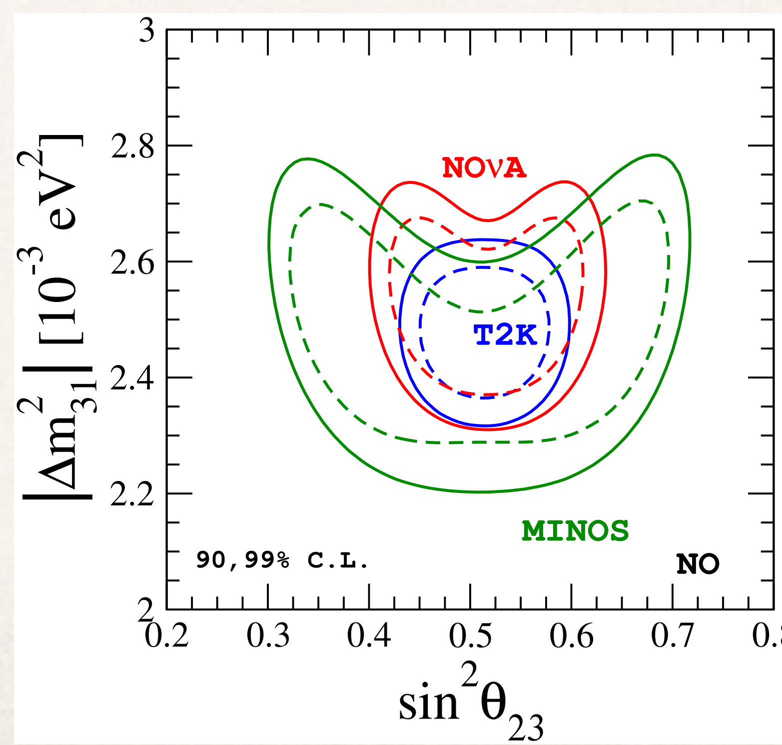
SBL reactors

Daya Bay

RENO

Double Chooz





LBL experiments

MINOS

T2K

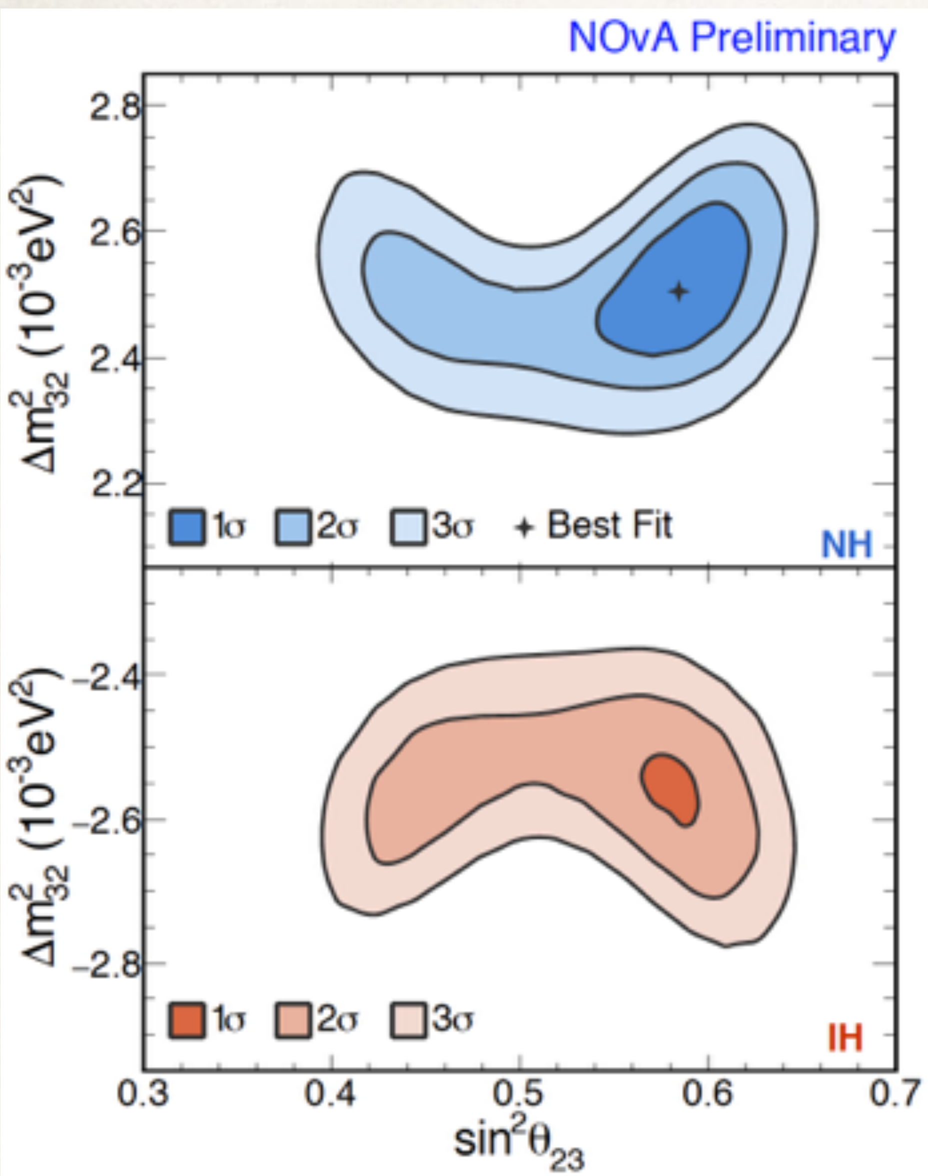
NOνA

New data presented @Nu2018

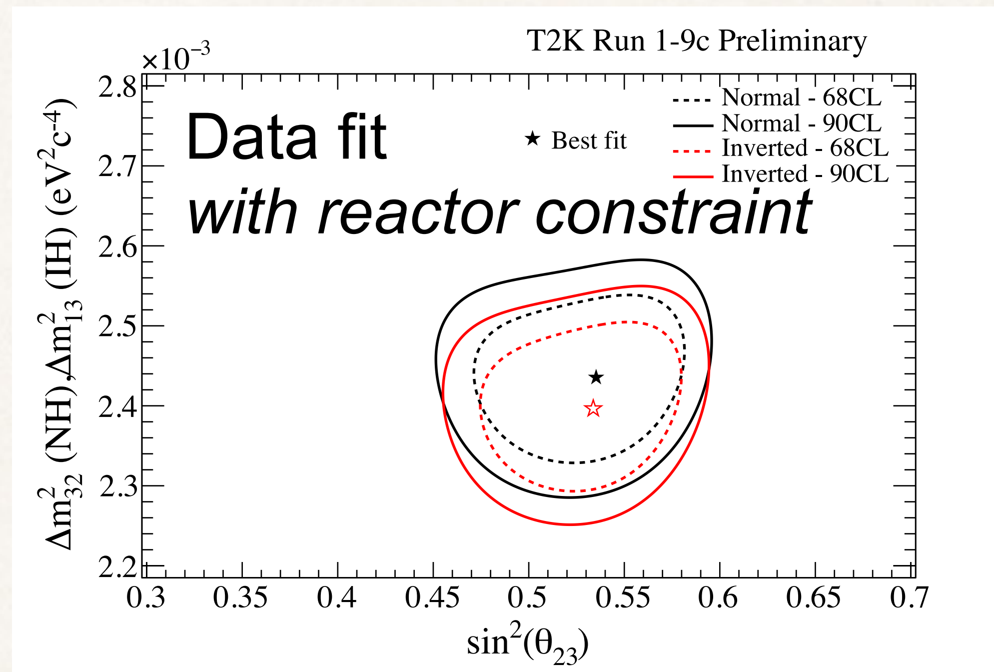
First NOνA antineutrino data

Talk by M. Sánchez

neutrino + antineutrino fit



New T2K antineutrino data

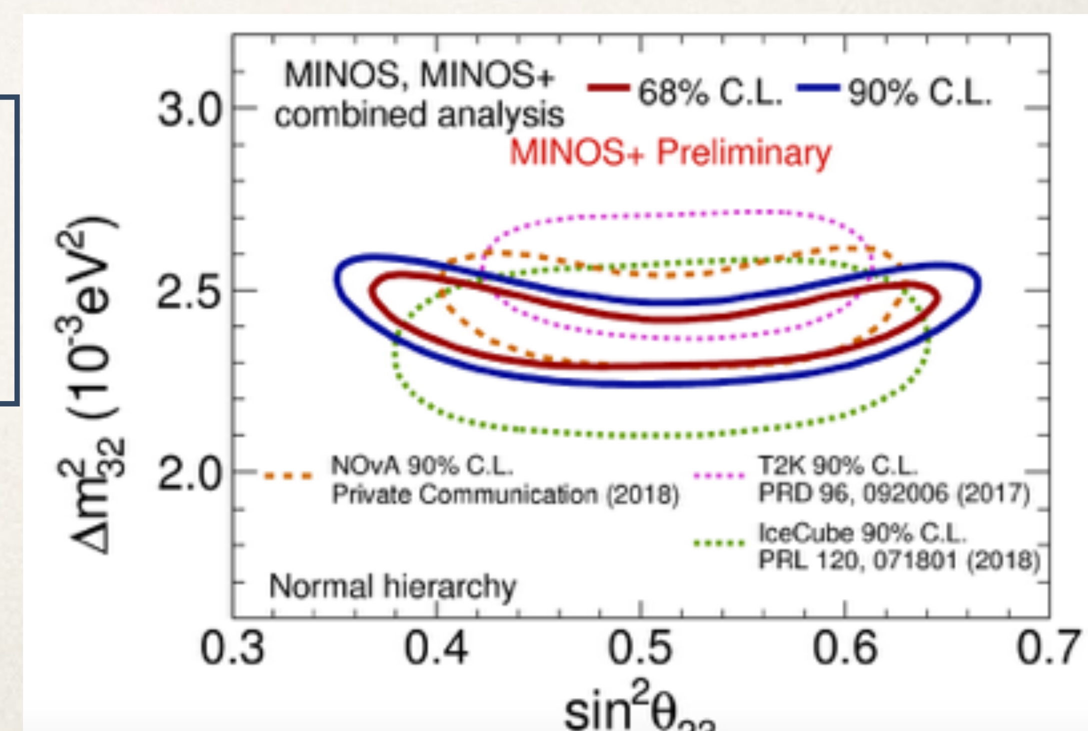


Monday
June 4th

Talk by
M.Wascko

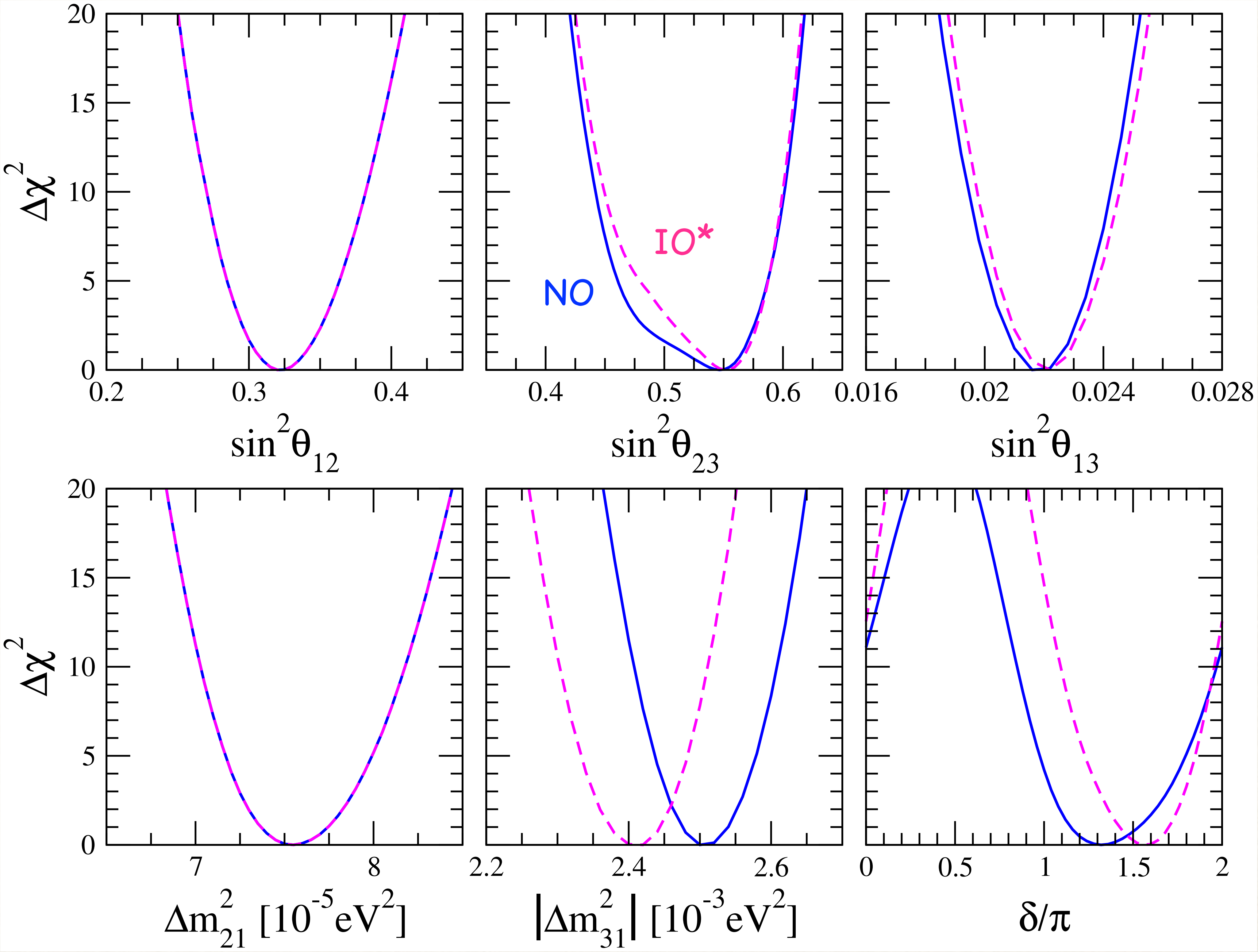
New combined analysis MINOS/ MINOS+

Talk by
A. Aurisano



Global fit to neutrino oscillations

https://globalfit.astroparticles.es/



deSalas et al, 1708.01186

* wrt local minimum in IO

Global fit to neutrino oscillations

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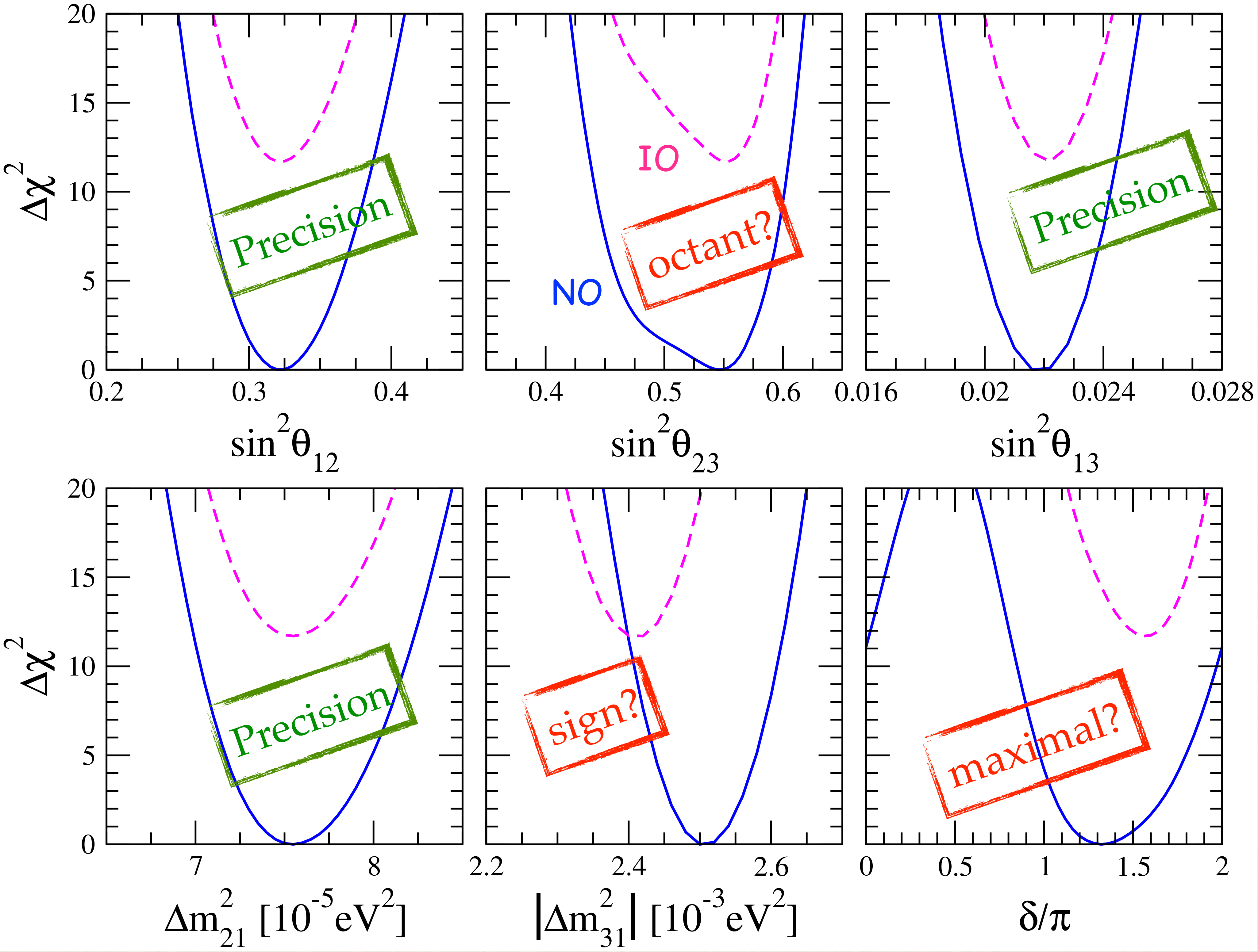


deSalas et al, 1708.01186

Precision measurements

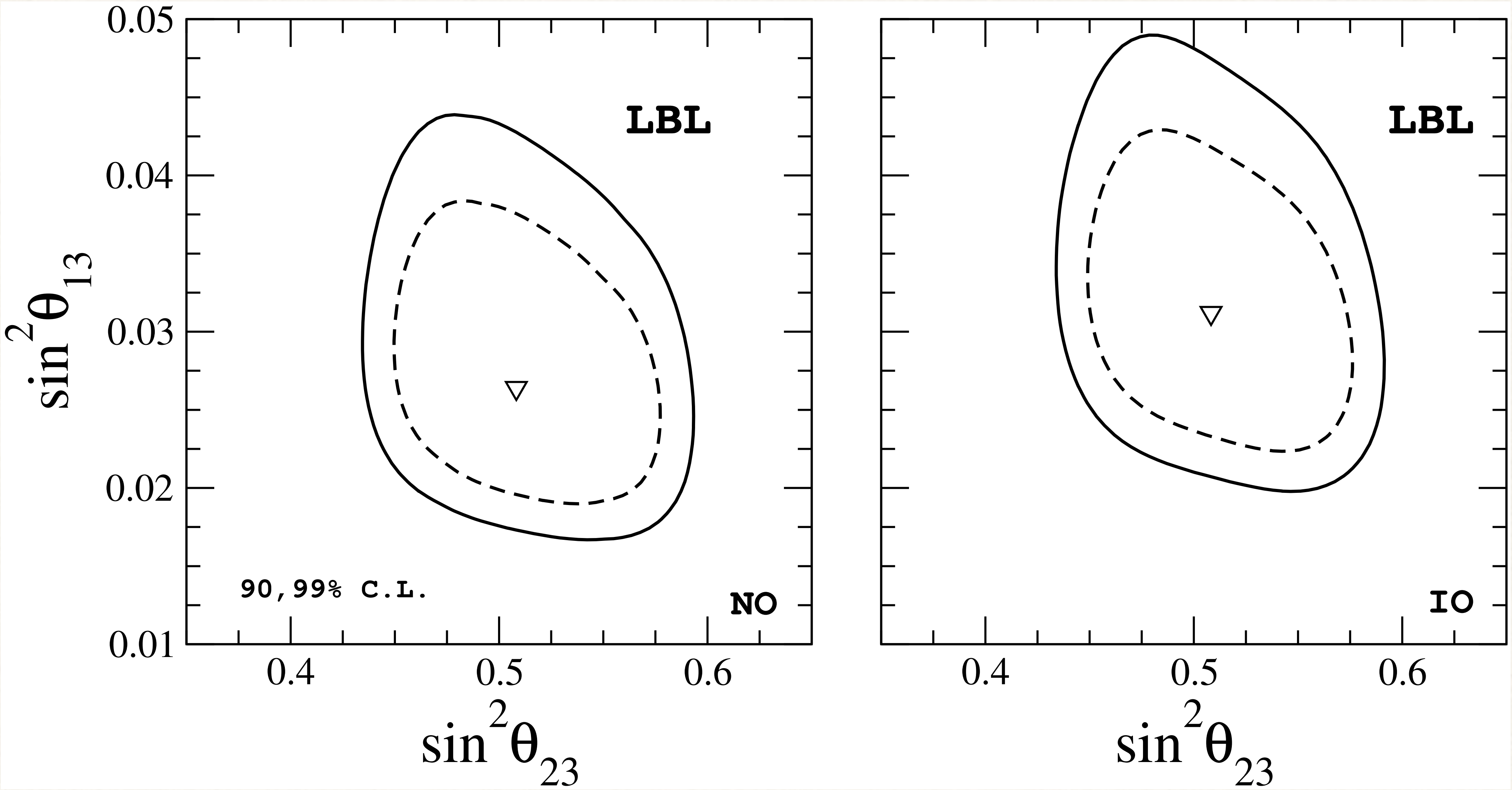
https://globalfit.astroparticles.es/

parameter	best fit $\pm$ 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NO)	2.50$\pm$0.03	2.41–2.60	1.3%
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

deSalas et al, 1708.01186 (May 2018)

Octant of the atmospheric angle

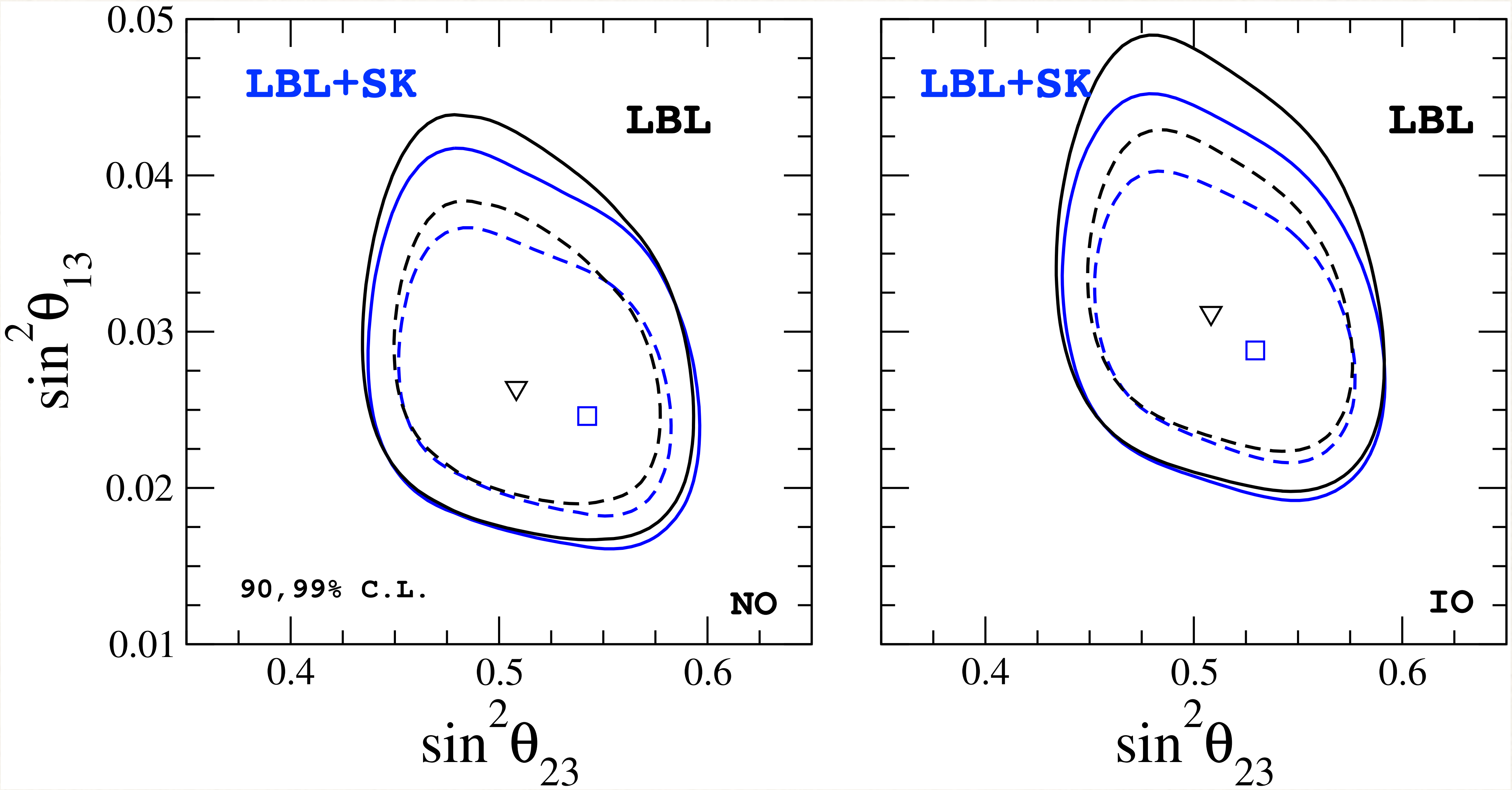
deSalas et al, 1708.01186



- combination of LBL experiments prefer θ_{23} close to maximal mixing for both orderings

Octant of the atmospheric angle

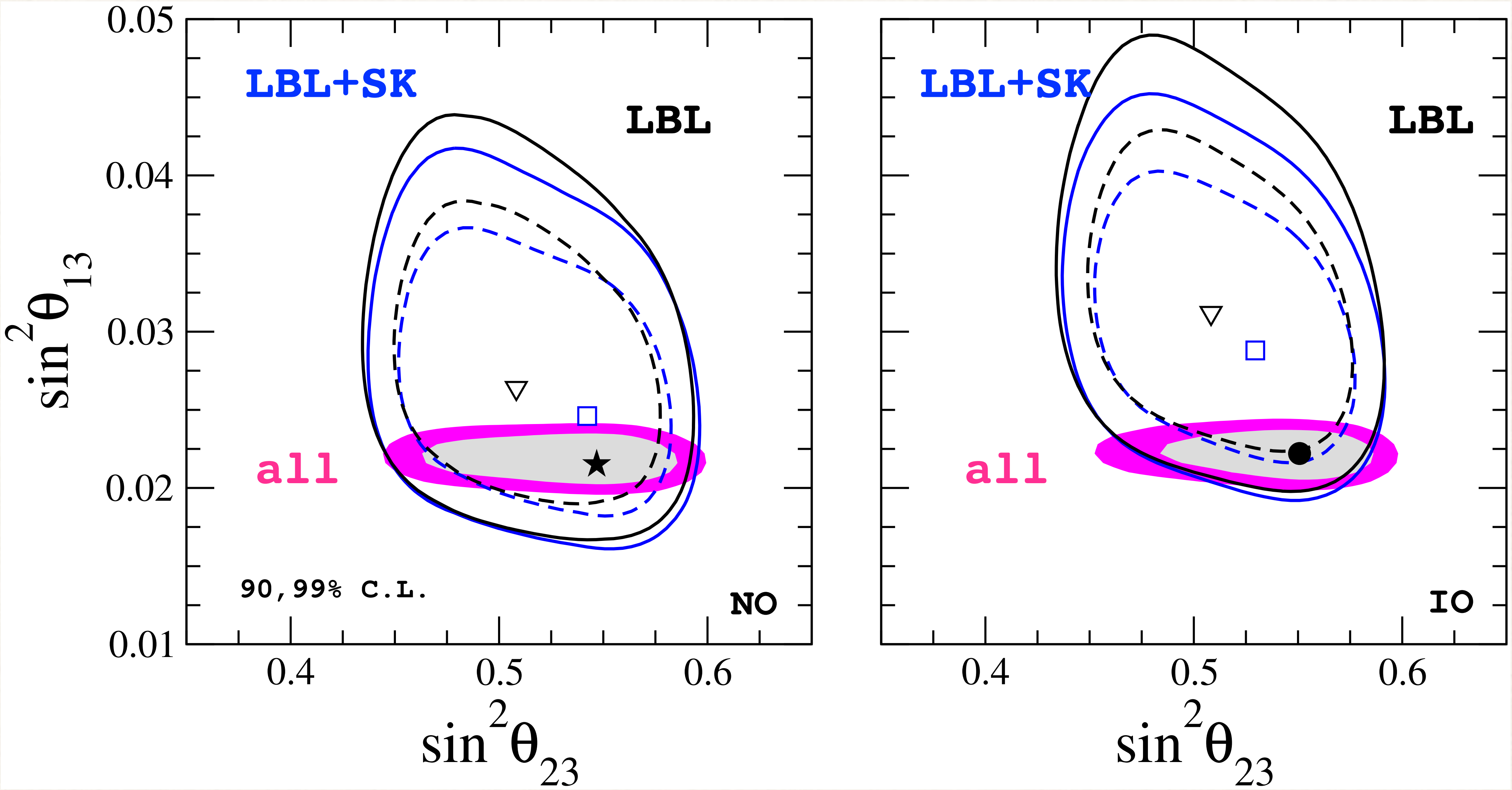
deSalas et al, 1708.01186



- combination of LBL experiments prefer θ_{23} close to maximal mixing for both orderings
- Super-K atmospheric data shift bfp to higher values: $\sin^2\theta_{23} = 0.54$ (0.53) for NO (IO)

Octant of the atmospheric angle

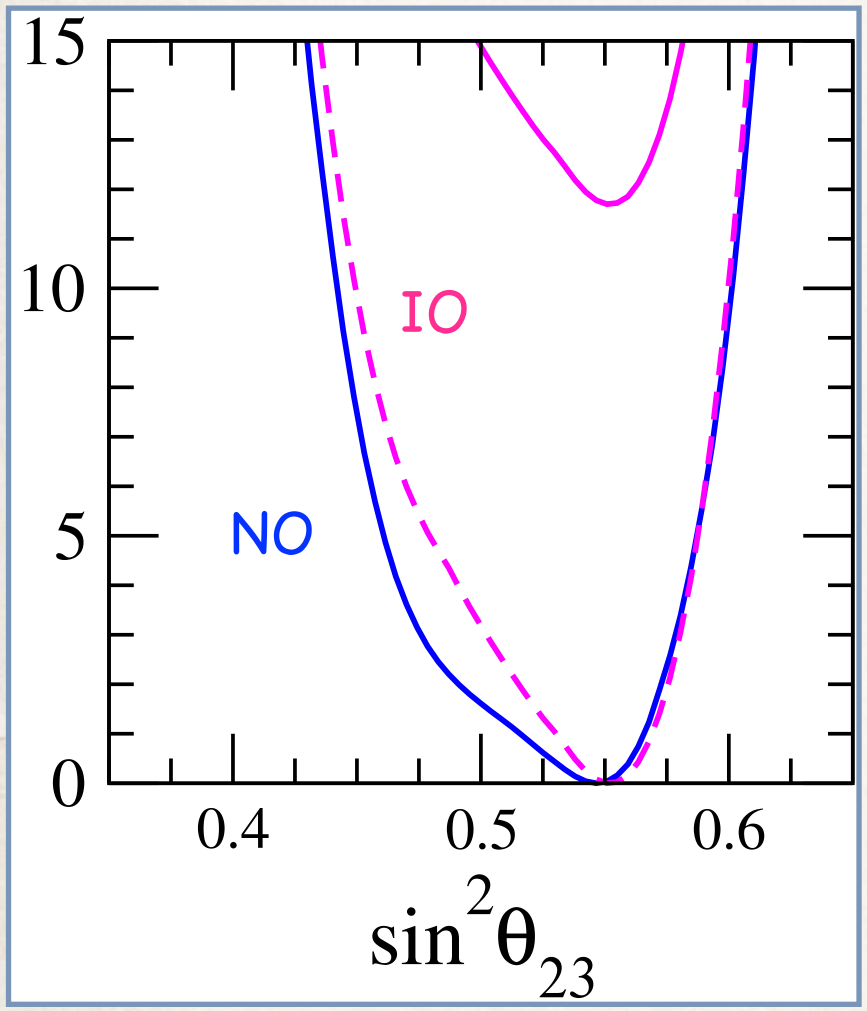
deSalas et al, 1708.01186



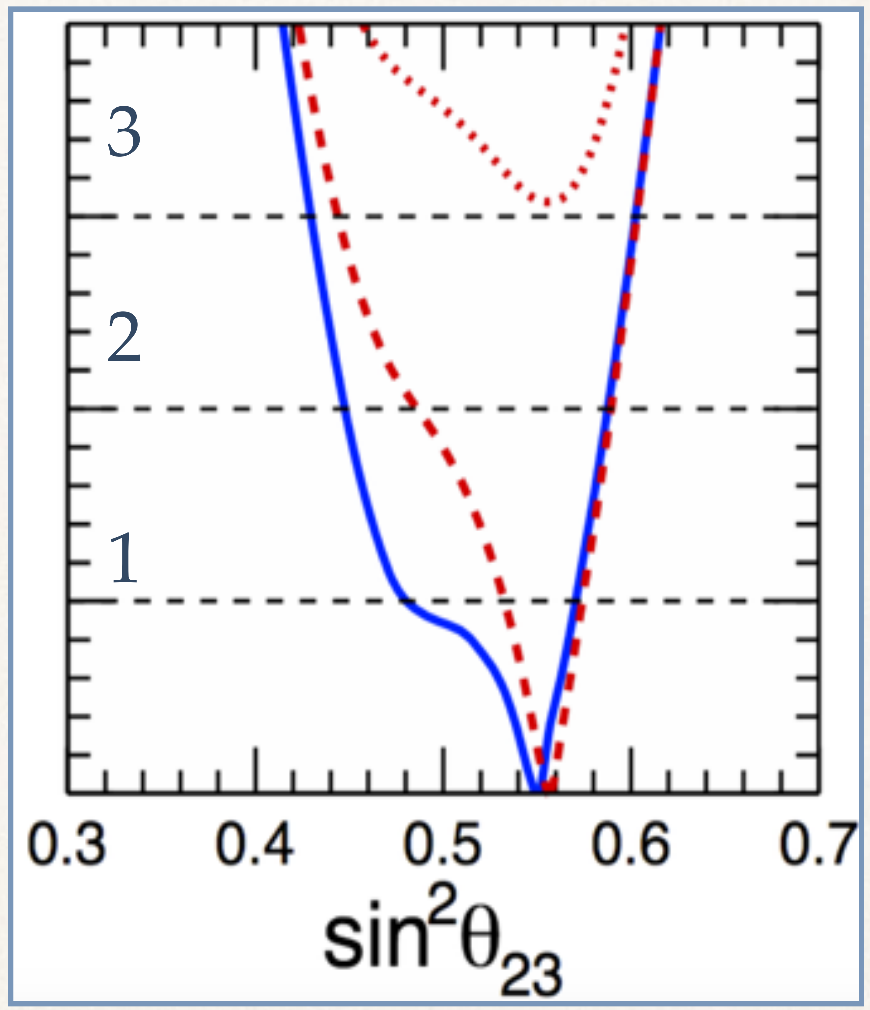
- combination of LBL experiments prefer θ_{23} close to maximal mixing for both orderings
- Super-K atmospheric data shift bfp to higher values: $\sin^2\theta_{23} = 0.54$ (0.53) for NO (IO)
- combination with SBL reactors pushes atmospheric angle to $\sin^2\theta_{23} \simeq 0.55$

Octant of the atmospheric angle

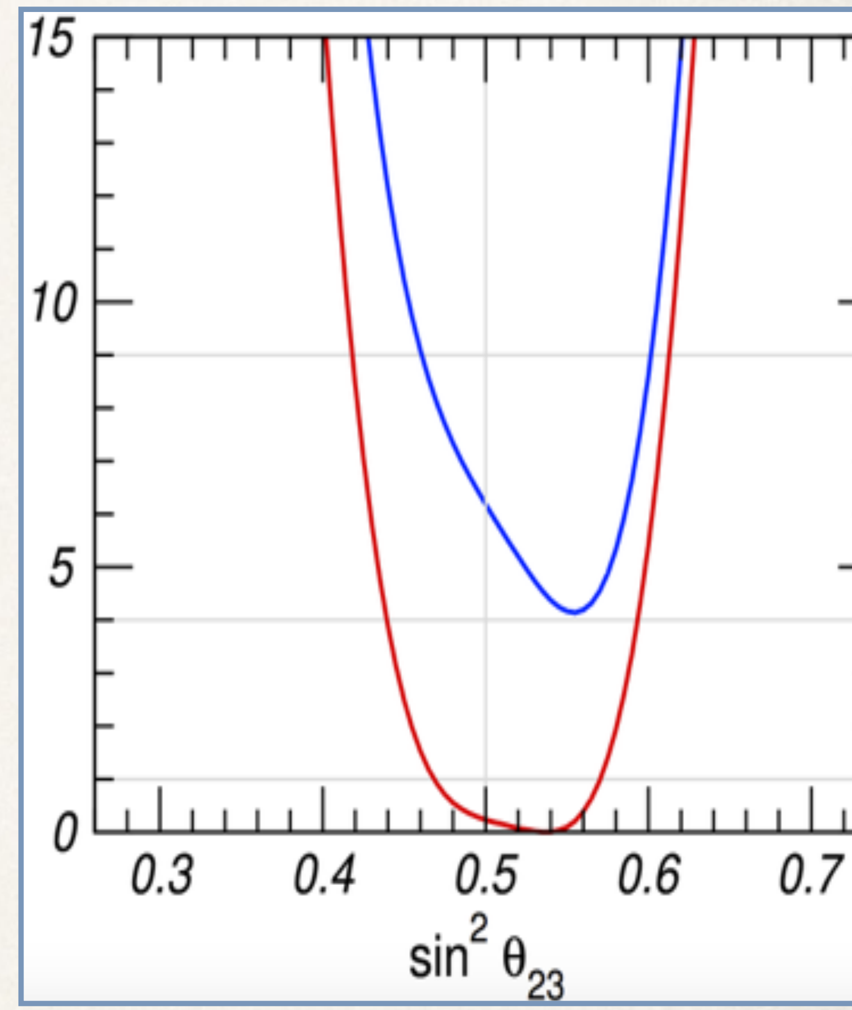
$\Delta\chi^2$, Valencia [1708.01186]



Nσ, Bari [1804.09678]



$\Delta\chi^2$, NuFit v3.2



SK-atm not included

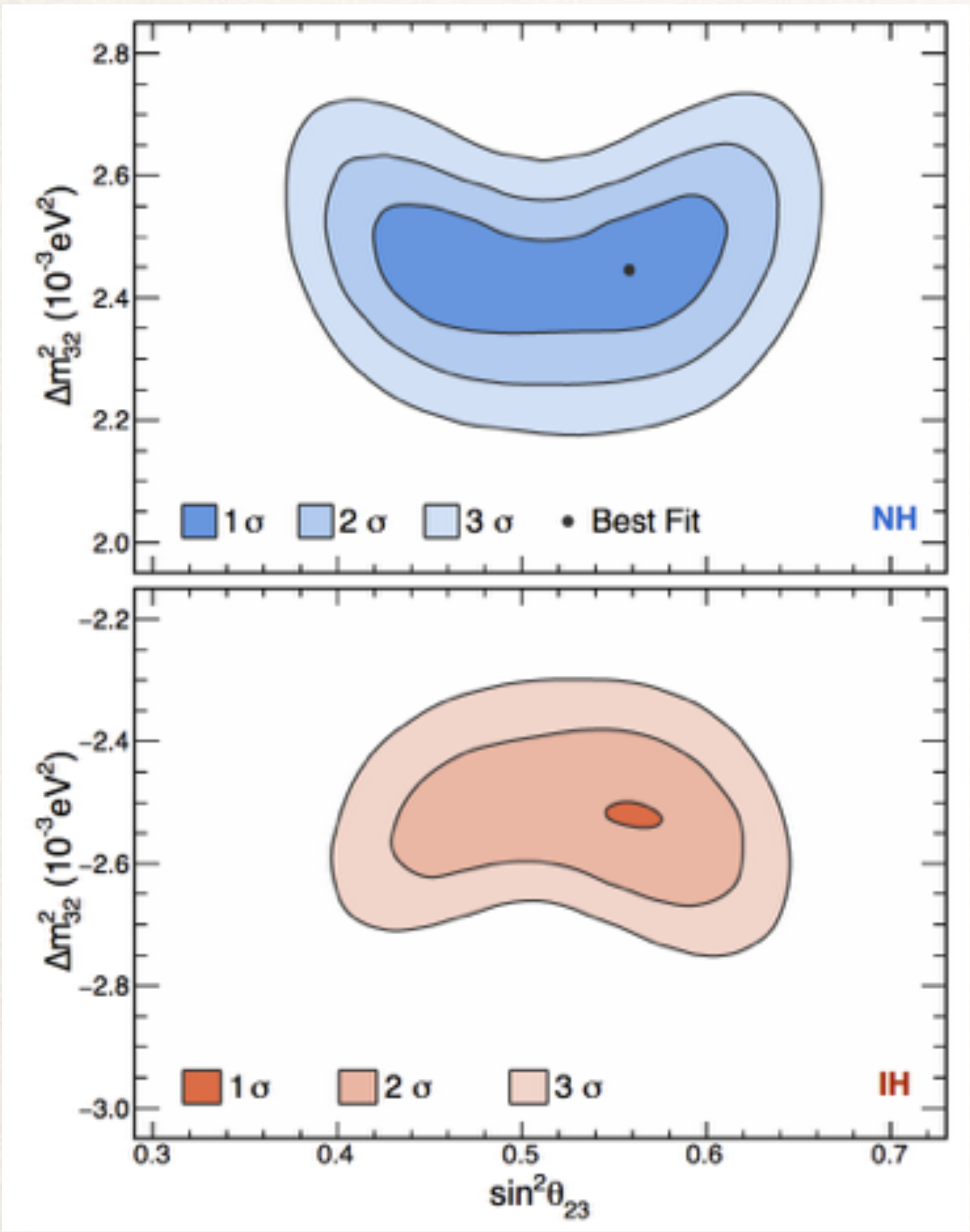
- General agreement in the preferred octant of global neutrino data
  - Values at the first octant allowed with $\Delta\chi^2 \geq 1.6$ (3.2) for NO (IO)

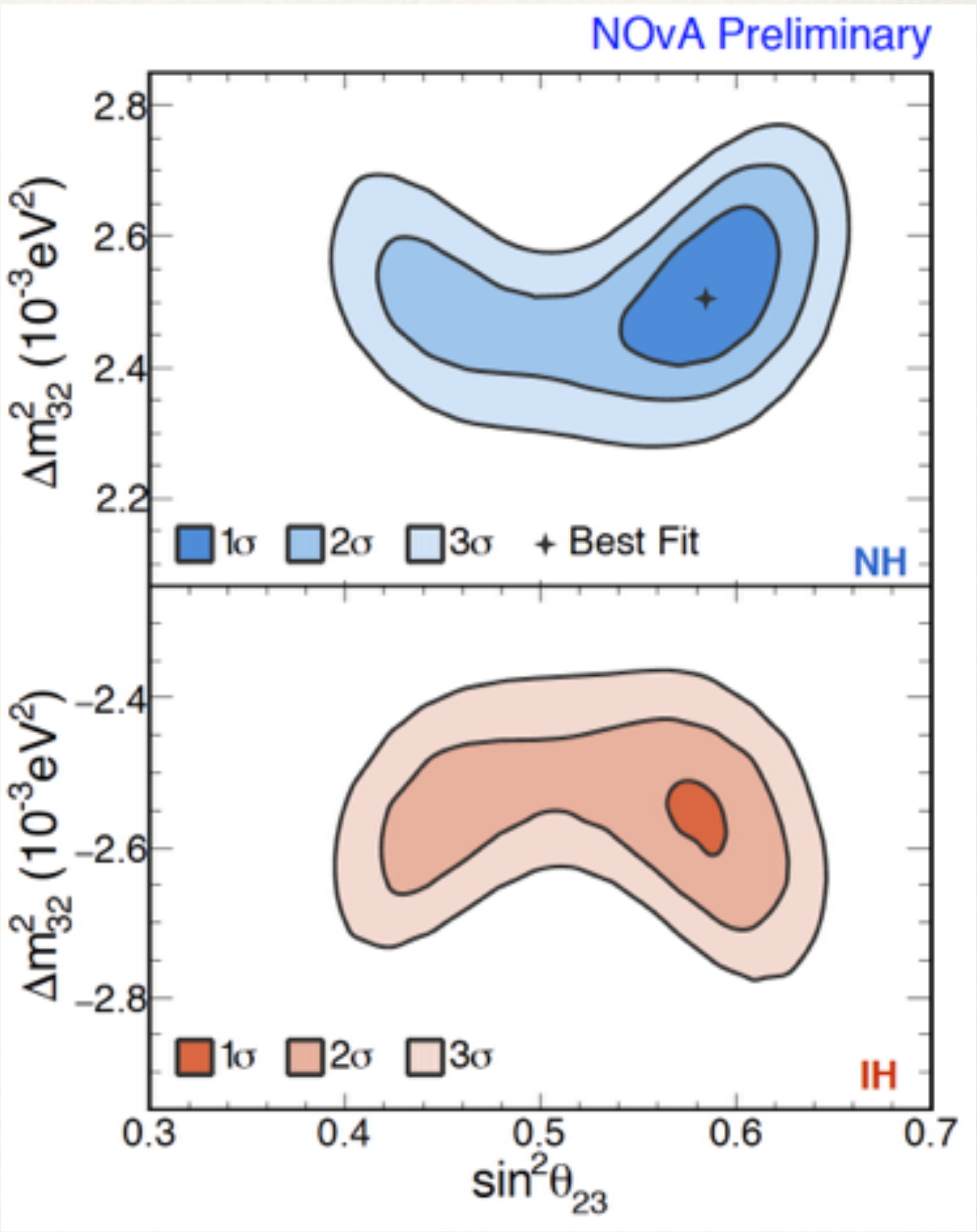
New results on θ_{23} octant

neutrino only

NOvA

neutrino + antineutrino





Acero et al, 1806.00096

Talk by M. Sánchez

more disfavoured lower octant?

Measurement of the CP phase

LBL experiments prefer $\delta \simeq 3\pi/2$ due to better agreement with observed ν_e events

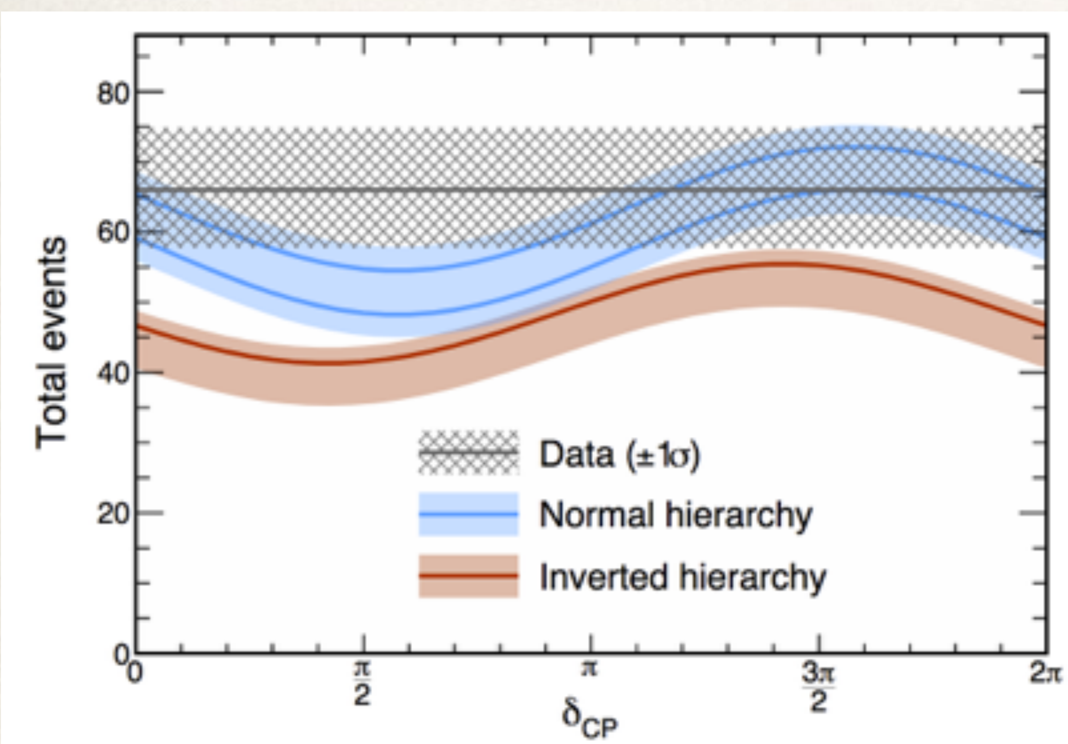
T2K

Mark Hartz, KEK Colloquium

Sample	Predicted Rates				Observed
	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Rates
CCQE 1-Ring e-like FHC	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like FHC	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like RHC	7.93	9.04	10.04	8.93	7

NOνA

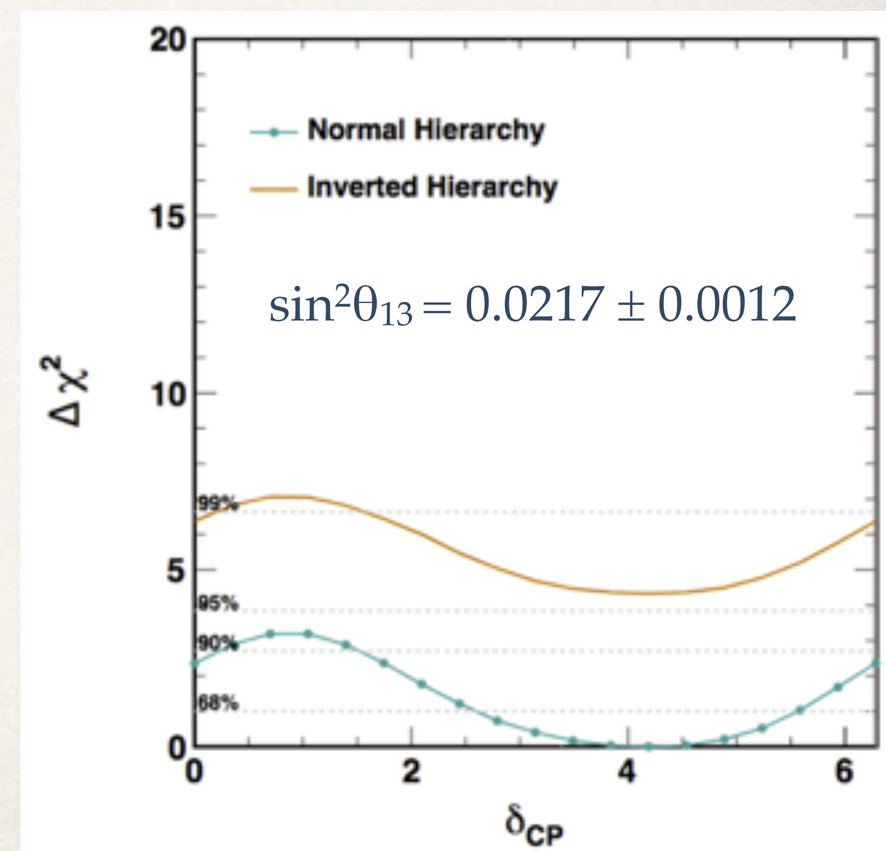
Acero et al, 1806.00096



66 ν_e events observed

Super-K

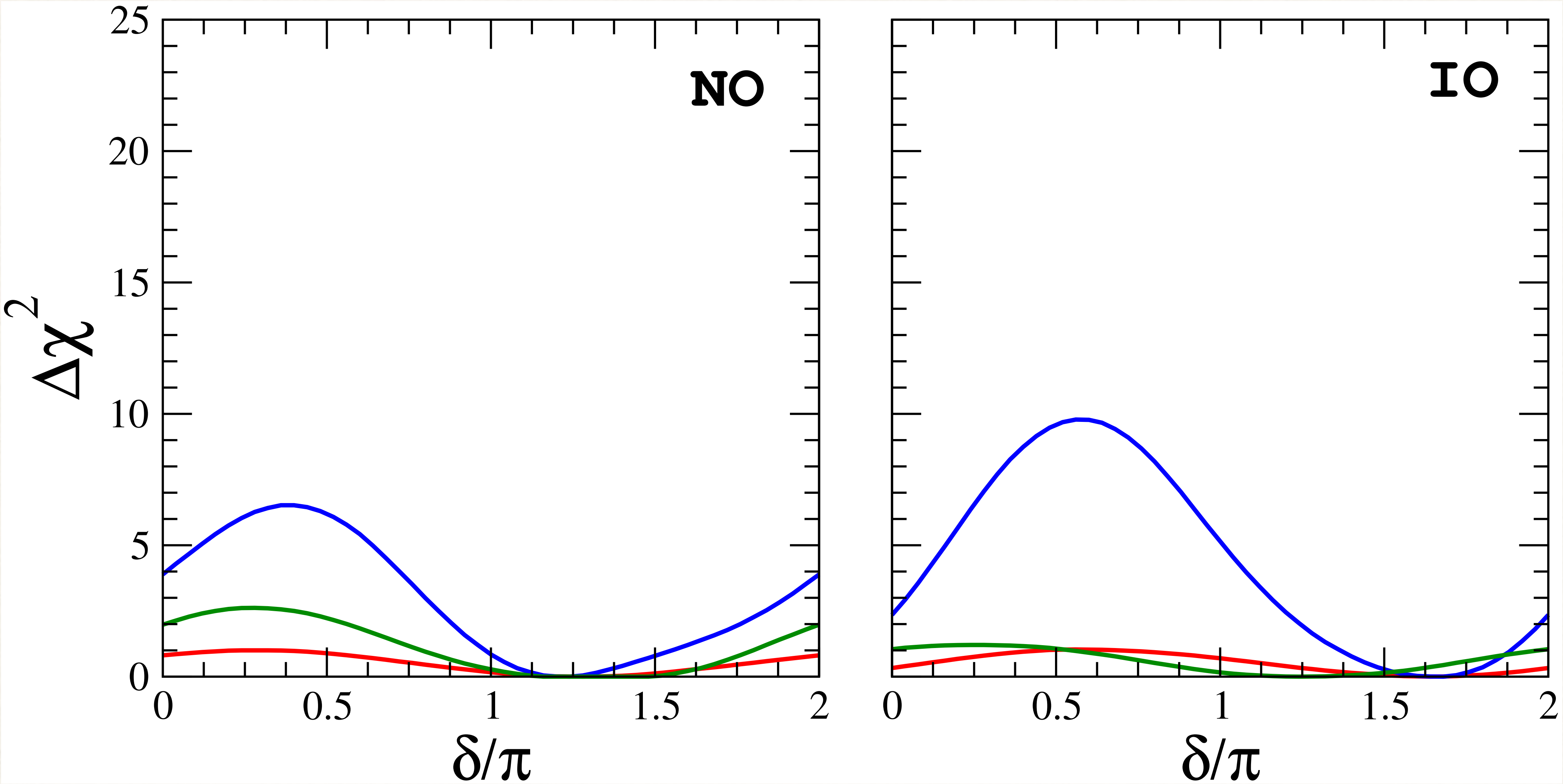
- $\delta = 1.5\pi$ for NO
- $\delta = 1.2\pi$ for IO
- preference driven mostly by sub-GeV e-like samples



SK Collab. PRD97 (2018)

Measurement of the CP phase

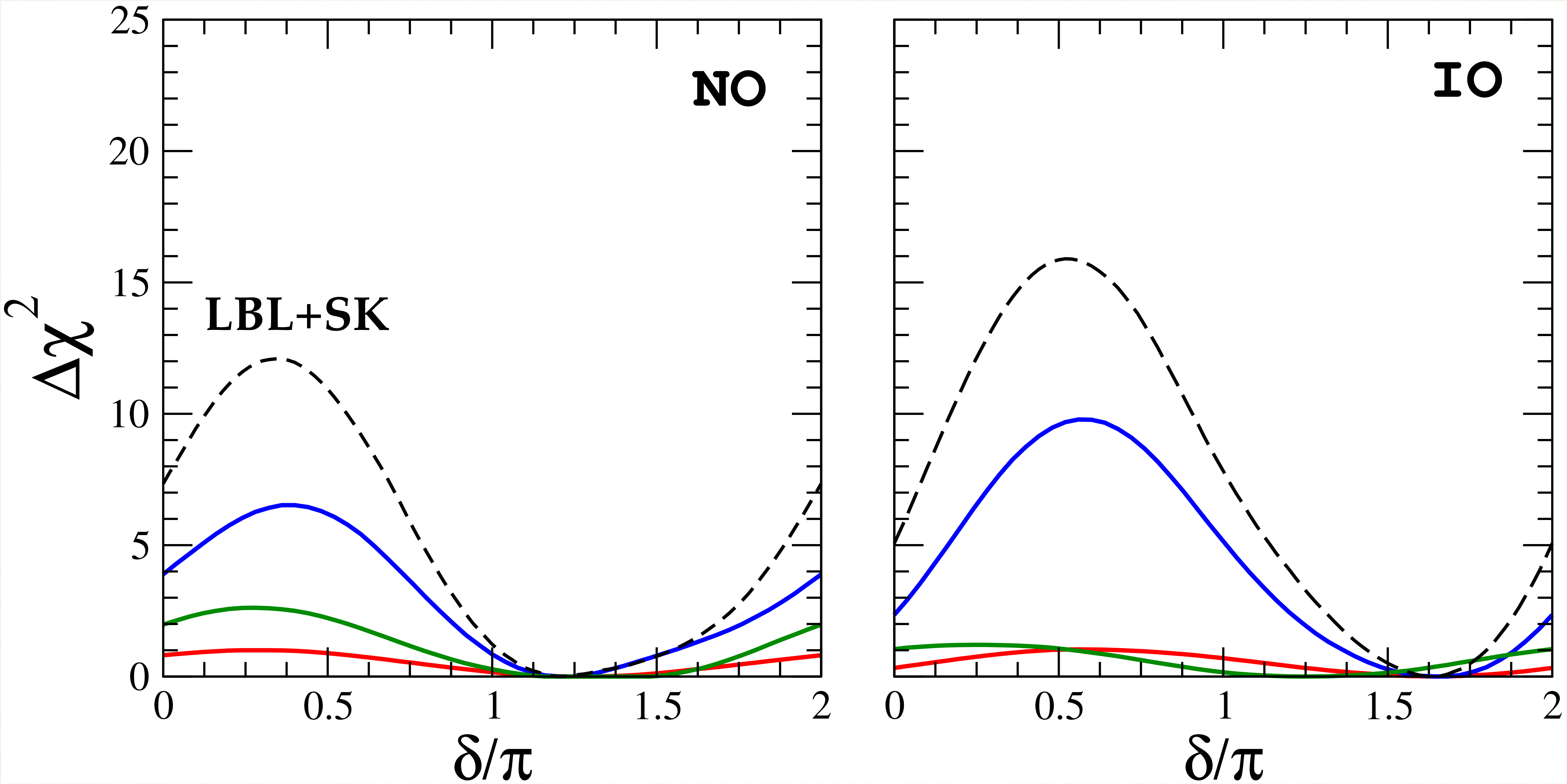
deSalas et al, 1708.01186



- **T2K**, **NOvA** and **Super-K** prefer $\pi < \delta < 2\pi$ (as well as NO)

Measurement of the CP phase

deSalas et al, 1708.01186



- **T2K**, **NOvA** and **Super-K** prefer $\pi < \delta < 2\pi$ (as well as NO)
- The combination of LBL and Super-K enhances rejection against $\delta = \pi/2$

Measurement of the CP phase

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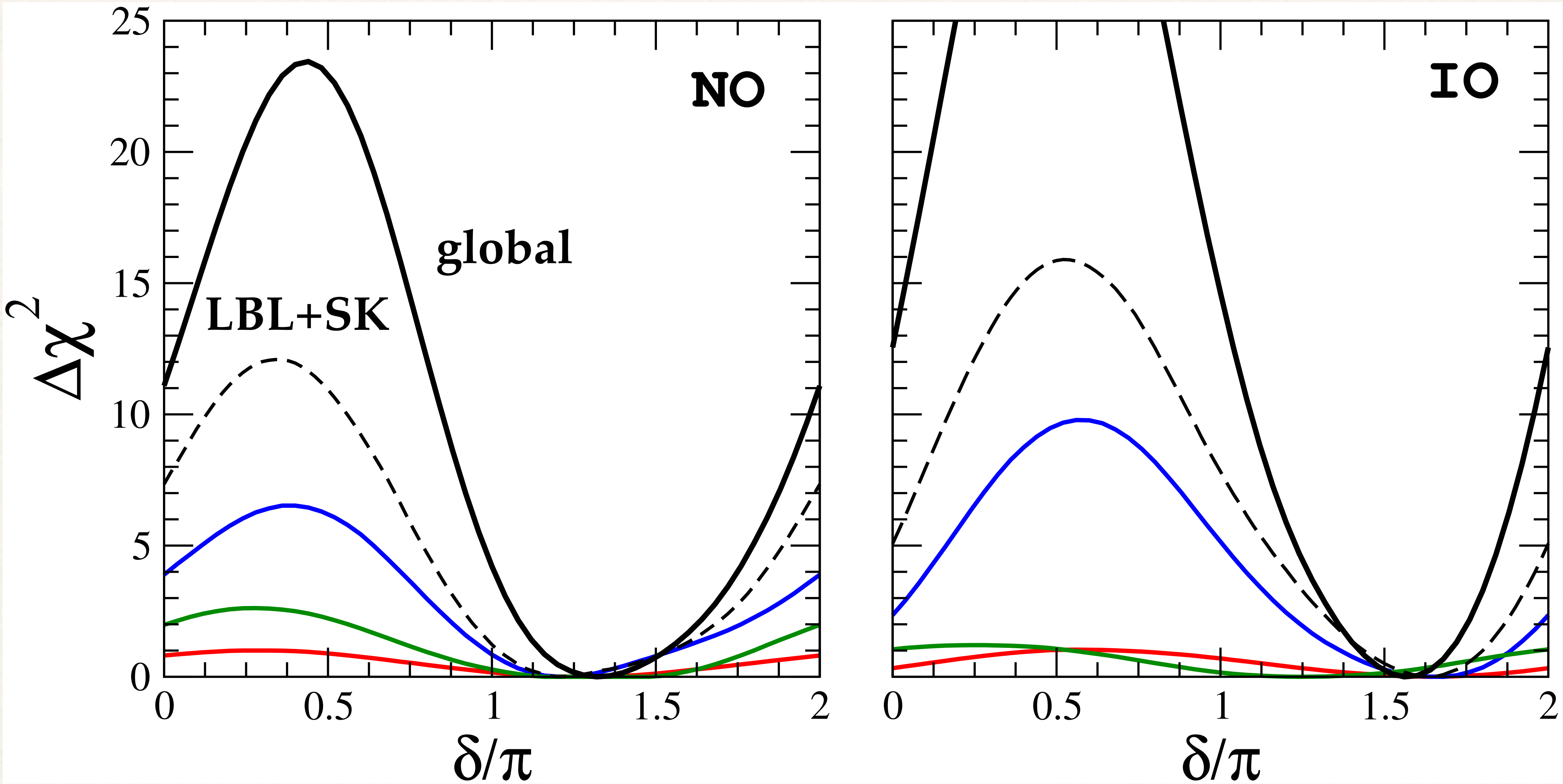
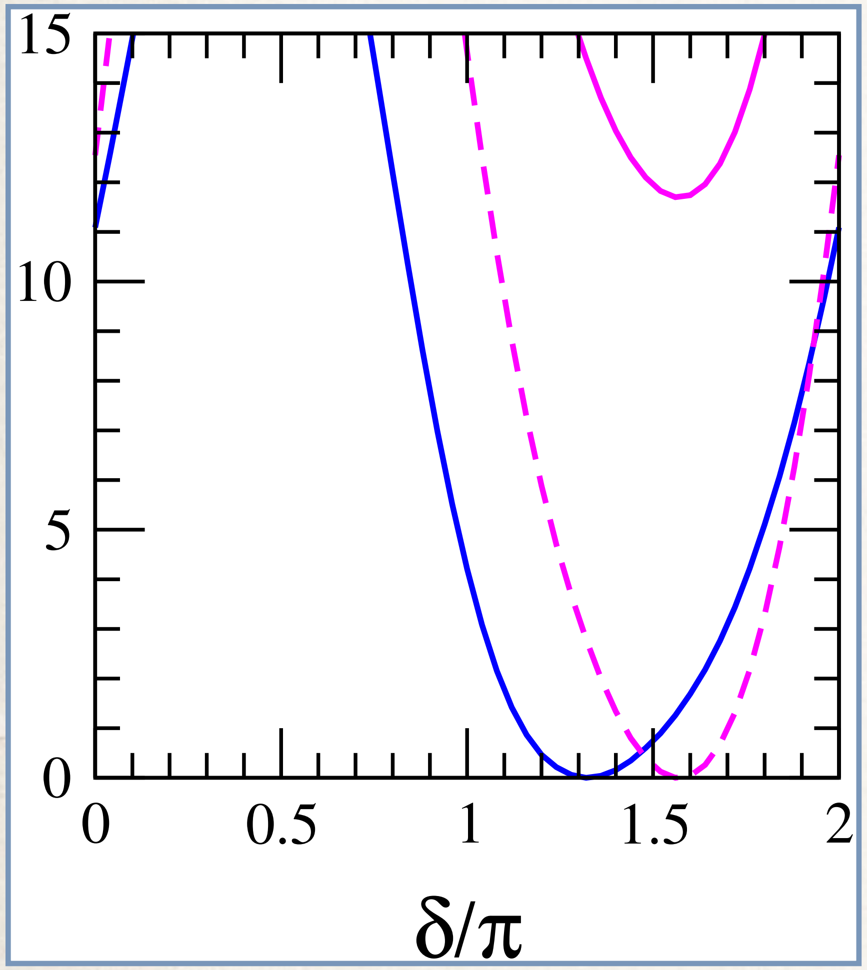


- **T2K**, **NOvA** and **Super-K** prefer $\pi < \delta < 2\pi$ (as well as NO)
- The combination of LBL and Super-K enhances rejection against $\delta = \pi/2$
- From the global analysis, $\delta = \pi/2$ is disfavoured at 4.8σ (6.1σ) for NO (IO)

Measurement of the CP phase

$\Delta\chi^2$, Valencia [1708.01186]



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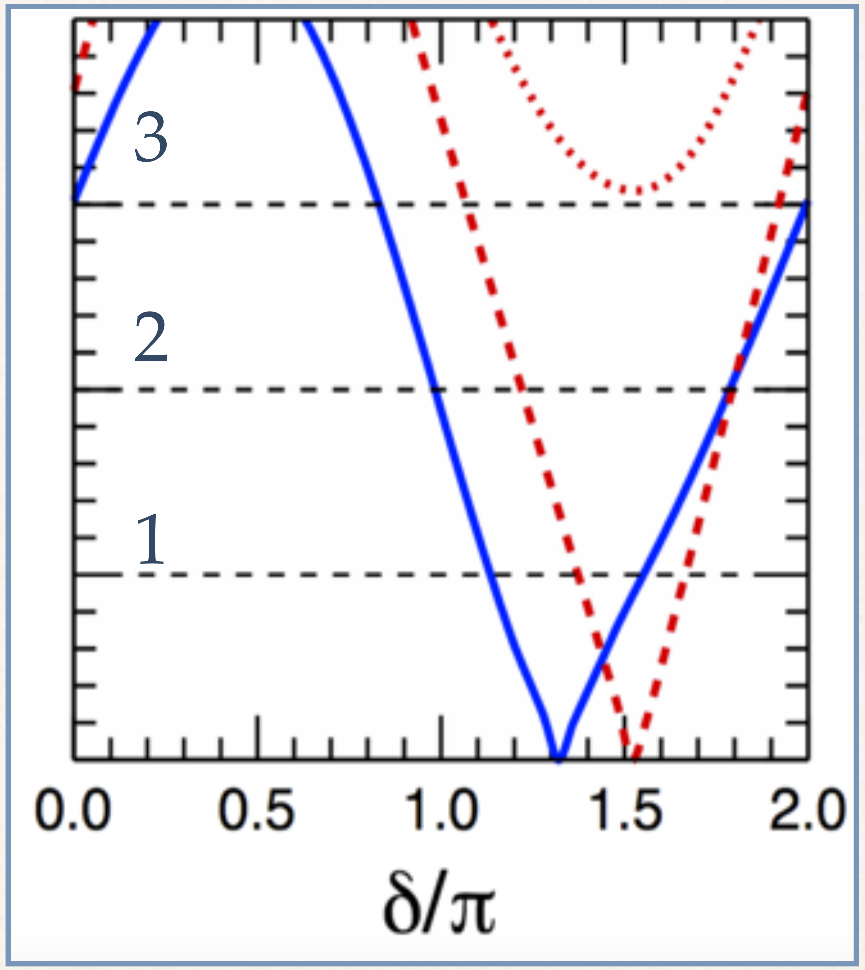
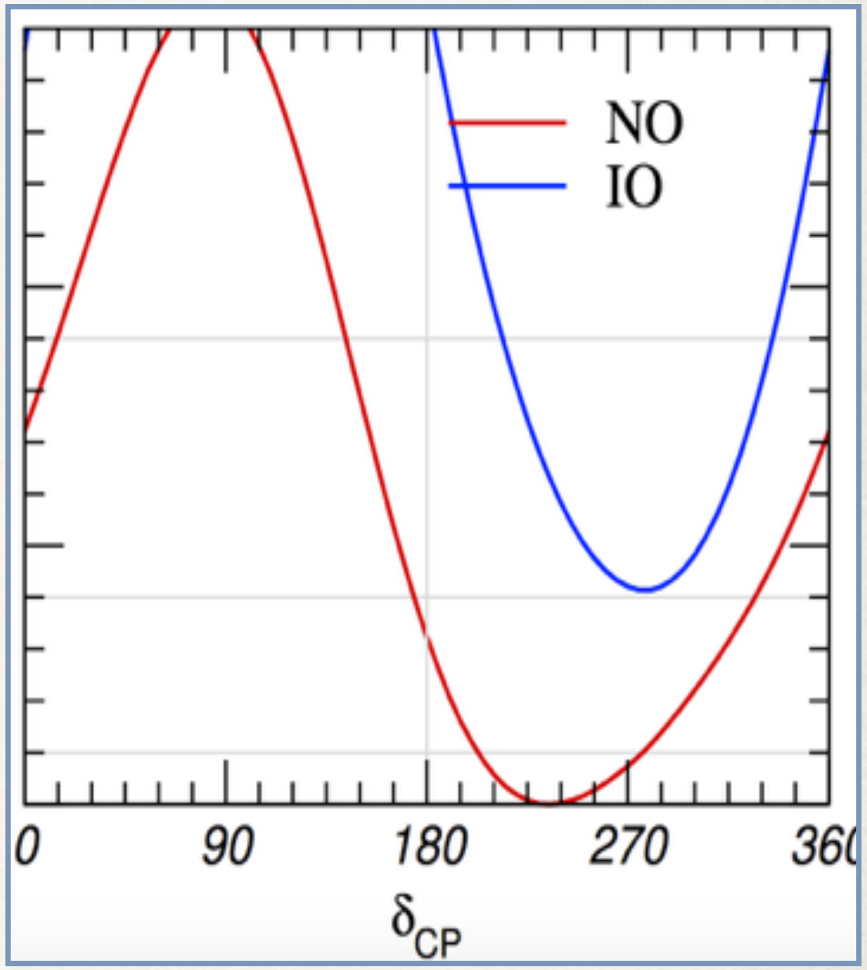


$\Delta\chi^2$, NuFit v3.2

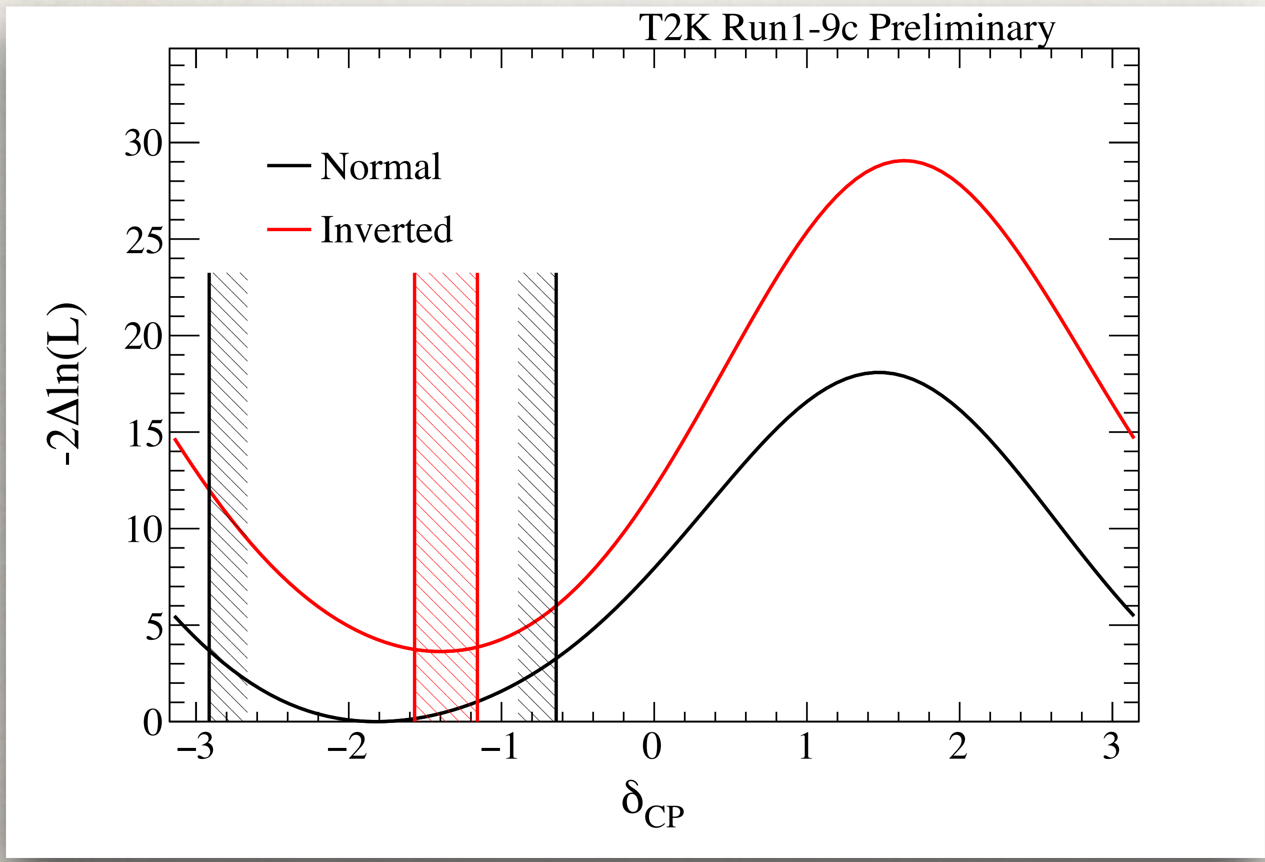


SK-atm not included

- preference for $\pi < \delta < 2\pi$, with CP conservation allowed at 2σ (3.8σ) for NO (IO)
- preferred value depends on mass ordering: $\delta_{NO}=1.32\,\pi$ $\delta_{IO}=1.56\,\pi$

New results on the CP phase

T2K **Talk by M.Wascko**

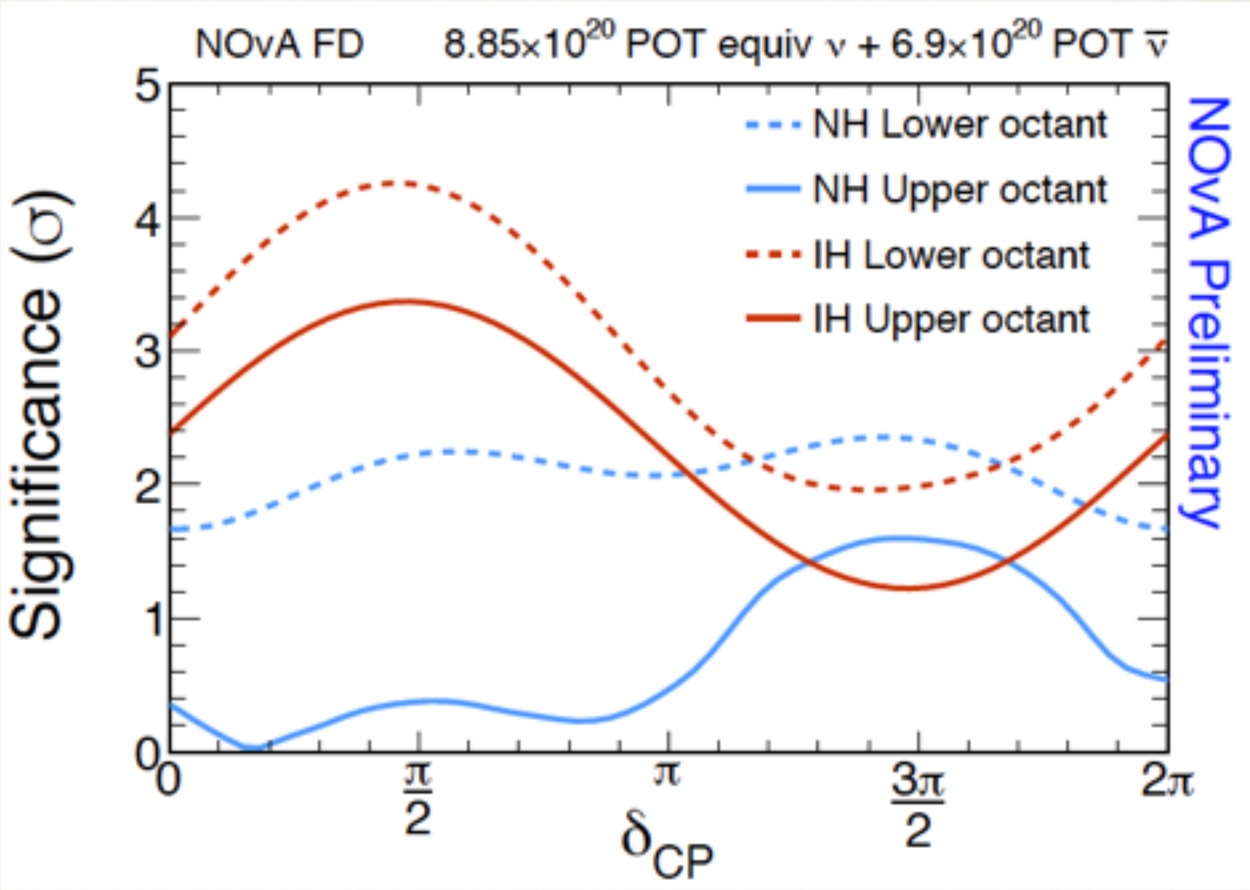


(fit with reactor constraint)

CP conservation more disfavoured
⇒ $\delta = 0, \pi$ outside 2σ region for NO & IO

?

NOνA **Talk by M. Sánchez**

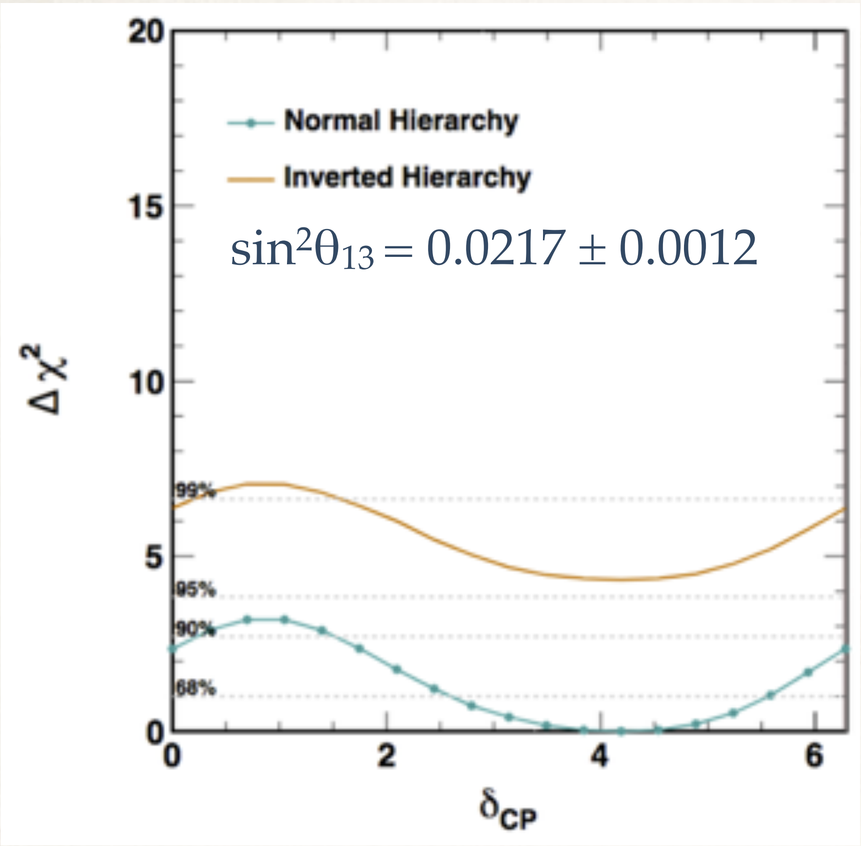


Best fit: δ_{NO}=0.17 δ_{IO}~1.5π

⇒ improved status for $\delta = 0$

Sensitivity to the mass ordering

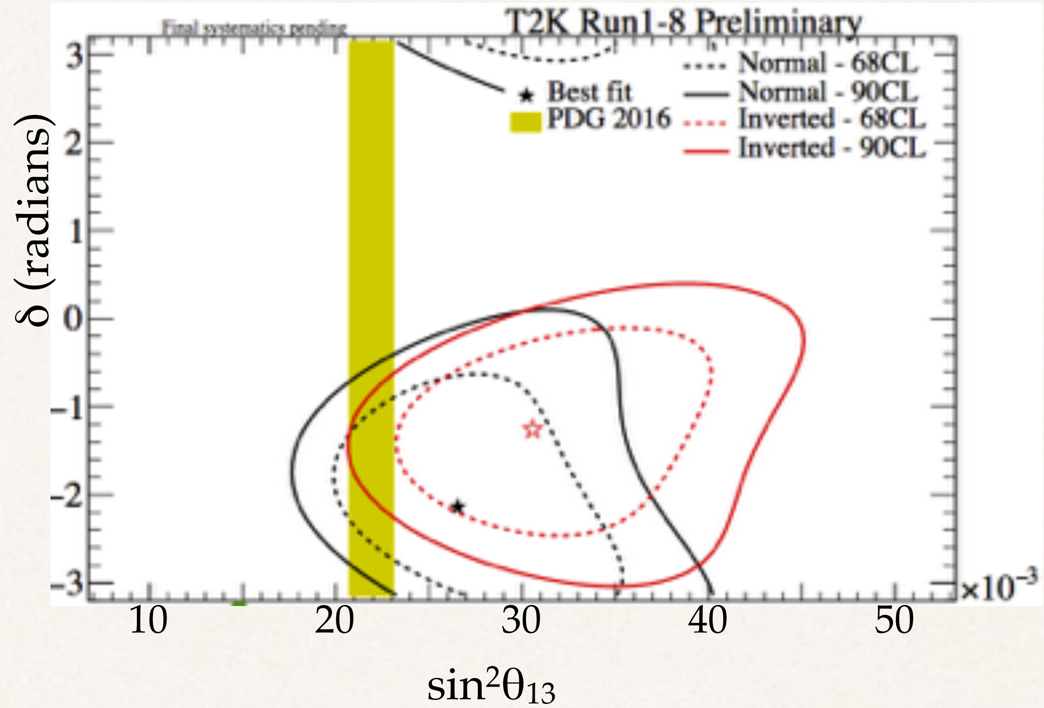
Super-Kamiokande



SK Collab. PRD97 (2018)

$\Delta\chi^2$ (IO-NO) = 4.34 (3.89)

⇒ driven by excess of upward going e-like events

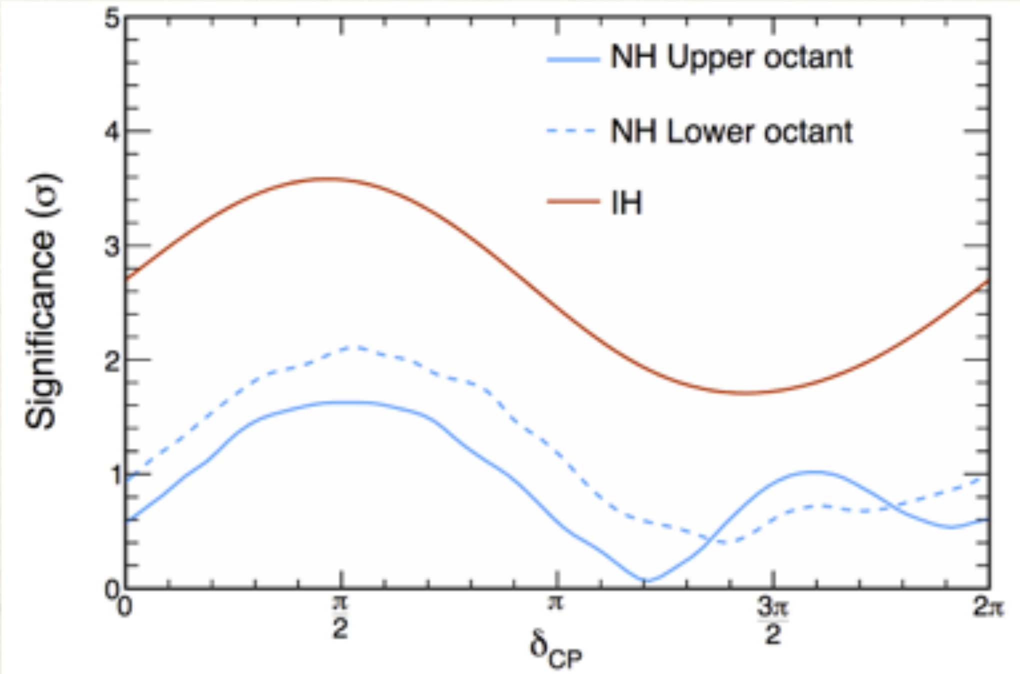


T2K

M. Hartz, KEK Colloquium

⇒ larger tension with reactors for IO

⇒ IO disfavored at ~2σ



NOνA

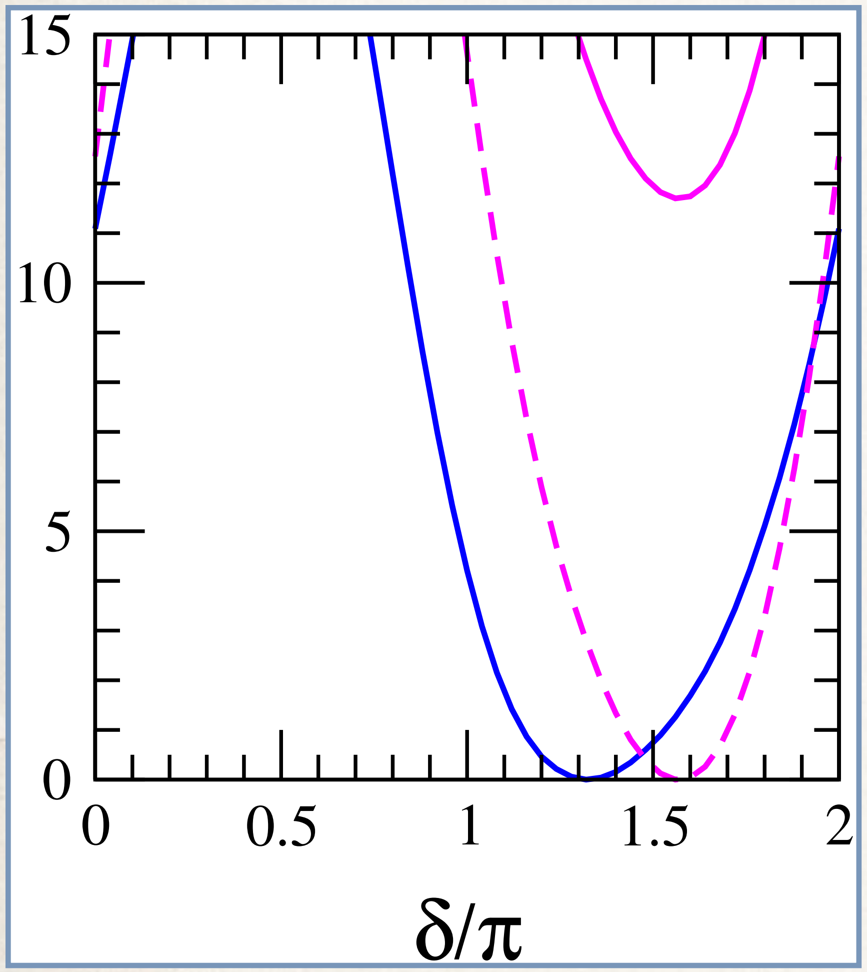
Acero et al, 1806.00096

⇒ better agreement with obs events for NO

⇒ IO disfavored at ~2σ

Sensitivity to the mass ordering

$\Delta\chi^2$, Valencia [1708.01186]



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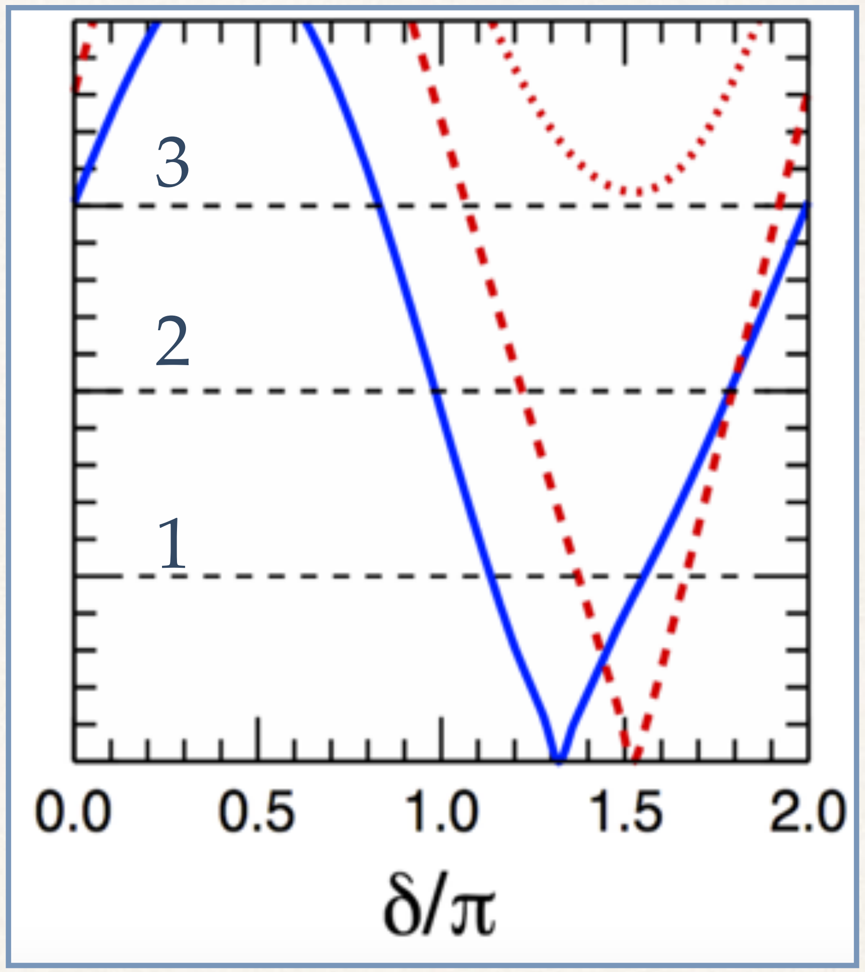
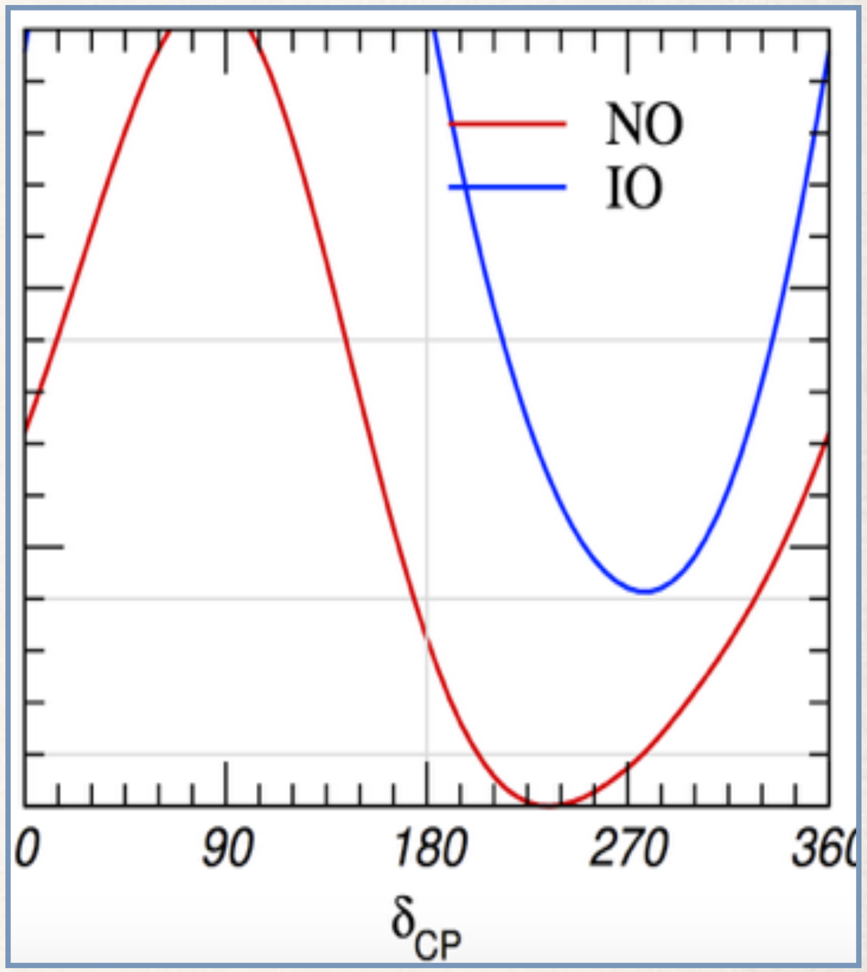


$\Delta\chi^2$, NuFit v3.2



IO disfavoured at 3.4σ

IO disfavoured at 3.1σ

IO disfavoured at 2σ*

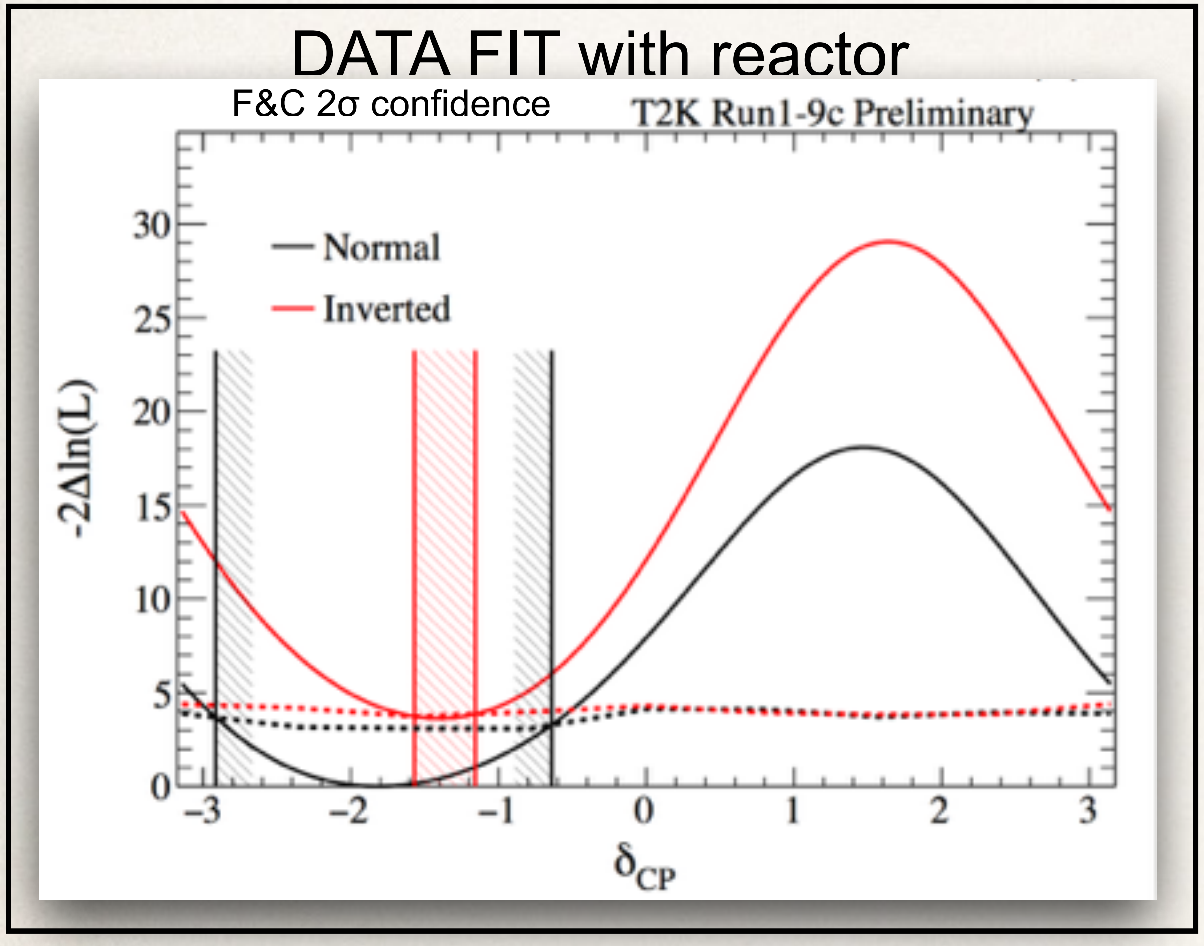
Preference for NO at ~3σ when all data are considered

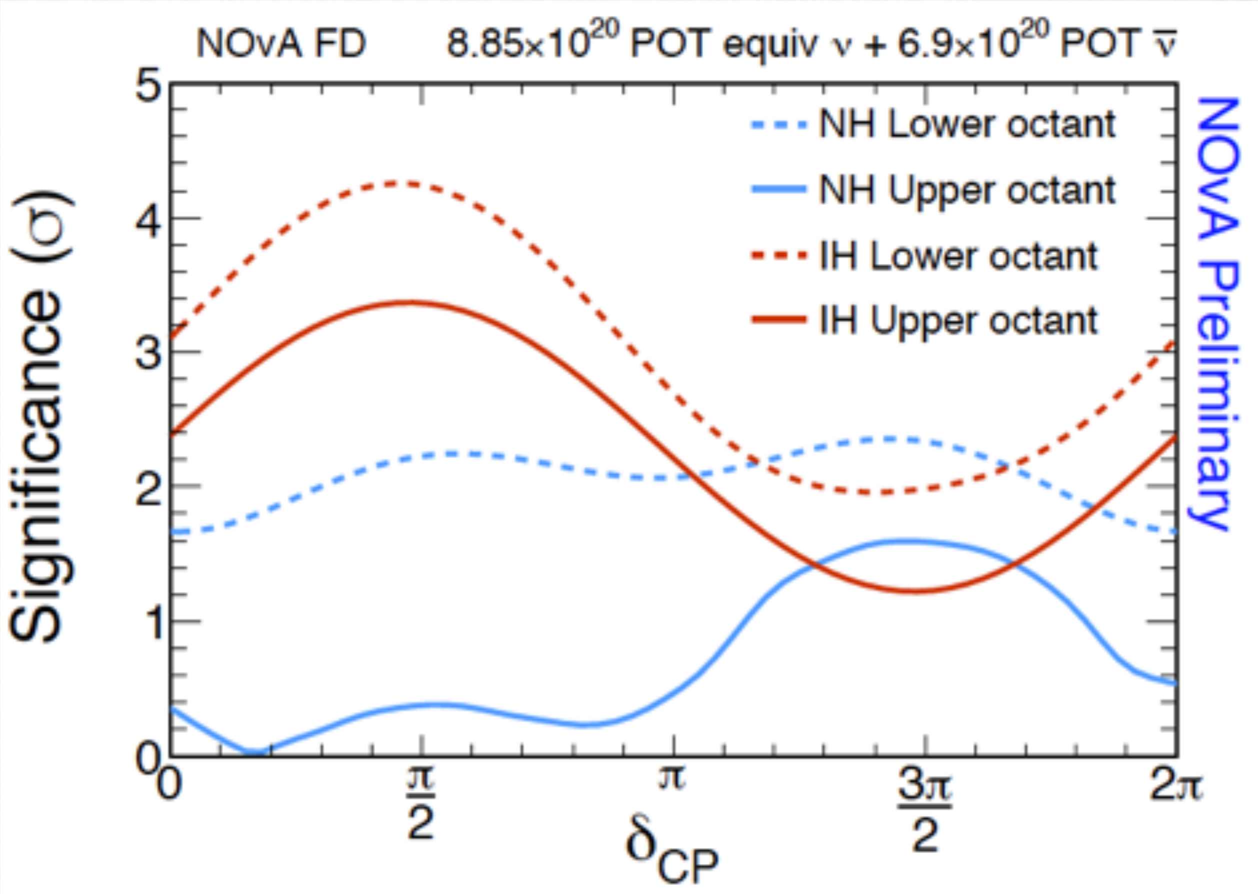
*SK-atm not included

New results on mass ordering

T2K **Talk by M.Wascko**

NOνA **Talk by M. Sánchez**





⇒ IO disfavored at ~2σ (with reactor constraint)

⇒ IO disfavored at 1.8σ (with reactor constraint)

similar result to pre-Nu2018: no big changes expected

Other inputs for mass ordering?

ν-oscillations: Δm^2_{ij}

cosmology: Σm_i

$0\nu\beta\beta$: $m_{\beta\beta}$

Case A
(m_1, m_2, m_3)

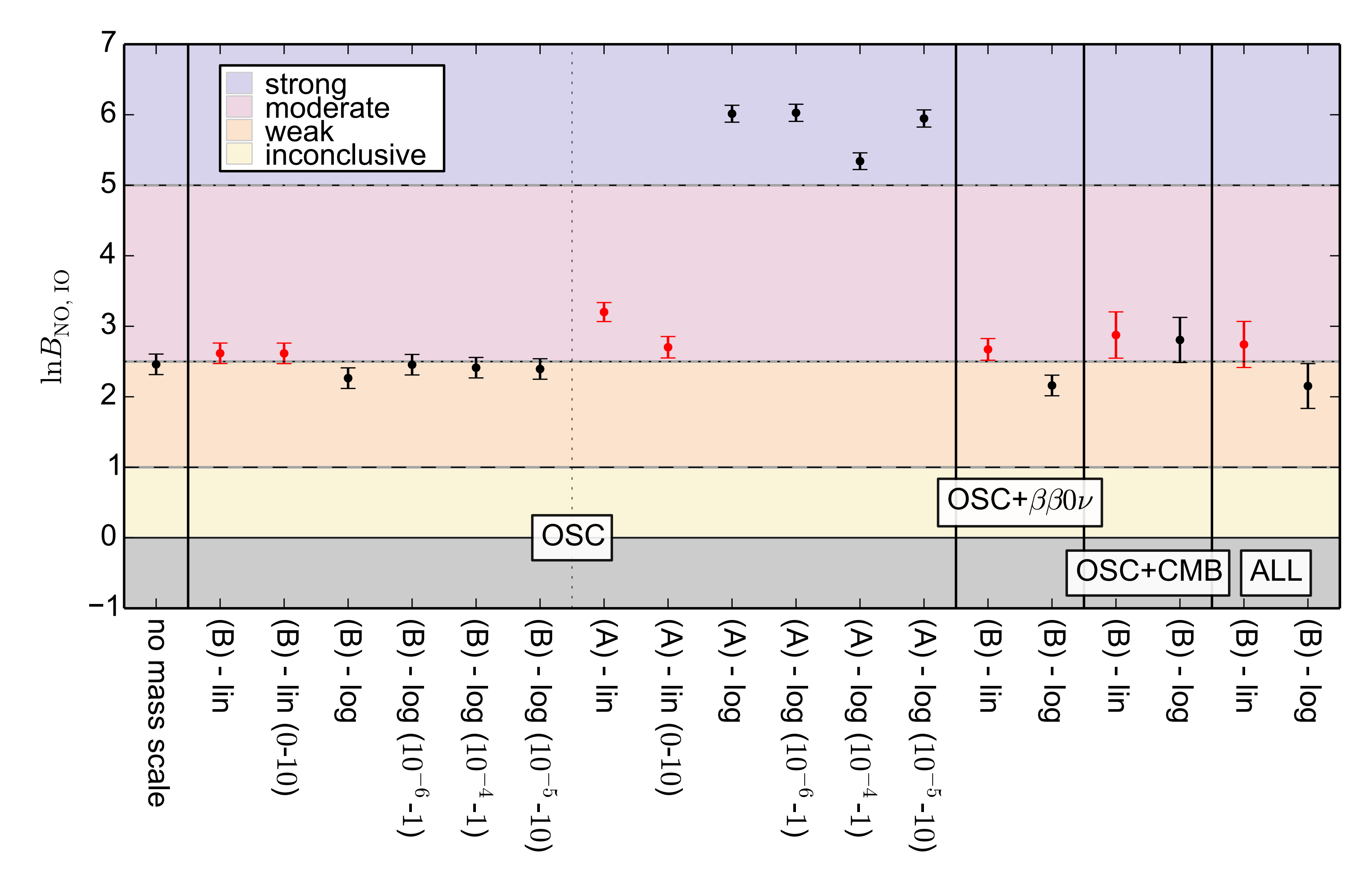
Case B
(m_0, Δm^2_{21}, Δm^2_{31})

- m_j: linear / log prior
- Δm^2_{ij}: always linear

⇒ case A: choice of priors is very relevant

⇒ preference for NO driven by oscillation data

⇒ cosmology can not contribute to determine MO yet



Gariazzo et al, JCAP03 (2018) 11

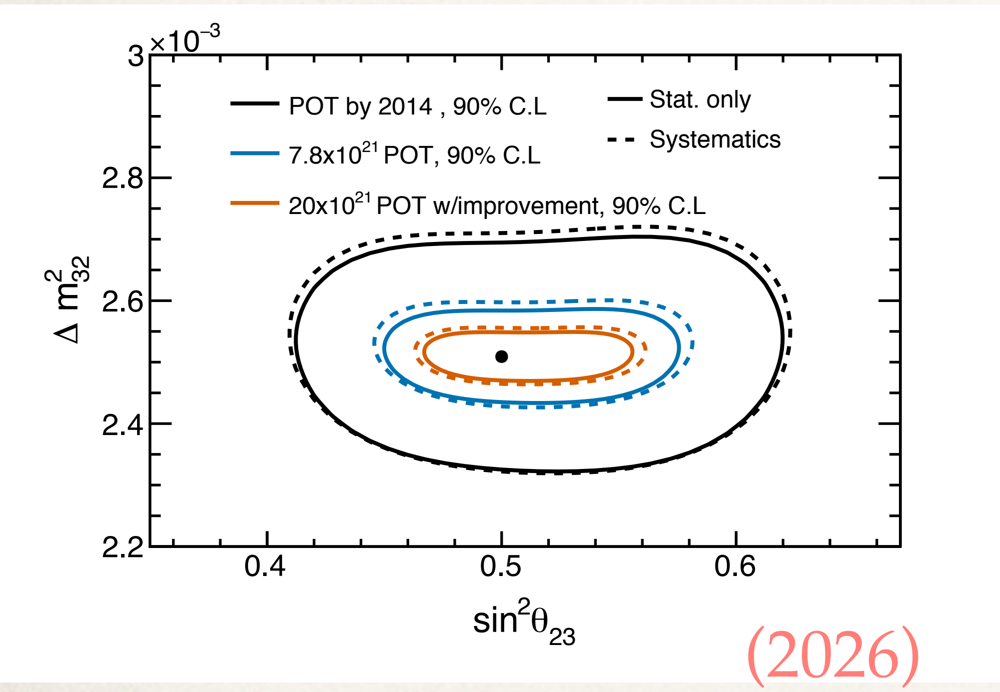
Using global fit-2017, wo SK I-IV, old LBL

Near future prospects ($\lesssim$ 2025)

Prospects for precision

T2K-II

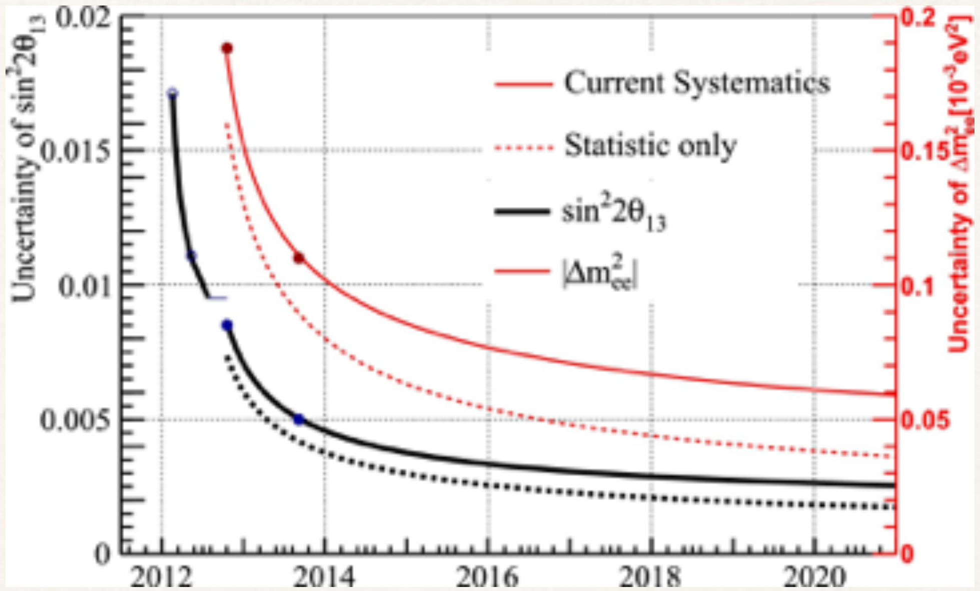
Abe et al, 1609.04111



(2026)

~1% precision on Δm^2_{32}

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



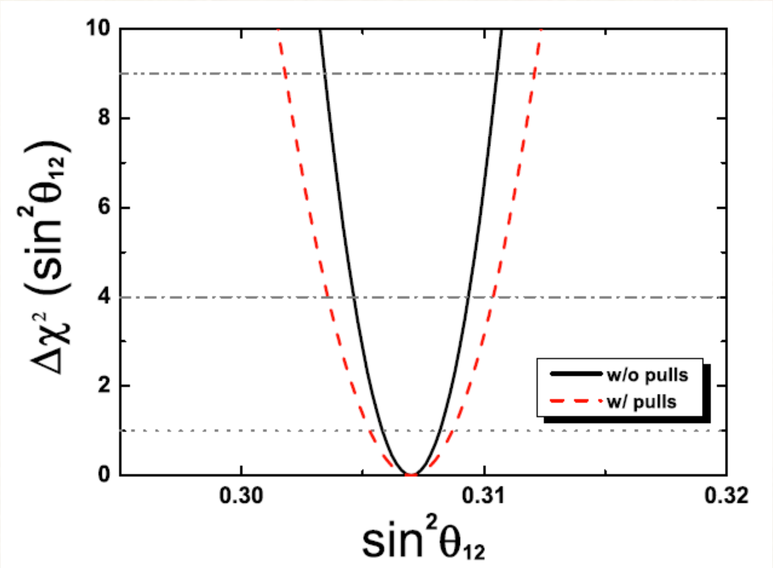
DayaBay

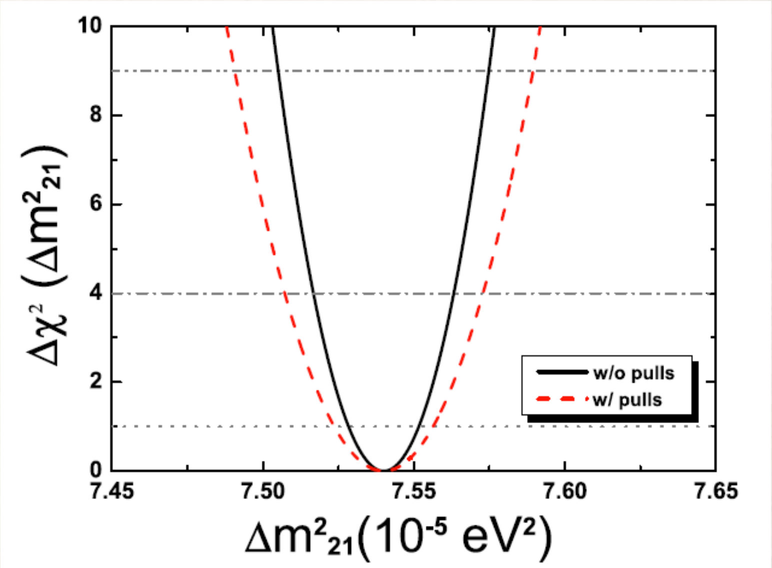
Cao and Luk, 1605.01502

< 3% precision in $\sin^2 2\theta_{13}$ and Δm^2_{ee} by 2020

JUNO

(6 years) **An et al, 1507.05613**

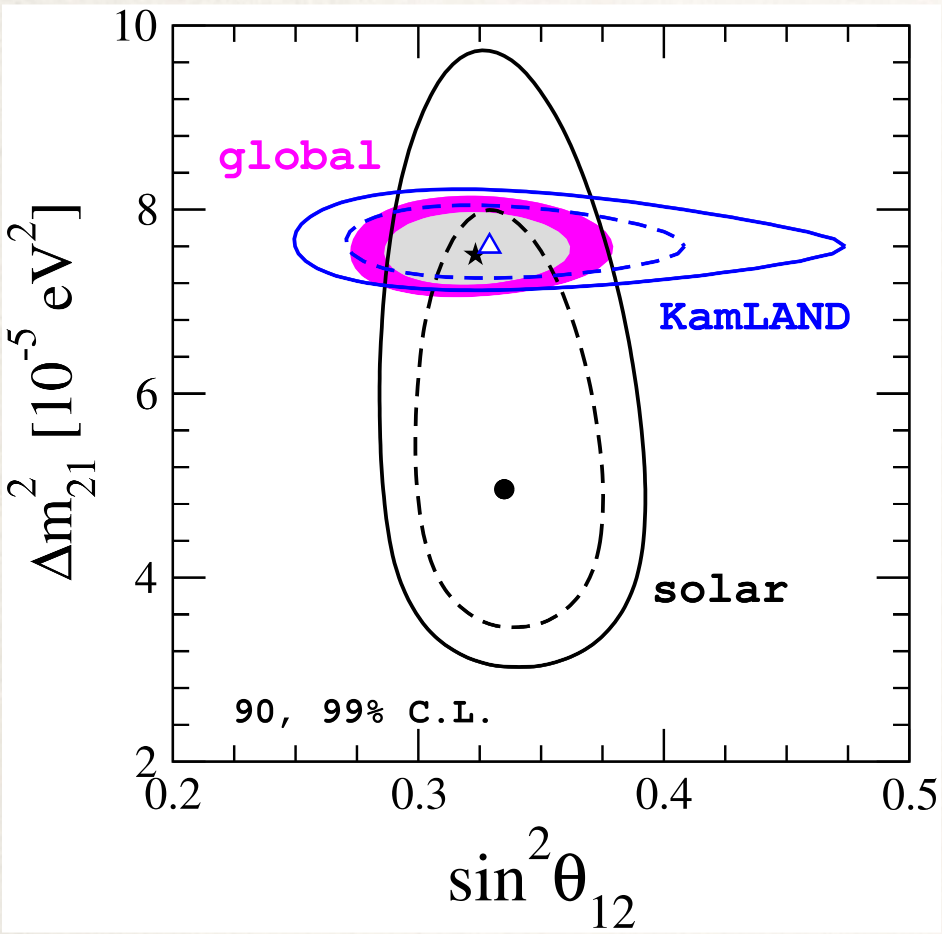




~0.7% precision on $\sin^2\theta_{12}$

~0.6% precision on Δm^2_{21}

Tension between solar and KamLAND



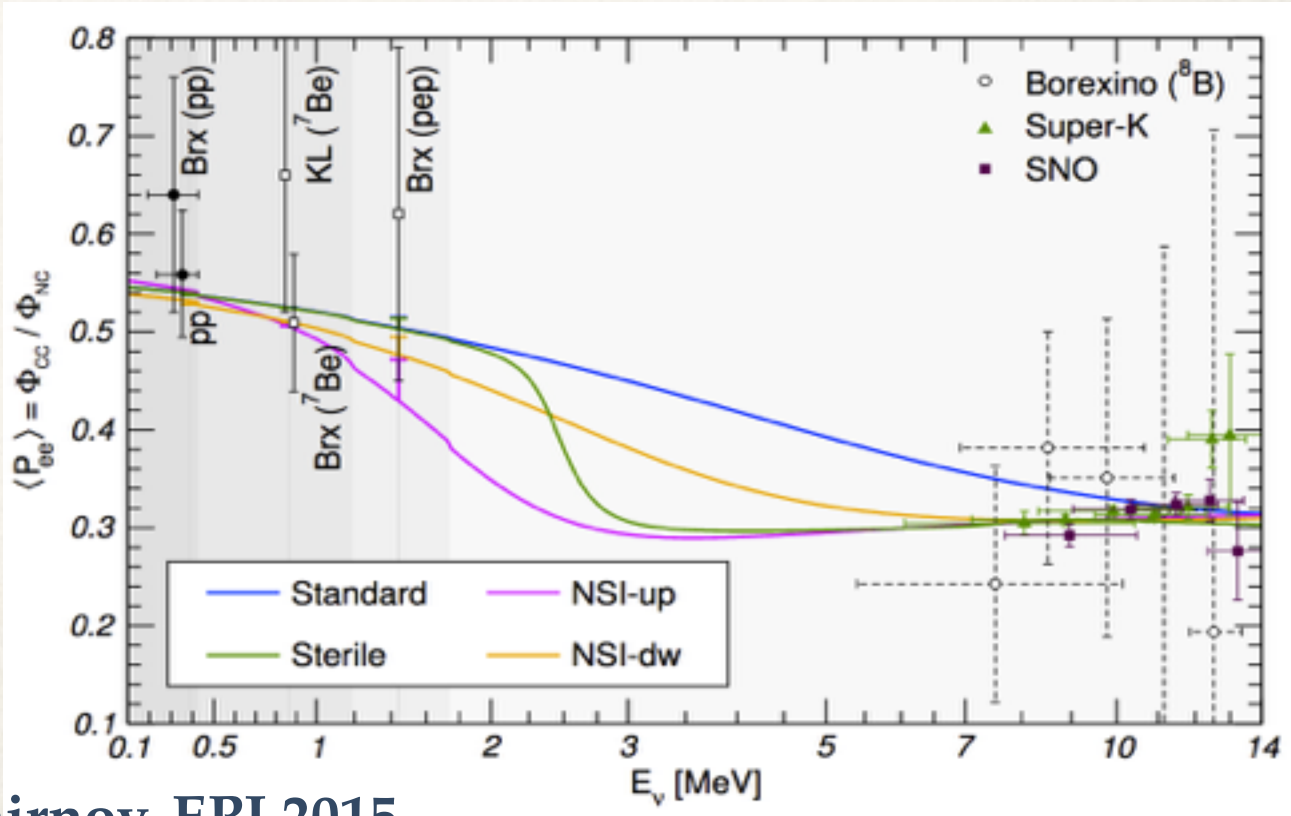
⇒ 2σ tension between preferred value of Δm^2_{21} from KamLAND and solar data

- Δm^2_{21} preferred by KamLAND predicts steep upturn at solar spectrum and smaller D/N asymmetry
- More precise measurements of Δm^2_{21} by reactor (JUNO,RENO-50) and solar experiments may help.

- NSI (ε ~0.3) can reconcile solar and KL data

⇒ flatter spectrum at intermediate E-region

⇒ larger D/N asymmetries can be expected



Escrihuela et al, PRD80 (2009)

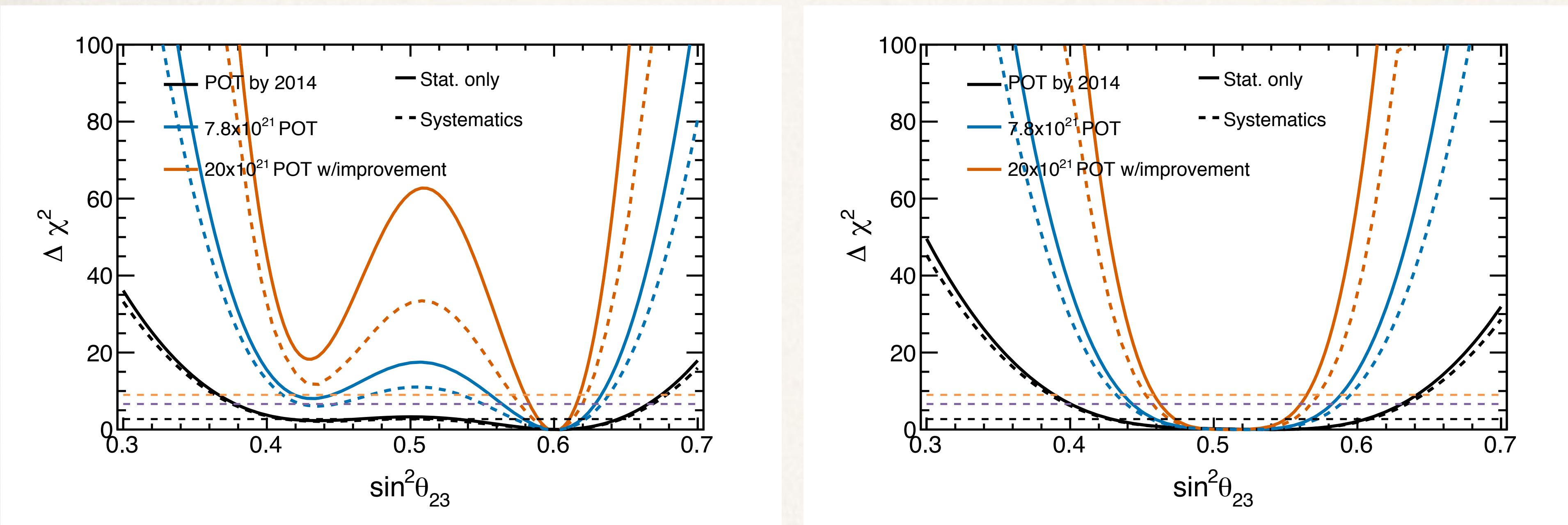
Coloma et al, PRD96 (2017)

Maltoni & Smirnov, EPJ 2015

Prospects for atmospheric octant

T2K-II

Abe et al, 1609.04111



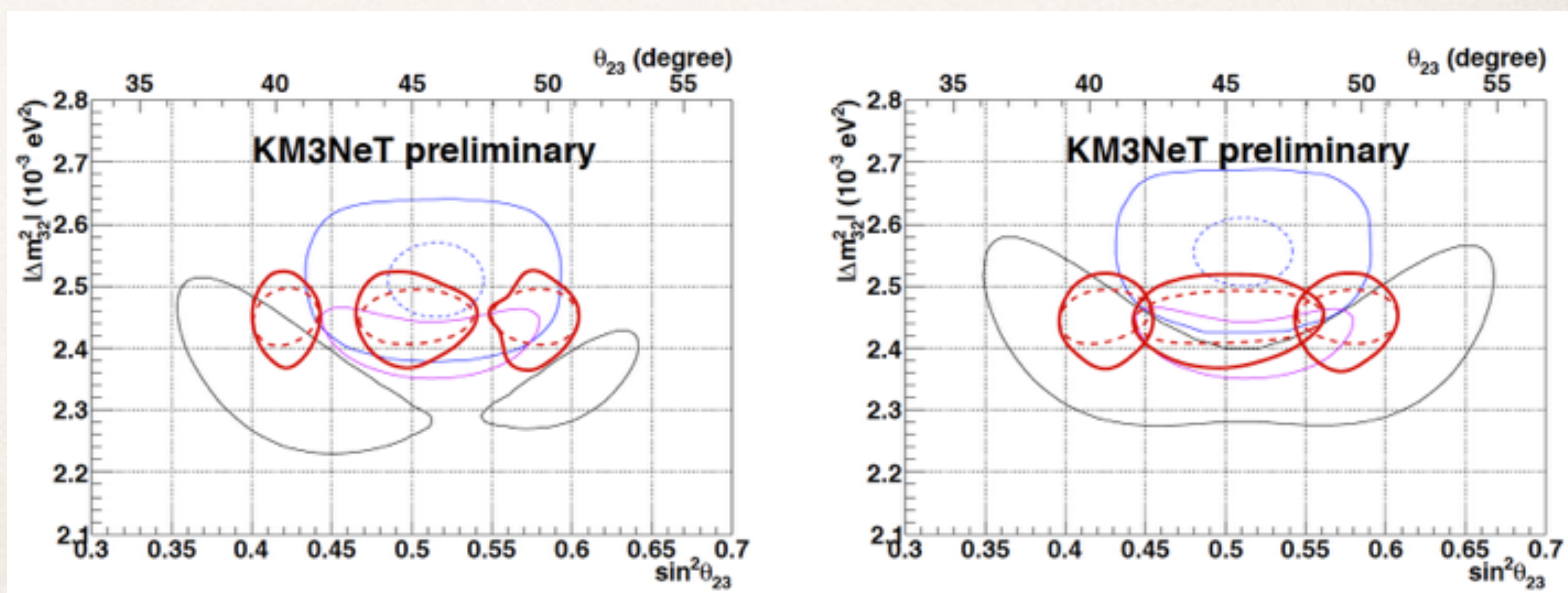
octant degeneracy can be resolved at ≳ 3σ for $\sin^2\theta_{23}$=0.60, 0.43

ORCA

Adrian-Martinez et al, 1601.07459

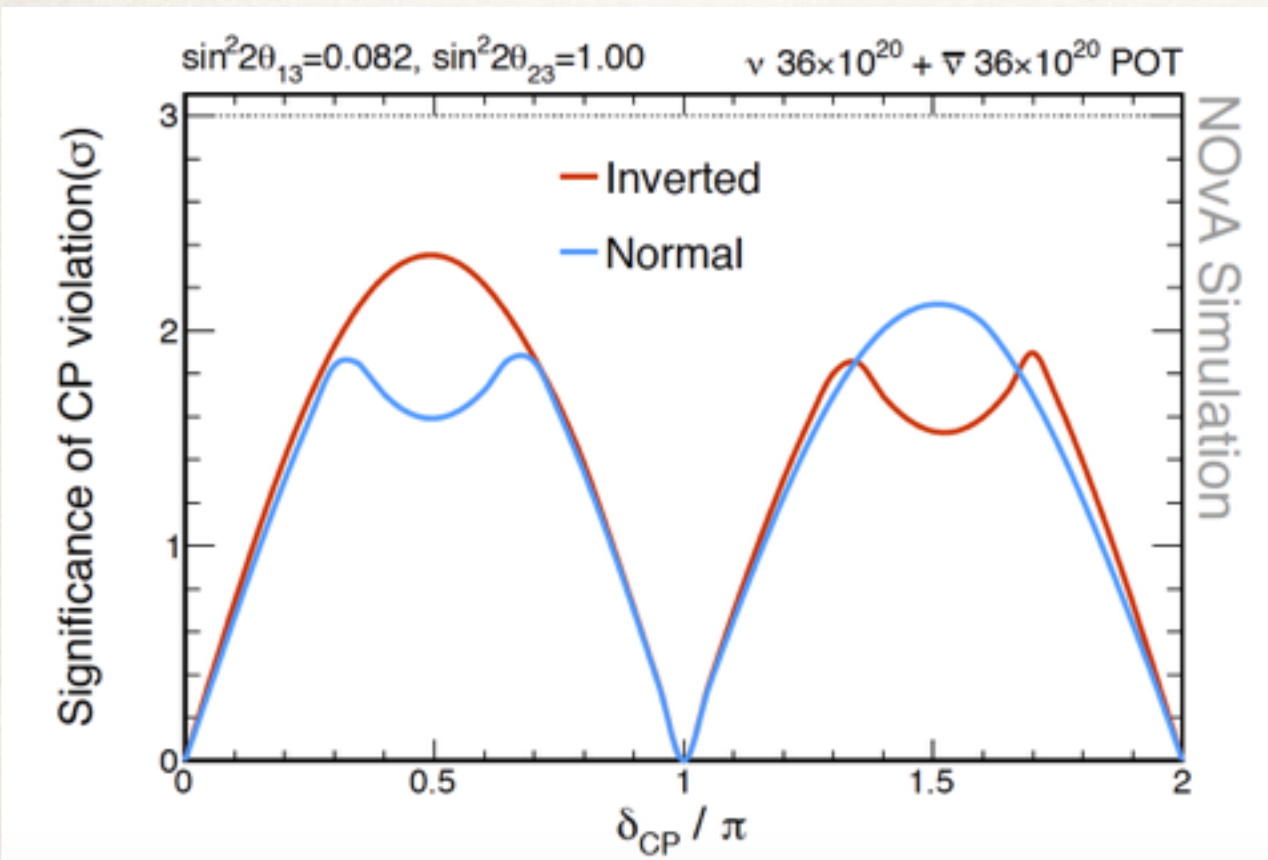
3 years of data

1σ contours



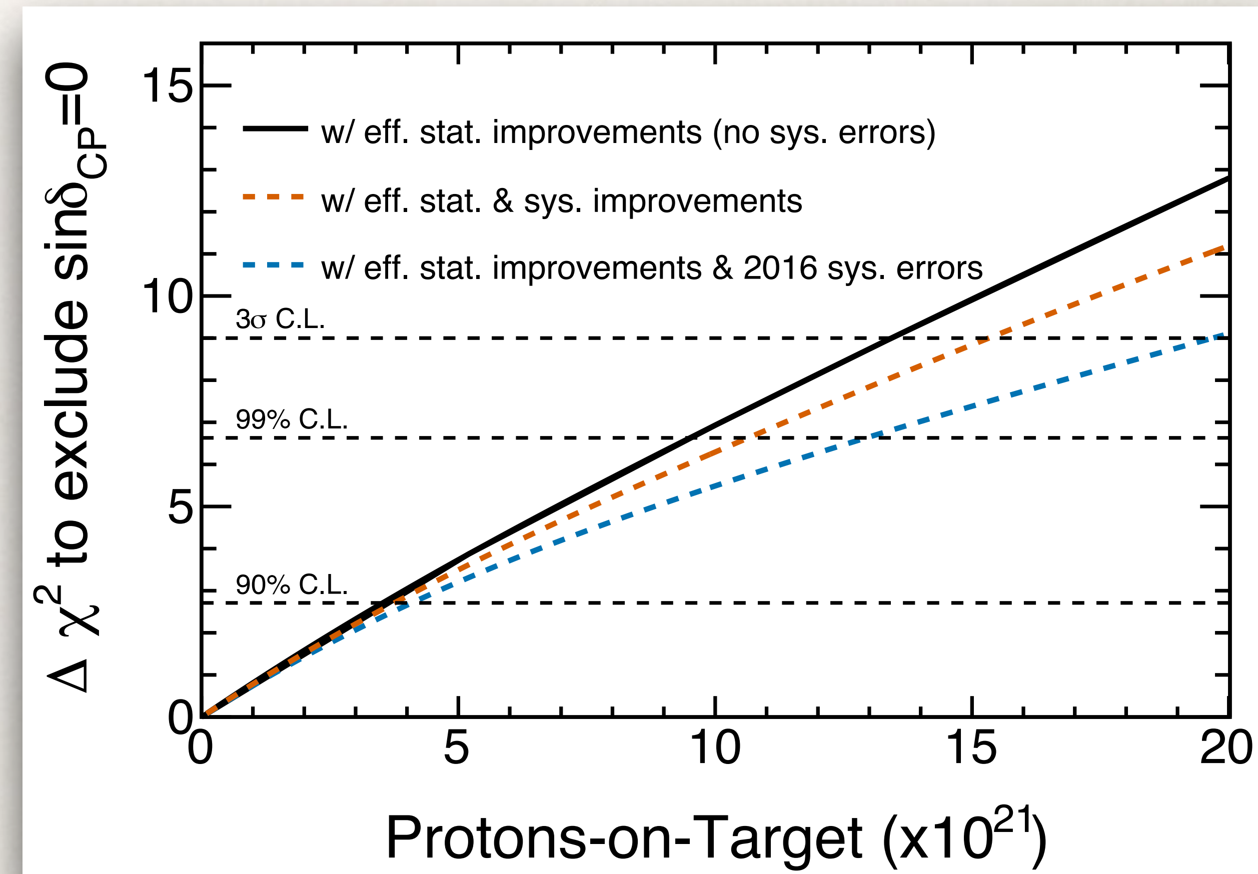
Prospects for CP violation

NOvA — **Talk by M. Sánchez**



- by 2024:
  > 2σ sensitivity on CP violation at max CP violation (π/2 & 3π/2)

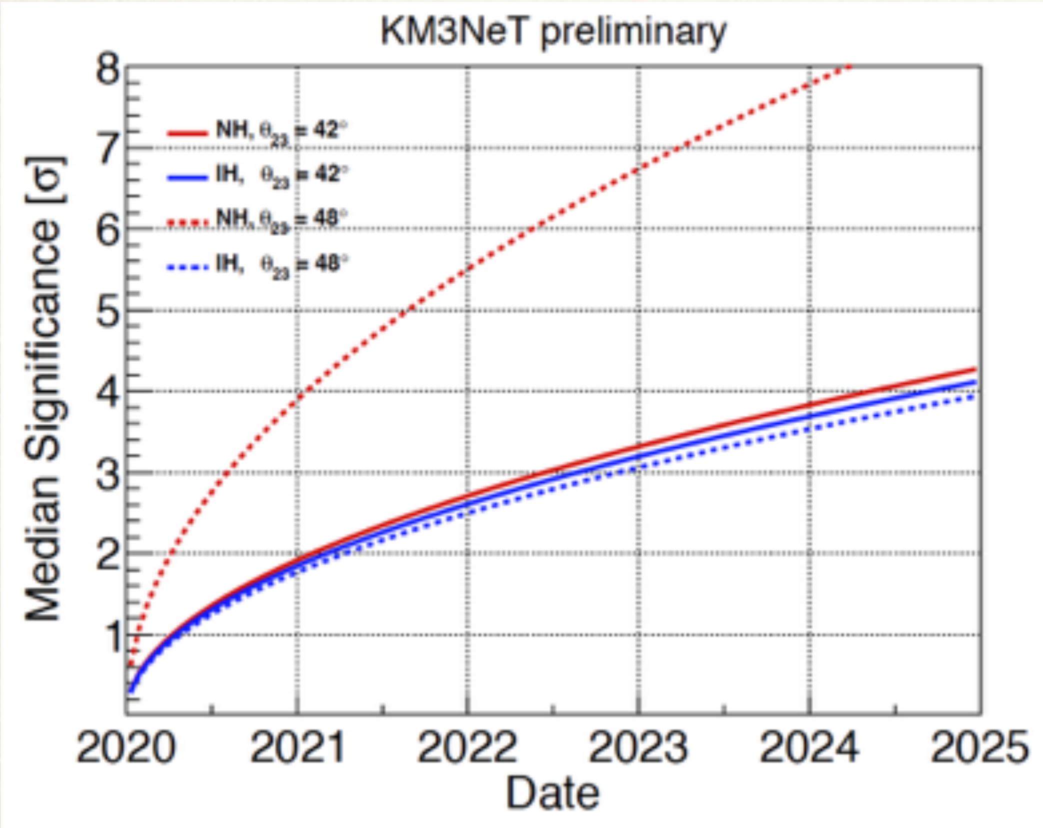
T2K-II — **Abe et al, 1609.04111**



- by 2026 (20×10^{21} POT):
  > 3σ sensitivity on CP violation

Prospects for mass ordering

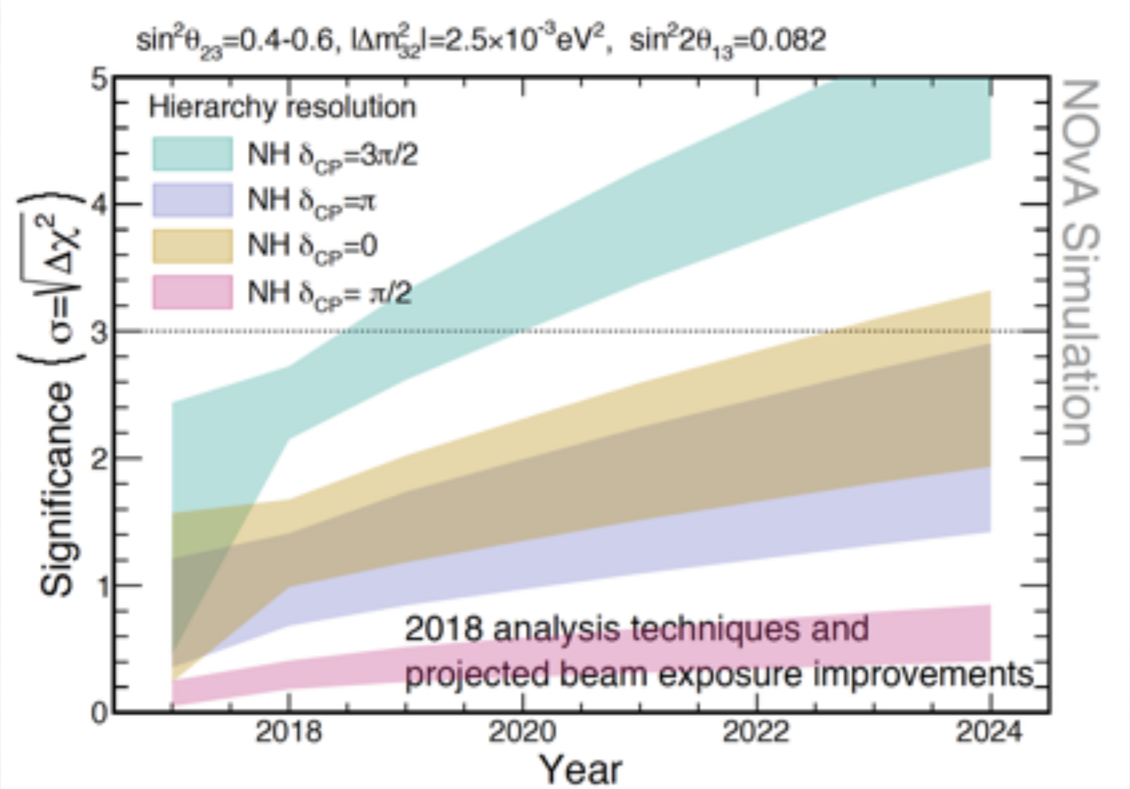
ORCA **Adrian-Martinez et al, 1601.07459**



- by 2023: 3σ determination of MO

(similar results for PINGU)

NOνA **Talk by M. Sánchez**



- by 2020: 3σ sensitivity (NO and δ=3π/2)
- by 2024: 3σ sensitivity for 30/50% of δ

JUNO ⇒ 3σ sensitivity on mass ordering after 6 years

Talk by B. Wonsak

Summary

- Current status of three-neutrino oscillation parameters:
    - very precise and robust determinations for most of them (1.3-10%)
    - slight preference for θ_{23} at the 2nd octant, with $\Delta\chi^2(45^o) = 1.6$ for NO
    - preference for $\pi < \delta < 2\pi$, with CP conservation allowed at 2σ
    - 3σ hint for NO from atmospheric, LBL and reactor data

    ⇒ new T2K and NOvA data may affect δ and θ_{23} octant results

- By 2025/2026:
    - oscillation parameters will be measured with precision 0.6-3%
    - θ_{23} octant can be resolved at more than 3σ (for some values)
    - 2-3σ sensitivity to CP violation at NOvA and T2K-II
    - 3σ sensitivity to MO from reactor, accelerator and nu-telescopes

    ⇒ combined/global analyses may exploit complementarities

- for sensitivities above 3σ from a single experiment

    ⇒ next generation of experiments: DUNE, Hyper-Kamiokande

Thank you!

Vielen Dank!

NEUTRINO 2018

4–9 June

Heidelberg