Neutrino oscillations in the standard three-neutrino framework and beyond

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IFT Seminar, March 11th 2019

Outline

- Current status of three-neutrino oscillation parameters

⇒ Based on **de Salas et al, PLB782 (2018) 633**

⇒ figures and **χ**2 tables publicly available at the website:

https://globalfit.astroparticles.es/

⇒ main unknowns in neutrino oscillations:

✦ maximality/octant of θ_{23}

✦ leptonic CP violation

✦ neutrino mass ordering

- Future prospects in neutrino oscillations

⇒ near future measurements

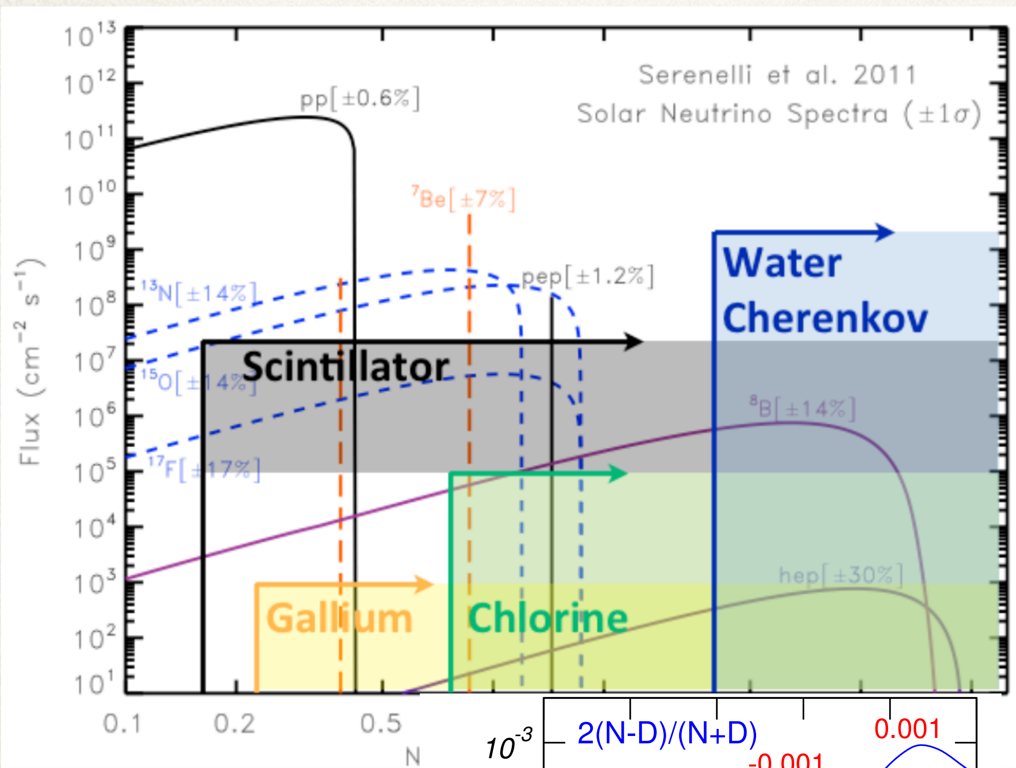
⇒ next generation of neutrino oscillation experiments

- Beyond the standard three-neutrino scenario

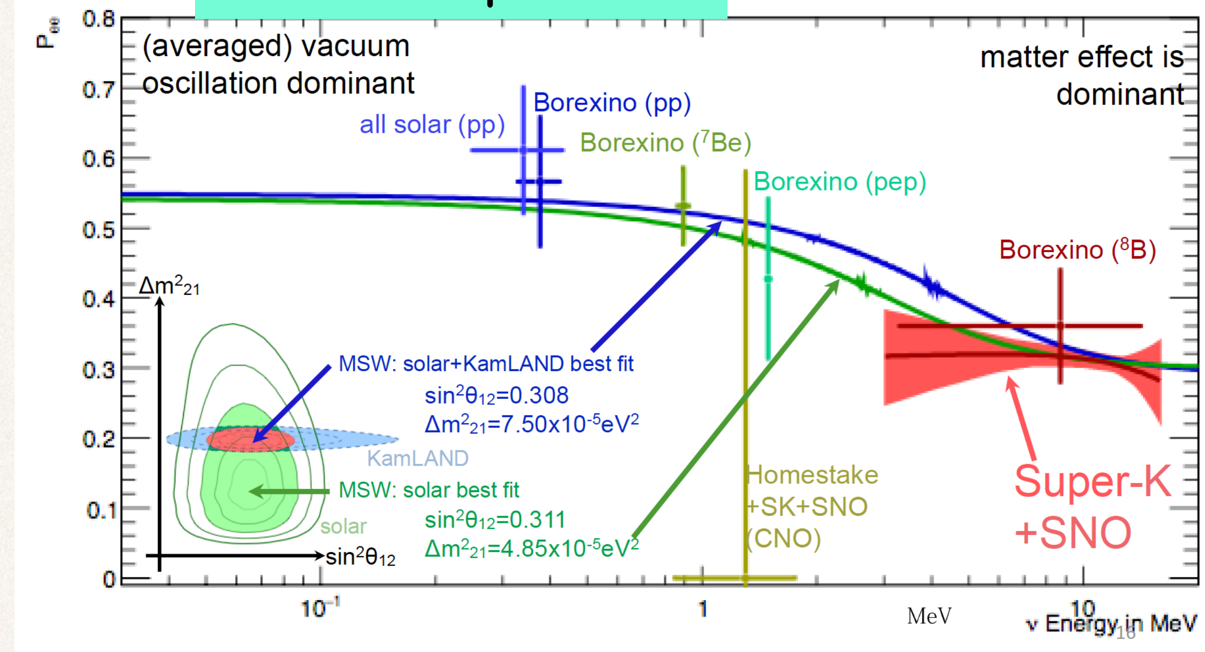
Neutrino oscillations: solar sector

Solar experiments have measured neutrino disappearance for ~ 50 years

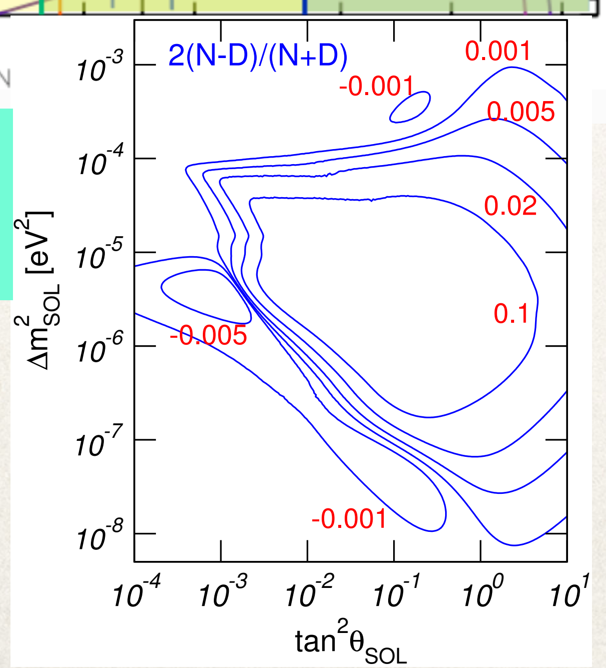
different exper. techniques



neutrino spectrum



day/night asymmetry



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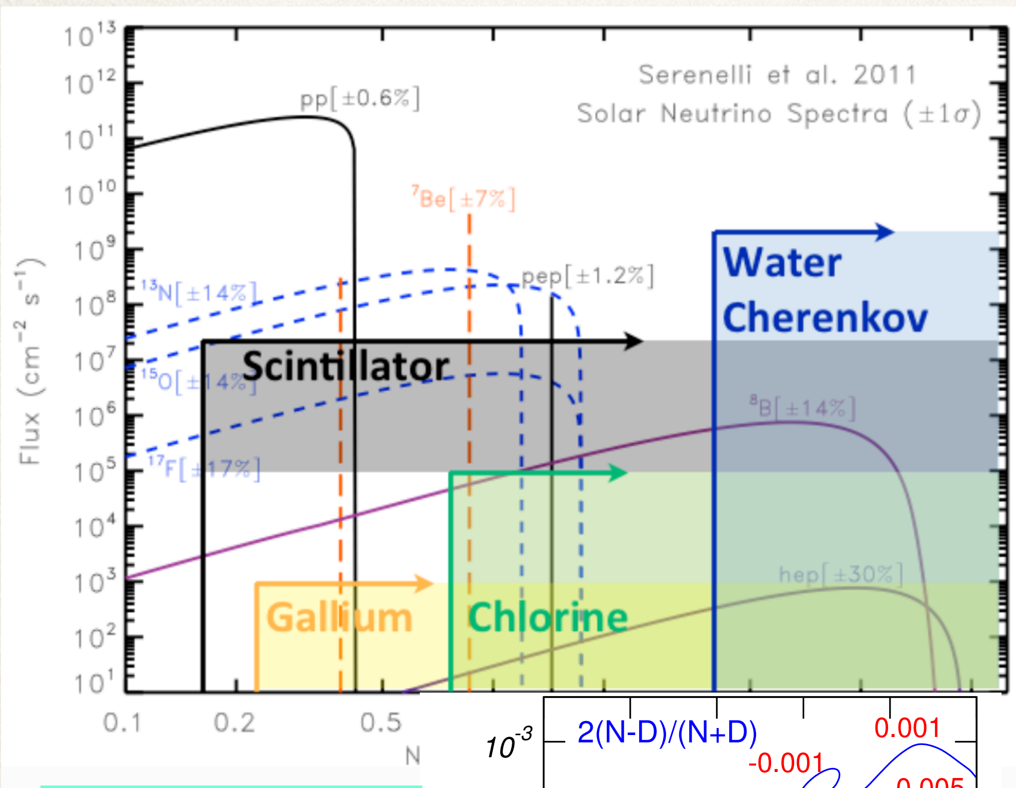

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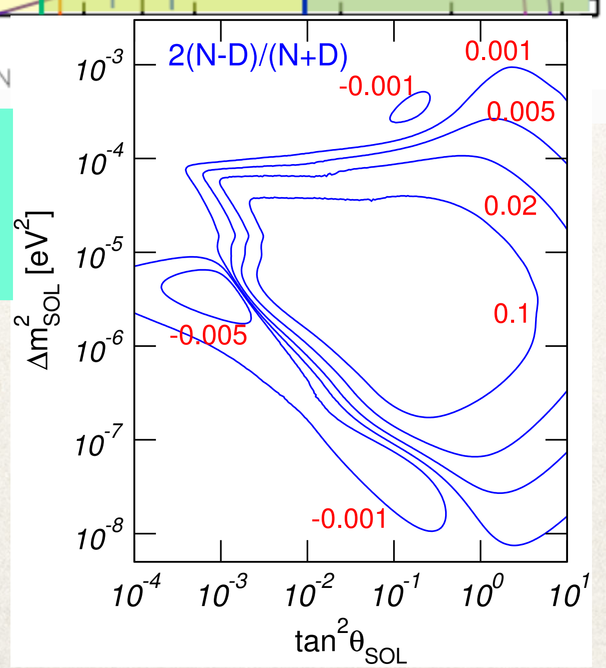

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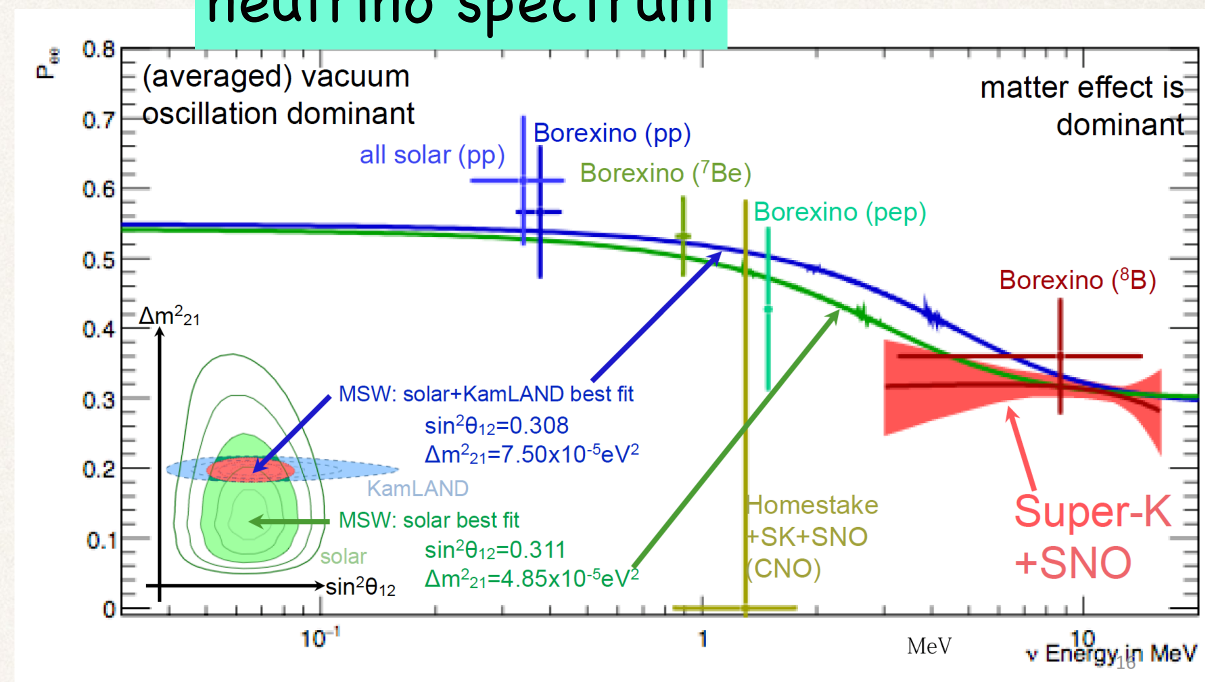
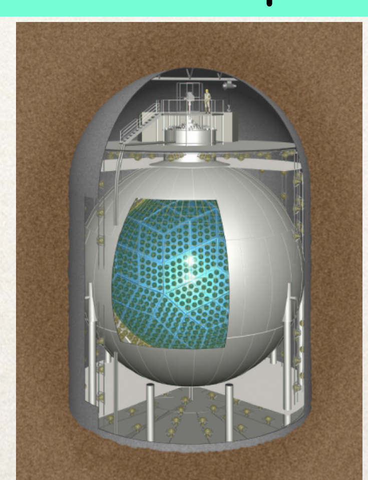
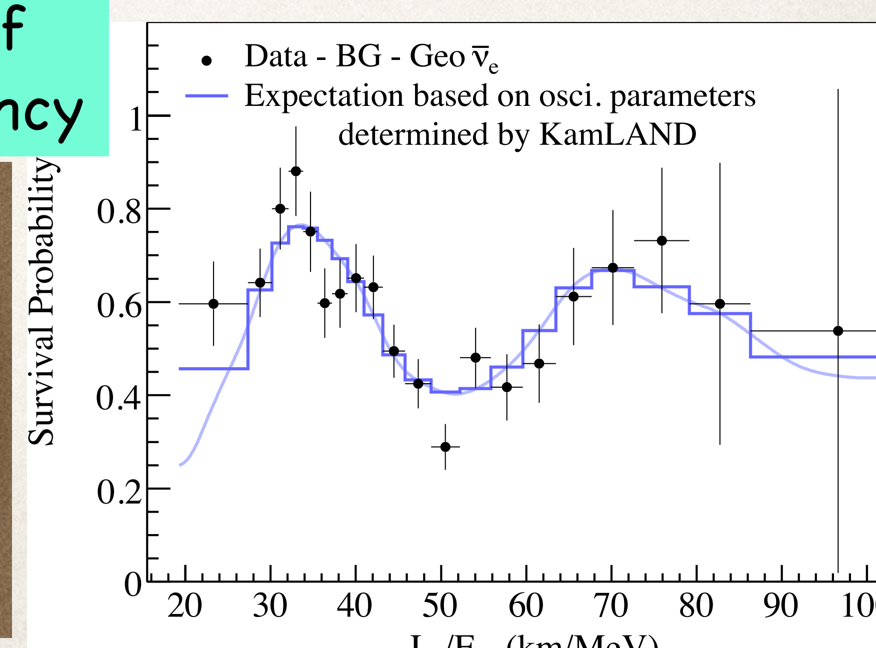


KamLAND: precise measurement of oscillation frequency

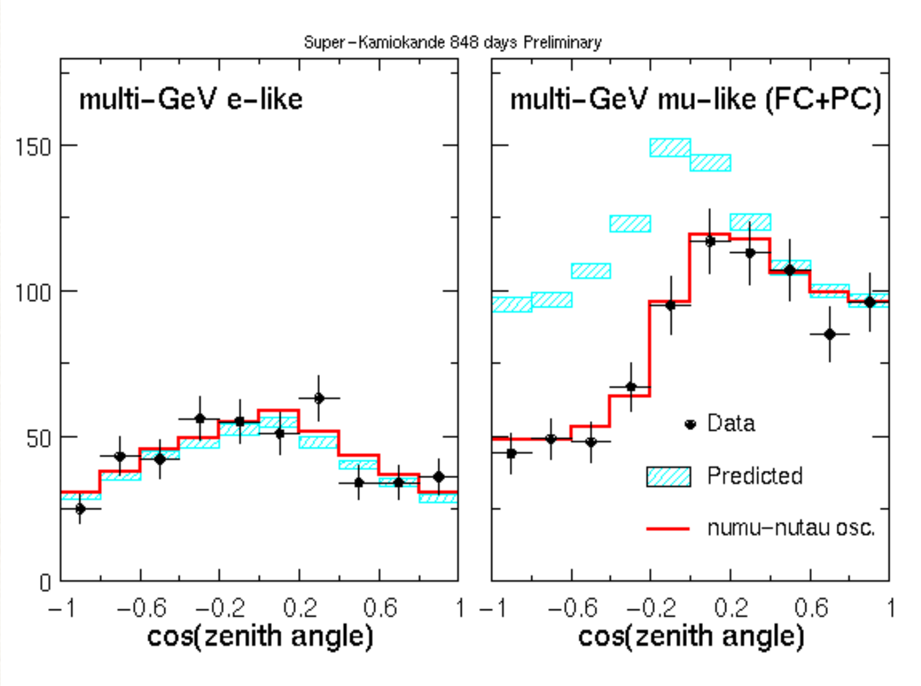




Neutrino oscillations: atmos. sector

Atmospheric experiments

Super-K: oscillations discovery, 1998



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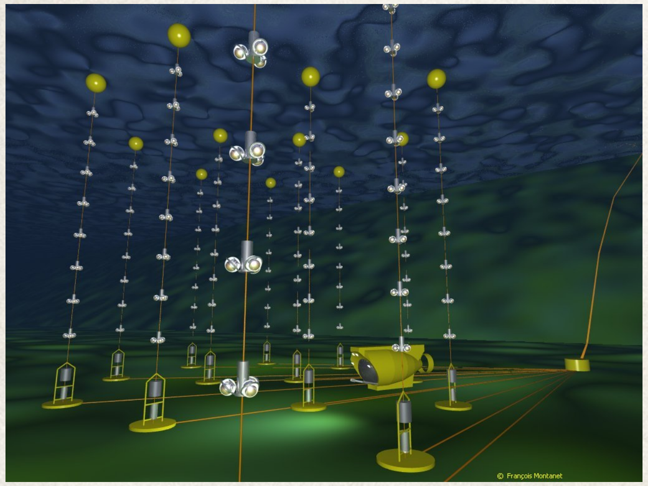
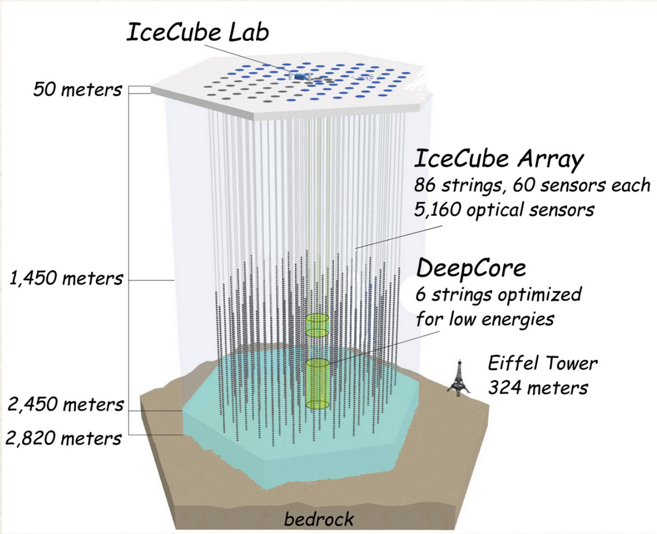


IceCube



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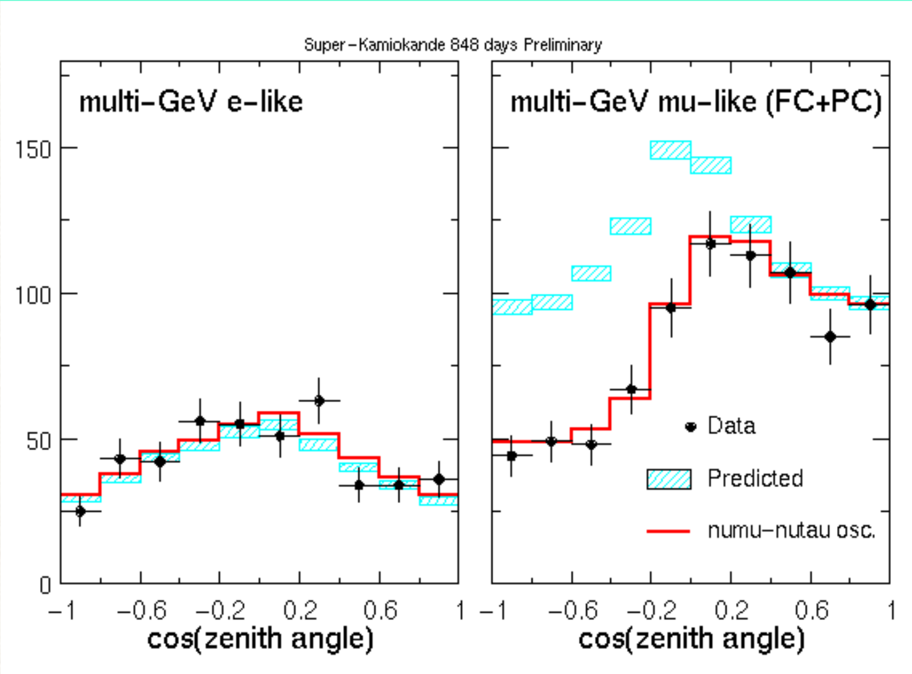

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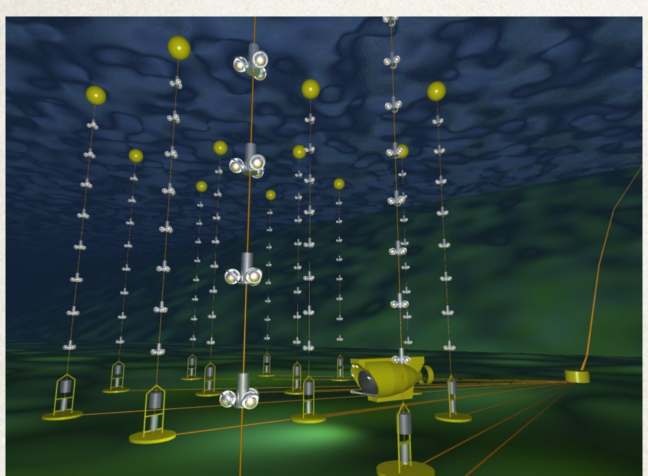

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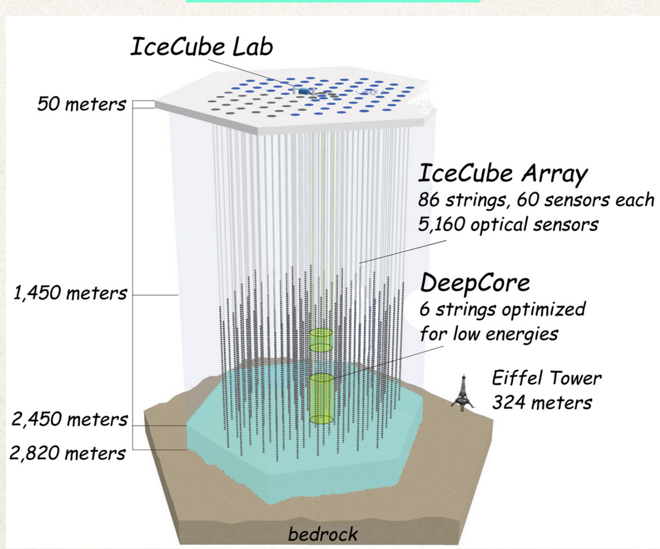
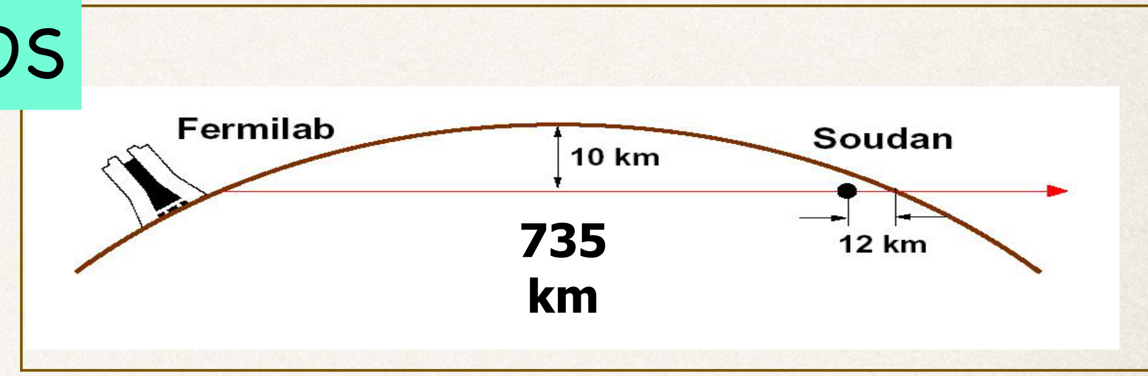
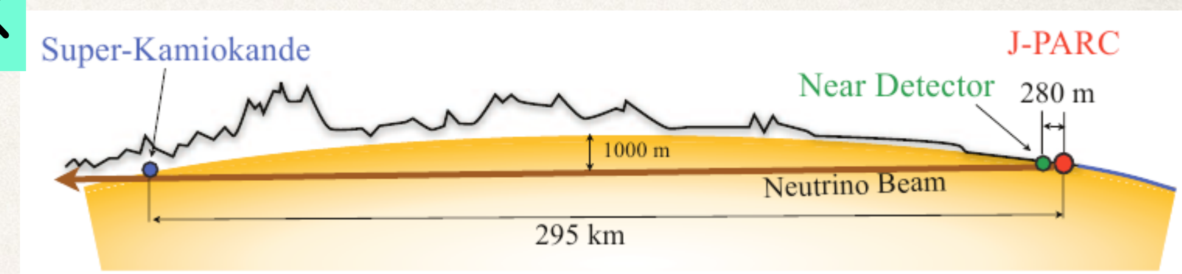


Accelerator long-baseline experiments

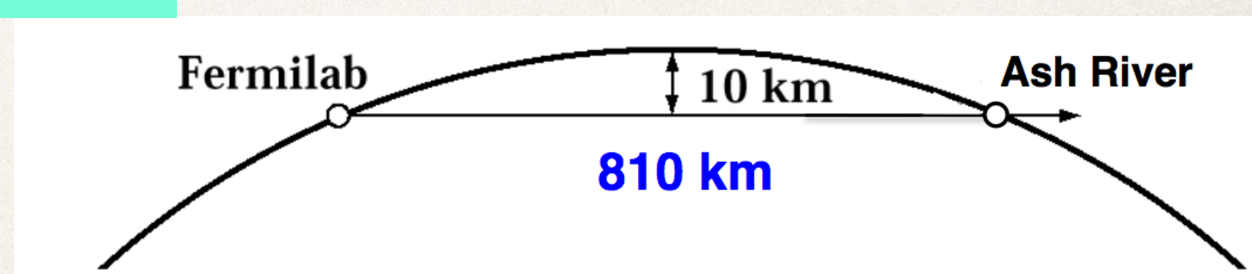
MINOS



T2K



NOvA

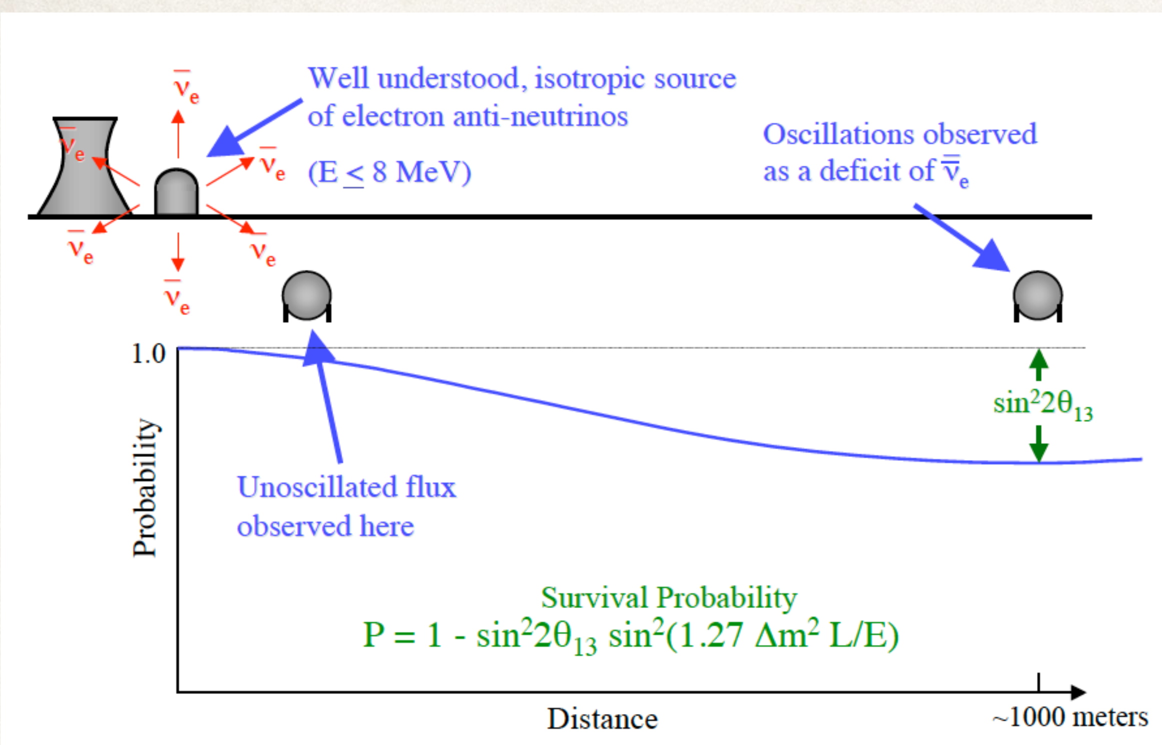


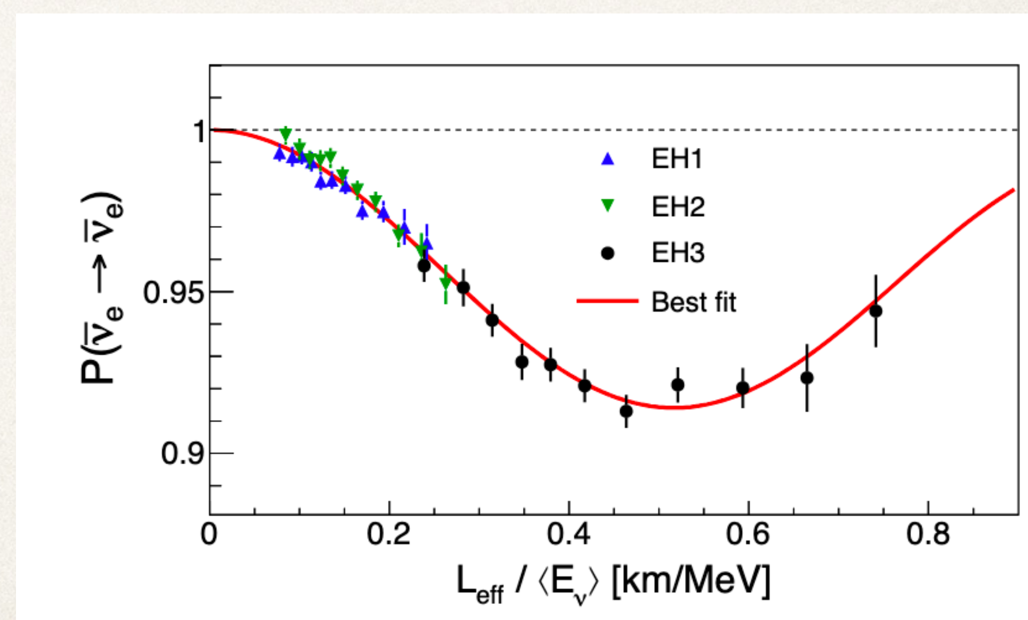
→ consistent with atmospheric data

→ atm ν oscillations confirmed by lab exps

Neutrino oscillations: reactor sector

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





Daya Bay Collab, PRD95 (2017) 072006

The three-flavour picture: notation

neutrino mixing

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

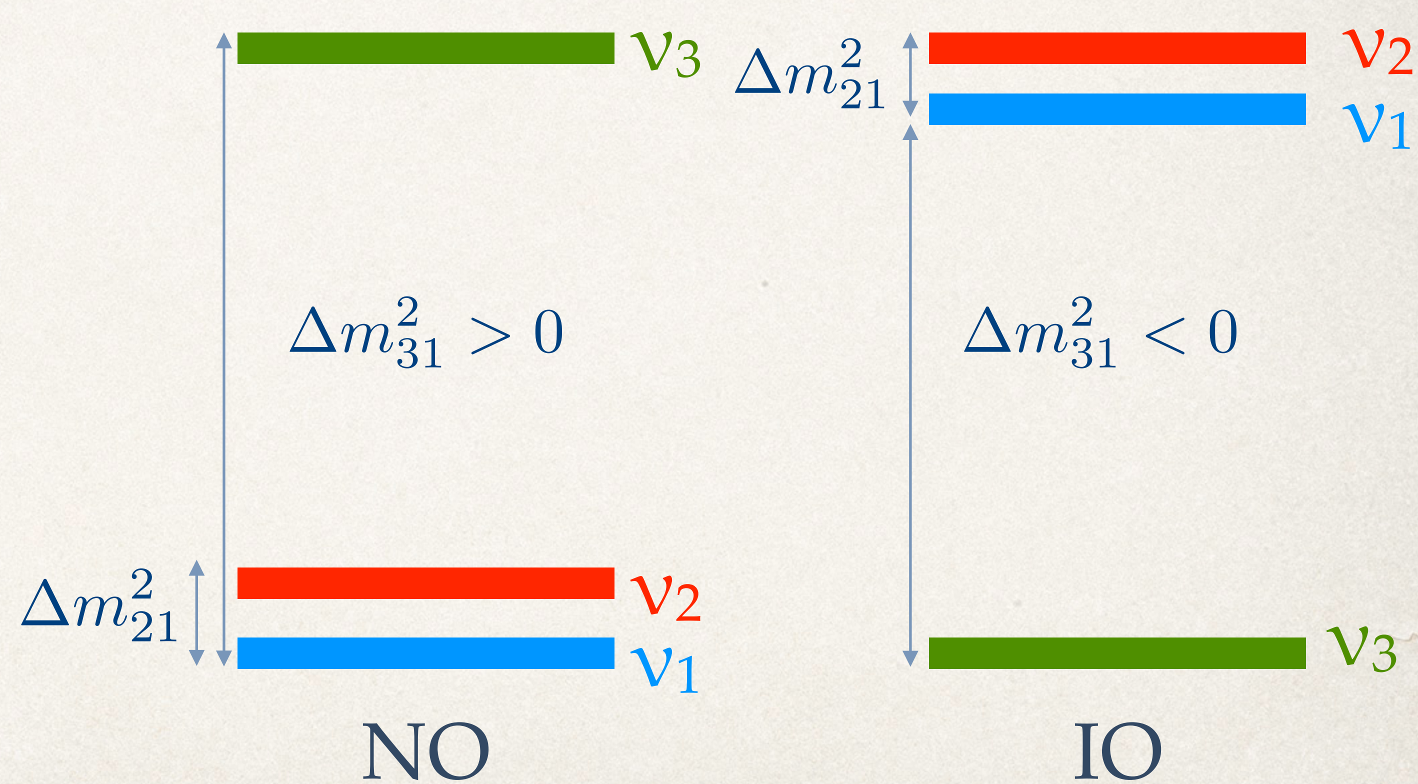
- three mixing angles: θ_{12}, θ_{23}, θ_{13}
- three CP phases: 1 Dirac + 2 Majorana
- three masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

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

neutrino mass spectrum



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

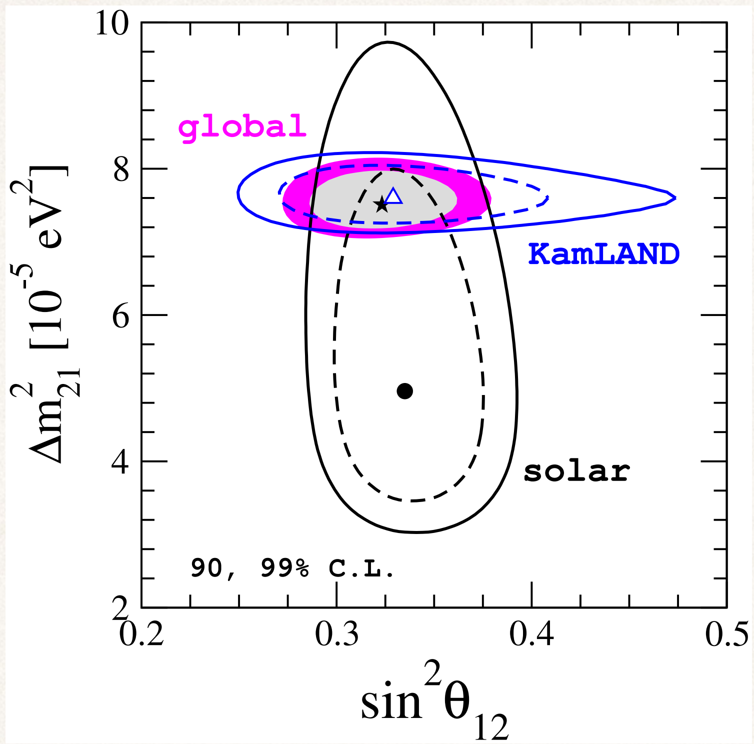
Experimental ν oscillation data

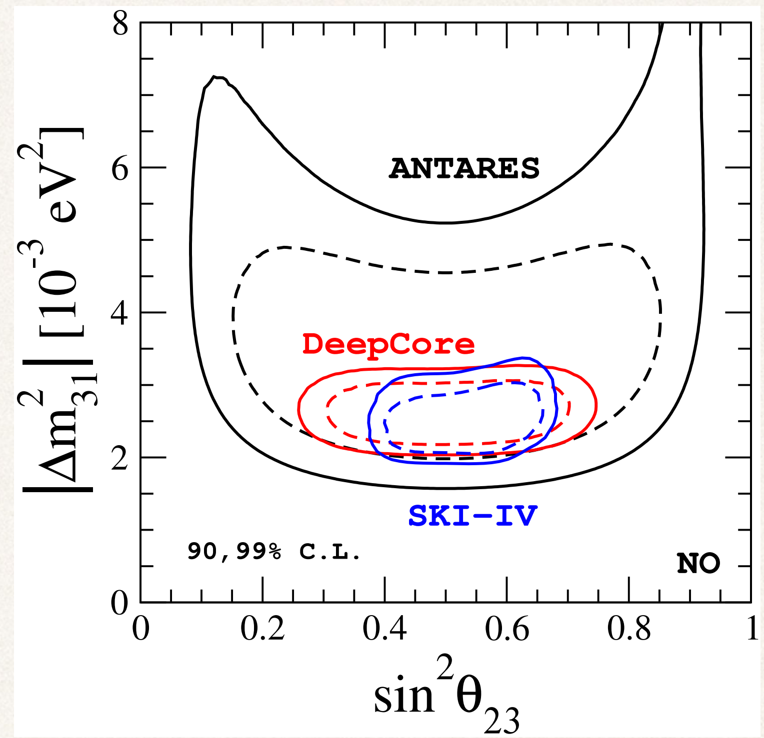
solar sector

Cl, Ga, SK

SNO, Borexino

KamLAND





atmospheric results

SK (official χ^2 maps)

IceCube-DeepCore

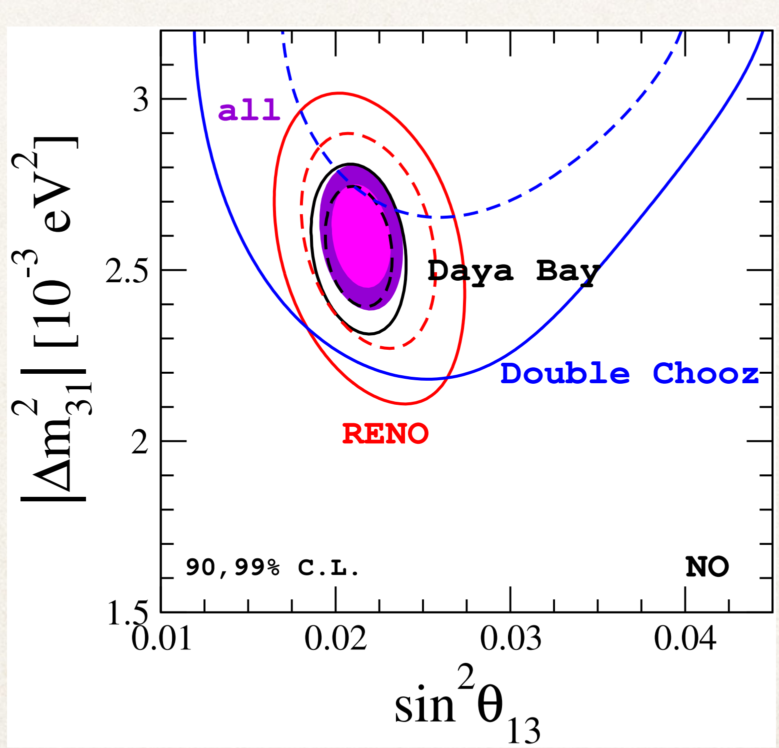
ANTARES

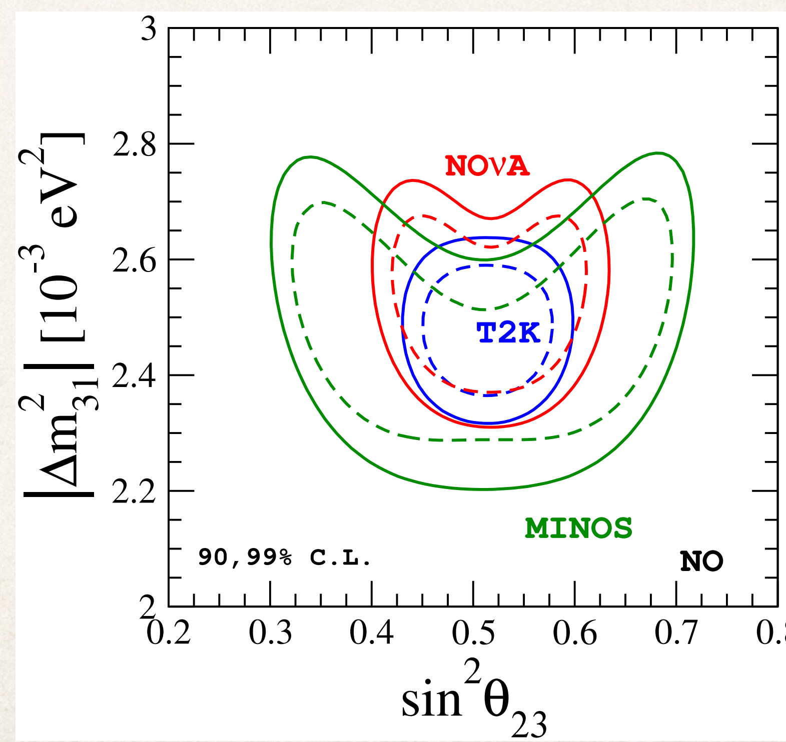
SBL reactors

Daya Bay

RENO

Double Chooz





LBL experiments

MINOS

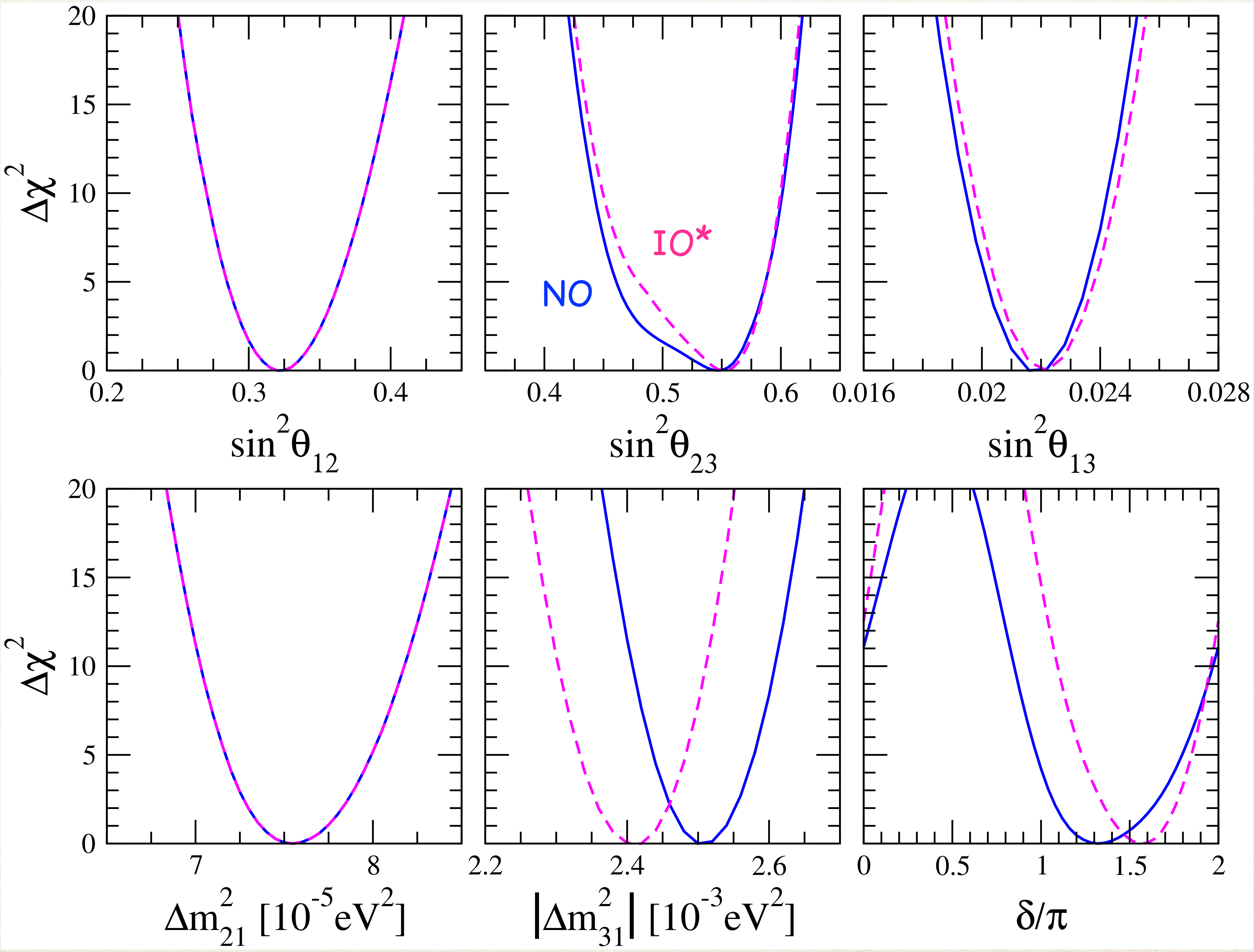
T2K

NOνA

de Salas et al, PLB782 (2018) 633

Global fit to neutrino oscillations

https://globalfit.astroparticles.es/



de Salas et al, PLB782 (2018) 633

* wrt local minimum in IO

Global fit to neutrino oscillations

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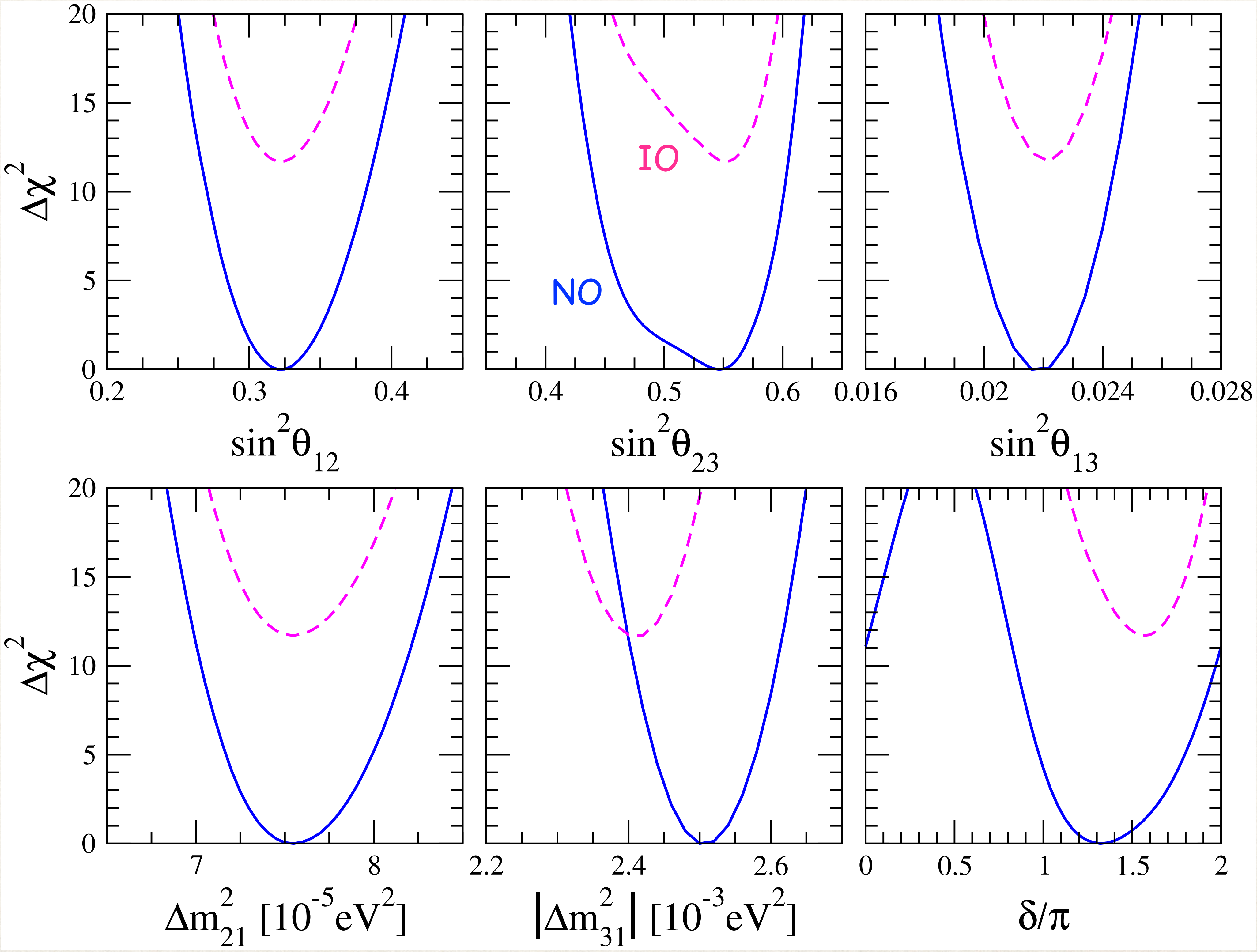

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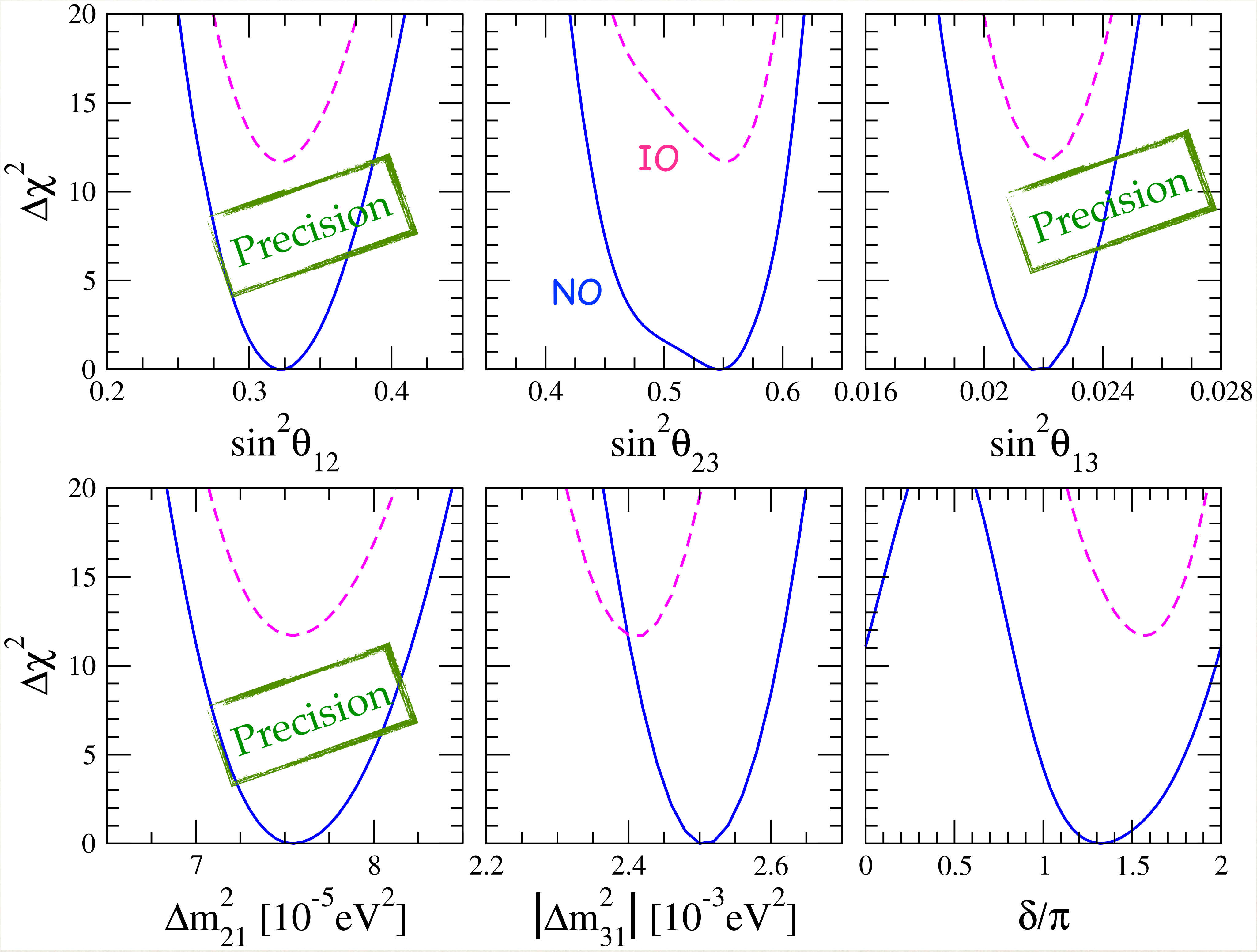

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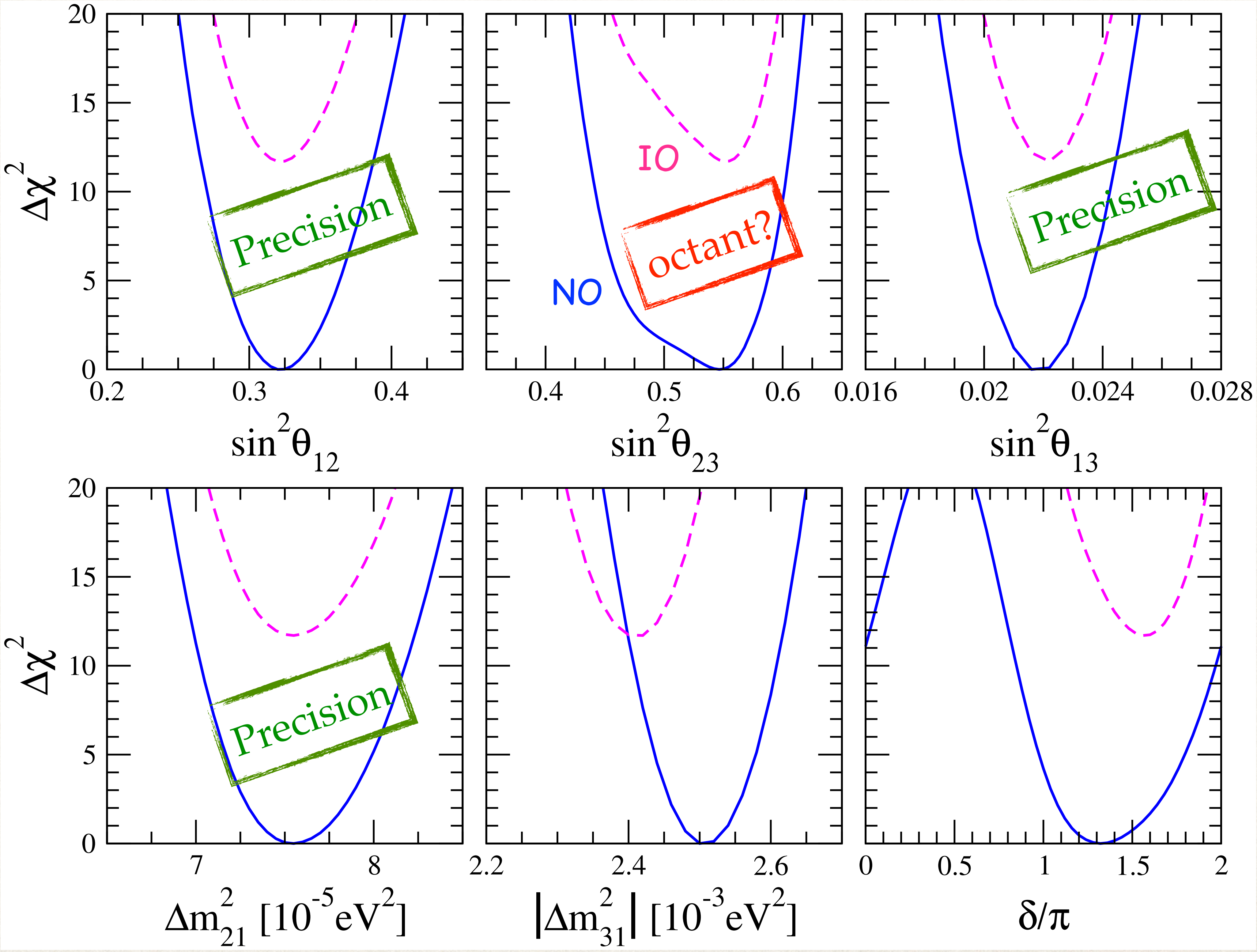

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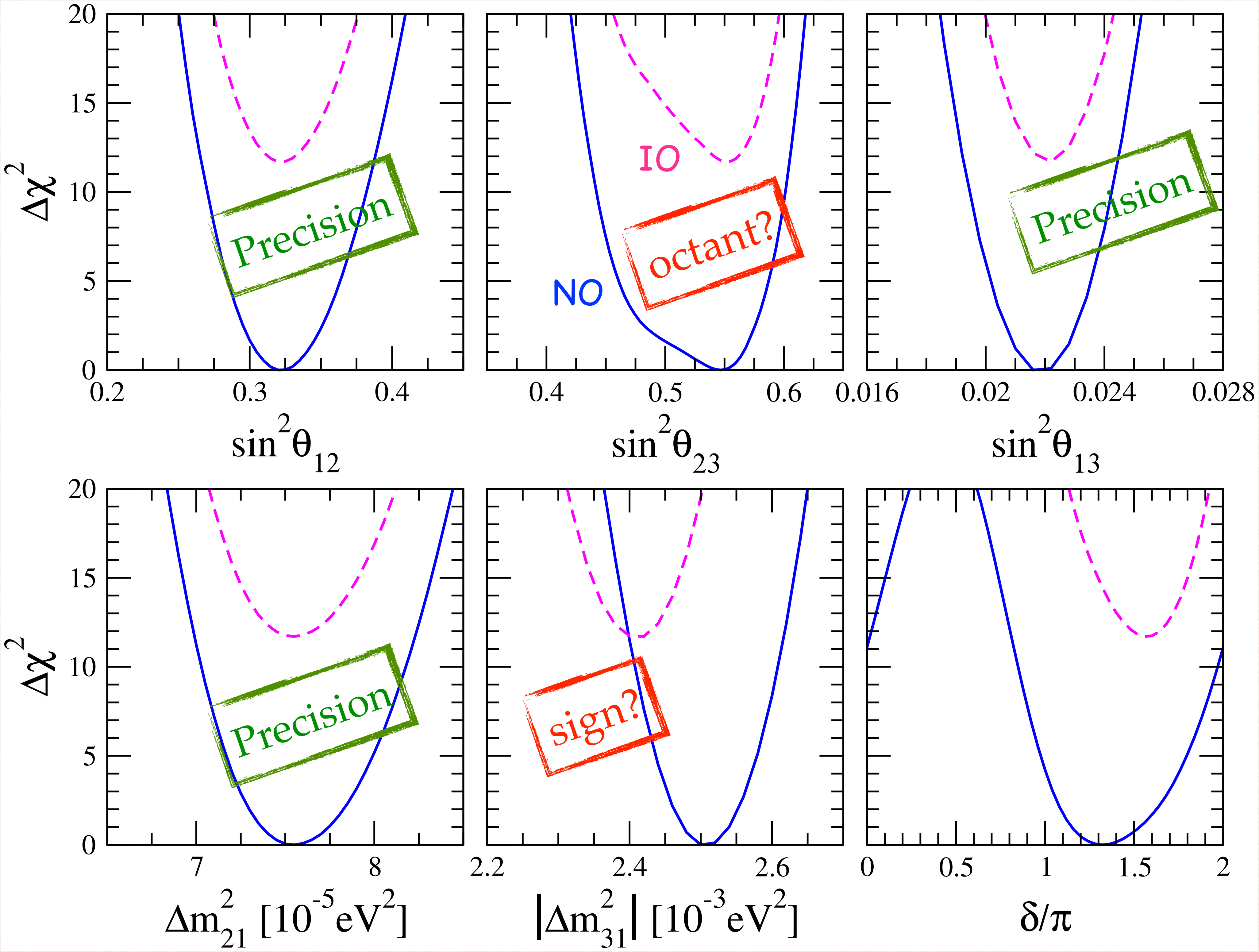

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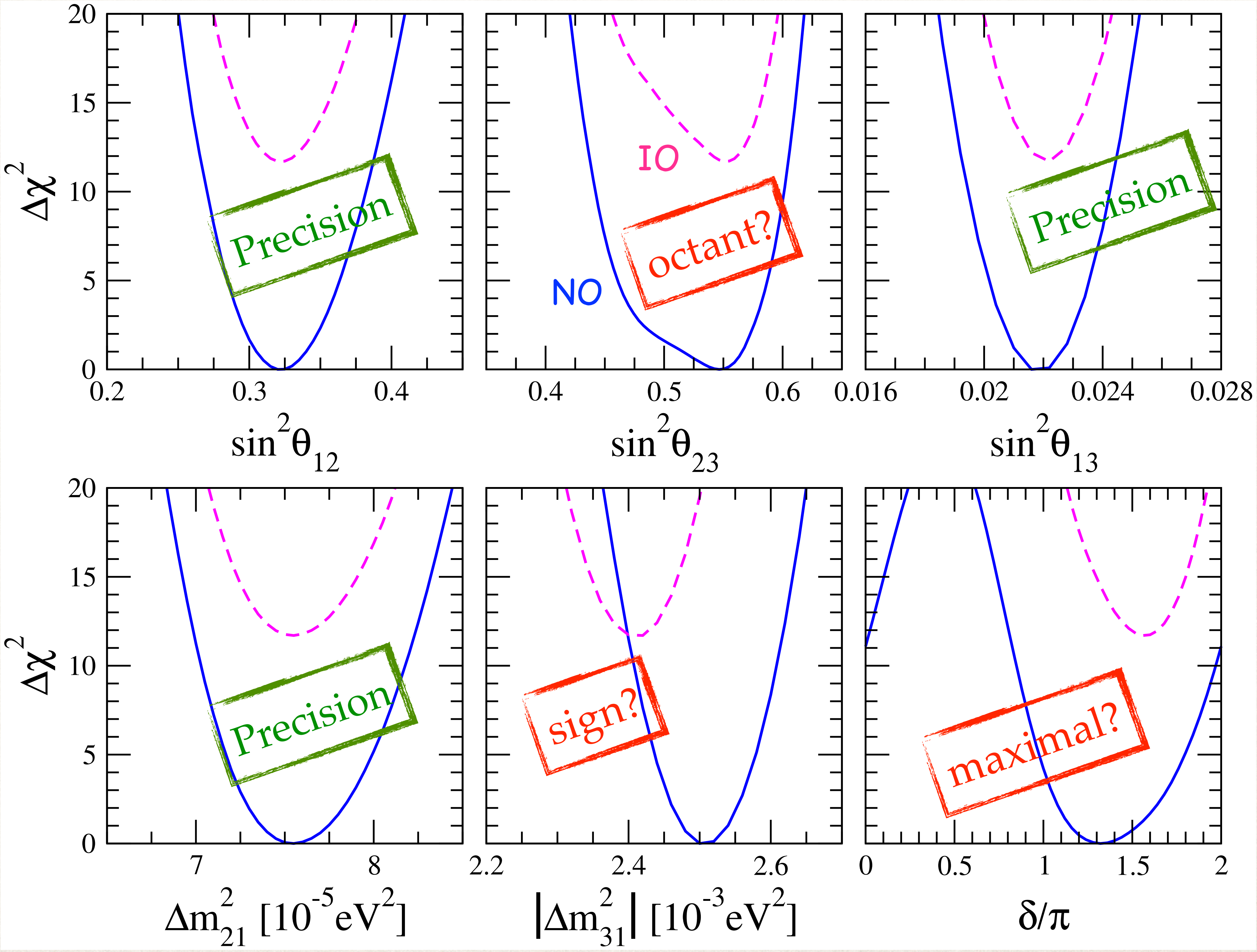

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Precision measurements

https://globalfit.astroparticles.es/

parameter	best fit $\pm 1\sigma$	3σ range	
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	**2.4%**
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (NO)	2.50±0.03	2.41–2.60	
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	**1.3%**
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	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	
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	**3.5%**
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%**

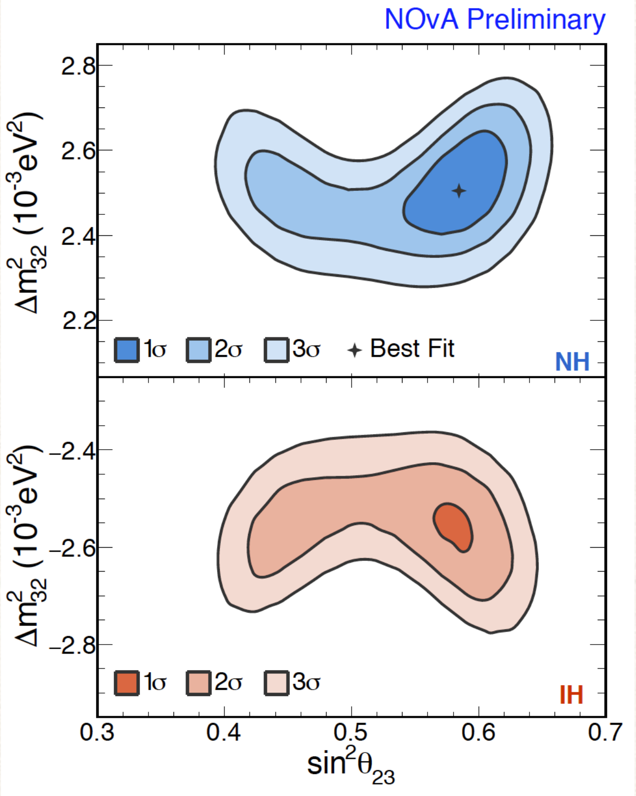
relative 1σ uncertainty

de Salas et al, PLB782 (2018) 633

New experimental data

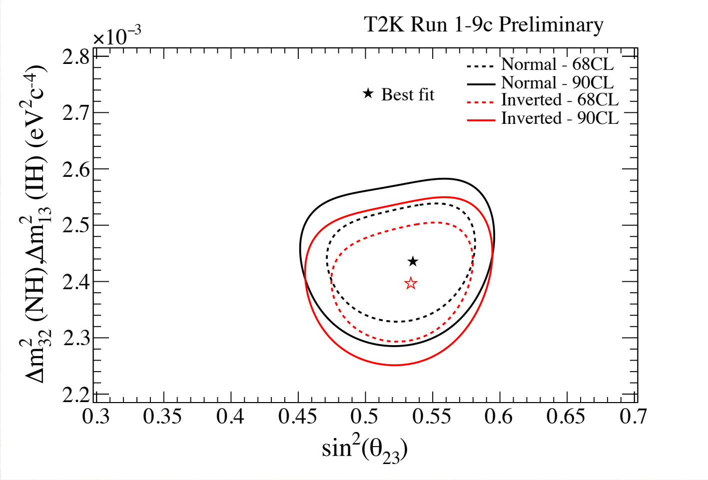
First NOνA antineutrino data

M. Sánchez, Neutrino'18



New T2K antineutrino data

M. Wascko, Neutrino'18



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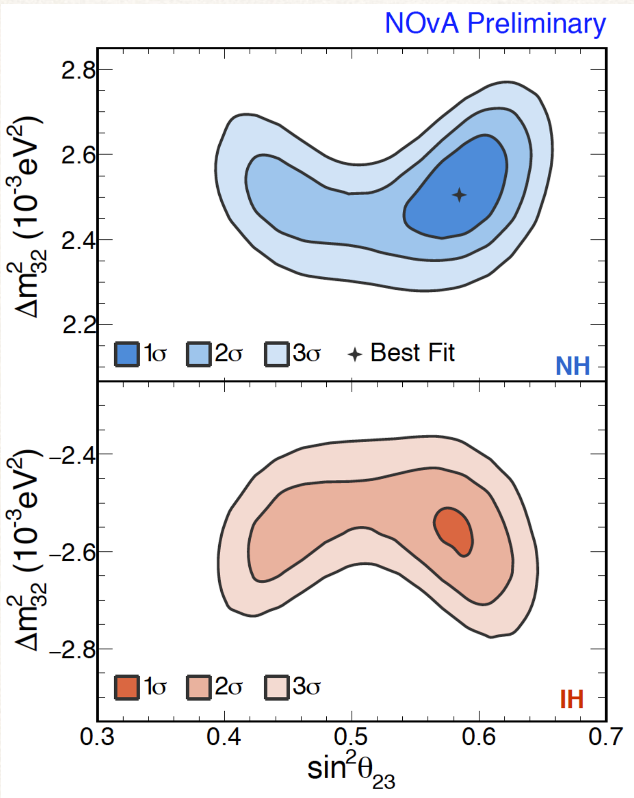

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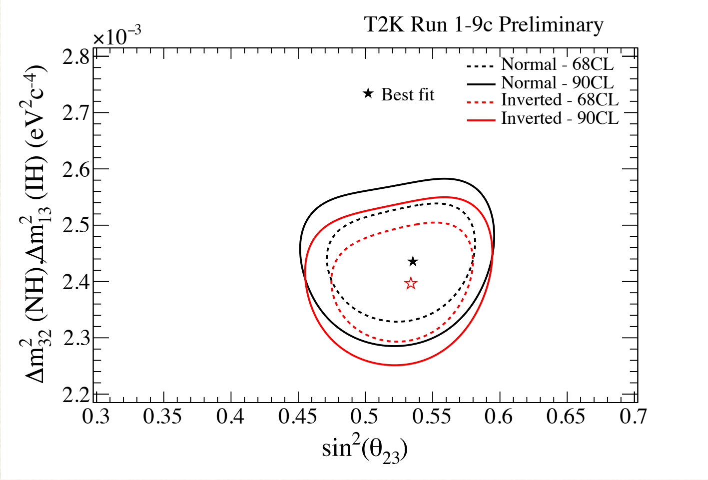
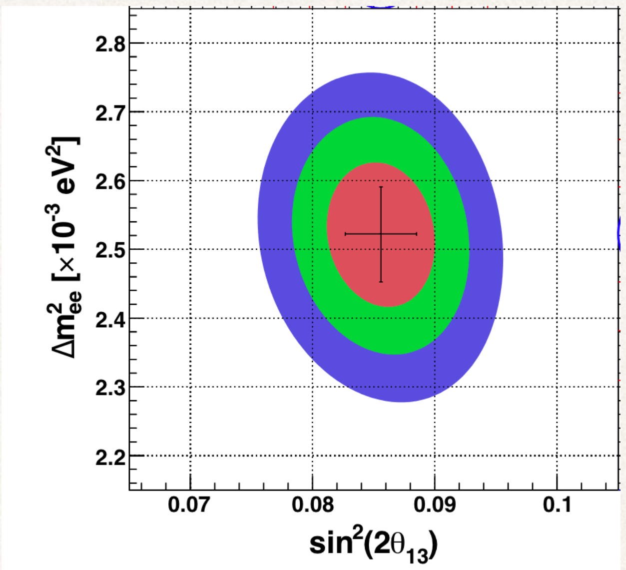
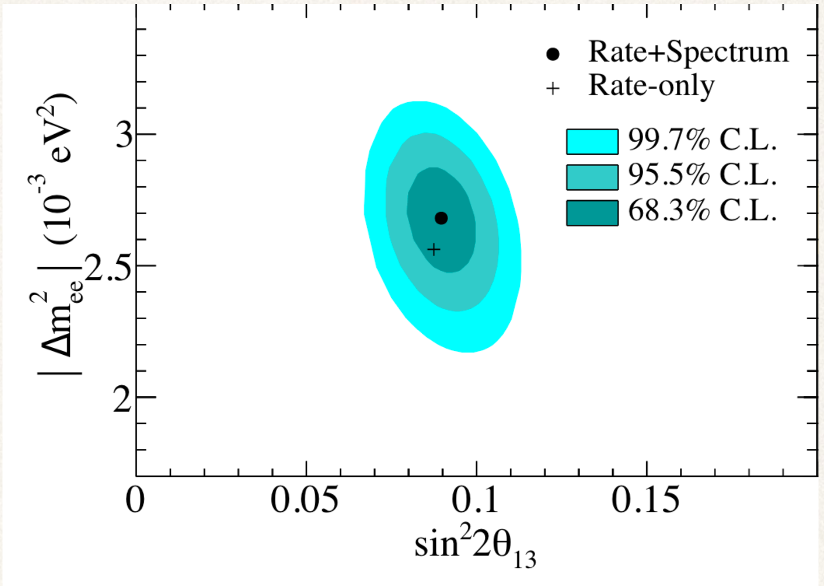




Daya Bay 1958-day data

Adey et al, 1809.02261



RENO 2200-day data

Bak et al, 1806.00248

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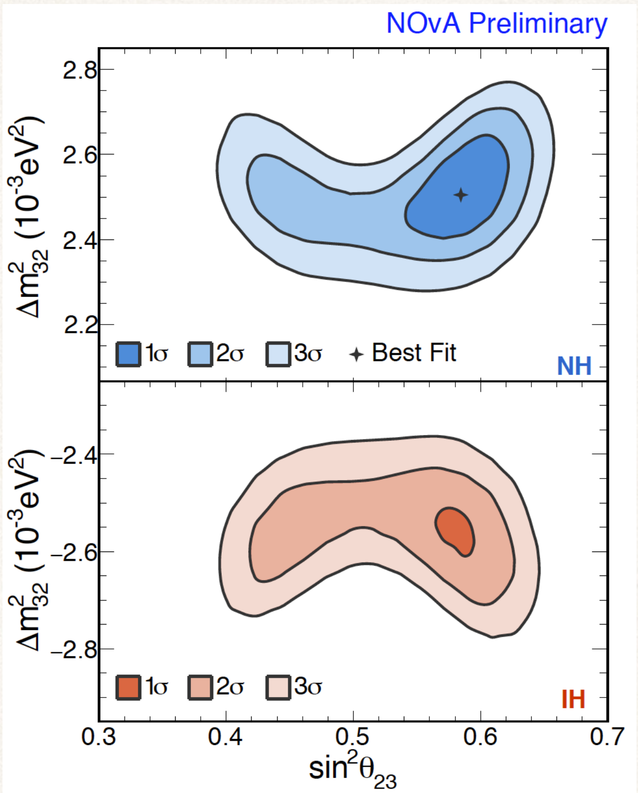

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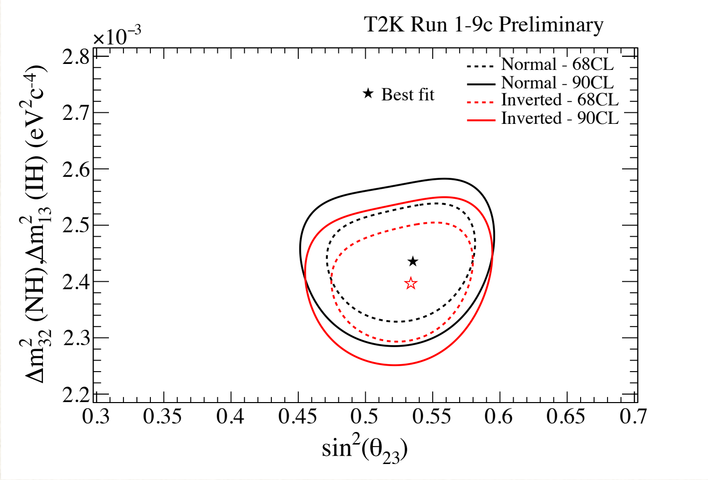

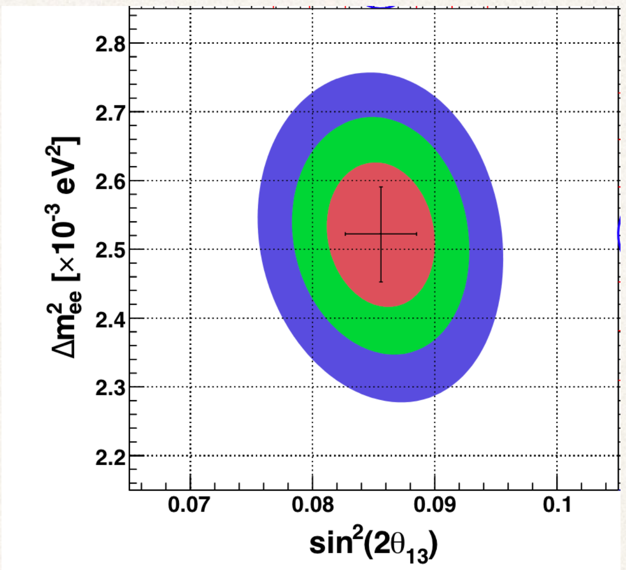

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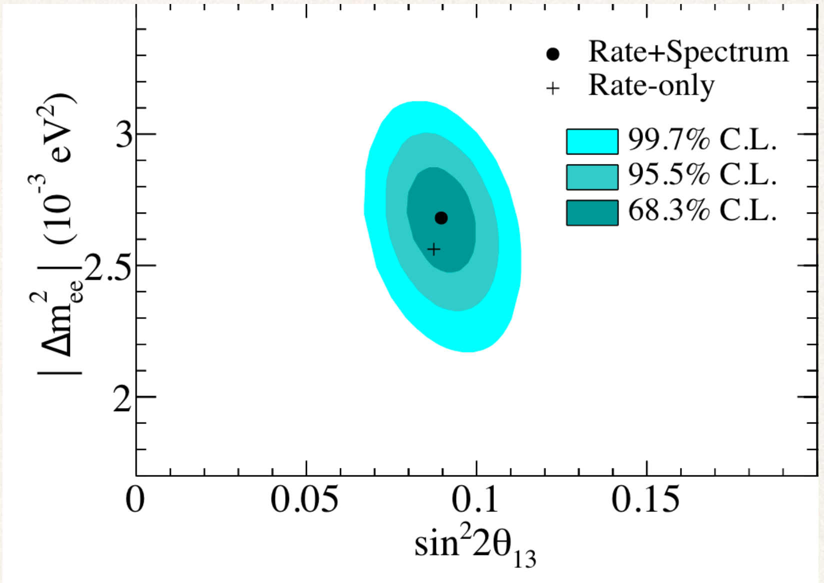


RENO 2200-day data

Bak et al, 1806.00248

Improved analysis SK-IV atmospheric data

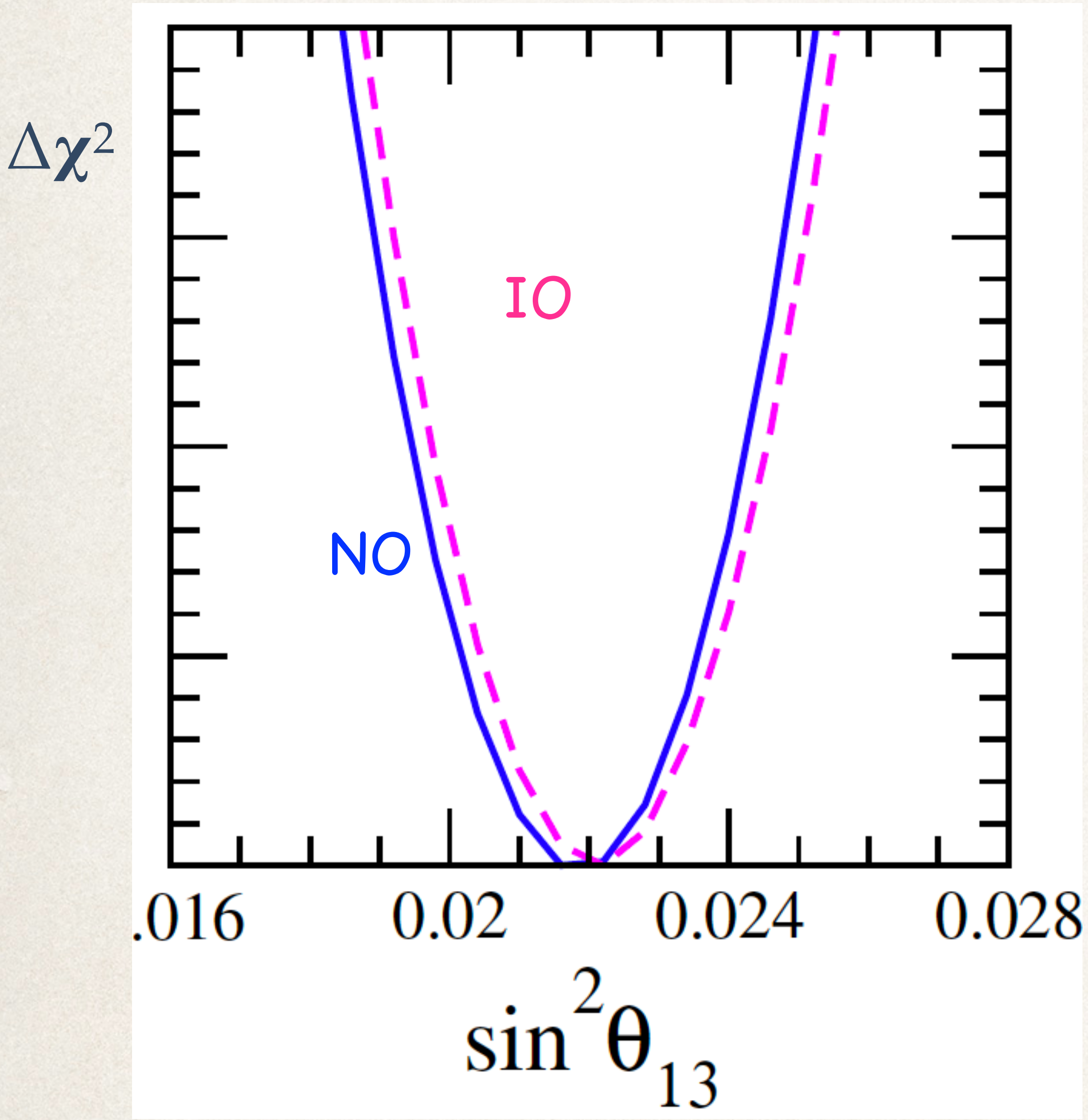
Jiang et al, 1901.03230

10 yr ANTARES atmospheric data

Albert et al, 1812.0865

Reactor mixing angle θ_{13}

de Salas et al, PLB782 (2018) 633



$$\sin^2\theta_{13} = 0.0216\,^{+0.00083}_{-0.00069}\ \text{(NO)}$$

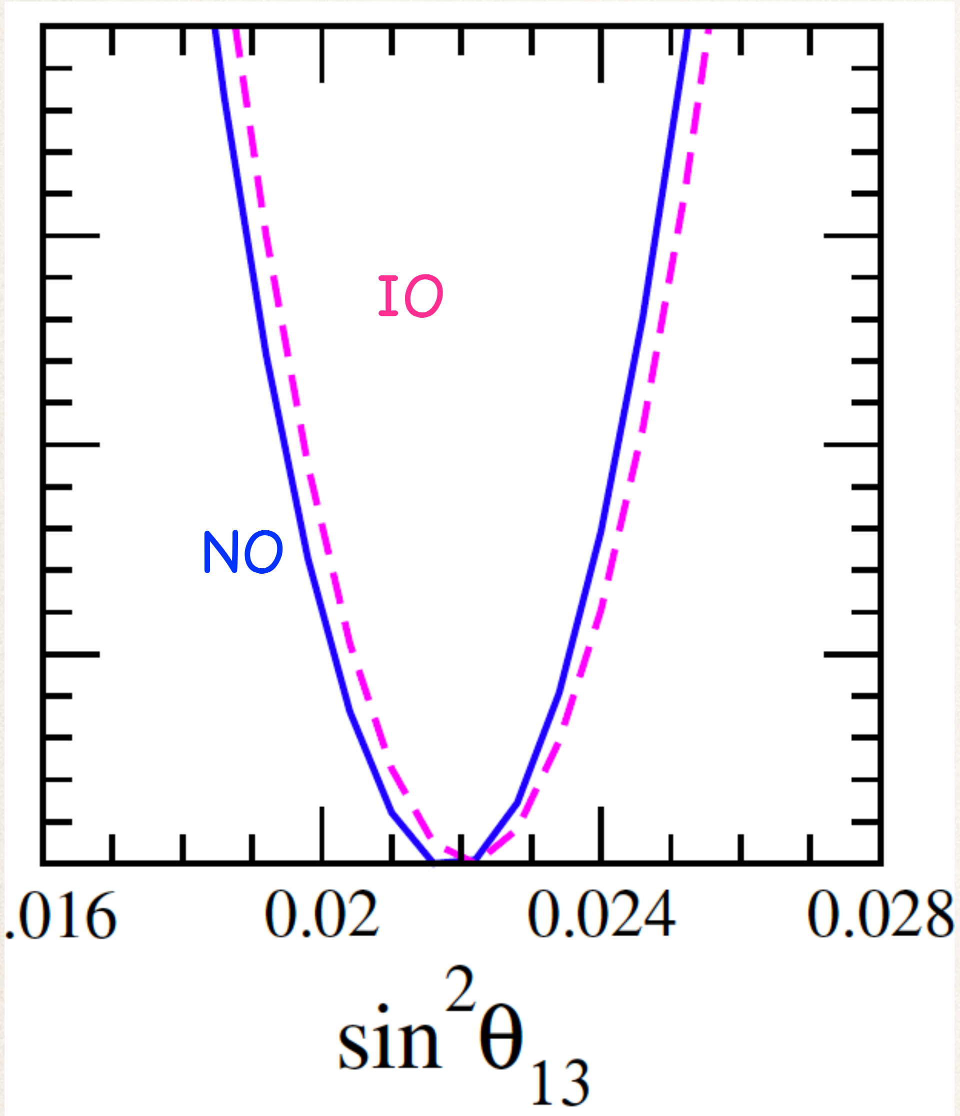
$$\sin^2\theta_{13} = 0.0222\,^{+0.00074}_{-0.00075}\ \text{(IO)}$$

Reactor mixing angle θ_{13}

de Salas et al, PLB782 (2018) 633

Latest reactor data

$\Delta\chi^2$



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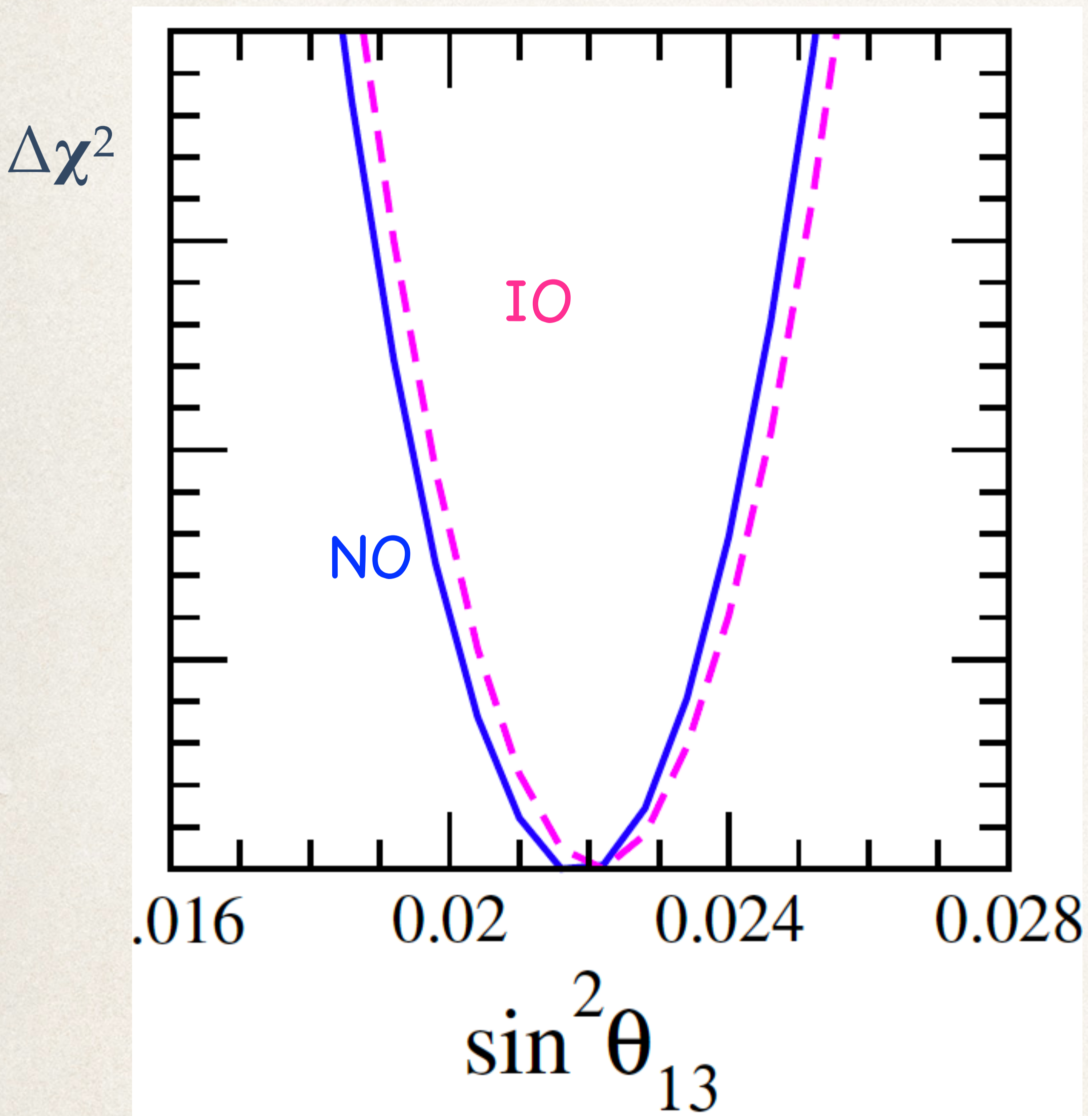
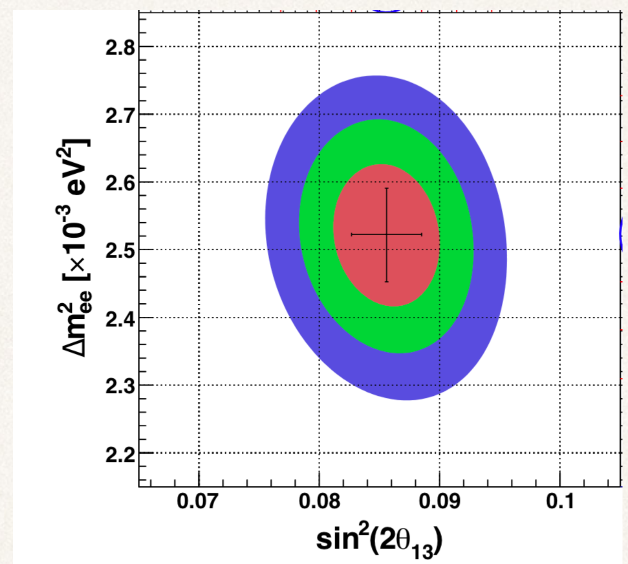
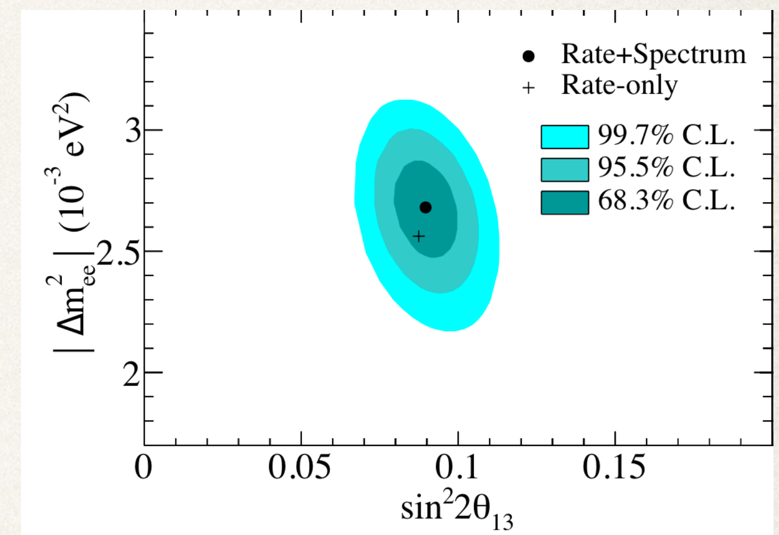


Daya Bay



RENO



$\sin^2 2\theta_{13}\,|_{\text{DayaBay}} = 0.0841 \Rightarrow 0.0856$

$\sin^2 2\theta_{13}\,|_{\text{RENO}} = 0.0860 \Rightarrow 0.0896$

$\sin^2\theta_{13} = 0.0216\,^{+0.00083}_{-0.00069}$ (NO)

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Reactor mixing angle θ_{13}

de Salas et al, PLB782 (2018) 633

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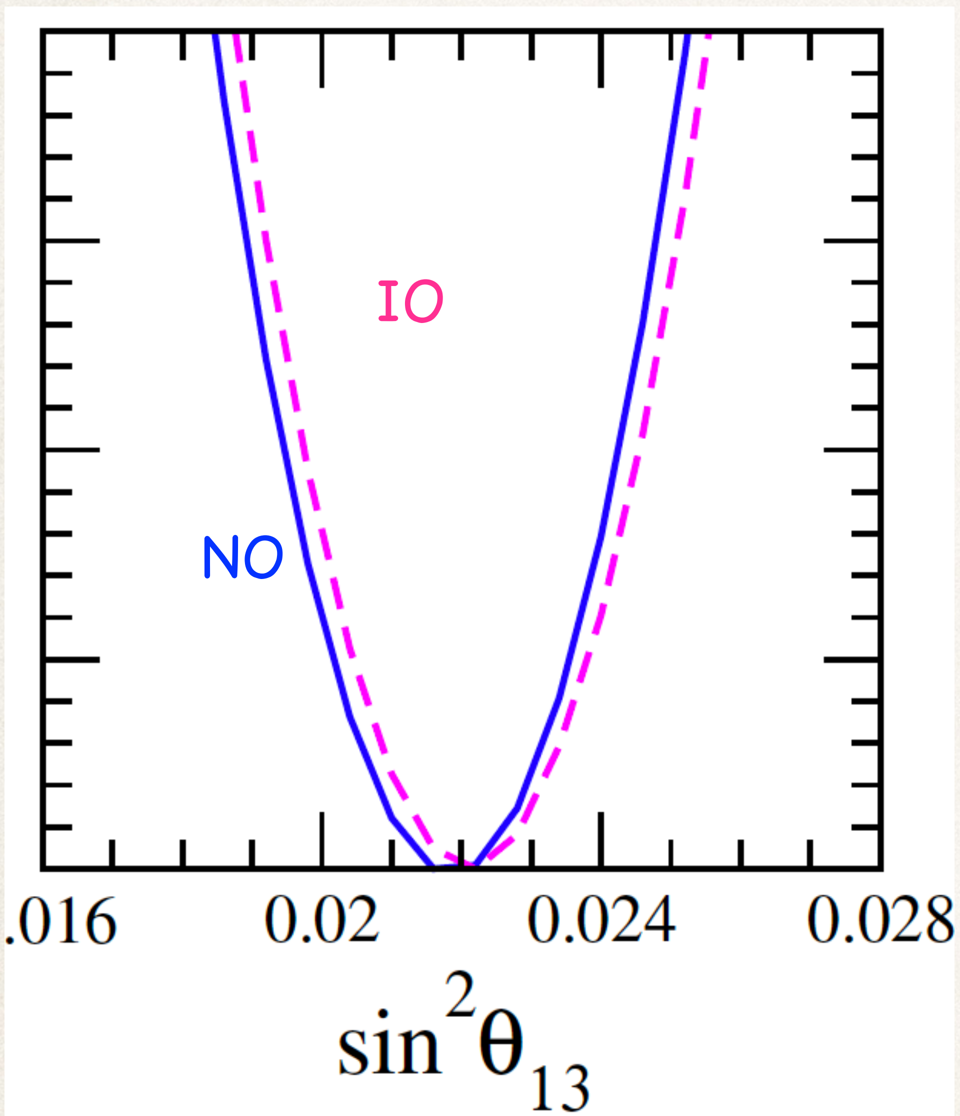

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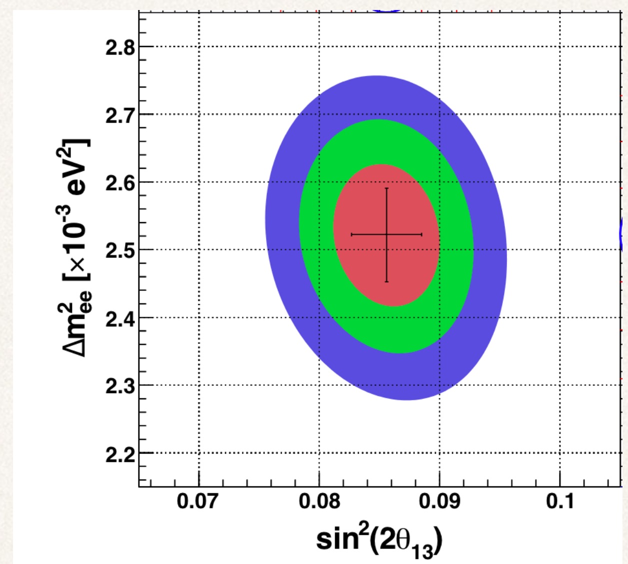
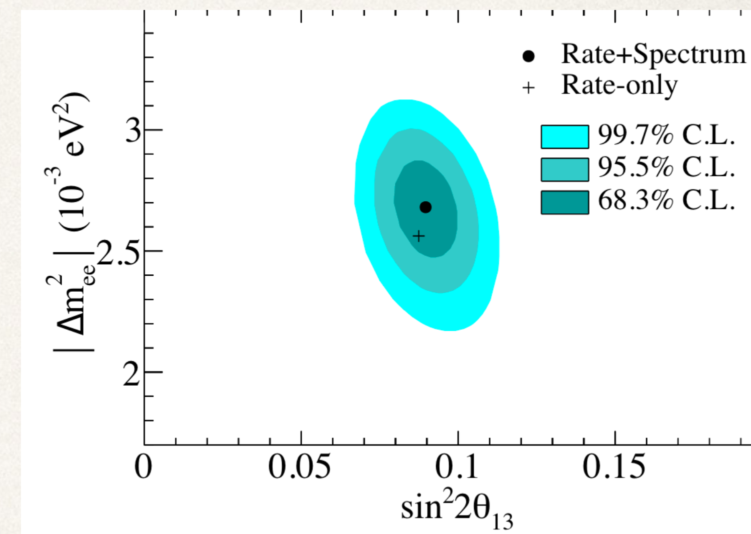
Daya Bay



RENO



$\sin^2 2\theta_{13}\,|_{\rm DayaBay} = 0.0841 \Rightarrow 0.0856$

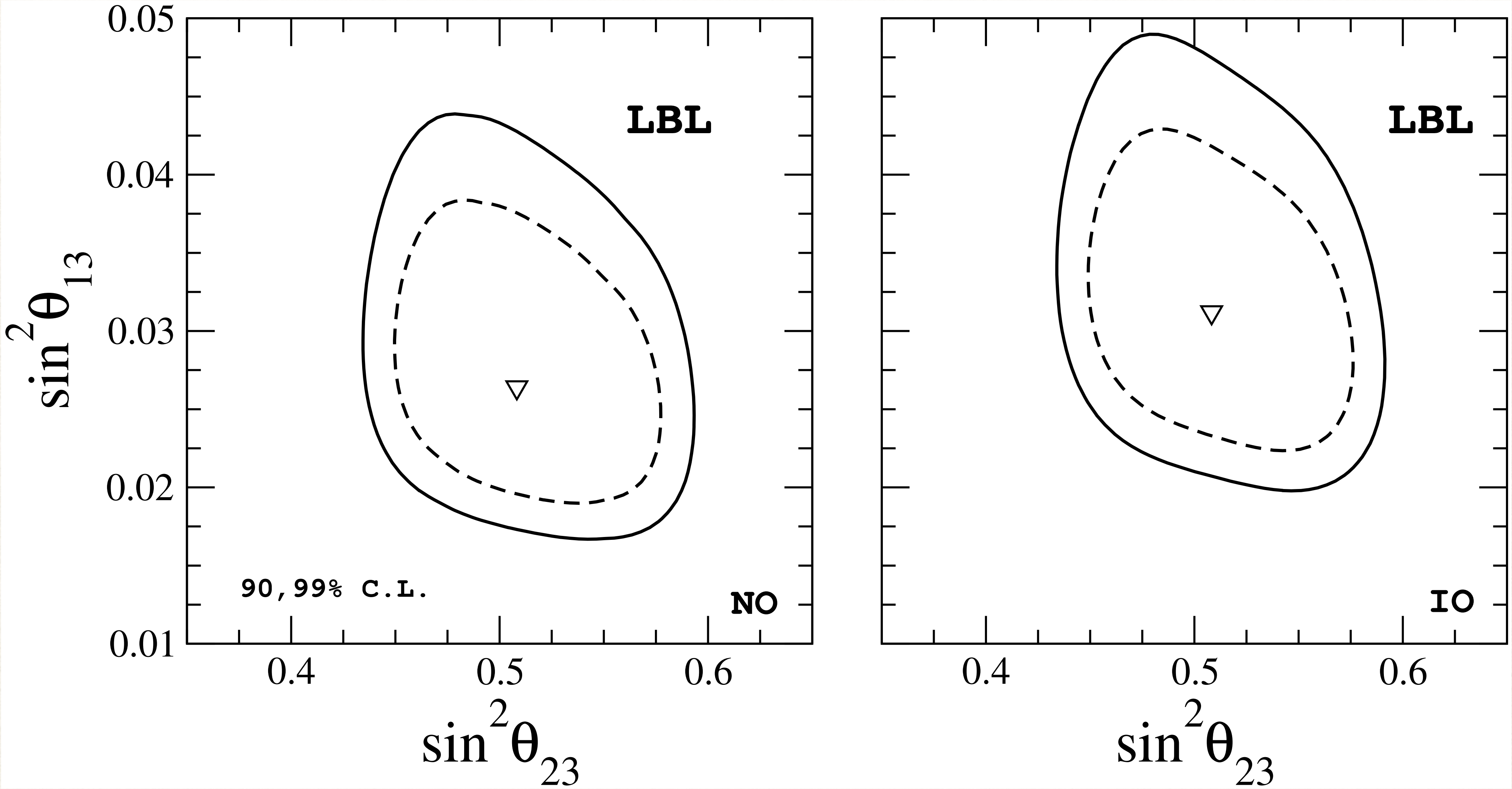
$\sin^2 2\theta_{13}\,|_{\rm RENO} = 0.0860 \Rightarrow 0.0896$

$\Rightarrow$ The best fit value will be shifted to larger values

$\Rightarrow$ reduced 1σ uncertainty (~3%)

Octant of the atmospheric angle

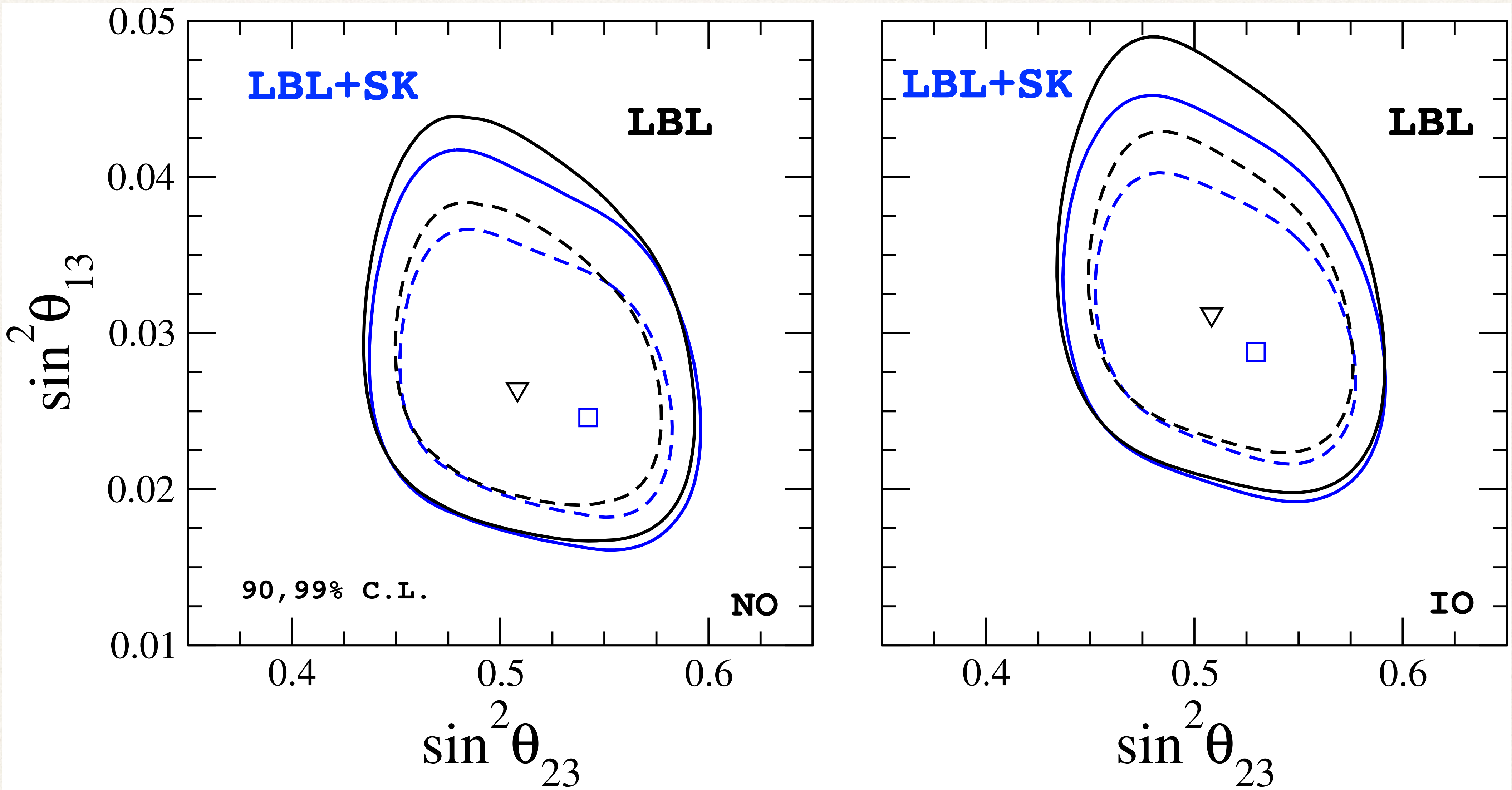
de Salas et al, PLB782 (2018) 633



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

Octant of the atmospheric angle

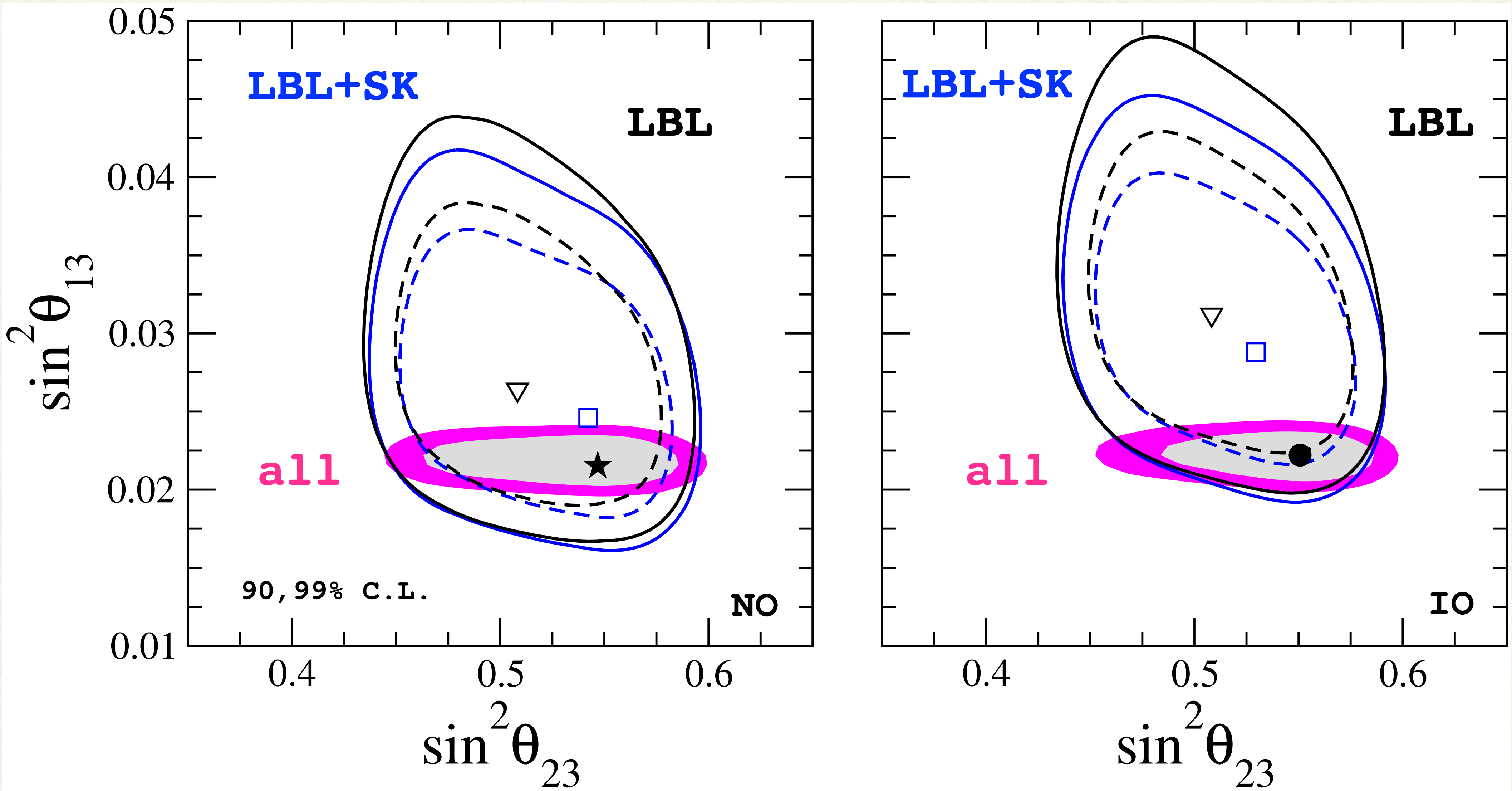
de Salas et al, PLB782 (2018) 633



- 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

de Salas et al, PLB782 (2018) 633

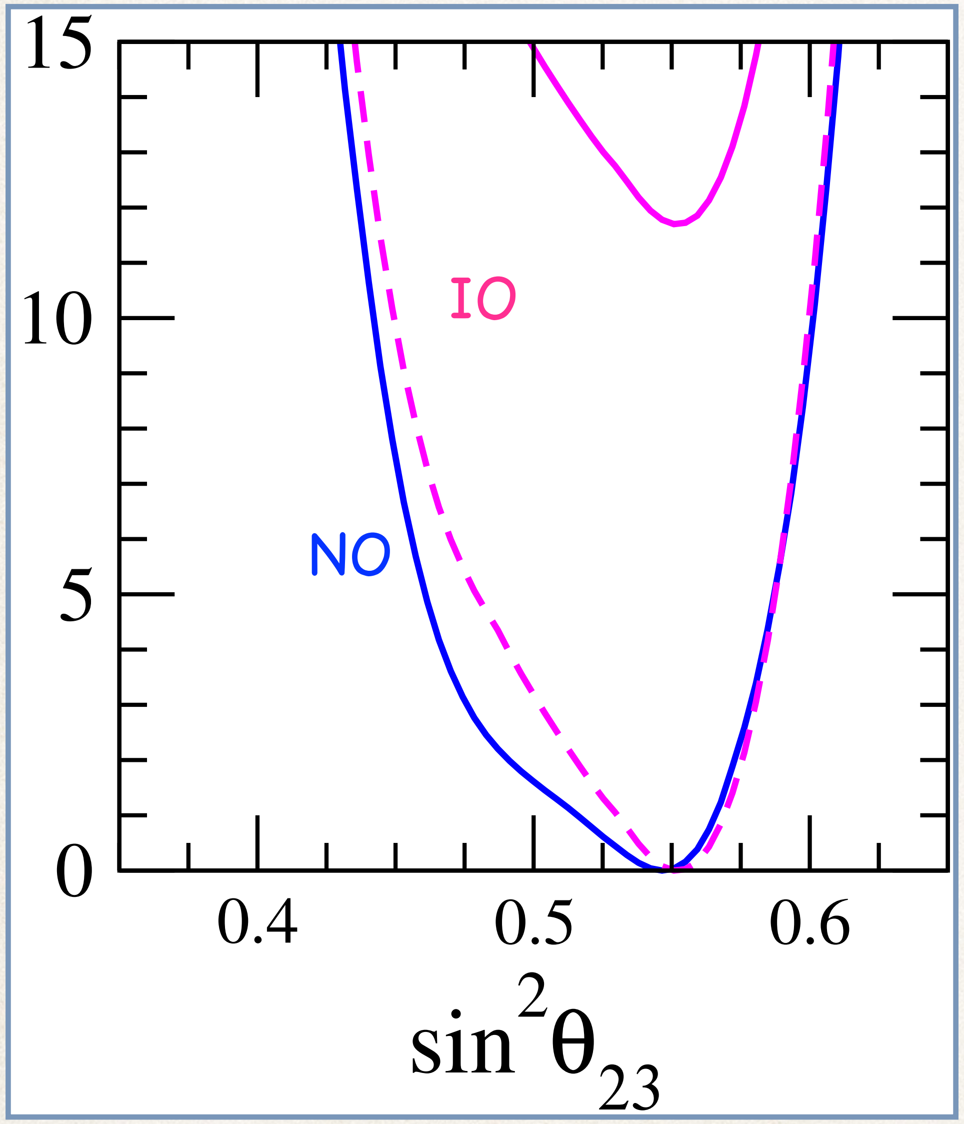


- combination of LBL experiments prefer θ_{23} close to maximal mixing for both orderings
- Super-K atmospheric data shift bfp to higher values: $\sin^2\theta_{23} = 0.54$ (0.53) for NO (IO)
- combination with SBL reactors pushes atmospheric angle to $\sin^2\theta_{23} \simeq 0.55$

Octant of the atmospheric angle

de Salas et al, PLB782 (2018) 633

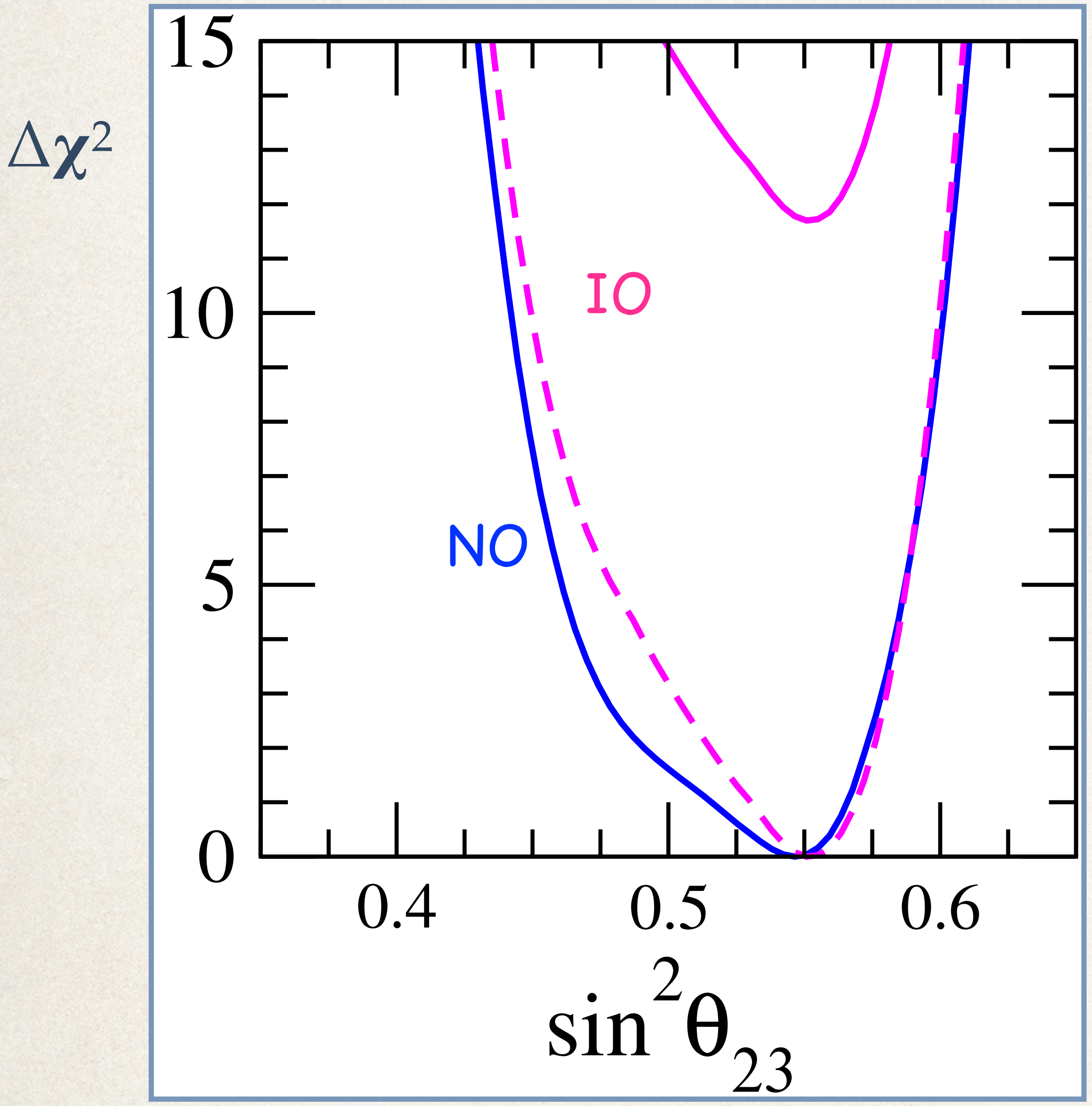
$\Delta\chi^2$



Values at the first octant allowed with $\Delta\chi^2 \geq 1.6$ (3.2) for NO (IO)

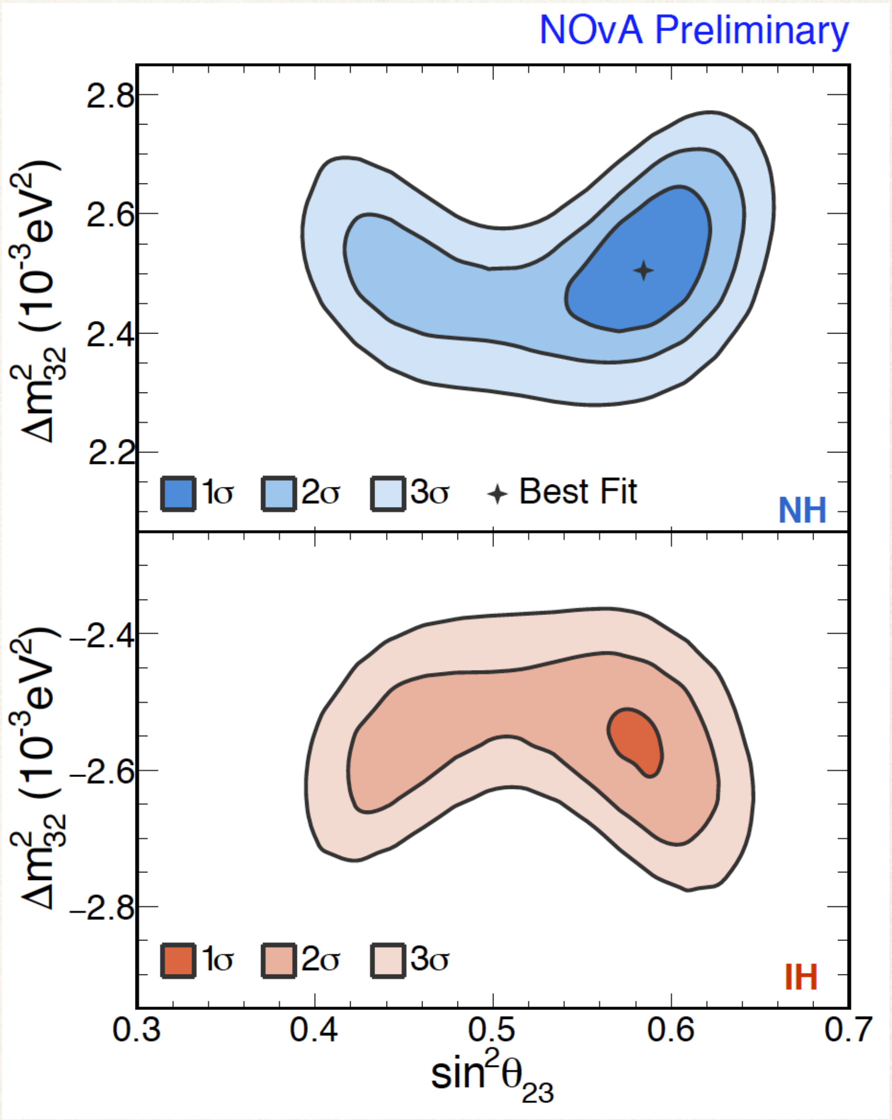
Octant of the atmospheric angle

de Salas et al, PLB782 (2018) 633



Values at the first octant allowed with $\Delta\chi^2 \geq 1.6$ (3.2) for NO (IO)

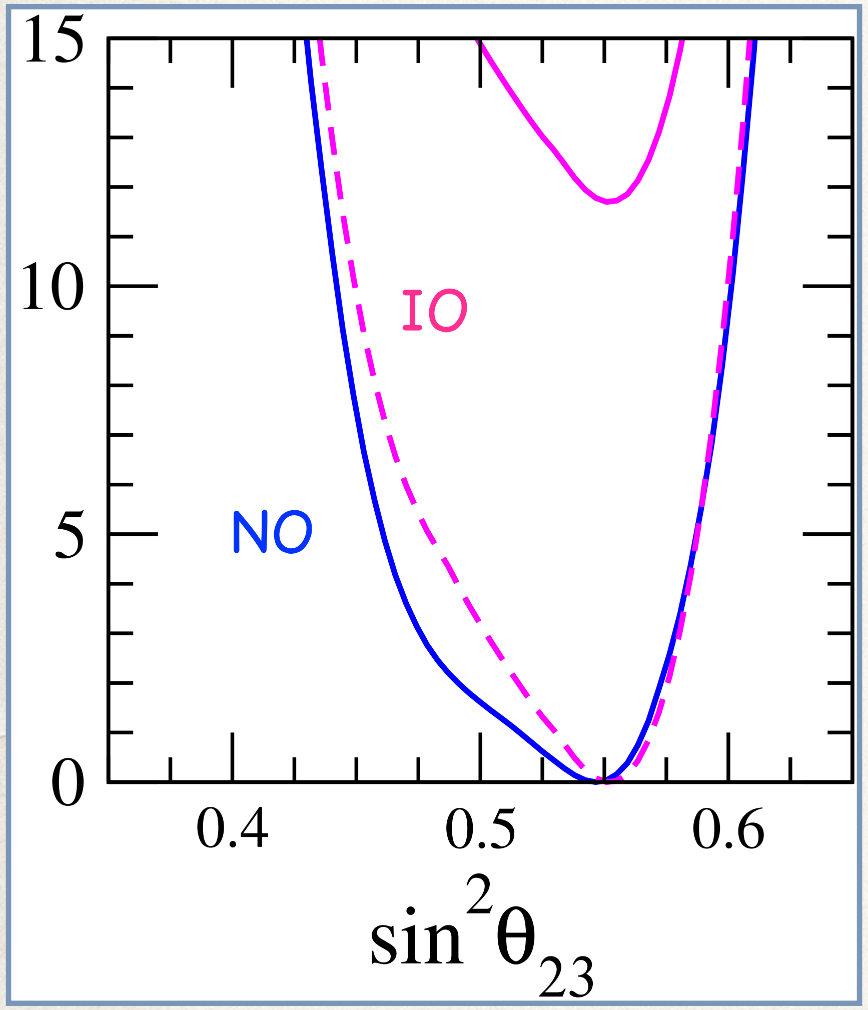
After first NOνA antineutrino data



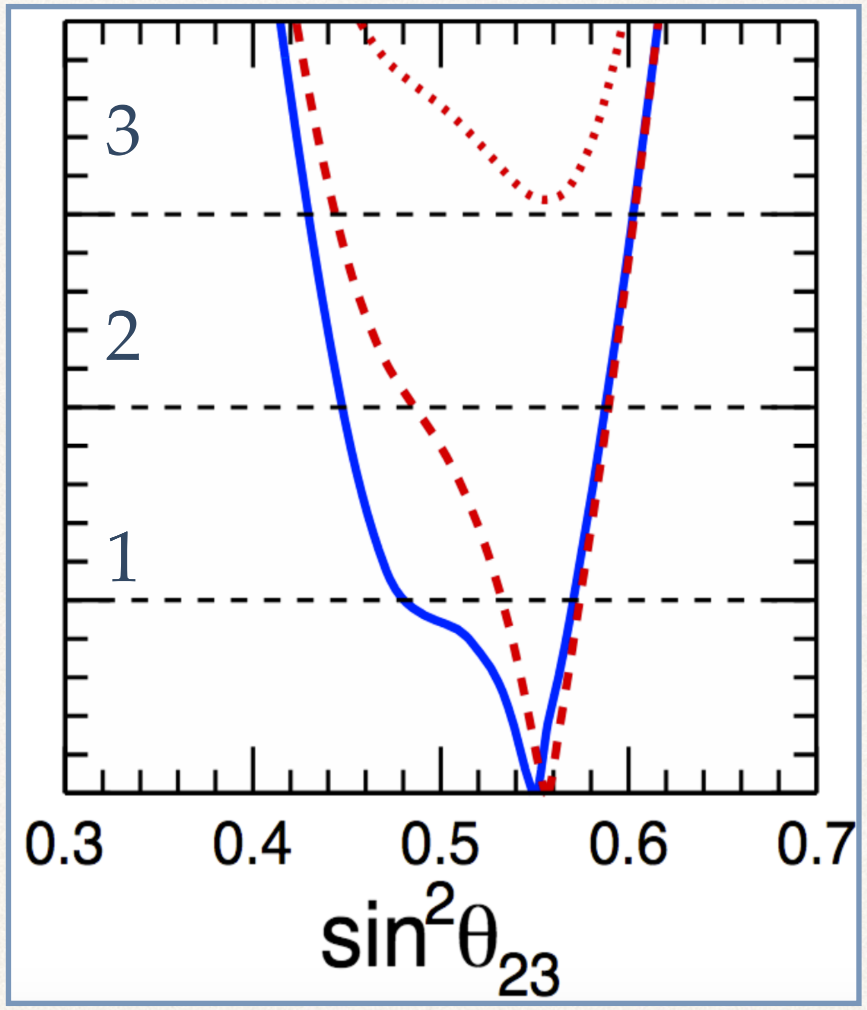
⇒ A stronger preference for the second octant is expected

Octant of the atmospheric angle

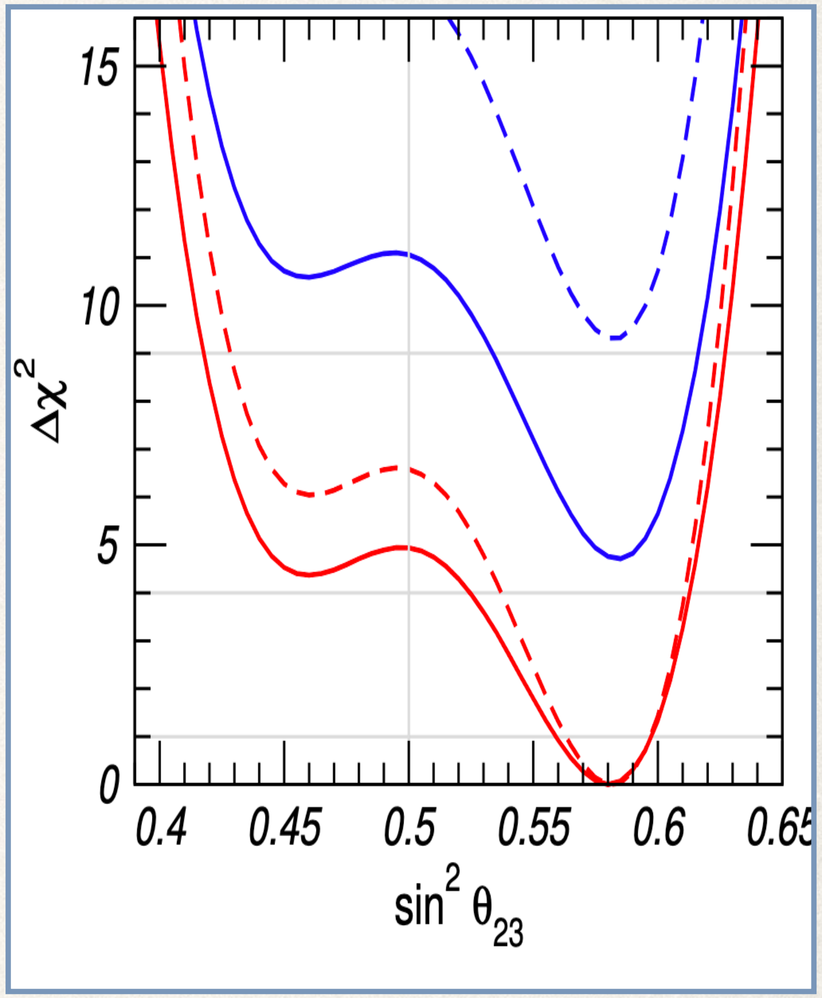
$\Delta\chi^2$, Valencia [PLB 2018]



$N\sigma$, Bari [PPNP 2018]



$\Delta\chi^2$, NuFit v4.0 [JHEP 2019]



New LBL included

- General agreement in the preferred octant of global neutrino data
- First octant more disfavoured due to new NOvA data, $\Delta\chi^2 = 4.4$ (NO, NuFit)

Measurement of the CP phase

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

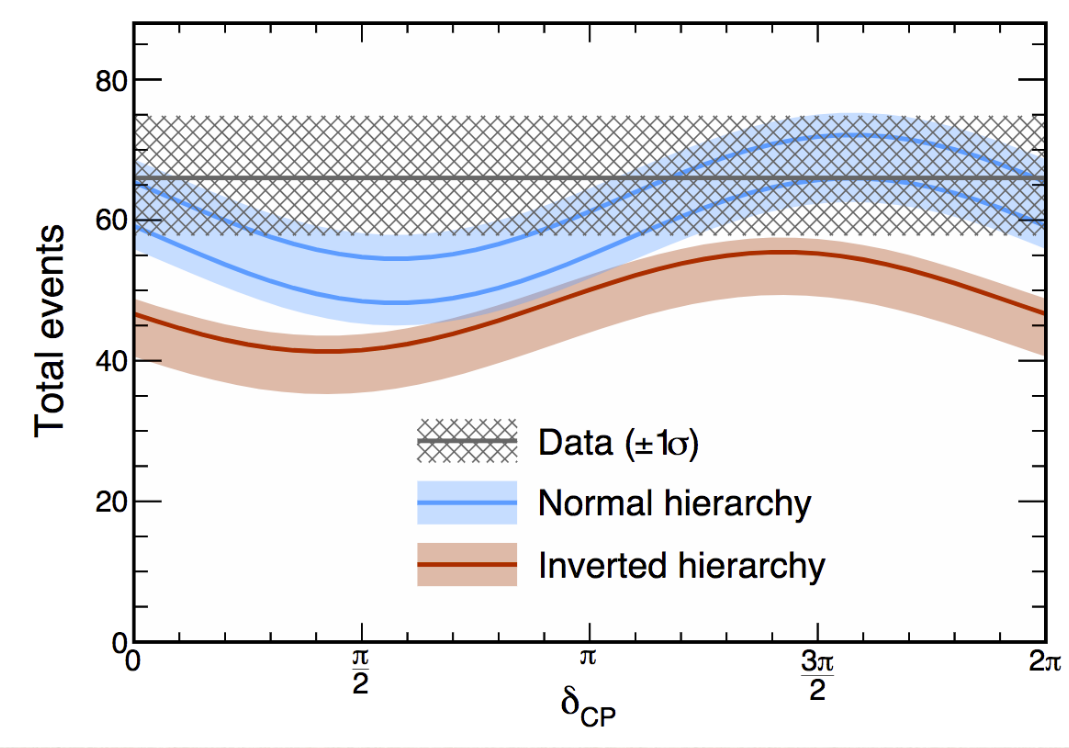
T2K

Mark Hartz, KEK Colloquium

Sample	Predicted Rates $\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Observed 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

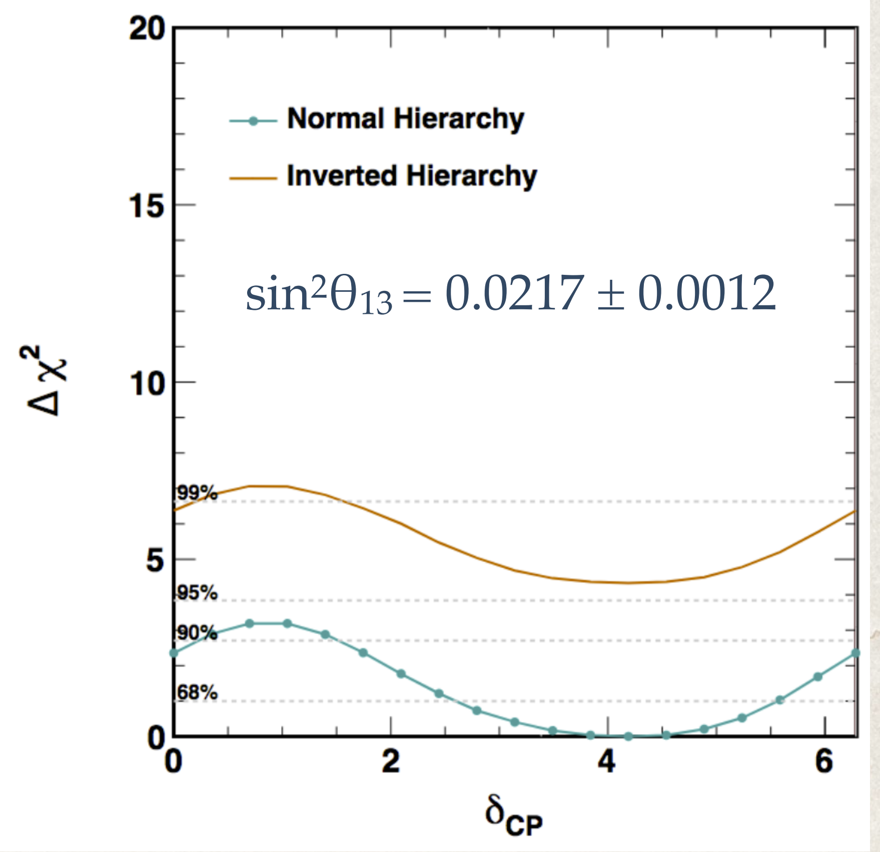
Acero et al, 1806.00096



66 ν_e events observed

Super-K

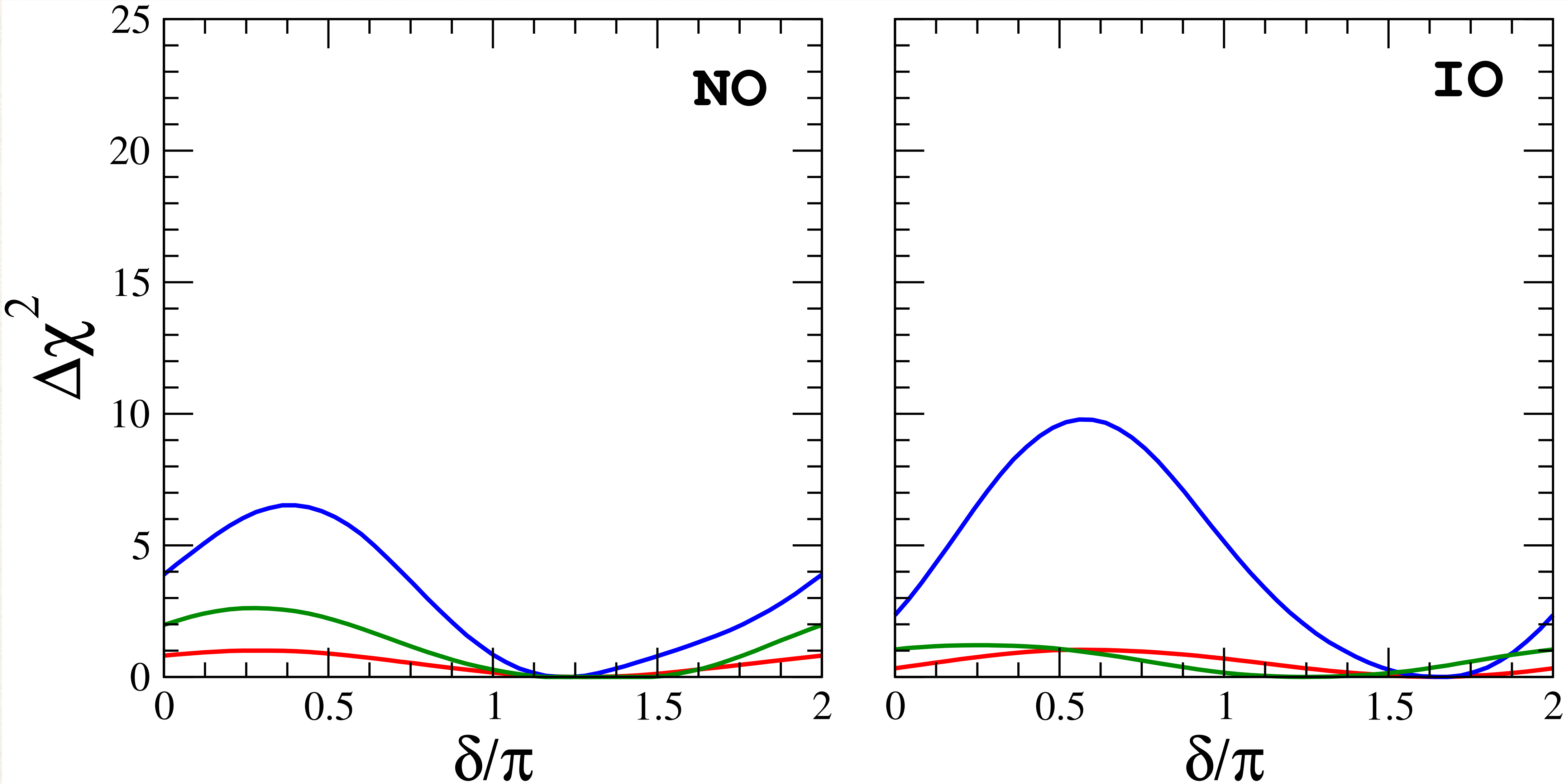
- $\delta = 1.5\pi$ for NO
- $\delta = 1.2\pi$ for IO
- preference driven mostly by sub-GeV e-like samples



SK Collab. PRD97 (2018)

Measurement of the CP phase

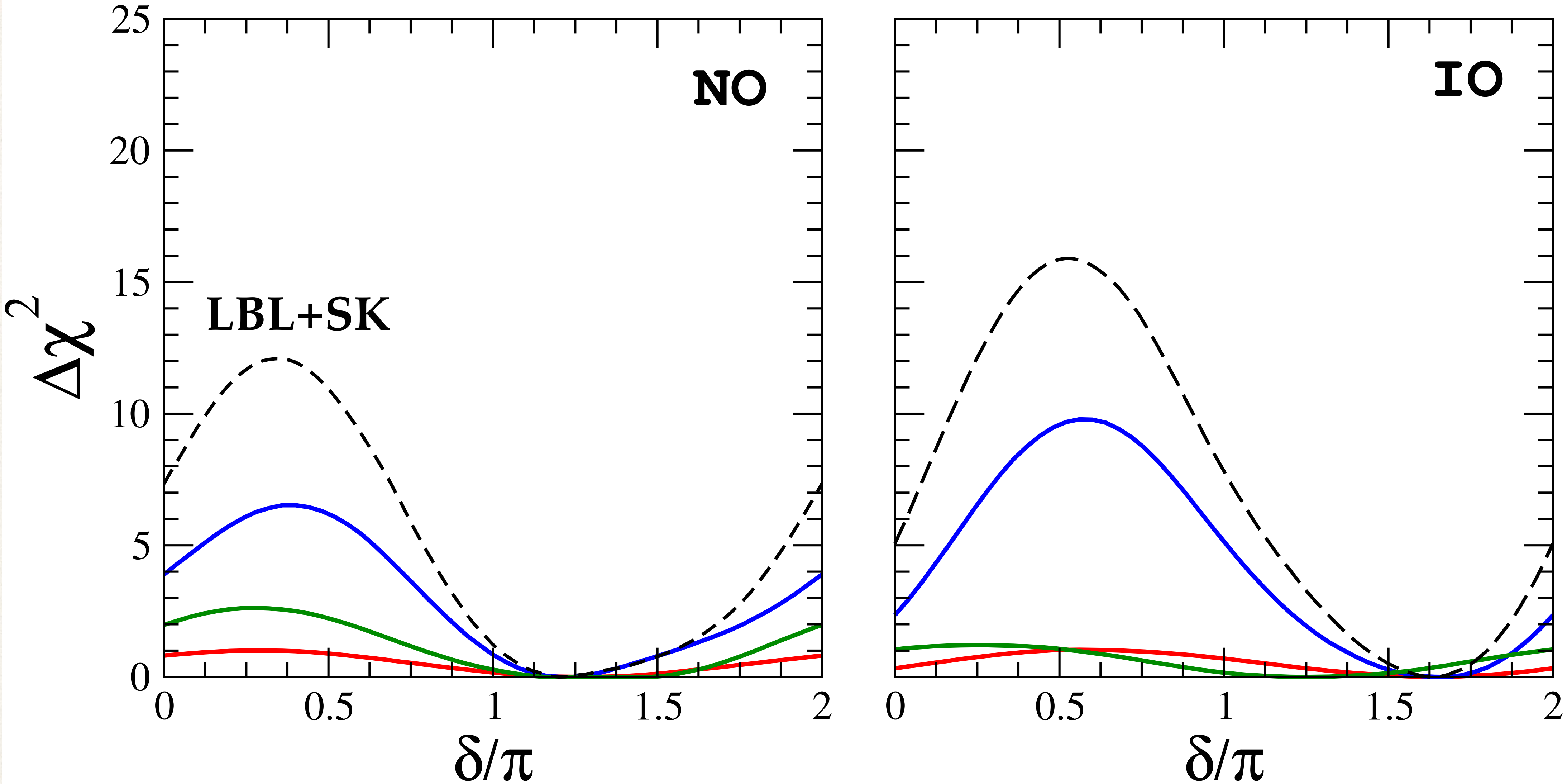
de Salas et al, PLB782 (2018) 633



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

Measurement of the CP phase

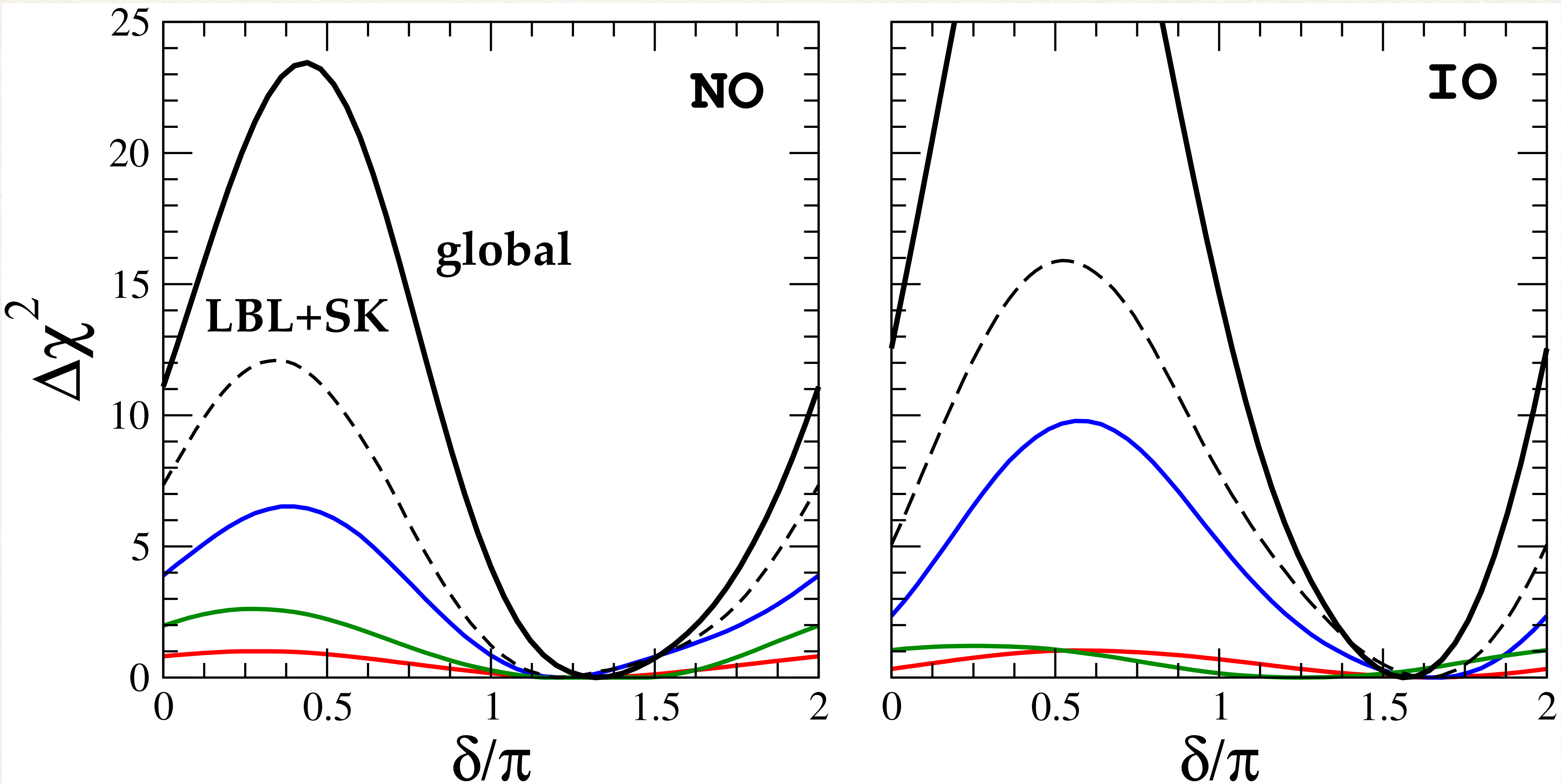
de Salas et al, PLB782 (2018) 633



- **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

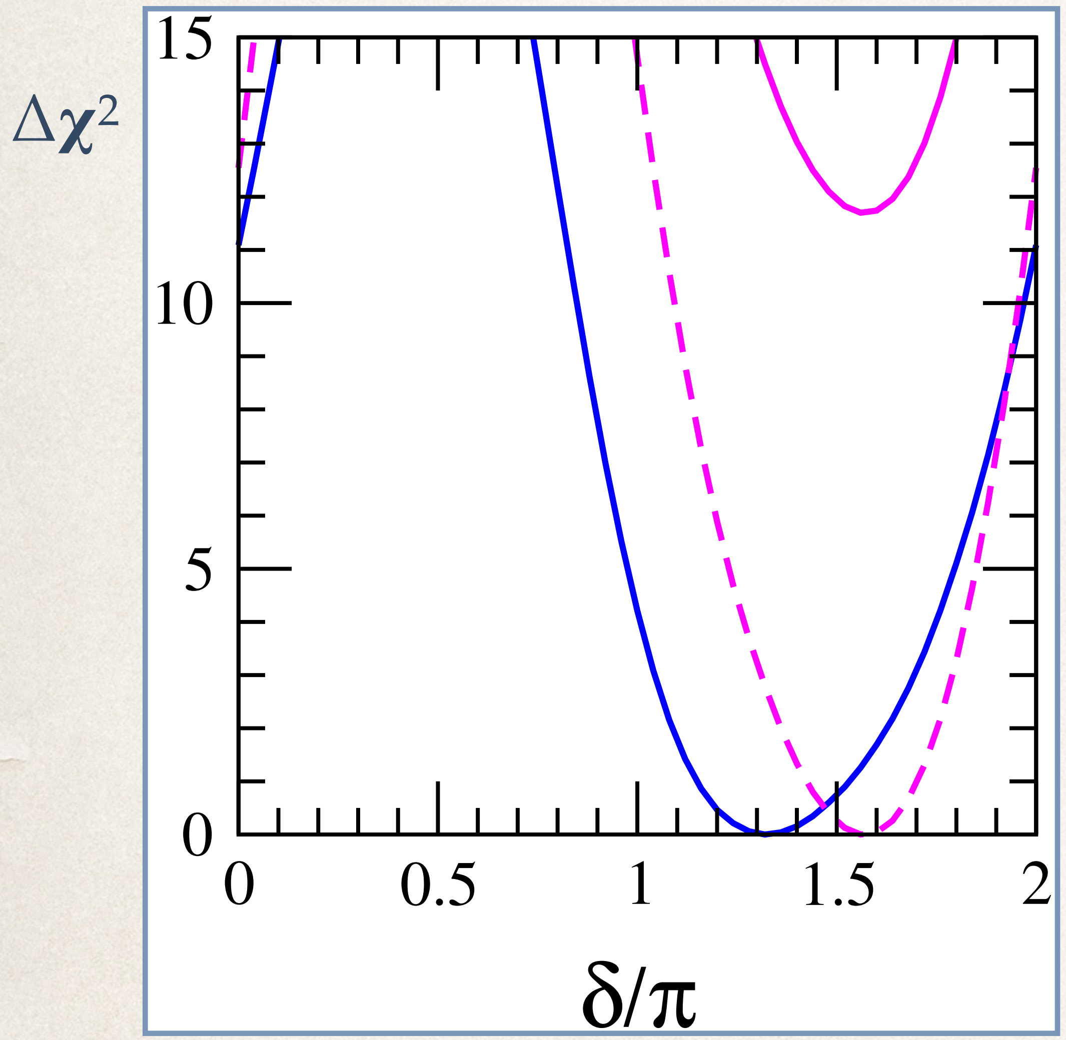
de Salas et al, PLB782 (2018) 633



- **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

de Salas et al, PLB782 (2018) 633

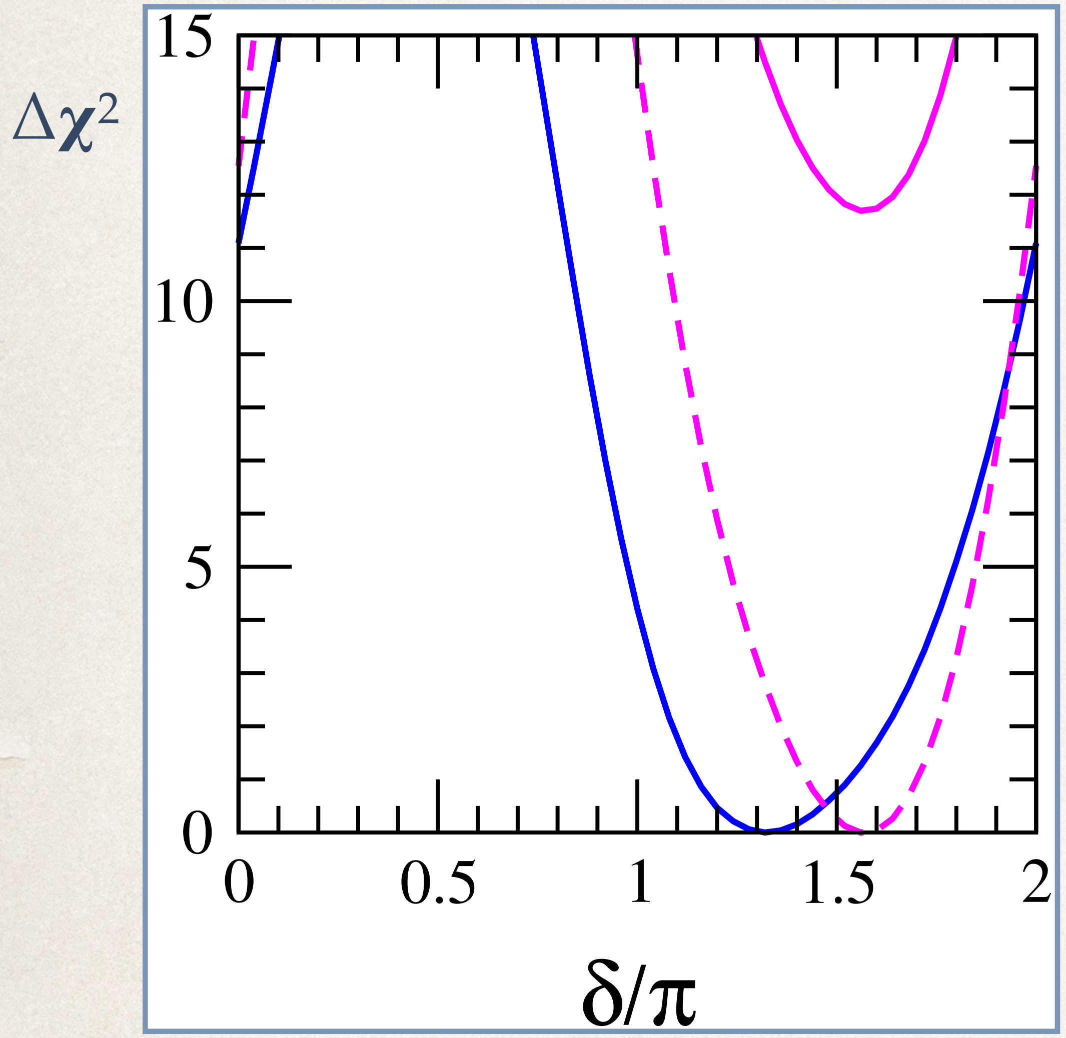


- preference for $\pi < \delta < 2\pi$, with CPC allowed at 2σ (3.8σ) for NO (IO)
- Exact preferred value depends on NMO

Measurement of the CP phase

de Salas et al, PLB782 (2018) 633

Latest T2K and NOνA data



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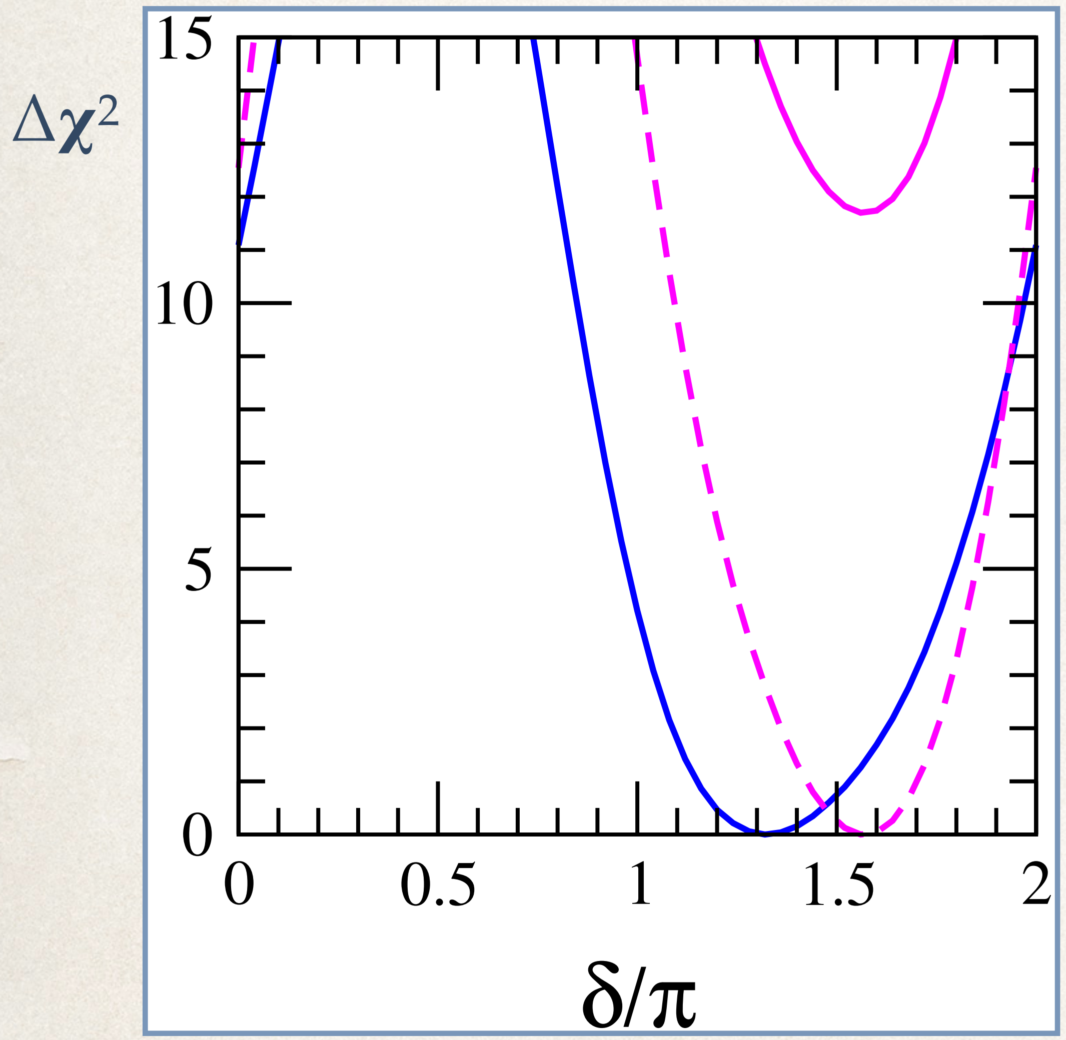
de Salas et al, PLB782 (2018) 633



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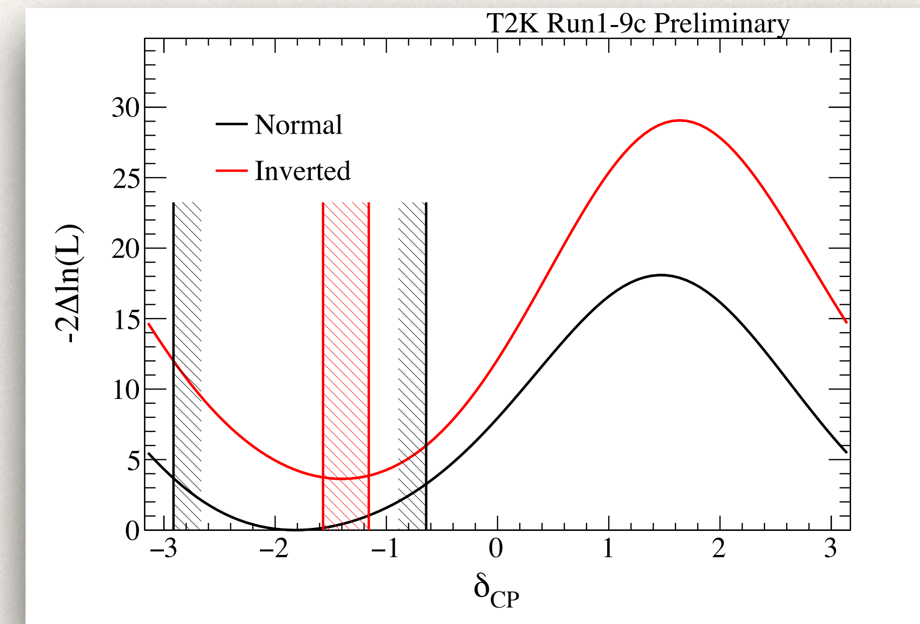
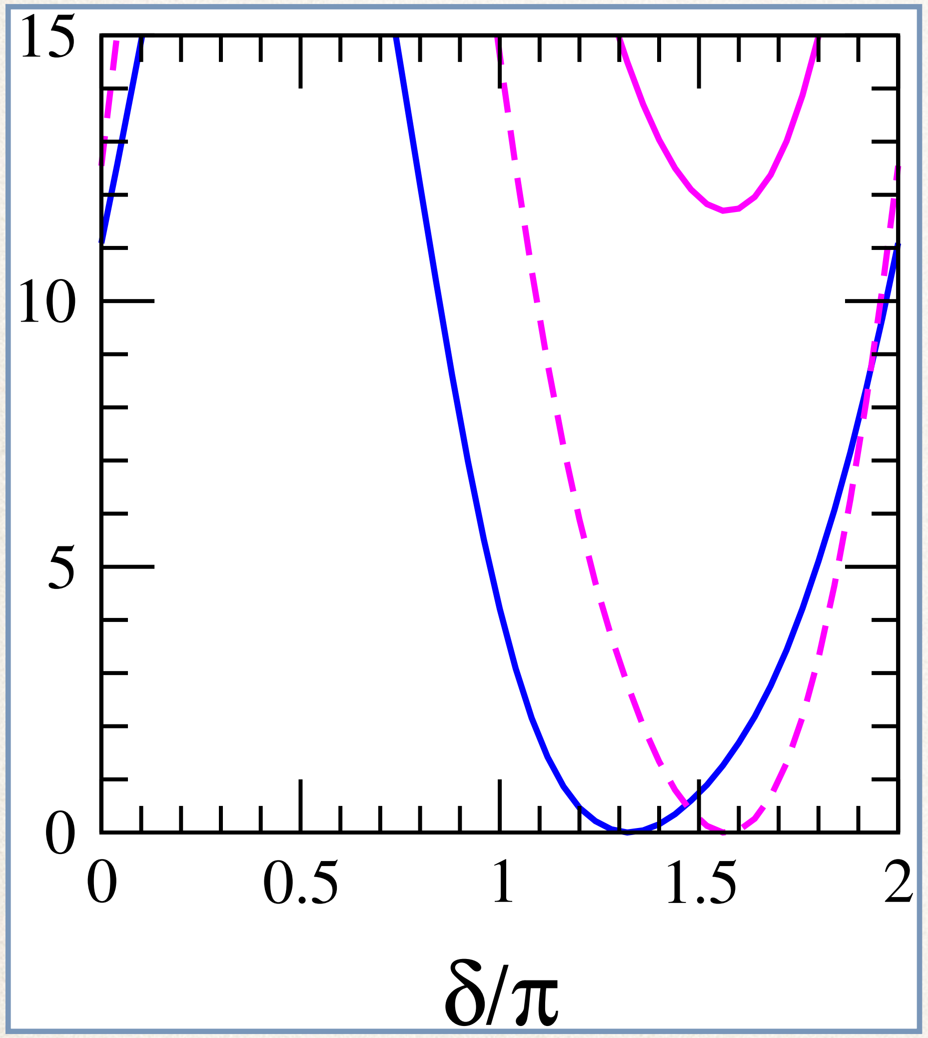


T2K enhances rejection against CPC (allowed at 2σ)

- preference for $\pi < \delta < 2\pi$, with CPC allowed at 2σ (3.8σ) for NO (IO)
- Exact preferred value depends on NMO

Measurement of the CP phase

de Salas et al, PLB782 (2018) 633



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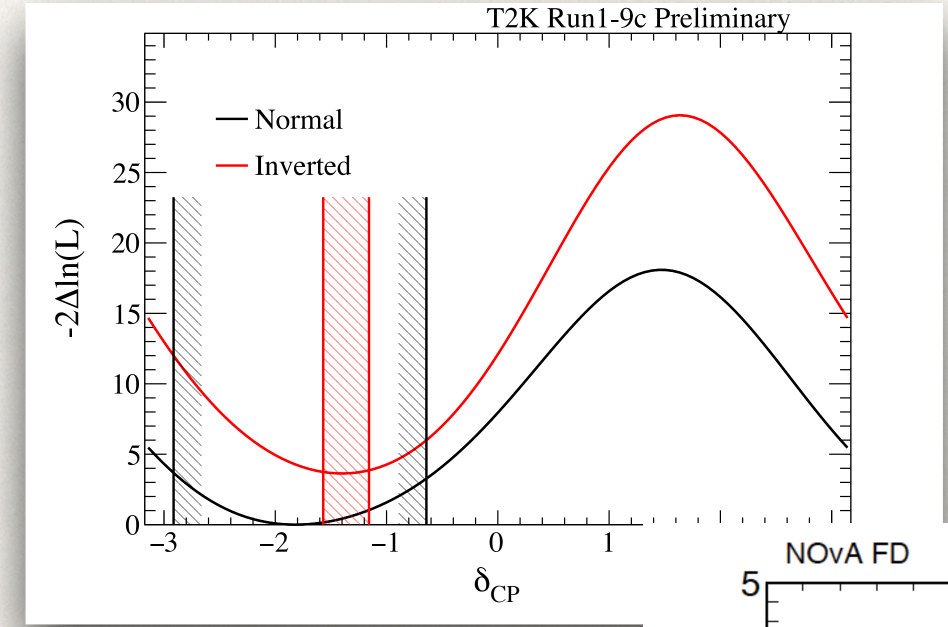
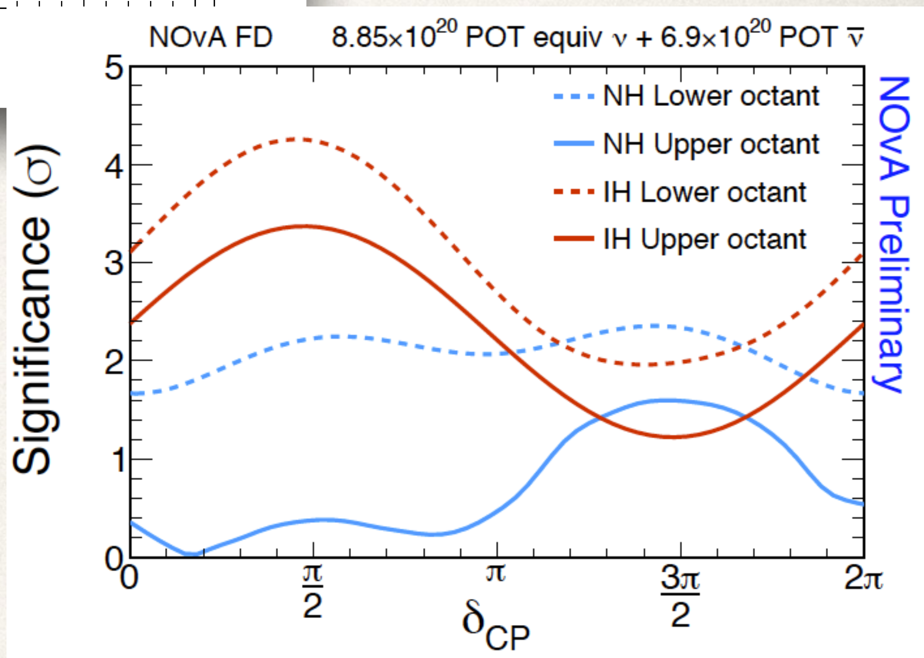


T2K enhances rejection against CPC (allowed at 2σ)

NOvA antineutrino data prefer δ~0 for NO



- preference for $\pi < \delta < 2\pi$, with CPC allowed at 2σ (3.8σ) for NO (IO)
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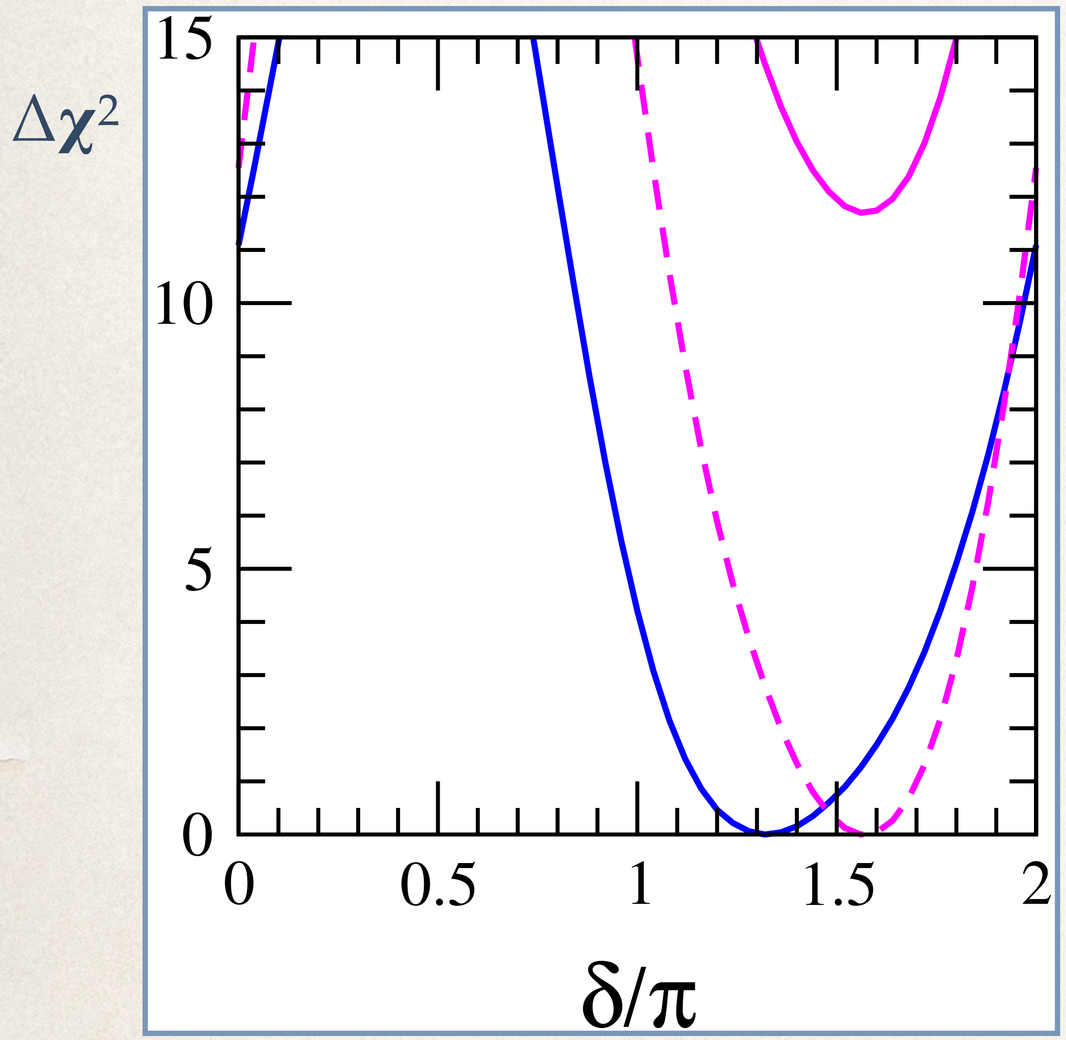
Measurement of the CP phase

de Salas et al, PLB782 (2018) 633



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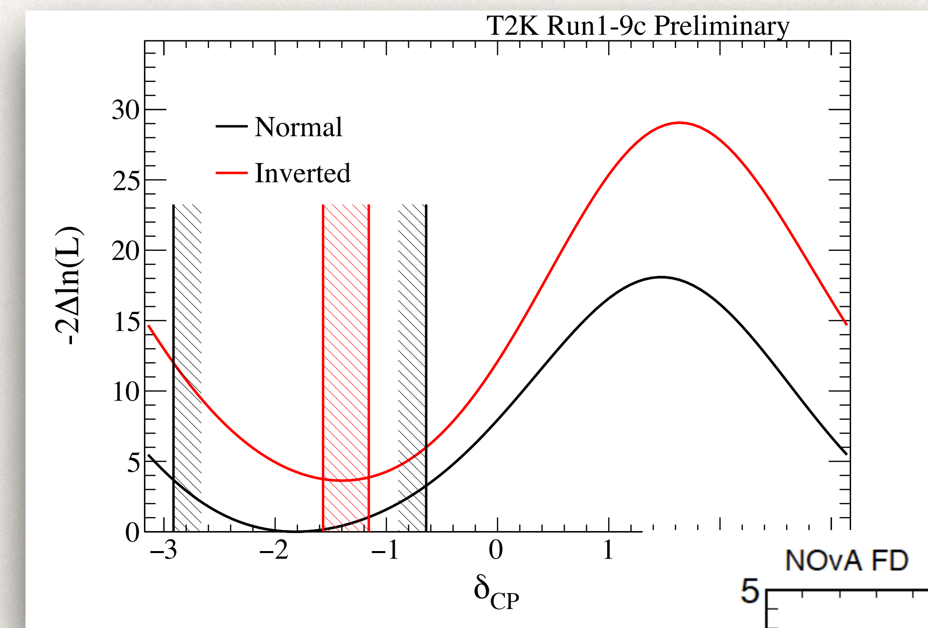

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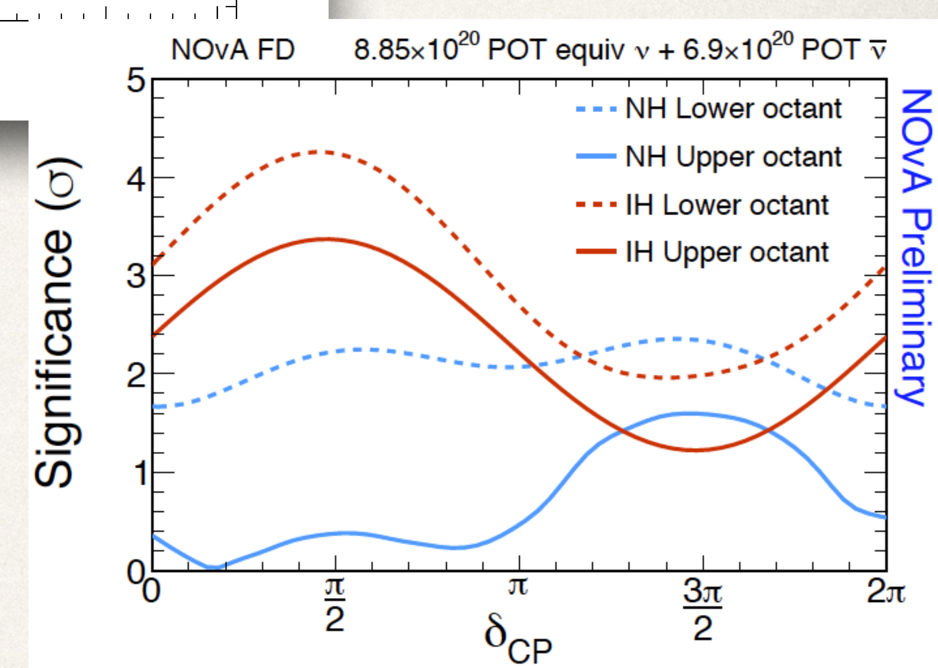
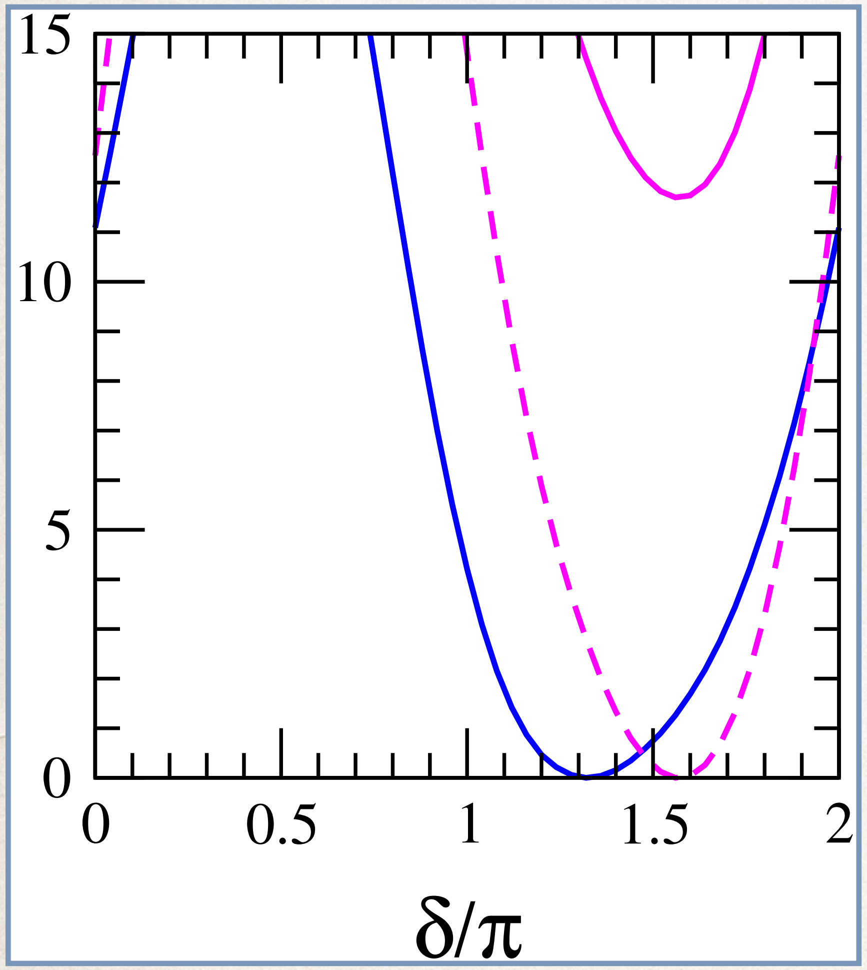


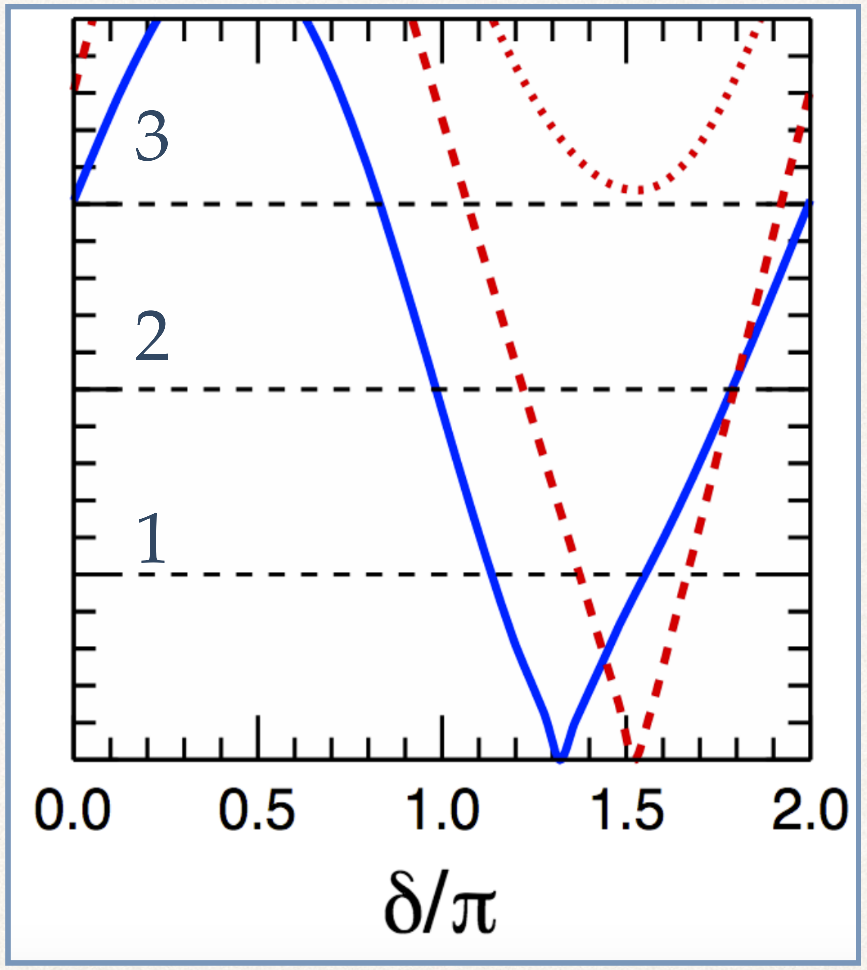
$\Rightarrow$ The best fit for NO will be shifted towards $\delta = \pi$

Measurement of the CP phase

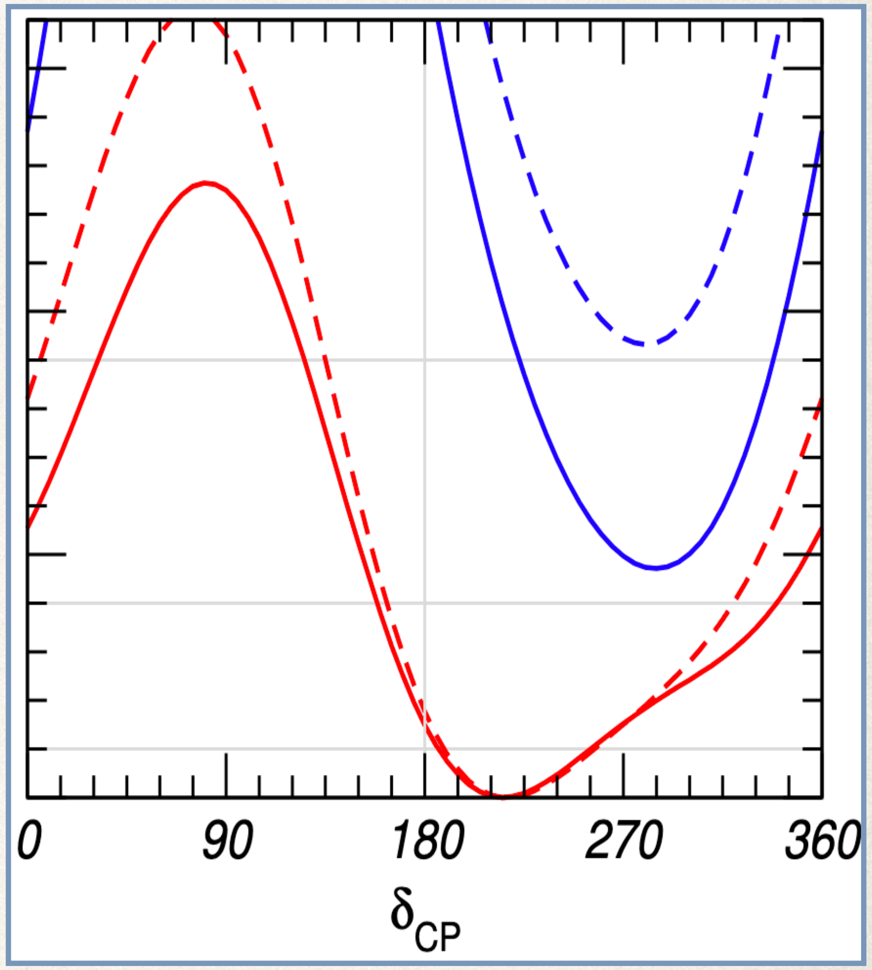
$\Delta\chi^2$, Valencia [PLB 2018]



Nσ, Bari [PPNP 2018]



$\Delta\chi^2$, NuFit v4.0 [JHEP 2019]

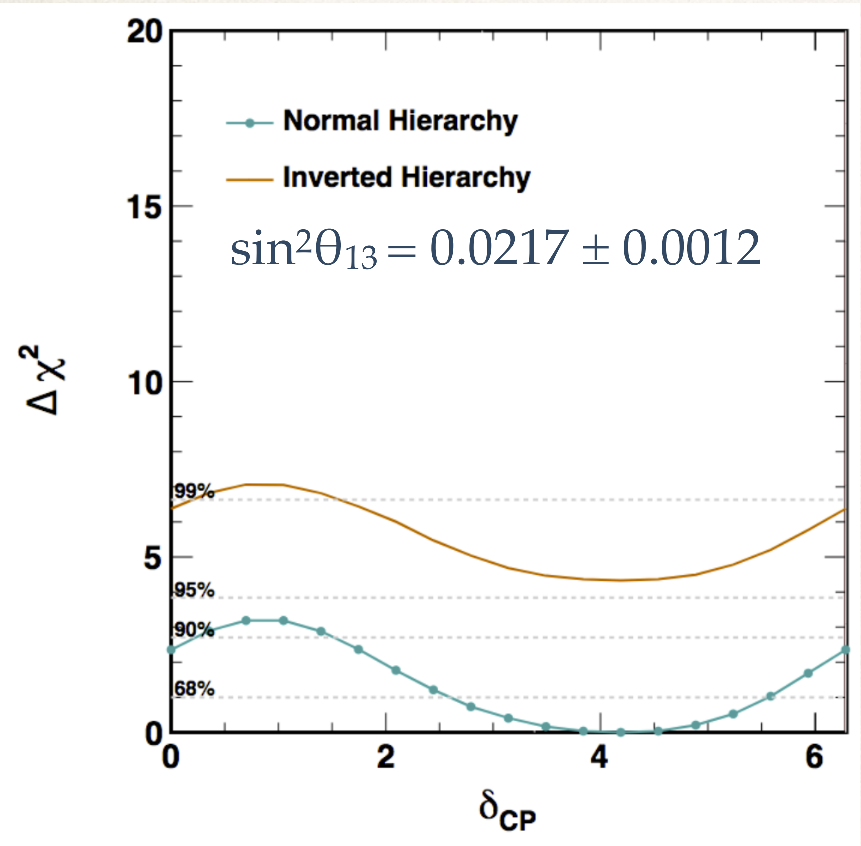


New LBL included

- General agreement in CP phase best fit values
- Best fit value for NO shifted to $\delta_{CP} = \pi$ due to new NOvA data (NuFit)

Sensitivity to the mass ordering

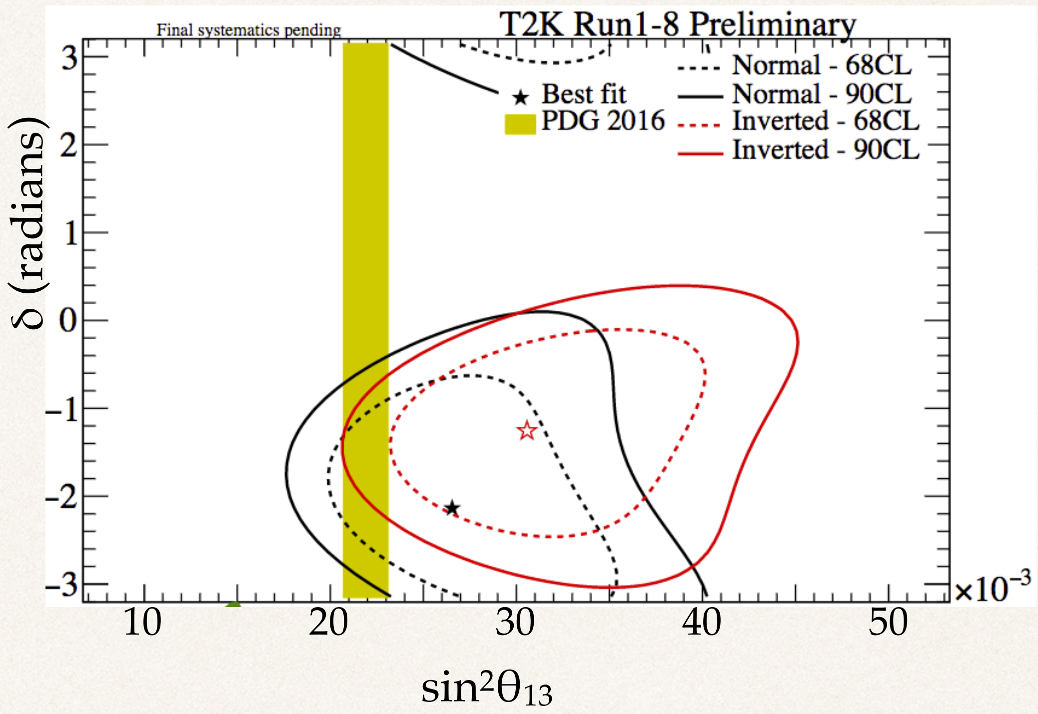
Super-Kamiokande



SK Collab. PRD97 (2018)

$\Delta\chi^2$ (IO-NO) = 4.33 (3.89)

⇒ driven by excess of upward going e-like events

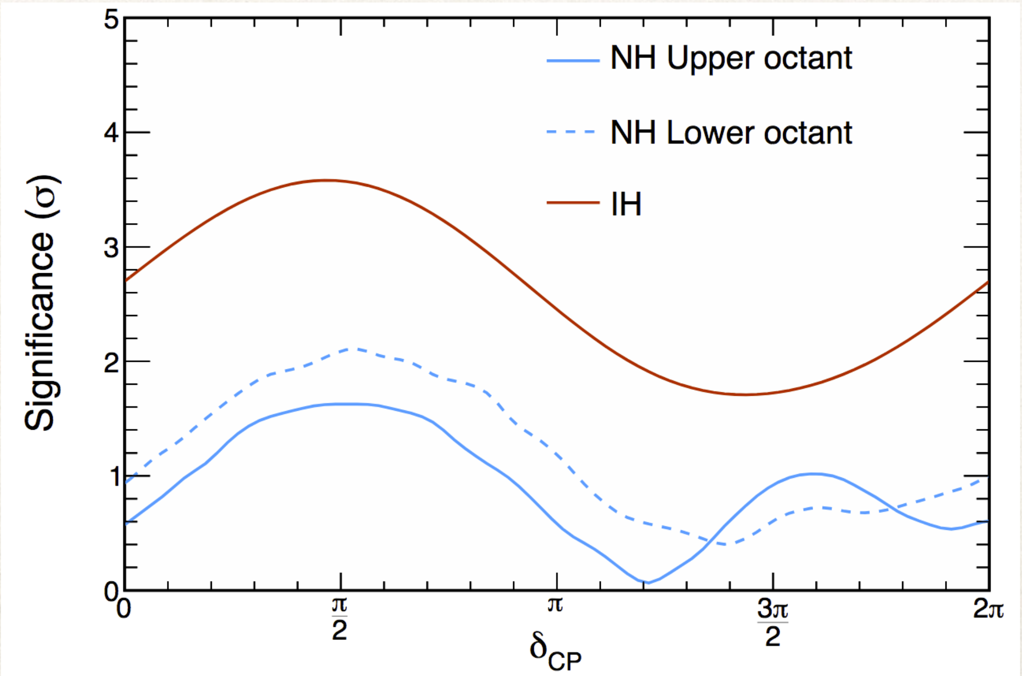


T2K

M. Hartz, KEK Colloquium

⇒ larger tension with reactors for IO

⇒ IO disfavored at ~2σ



NOνA

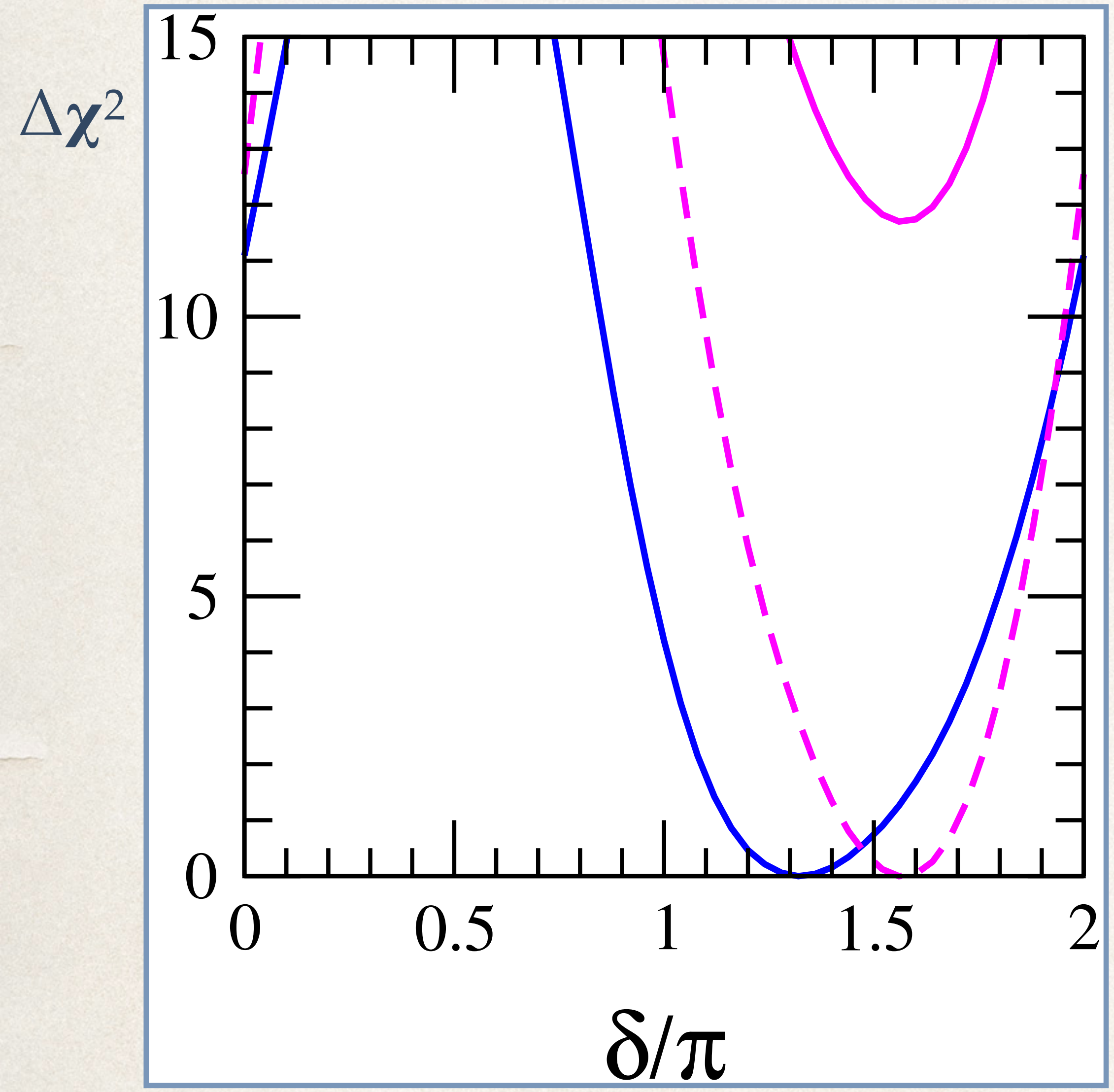
Acero et al, 1806.00096

⇒ better agreement with obs events for NO

⇒ IO disfavored at ~2σ

Sensitivity to the mass ordering

de Salas et al, PLB782 (2018) 633

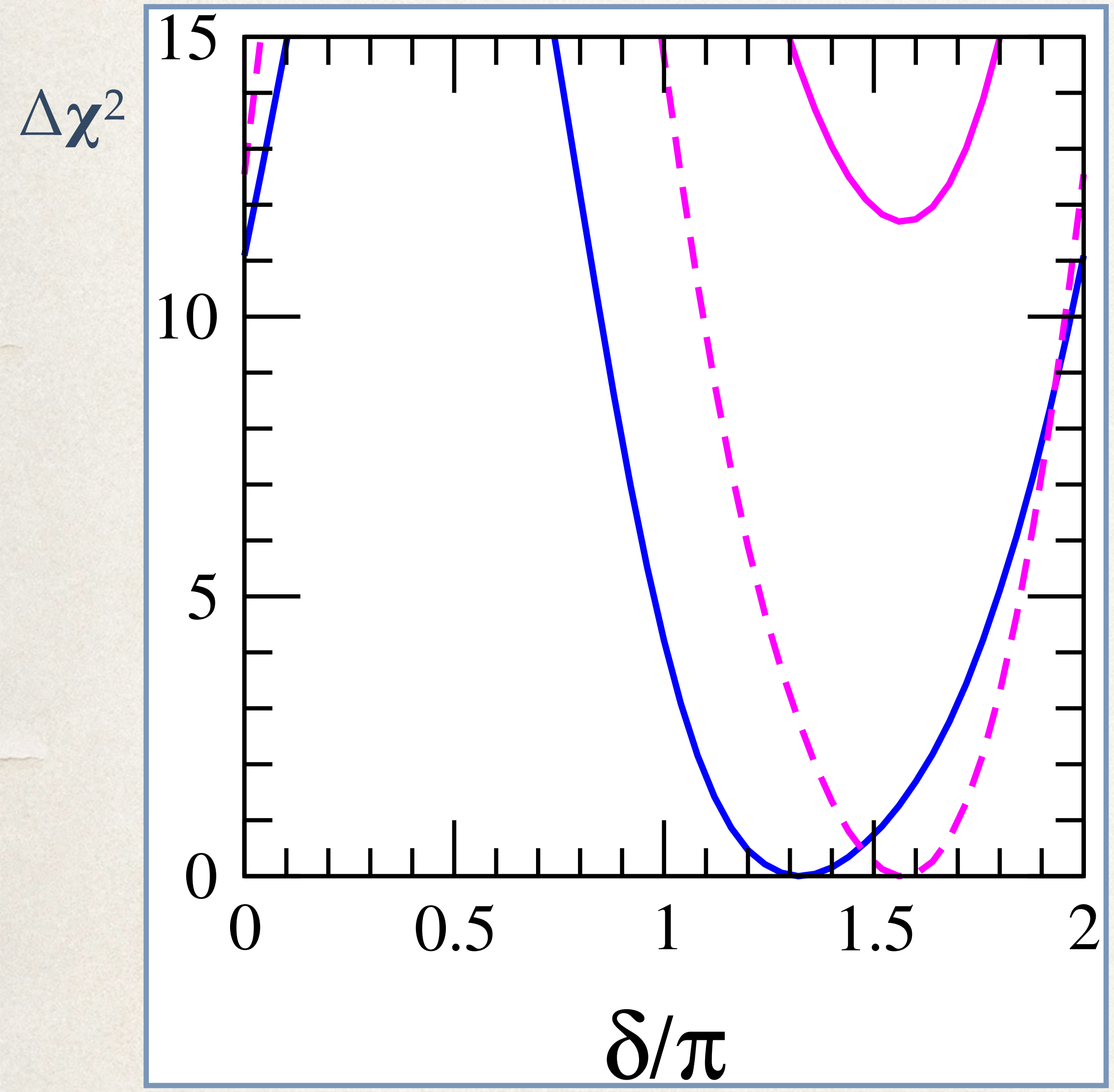


IO disfavoured at 3.4σ

Sensitivity to the mass ordering

de Salas et al, PLB782 (2018) 633

Latest T2K and NOνA data



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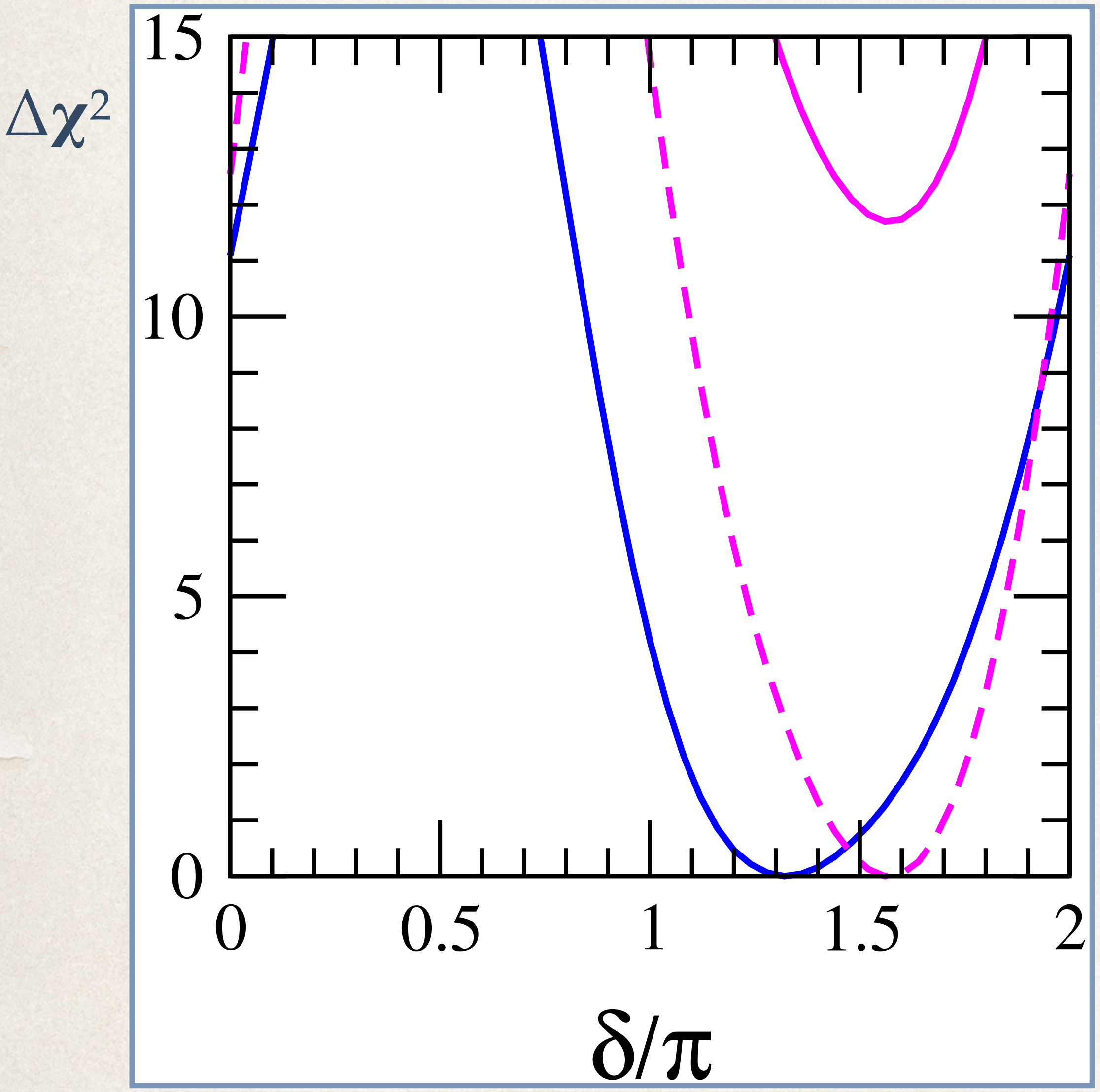
de Salas et al, PLB782 (2018) 633



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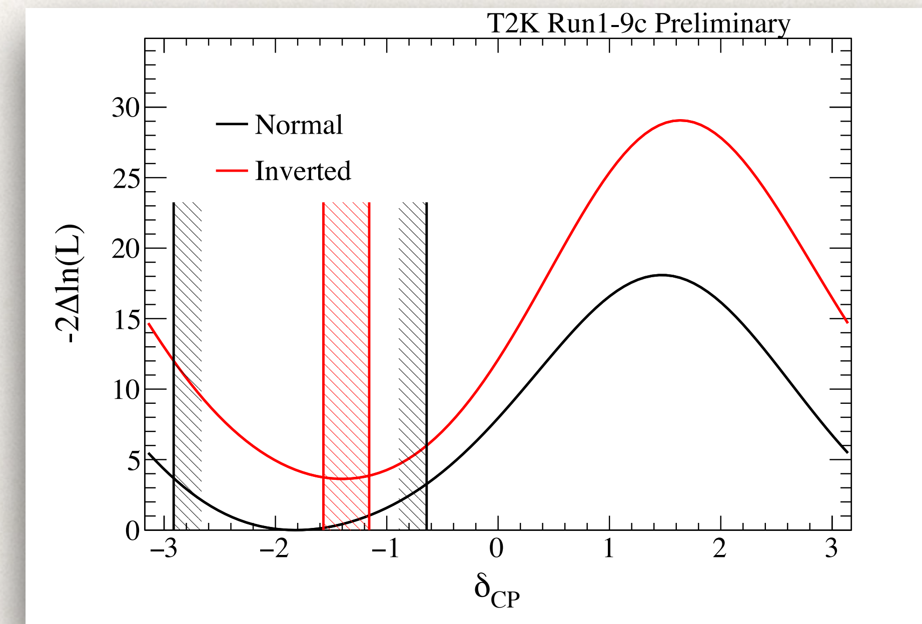
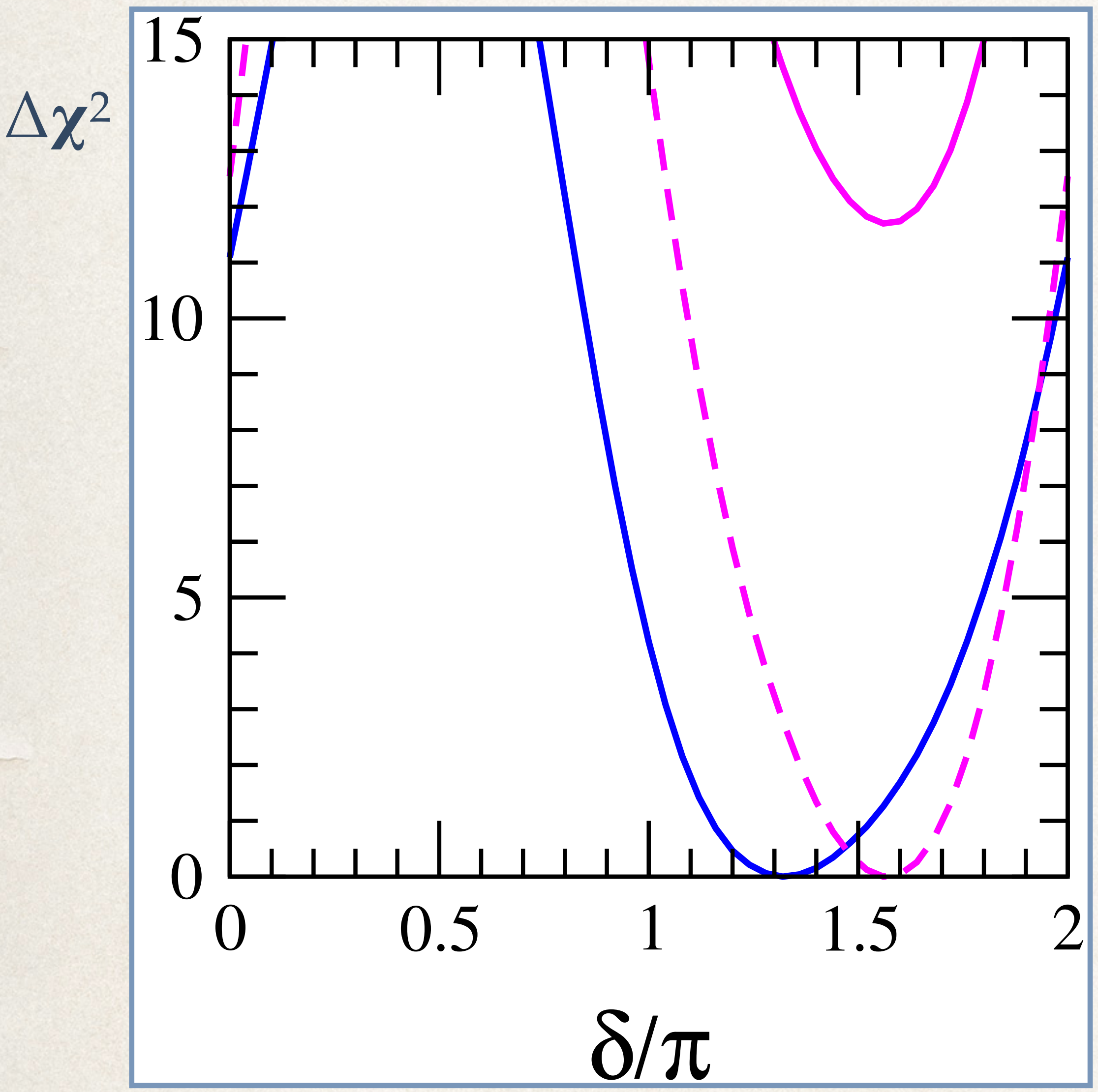


T2K disfavors IO at ~2σ (with reactor constraint)

Sensitivity to the mass ordering

de Salas et al, PLB782 (2018) 633



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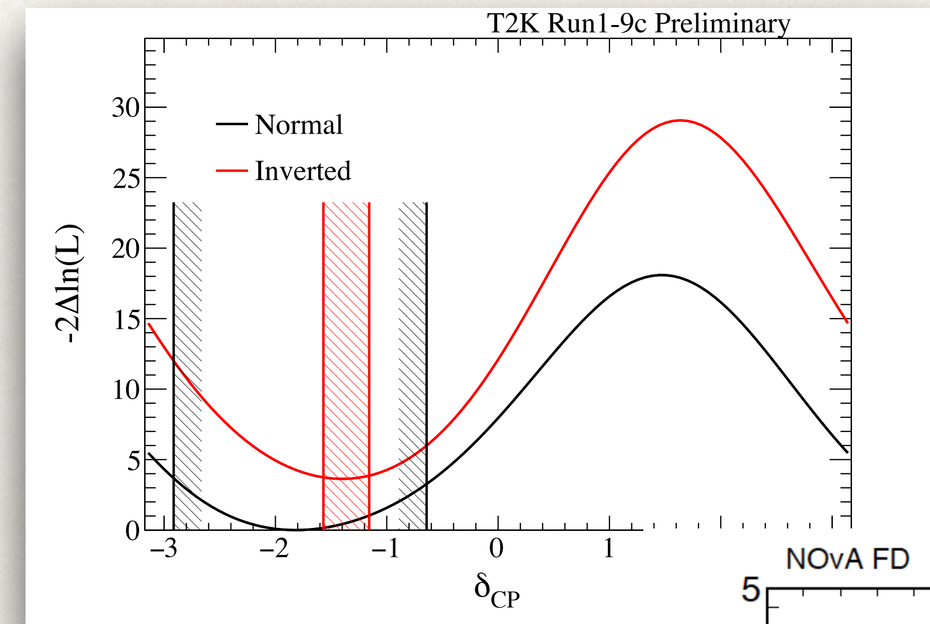

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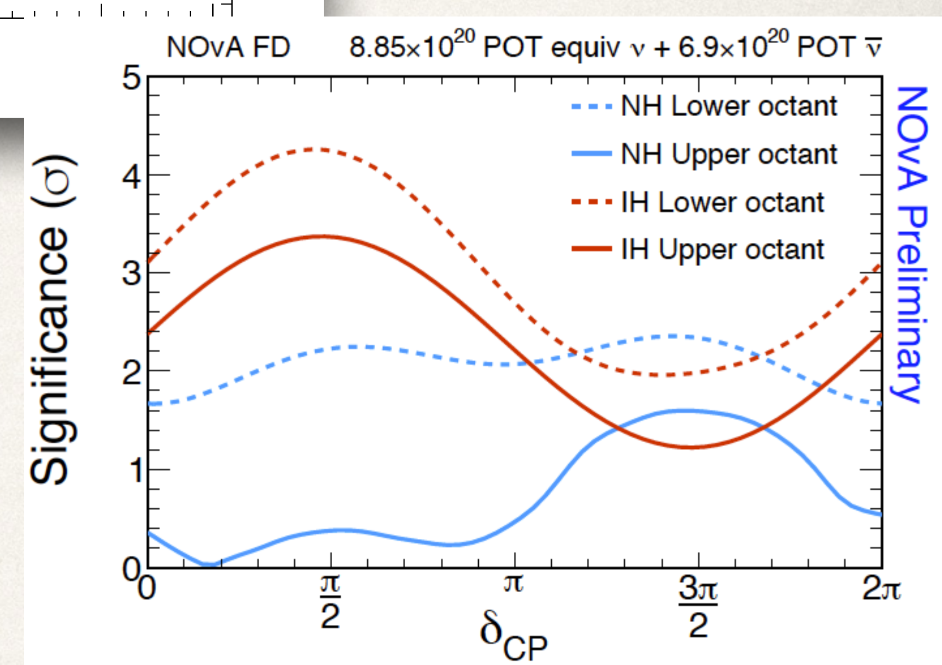
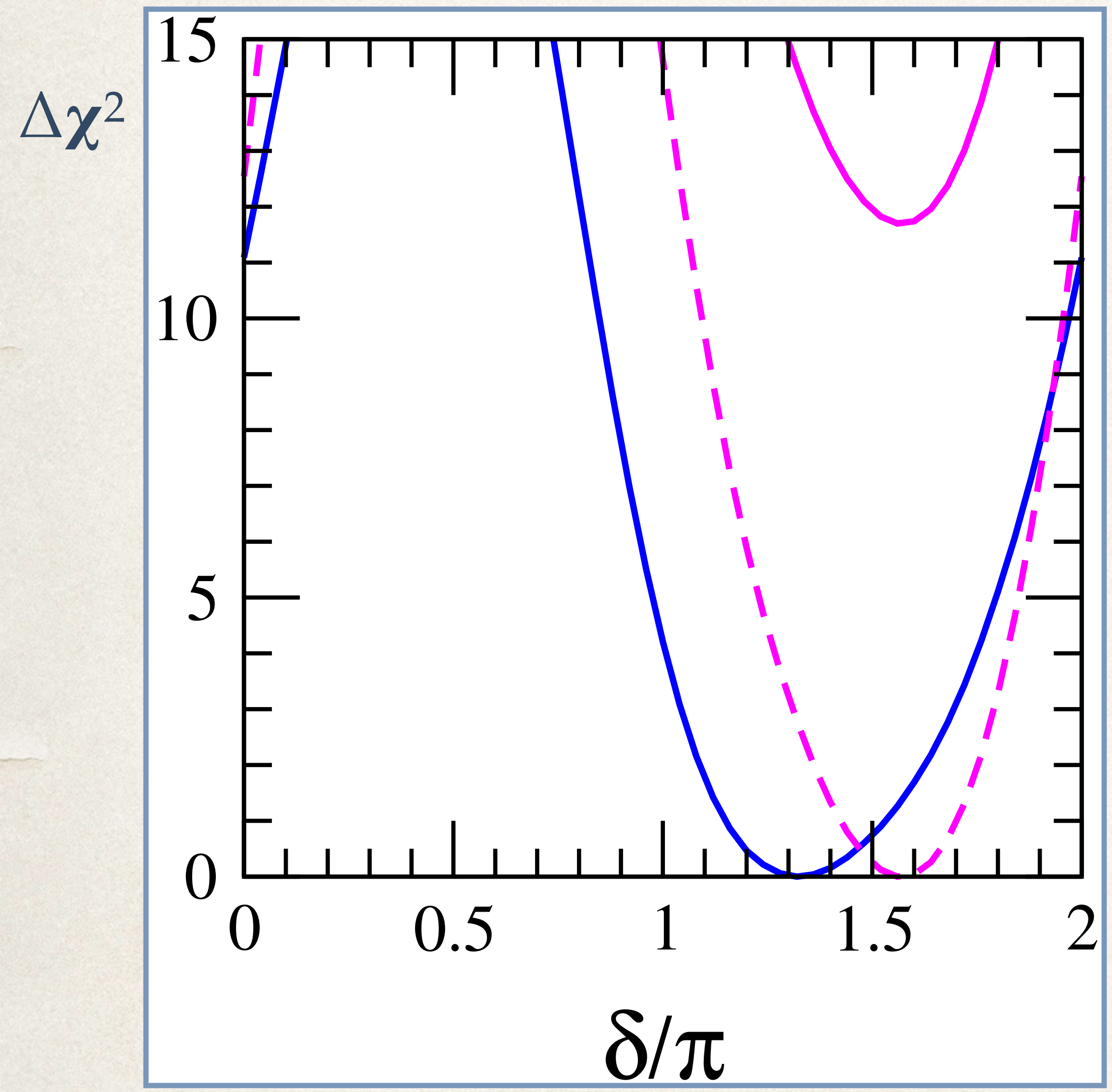


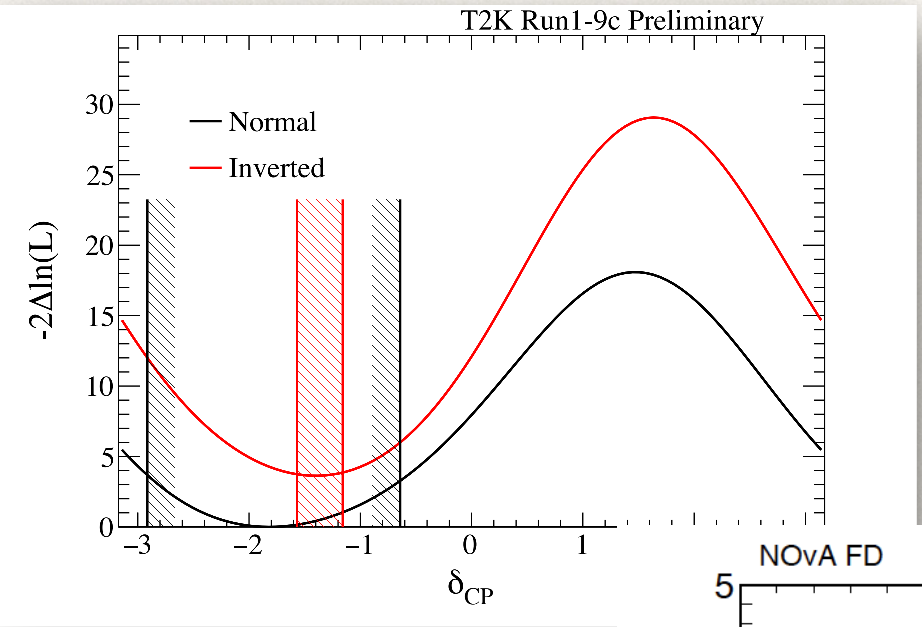
NOνA disfavors IO at 1.8σ (with reactor constraint)

Sensitivity to the mass ordering

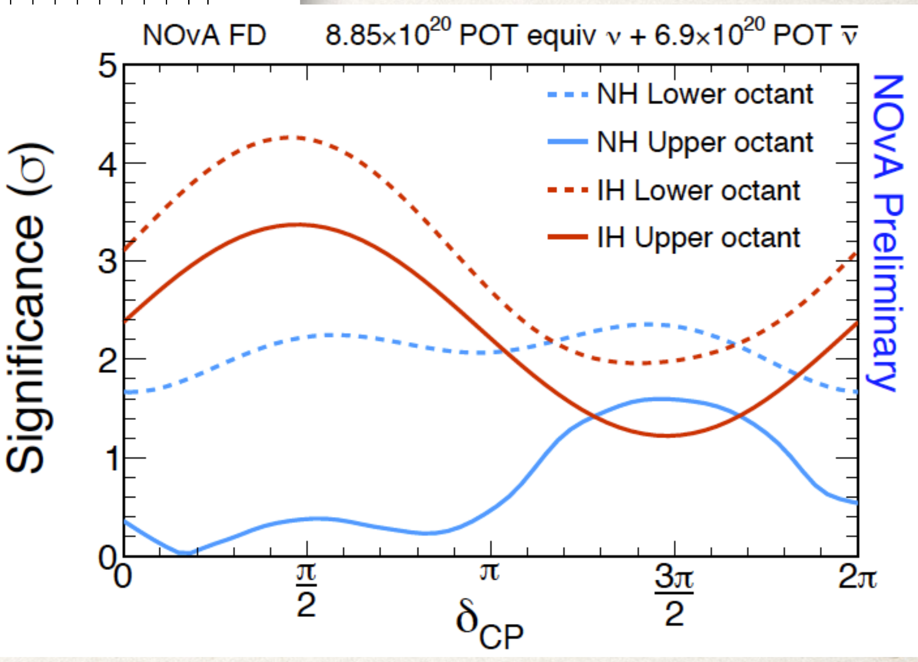
de Salas et al, PLB782 (2018) 633

Latest T2K and NOνA data





T2K disfavors IO at ~2σ (with reactor constraint)



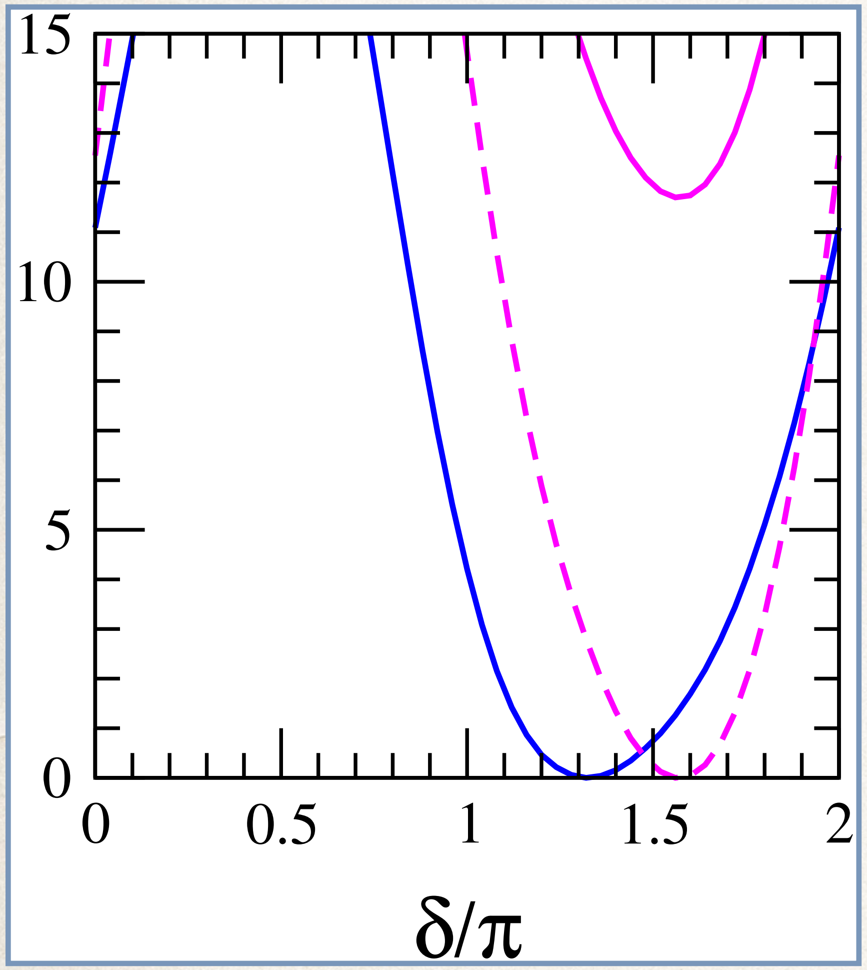
NOνA disfavors IO at 1.8σ (with reactor constraint)

IO disfavoured at 3.4σ

⇒ similar results to previous data analyses: no big changes expected

Sensitivity to the mass ordering

$\Delta\chi^2$, Valencia [PLB 2018]



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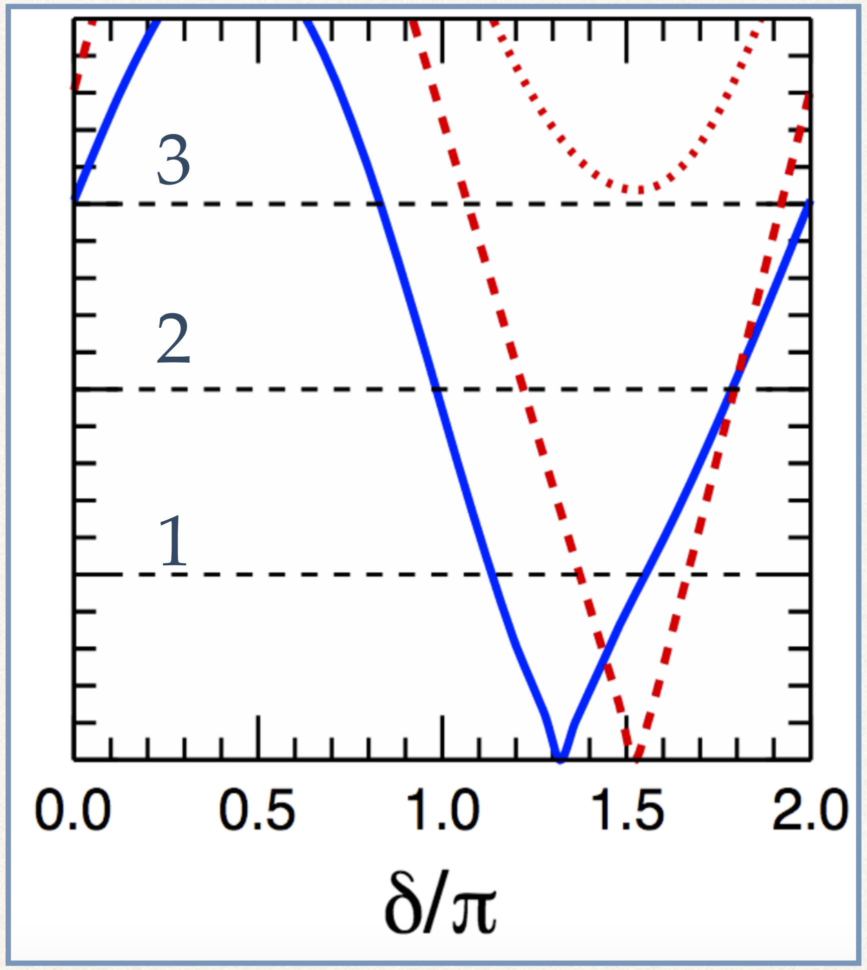

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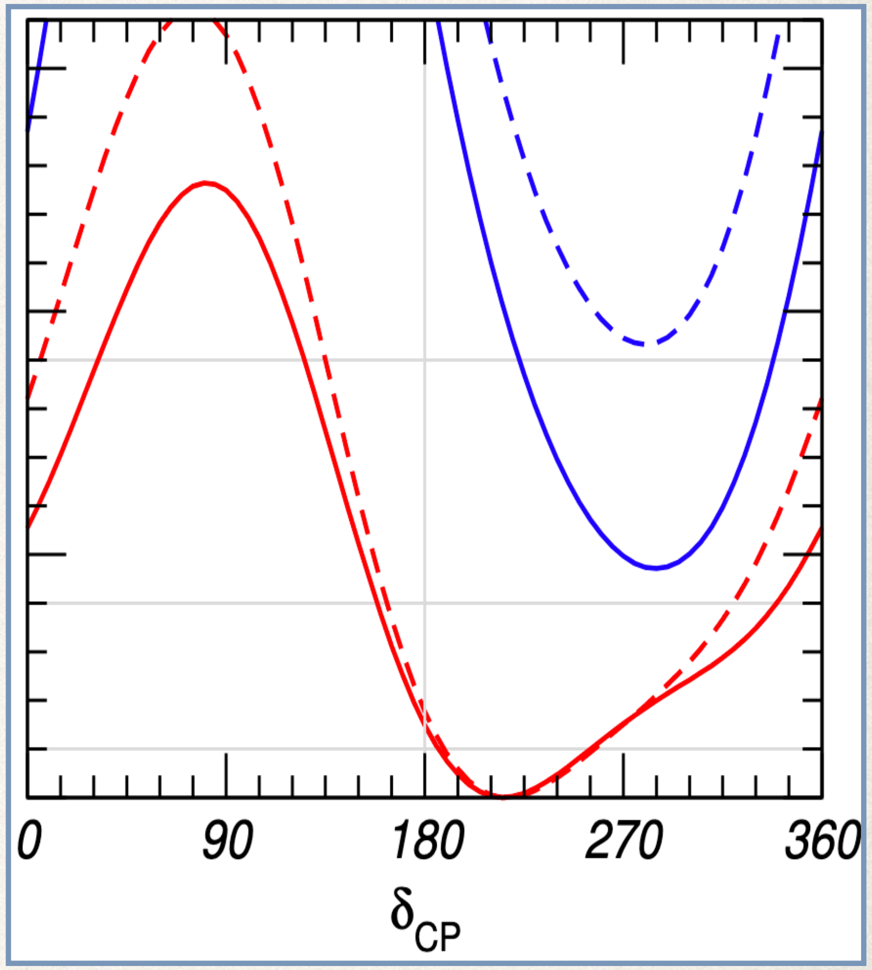

IO disfavoured at 3.4σ

IO disfavoured at 3.1σ

New LBL included

IO disfavoured at 3.0σ

- Preference for NO at ~3σ when all data are considered
- As expected, the result is not changed after considering new LBL data (NuFit)

Recent SK atmospheric analysis

Recent SK atmospheric analysis

arXiv:1901.03230v1 [hep-ex] 10 Jan 2019

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

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

New **event reconstruction algorithm** with improved kinematic and particle ID

- ⇒ 32% larger volume detector compared to previous analyses
- ⇒ increased sensitivity to the neutrino mass ordering

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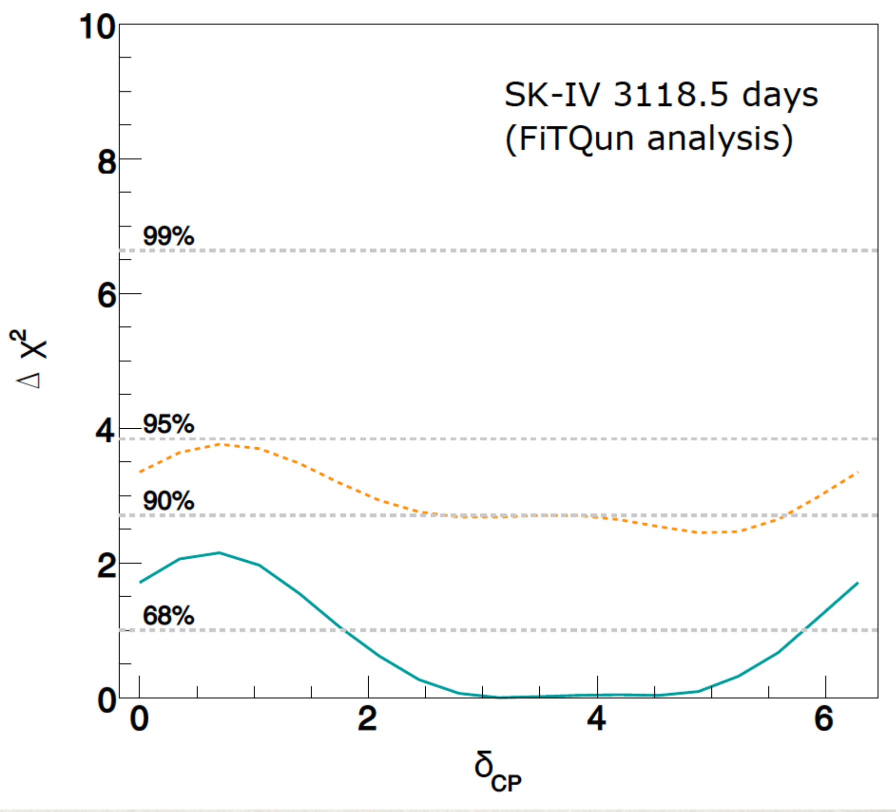
RESULT:

⇒ preference for NO with $\Delta\chi^2$ (IO-NO) = 2.45 (1.81) (SK-IV only data)

⇒ previously: $\Delta\chi^2$ (IO-NO) = 4.33 (3.48) (SK-I to IV data)



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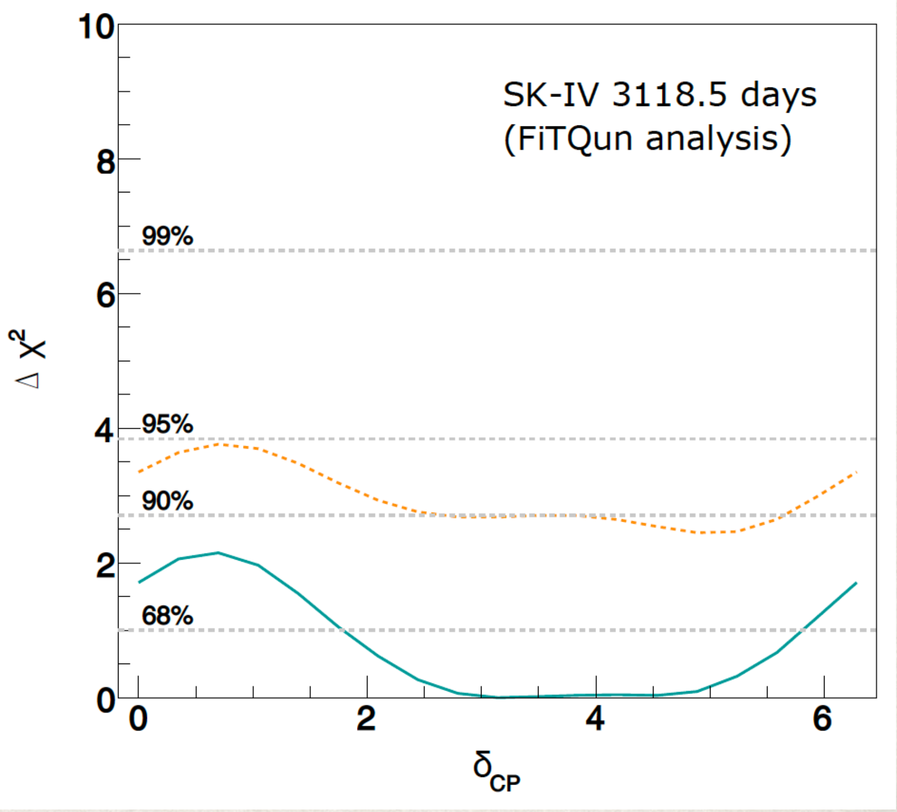

→ weaker preference for NO in global fit!

Other inputs for mass ordering?

Experimental sensitivity to neutrino masses:

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

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- 0νββ: $m_{\beta\beta} = f(m_i, \theta_{ij}, \phi_i)$
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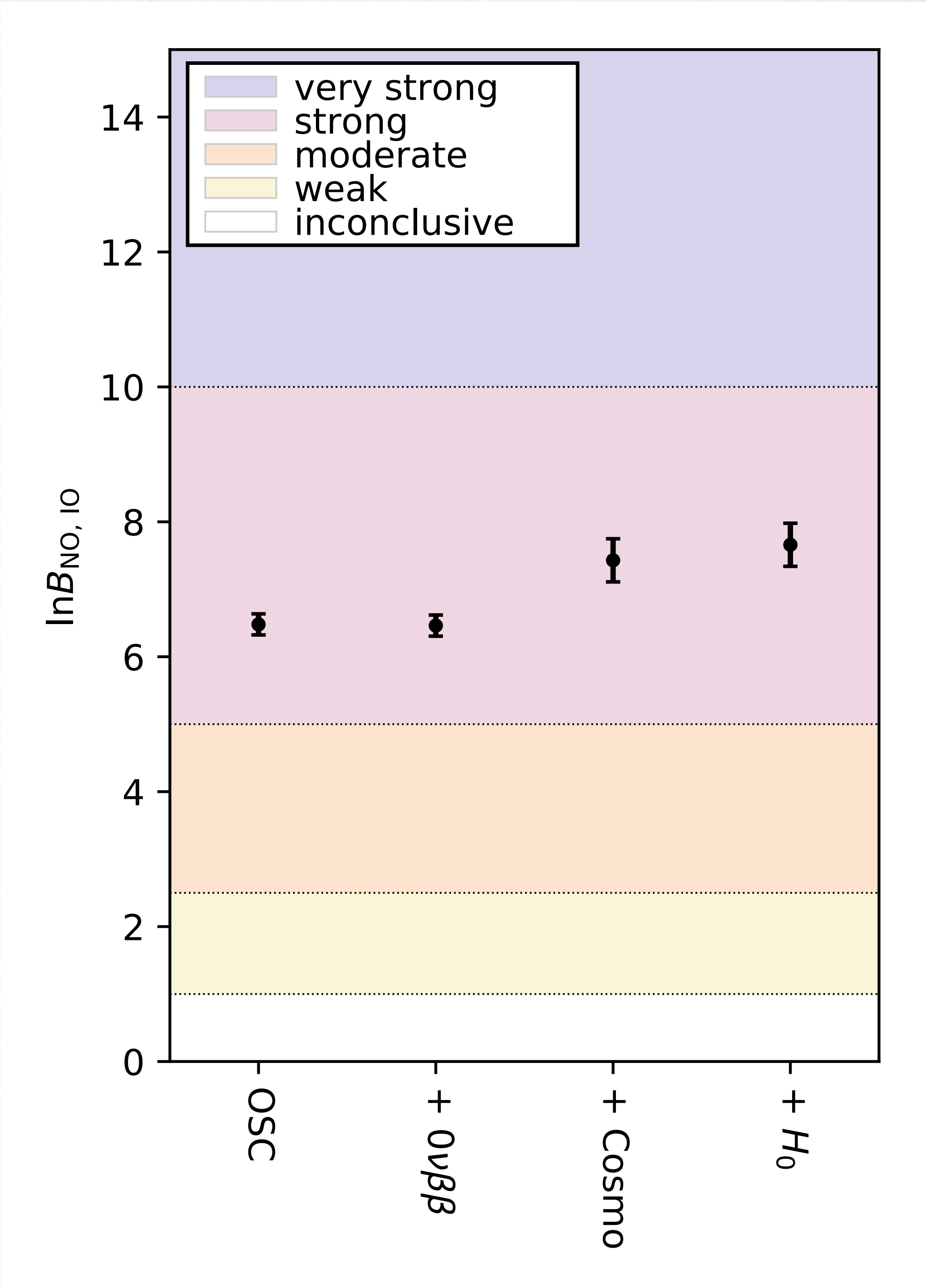
Results from the combined bayesian analysis:



de Salas et al, Front.Astron.Space Sci. 5 (2018) 36

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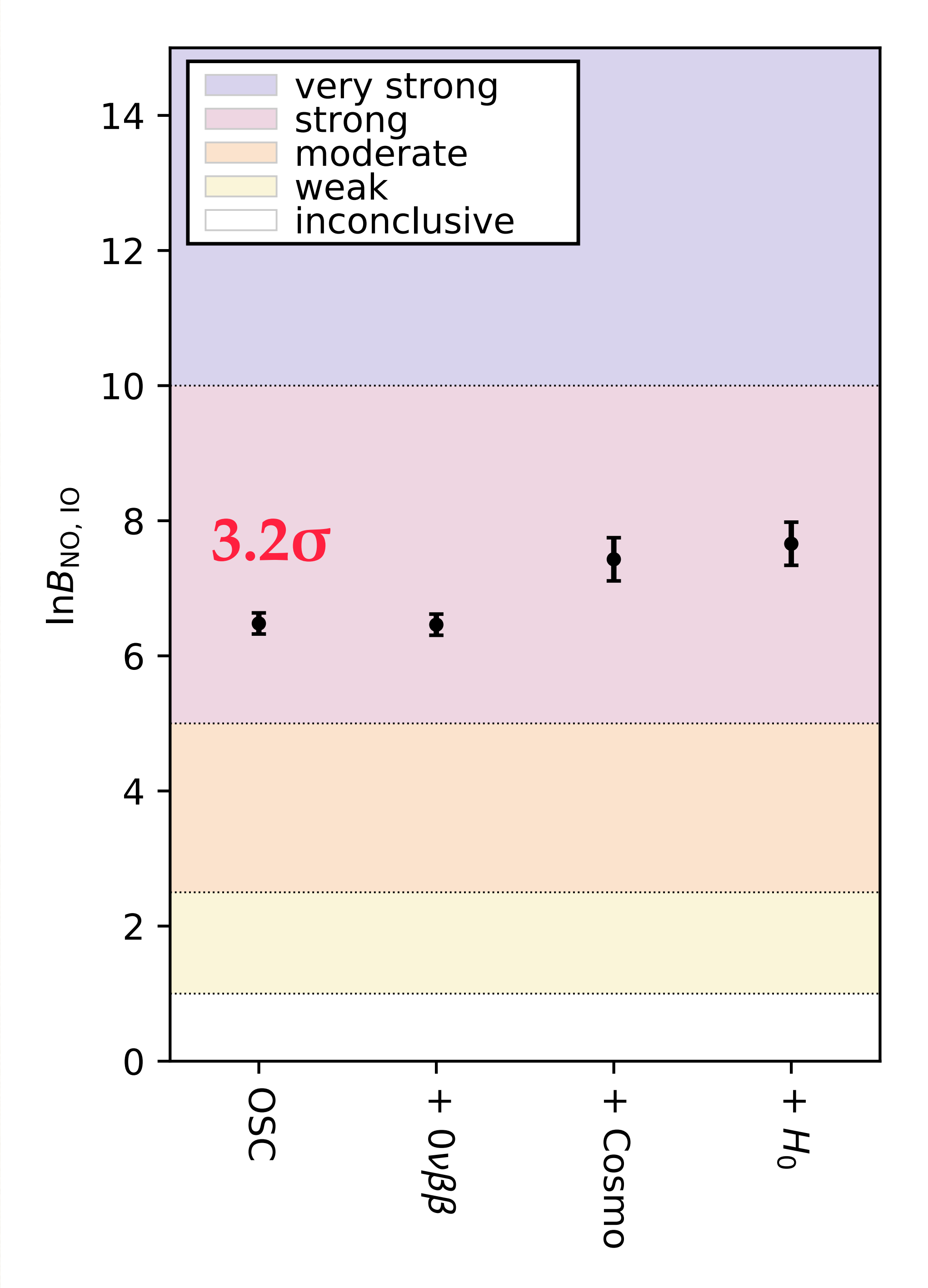
Results from the combined bayesian analysis:

$\Rightarrow$ strong preference for NO driven by oscillation data (3.2σ)



de Salas et al, Front.Astron.Space Sci. 5 (2018) 36

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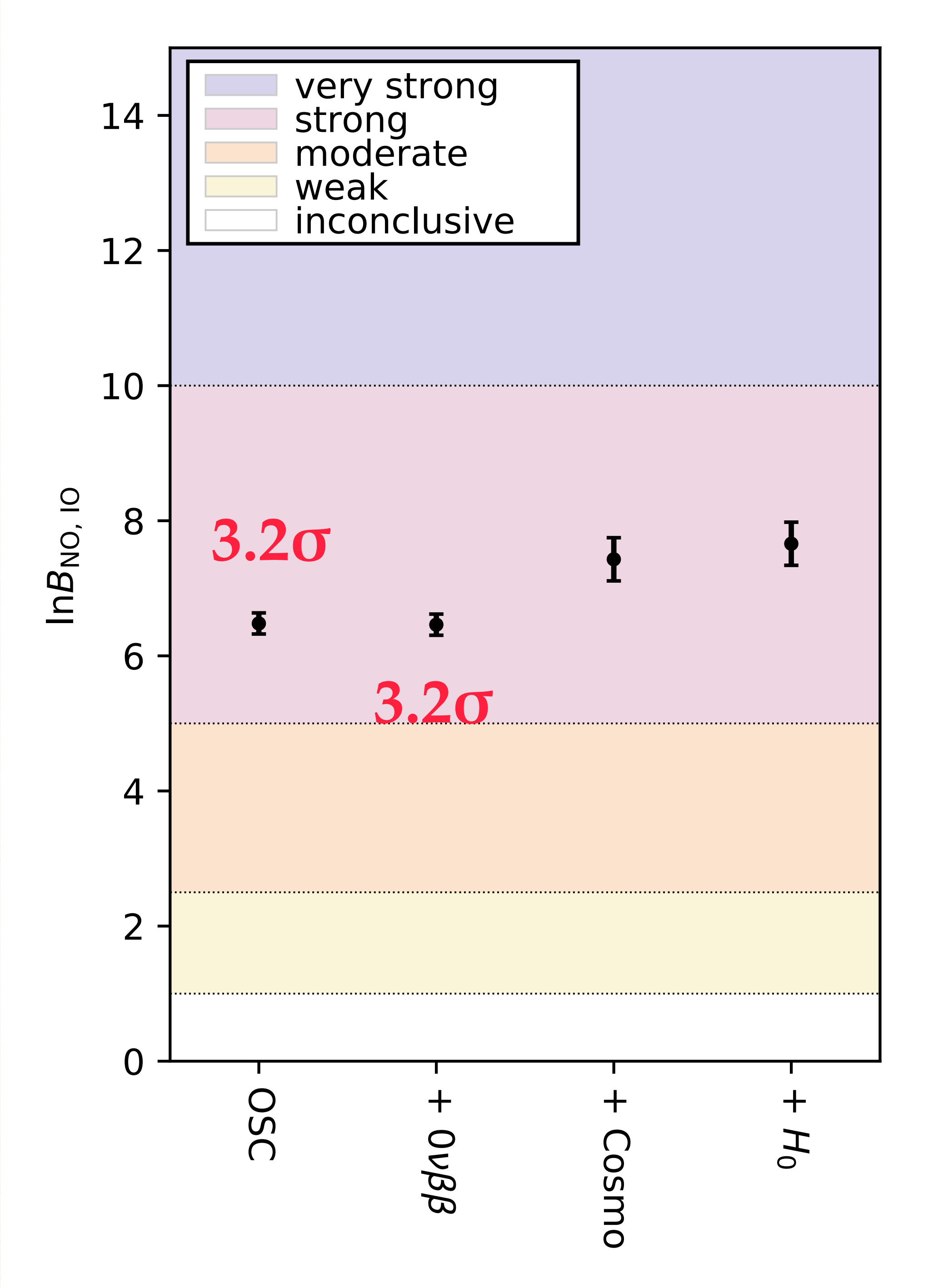
Results from the combined bayesian analysis:

⇒ strong preference for NO driven by oscillation data (3.2σ)

⇒ 0νββ do not have any impact on NMO.



de Salas et al, Front.Astron.Space Sci. 5 (2018) 36

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Experimental sensitivity to neutrino masses:

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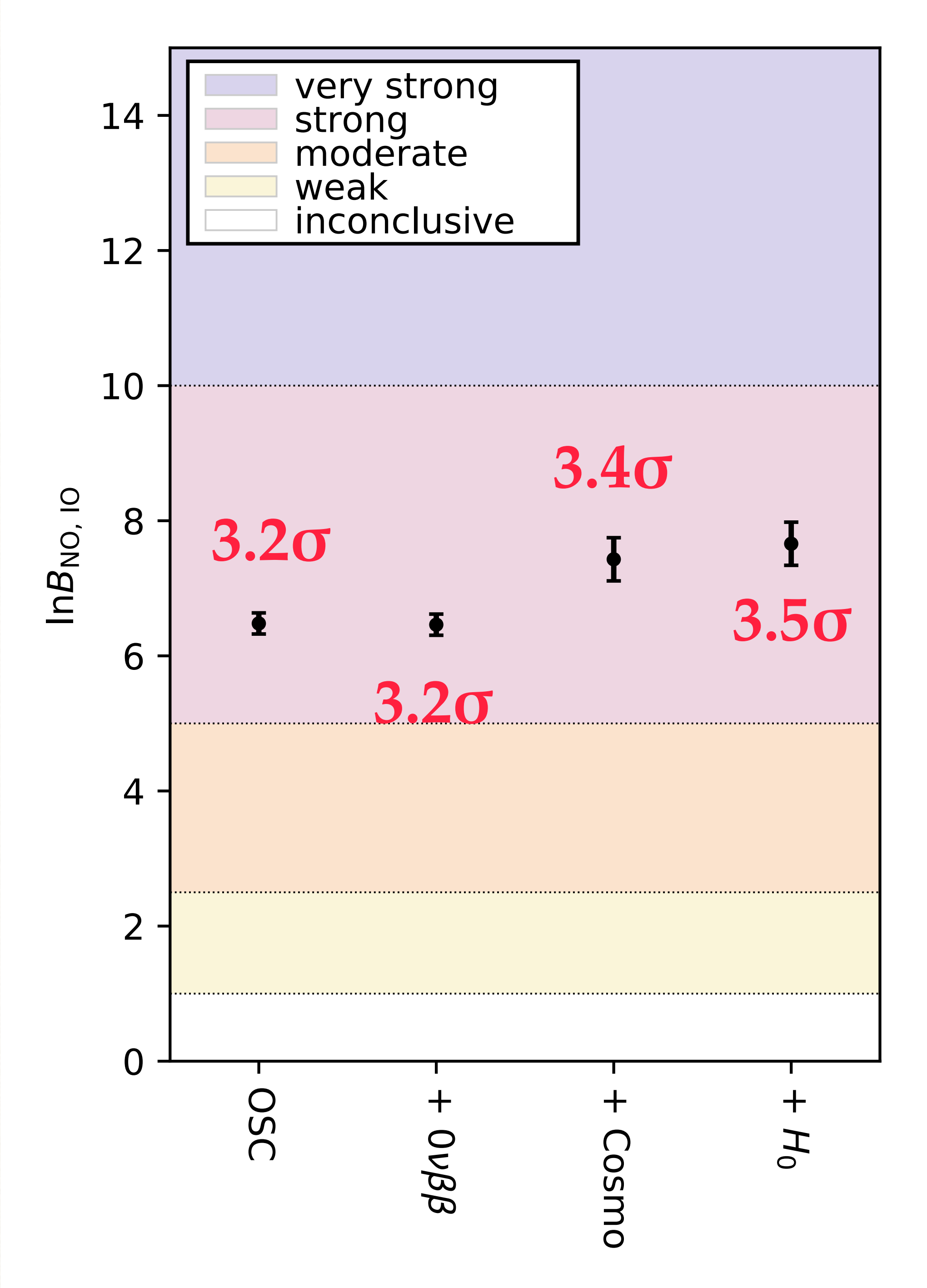
- 0νββ: $m_{\beta\beta} = f(m_i, \theta_{ij}, \phi_i)$
- cosmology: Σm_i

Results from the combined bayesian analysis:

⇒ strong preference for NO driven by oscillation data (3.2σ)

⇒ 0νββ do not have any impact on NMO.

⇒ cosmological data enhances the preference for NO from 3.2σ to 3.5σ



de Salas et al, Front.Astron.Space Sci. 5 (2018) 36

Other inputs for mass ordering?

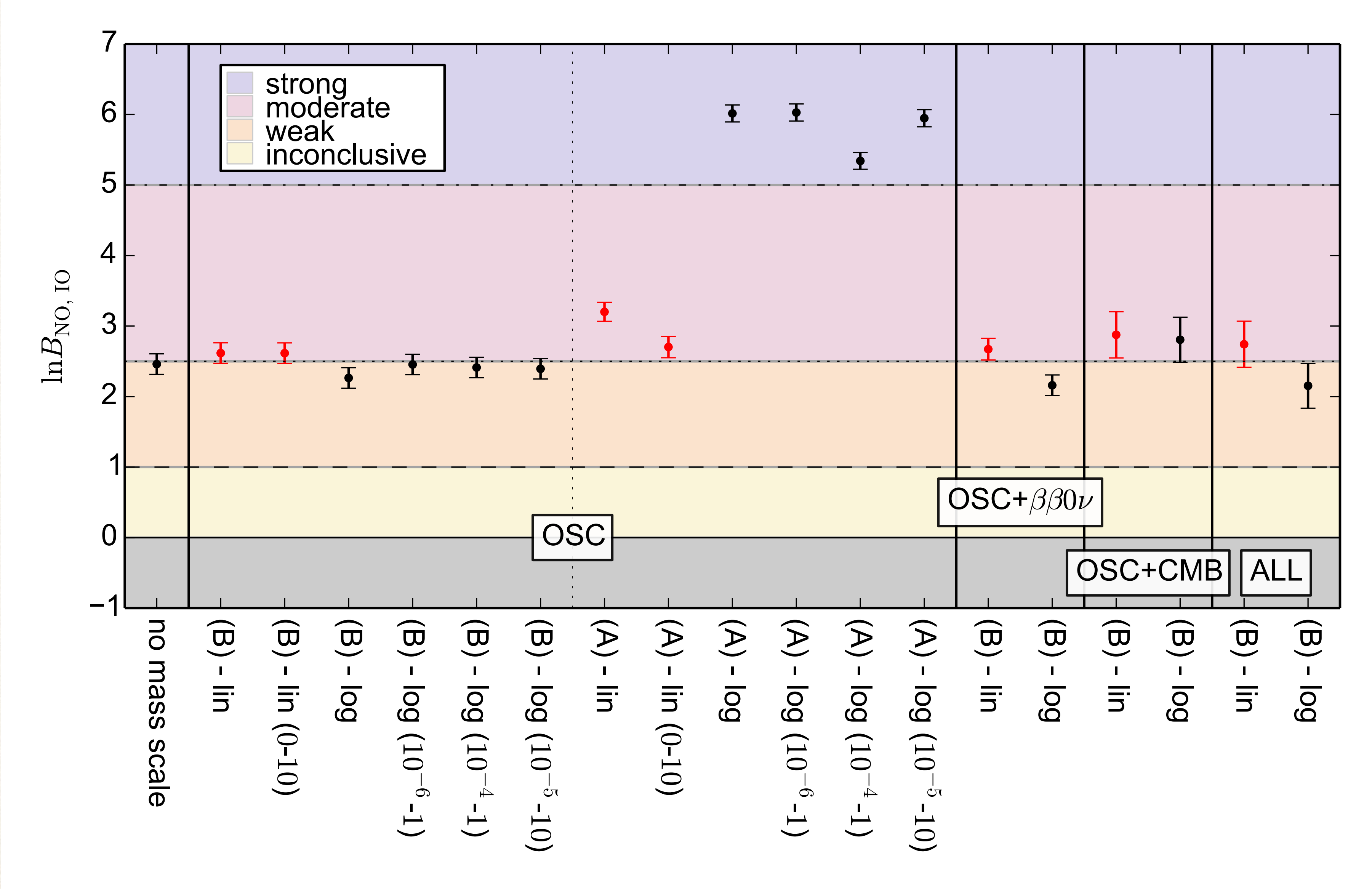
The importance of parametrization and priors:

Parametrization A
(m_1, m_2, m_3)

Parametrization B
$(m_0, \Delta m^2_{21}, \Delta m^2_{31})$

Choice of priors:

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



Gariazzo et al, JCAP03 (2018) 11

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

Other inputs for mass ordering?

The importance of parametrization and priors:

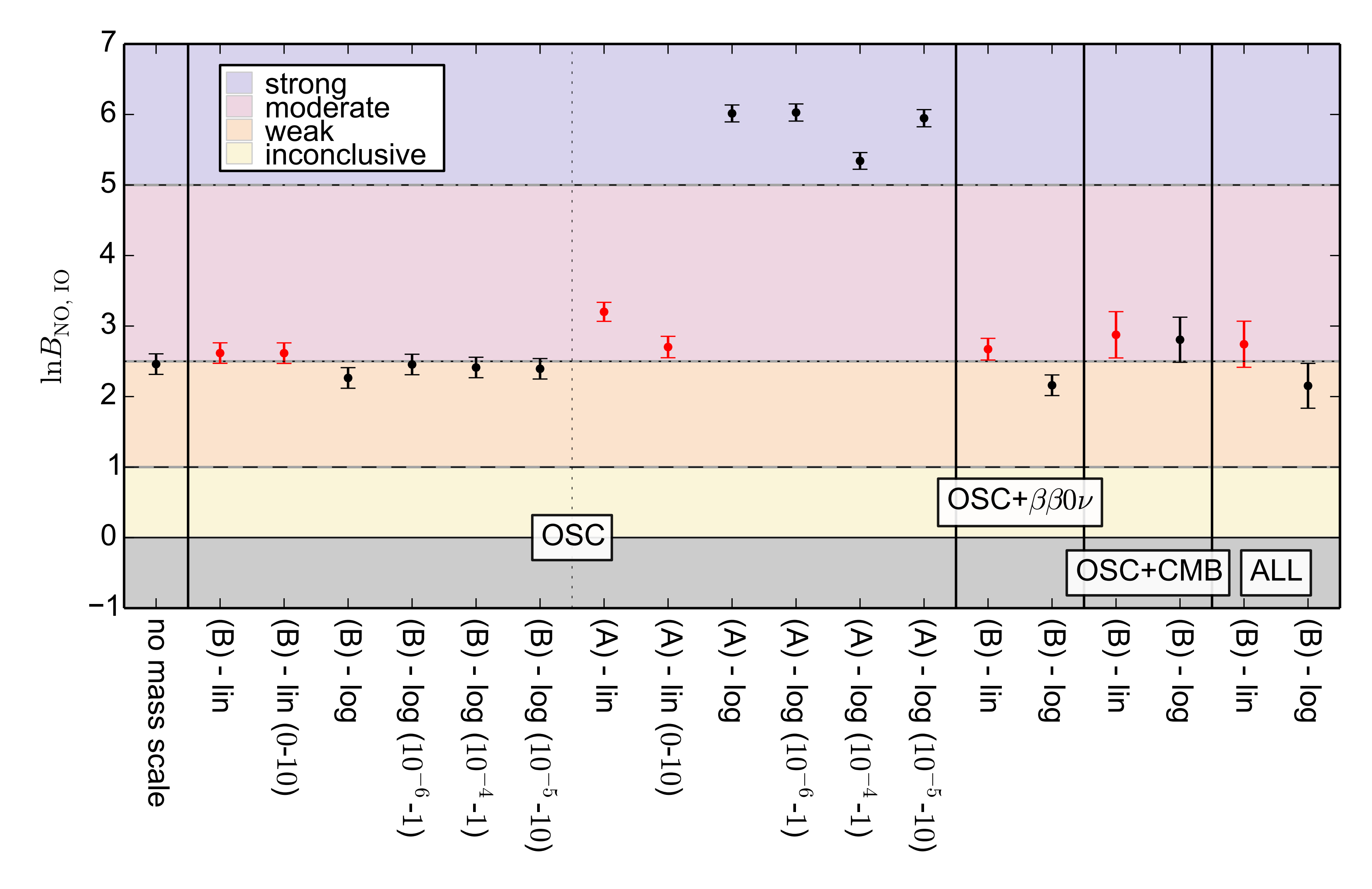
Parametrization A
(m_1, m_2, m_3)

Parametrization B
(m_0, Δm^2_{21}, Δm^2_{31})

Choice of priors:

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

⇒ case B seems closer to experimental data



Gariazzo et al, JCAP03 (2018) 11

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

Other inputs for mass ordering?

The importance of parametrization and priors:

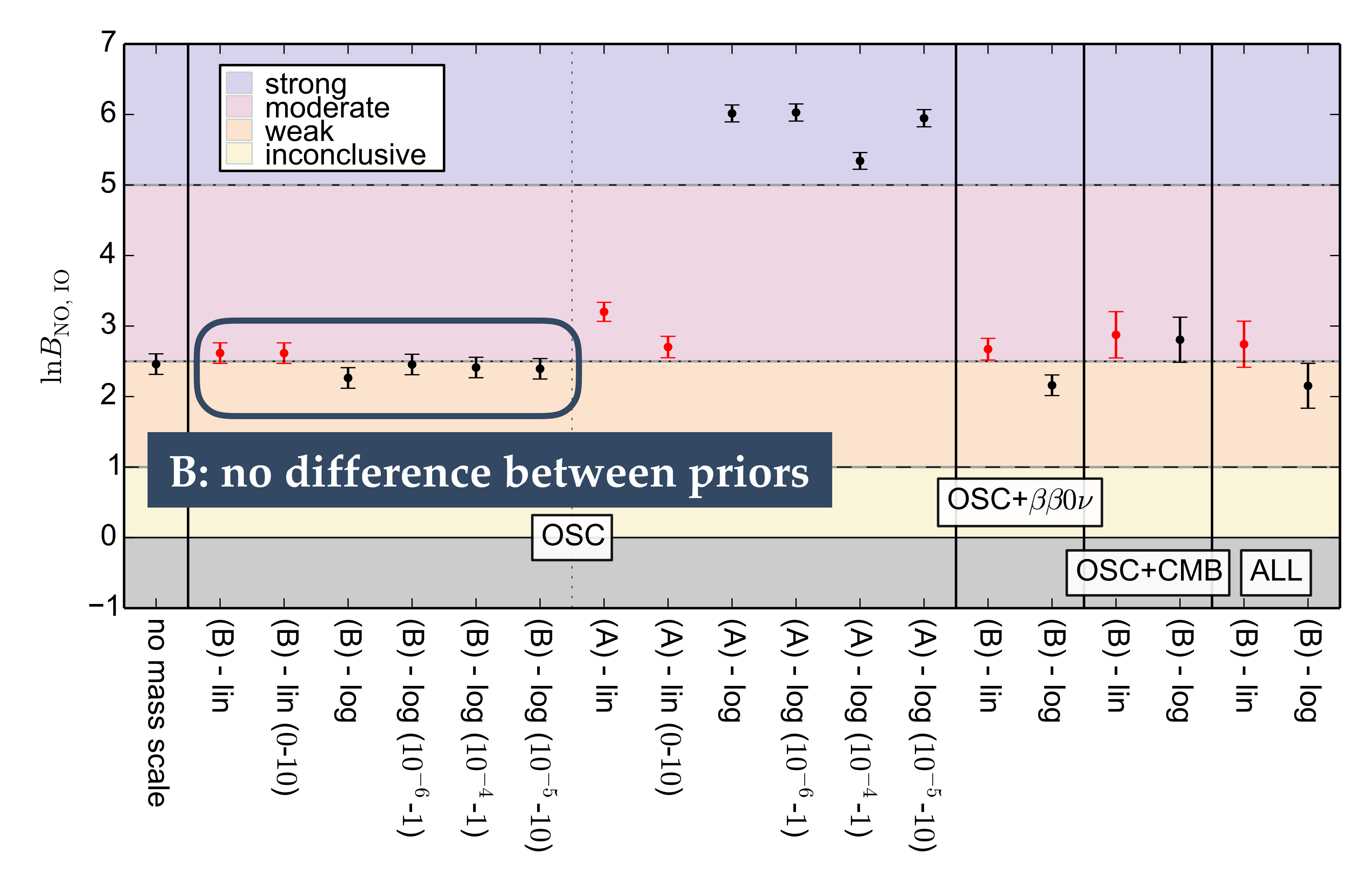
Parametrization A
(m_1, m_2, m_3)

Parametrization B
$(m_0, \Delta m^2_{21}, \Delta m^2_{31})$

Choice of priors:

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

⇒ case B seems closer to experimental data



Gariazzo et al, JCAP03 (2018) 11

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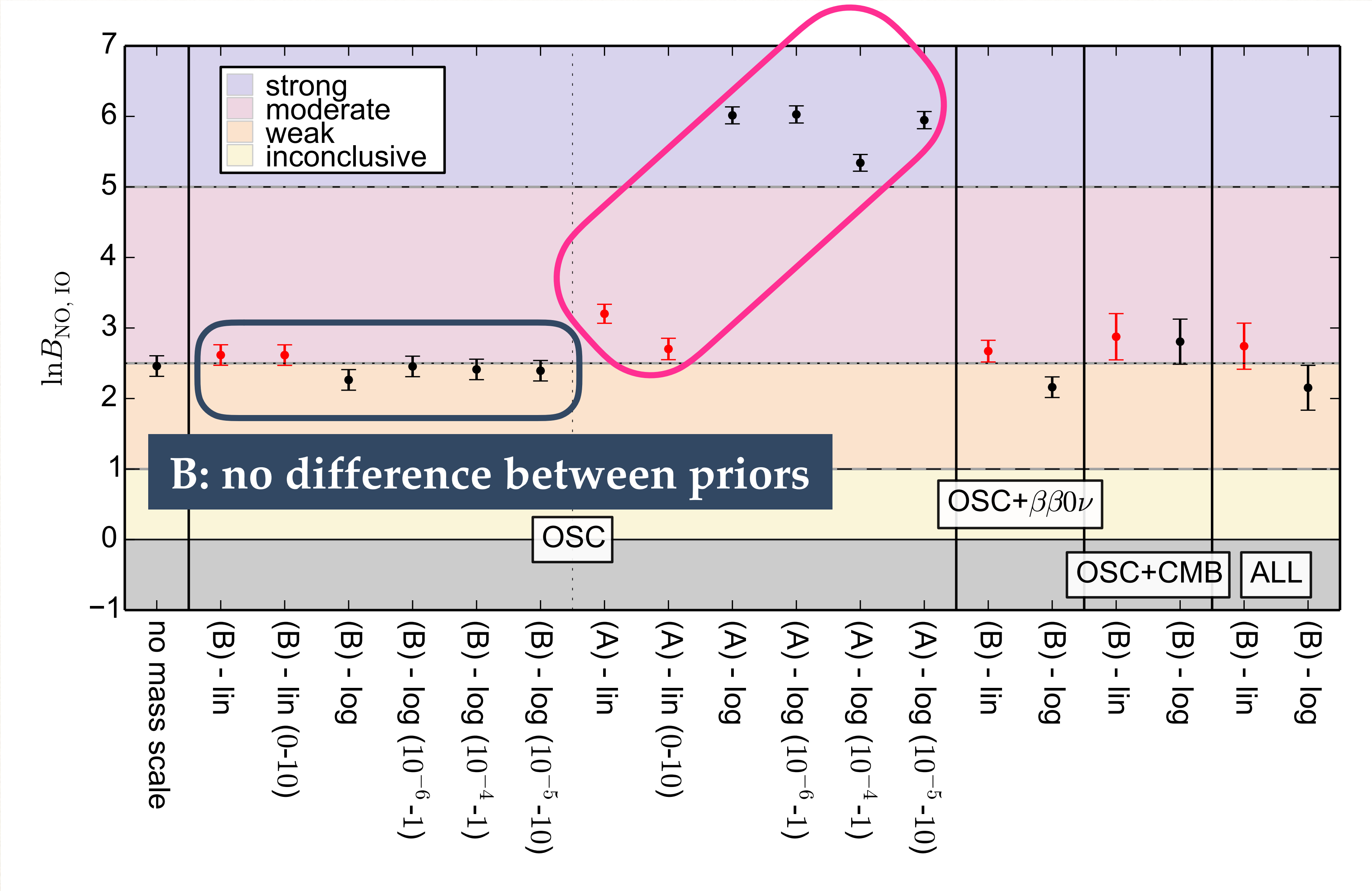

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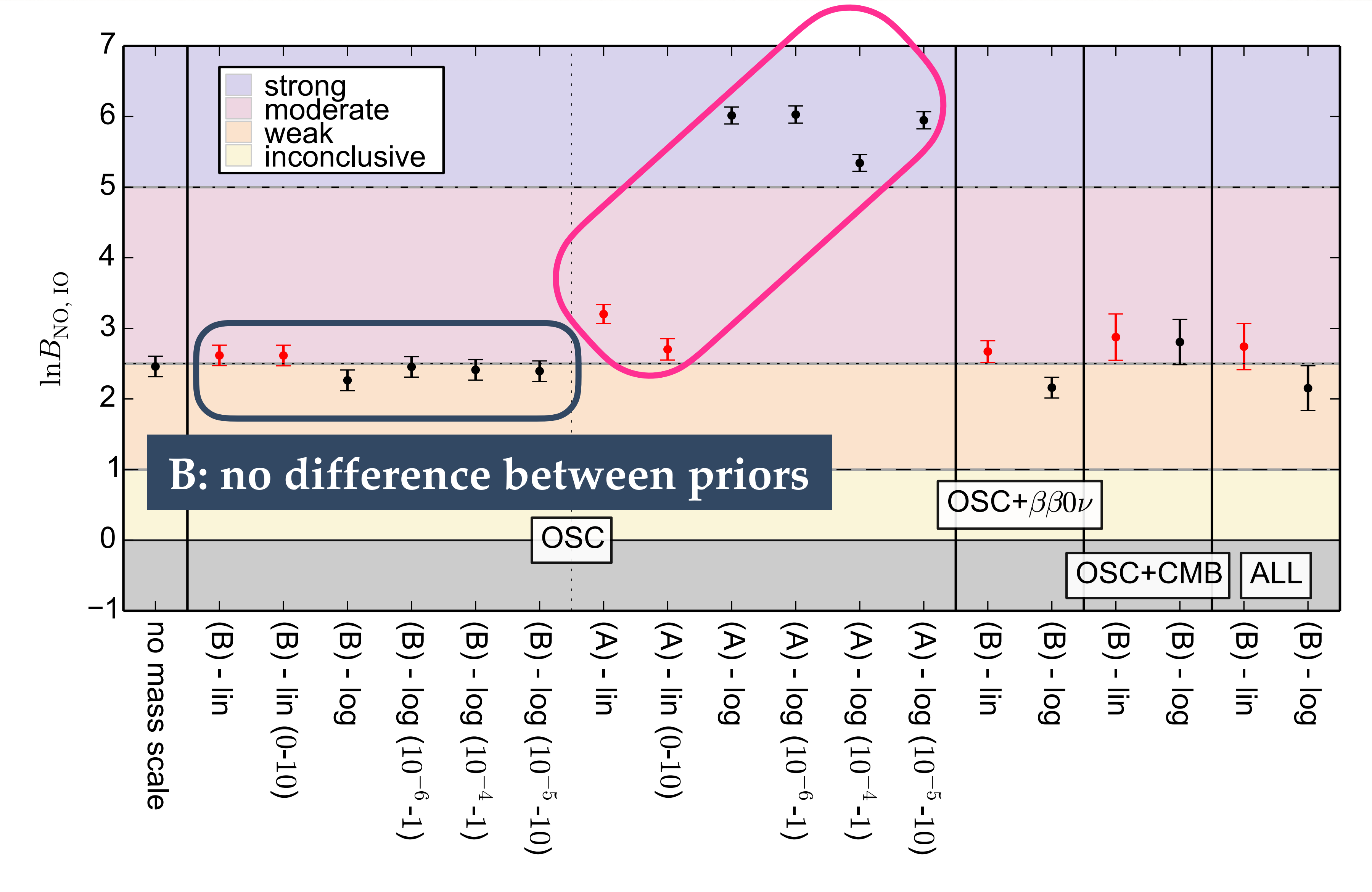


⇒ **best choice:** parametrization B + log prior in m_0

Gariazzo et al, JCAP03 (2018) 11

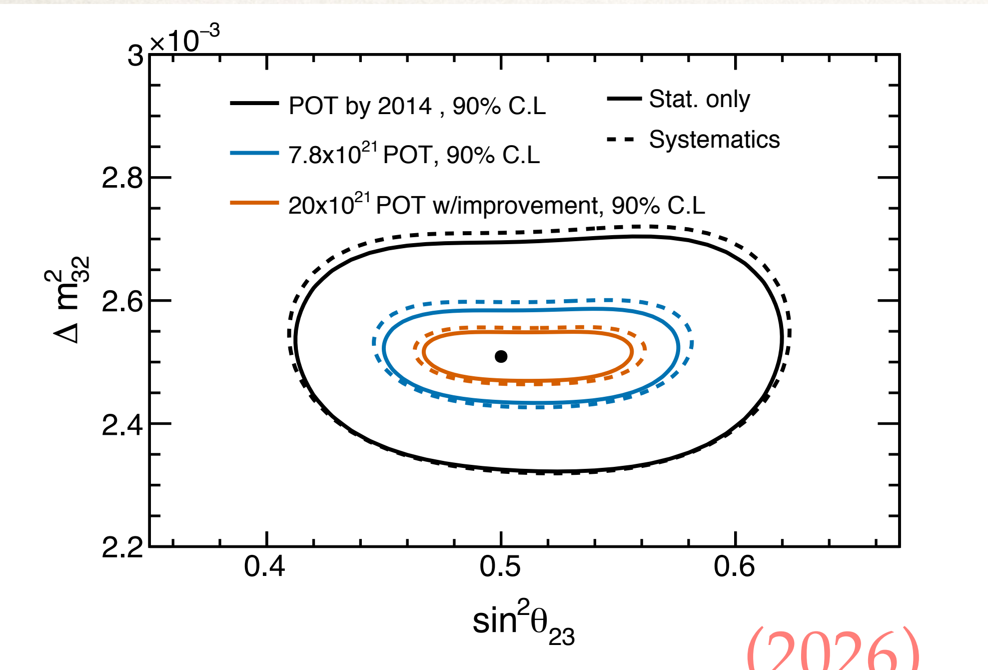
Using global fit-2017, wo SK I-IV, old LBL

Future prospects

Prospects for precision

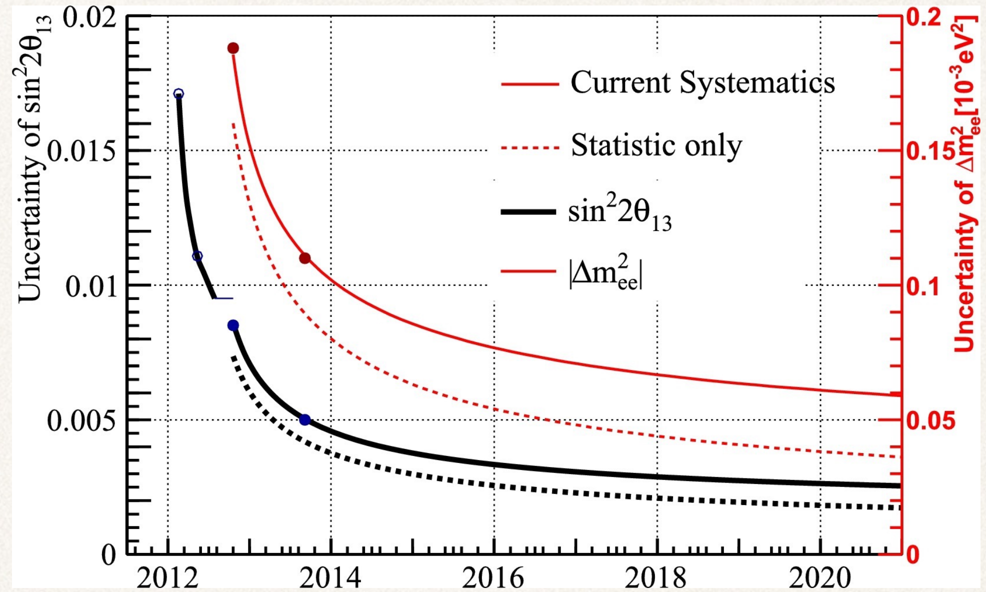
T2K-II

Abe et al, 1609.04111



~1% precision on Δm^2_{32}

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



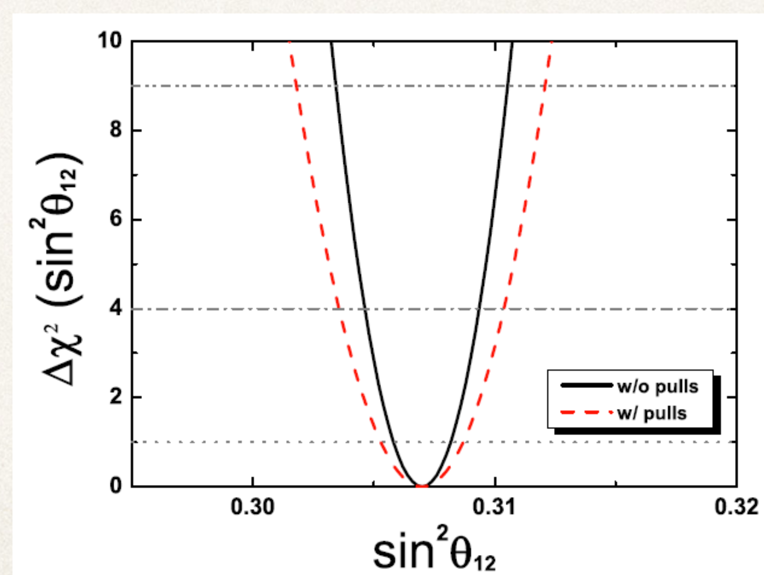
DayaBay

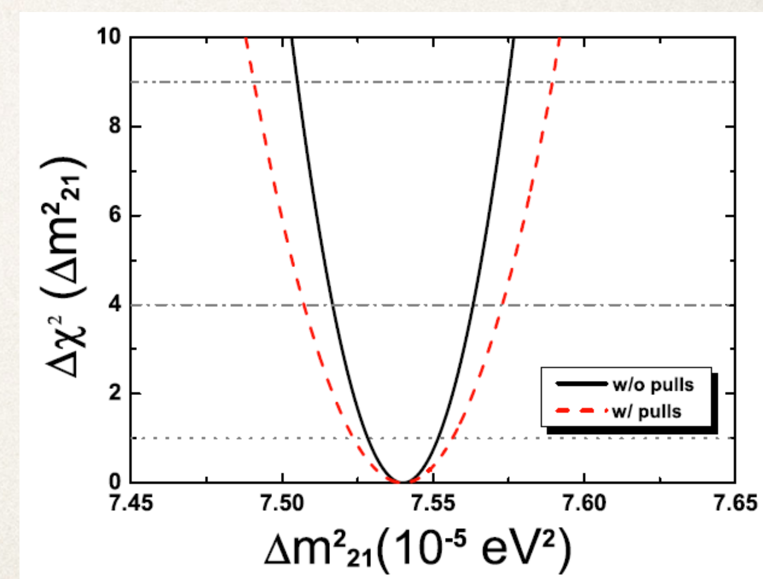
Cao and Luk, 1605.01502

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

JUNO

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





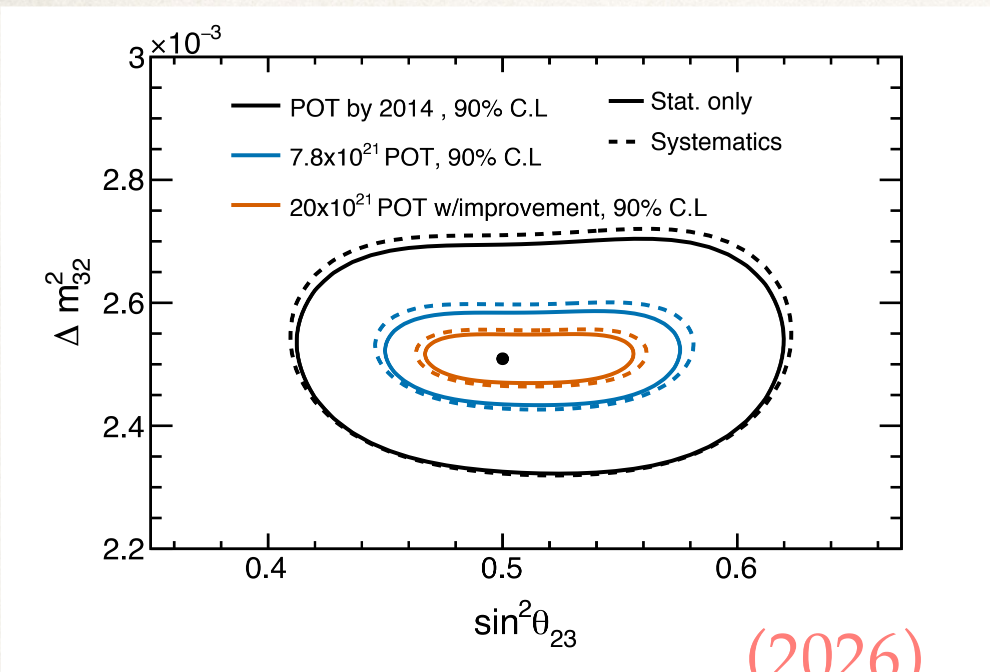
~0.7% precision on $\sin^2\theta_{12}$

~0.6% precision on Δm^2_{21}

Prospects for precision

T2K-II

Abe et al, 1609.04111



(2026)

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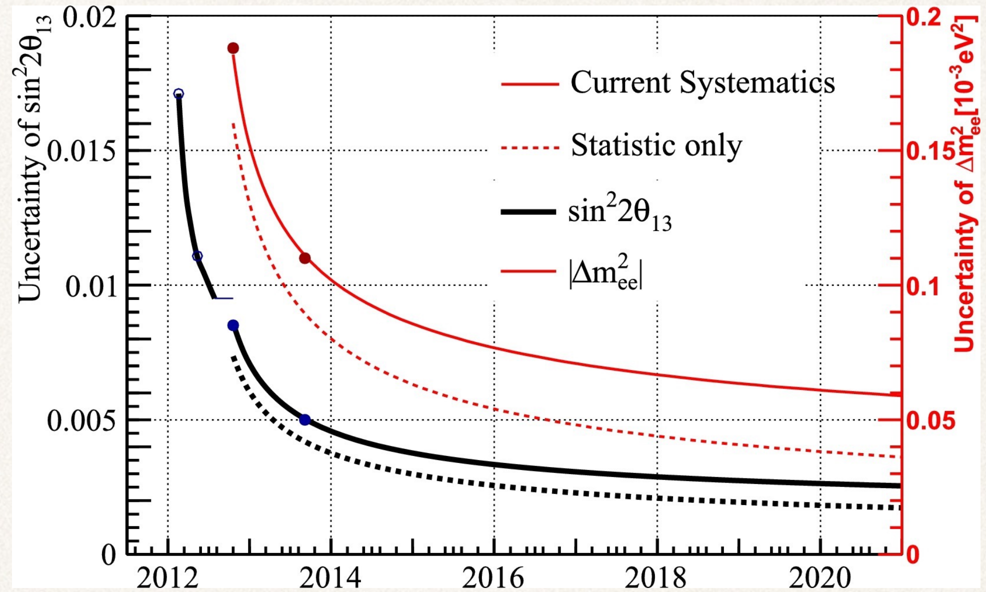

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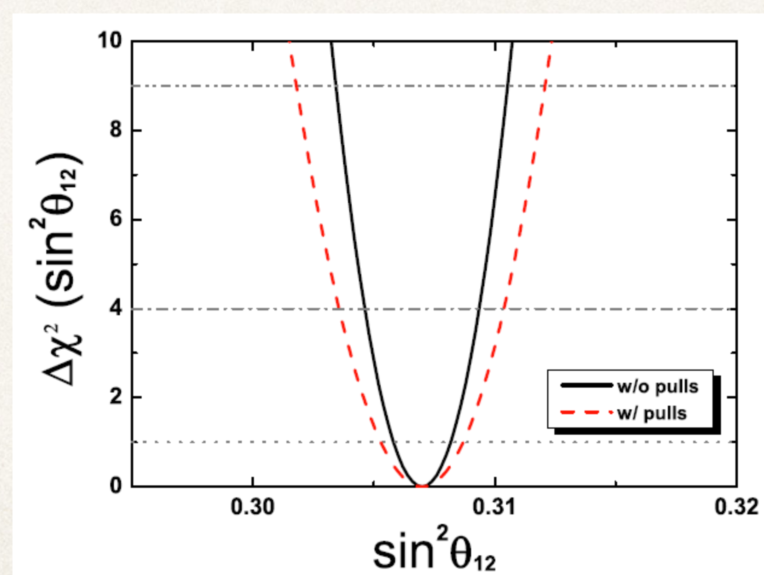
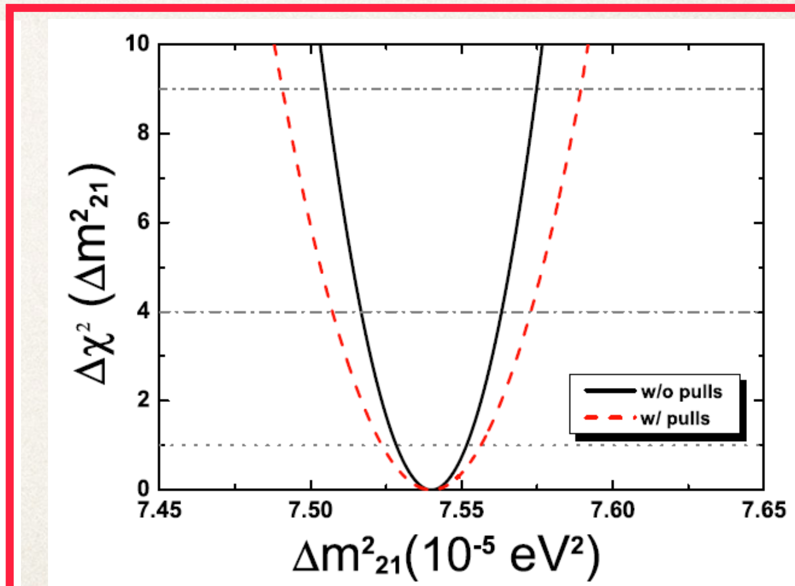
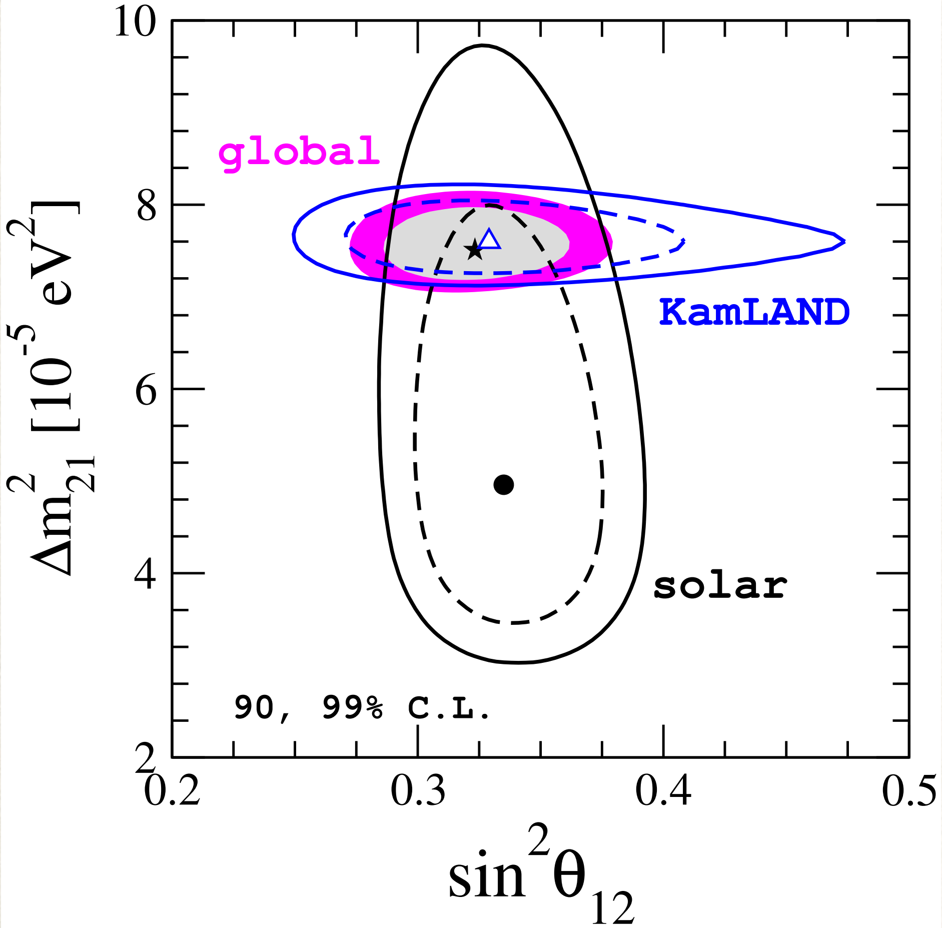




~0.7% precision on $\sin^2\theta_{12}$

~0.6% precision on Δm^2_{21}

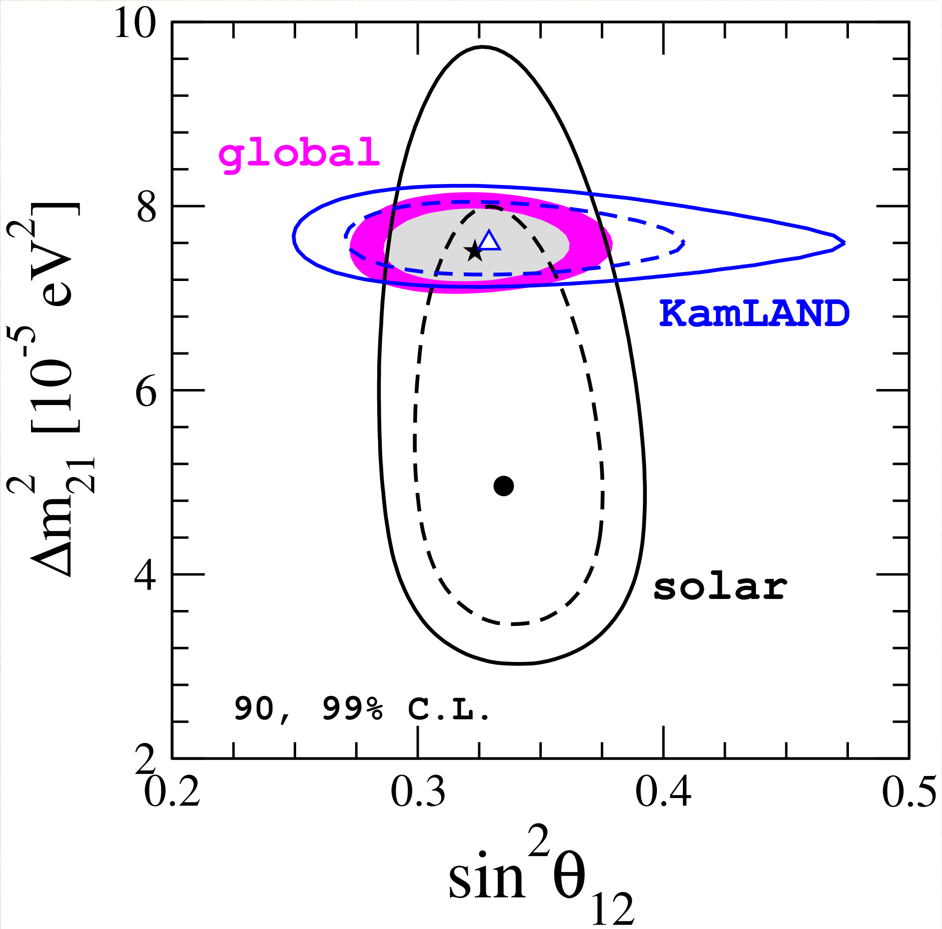
Tension in Δm^2_{21} measurement



⇒ 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

Tension in Δm^2_{21} measurement



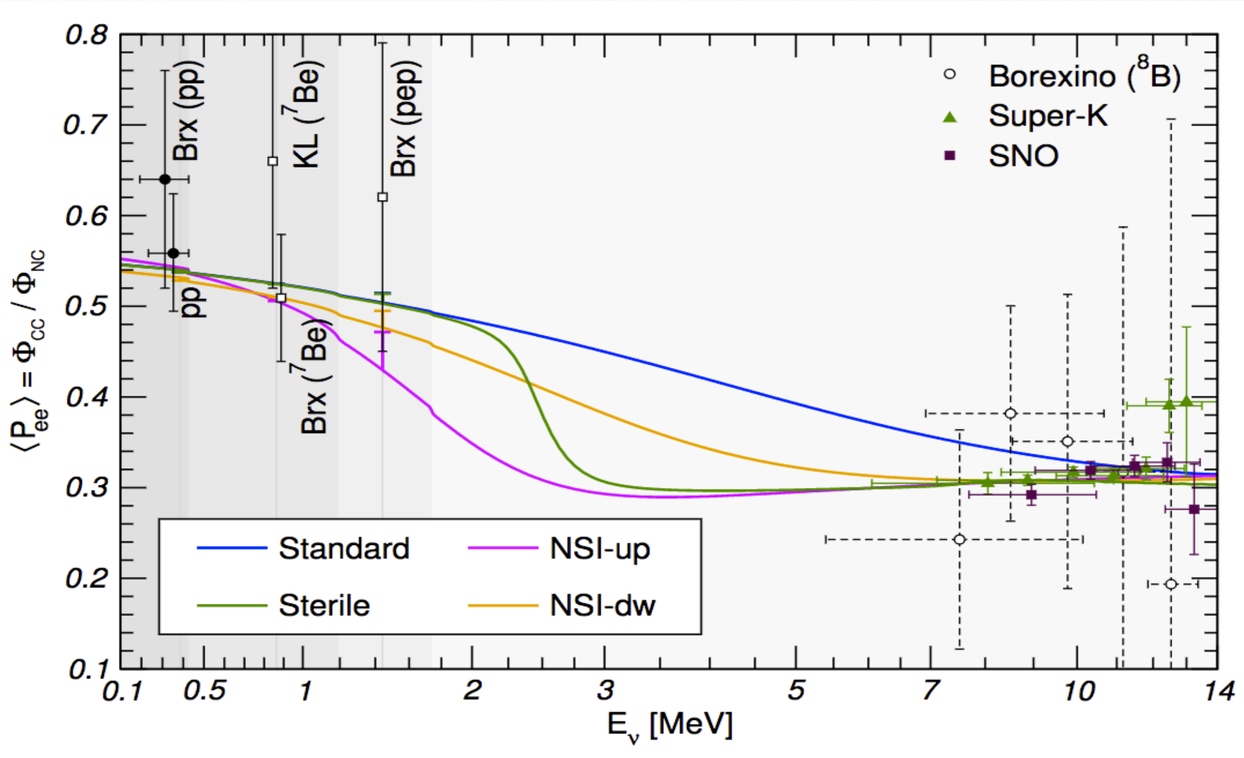
⇒ 2σ tension between preferred value of Δm^2_{21} from KamLAND and solar data

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

- 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)

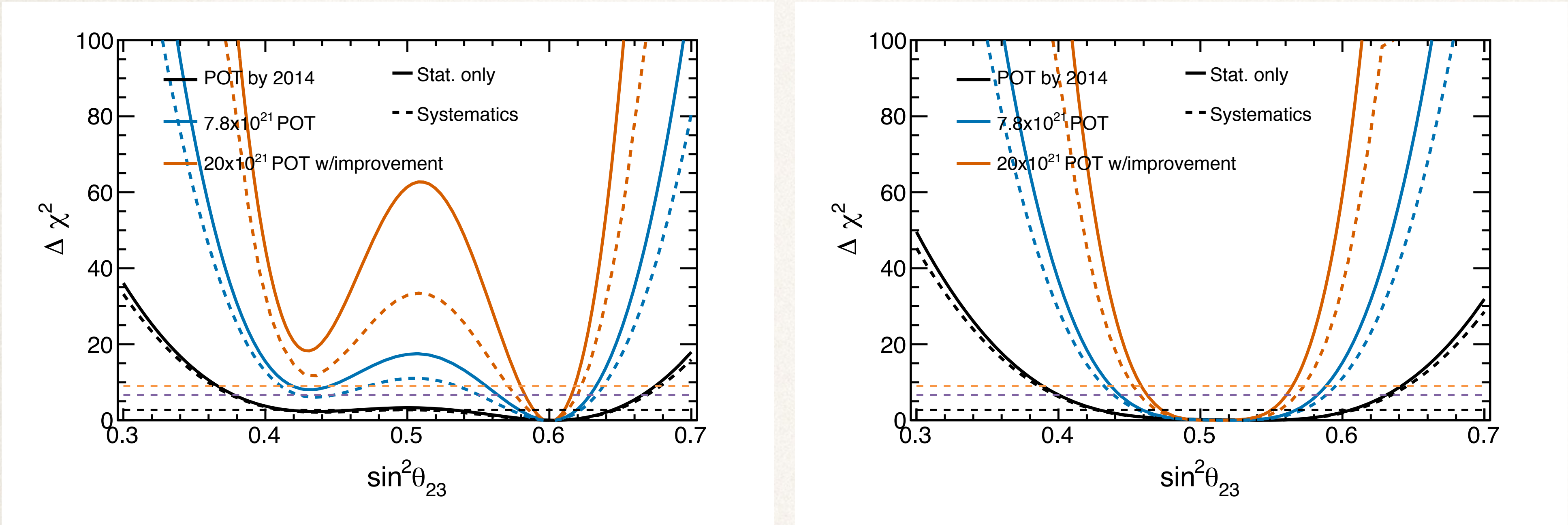
Coloma et al, PRD96 (2017)

Maltoni & Smirnov, EPJ 2015

Prospects for atmospheric octant

T2K-II

Abe et al, 1609.04111



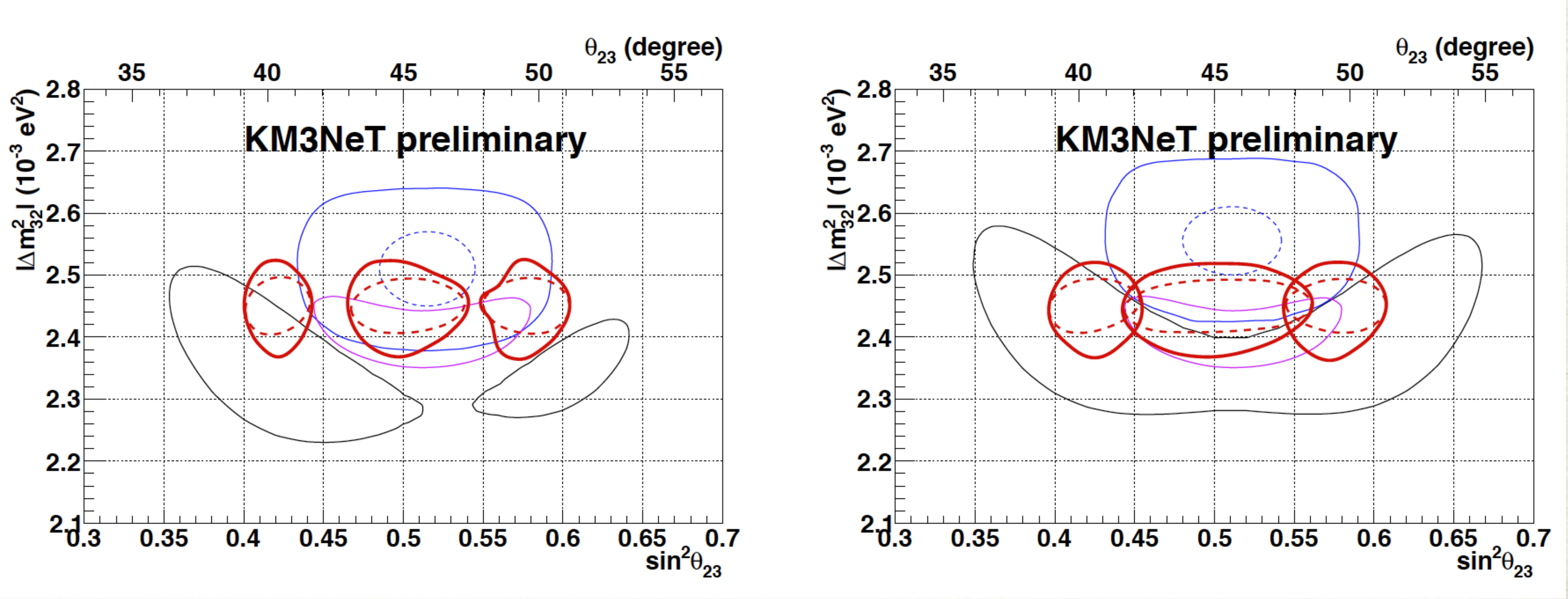
octant degeneracy can be resolved at ≳ 3σ for $\sin^2\theta_{23}$=0.60, 0.43

ORCA

Adrian-Martinez et al, 1601.07459

3 years of data

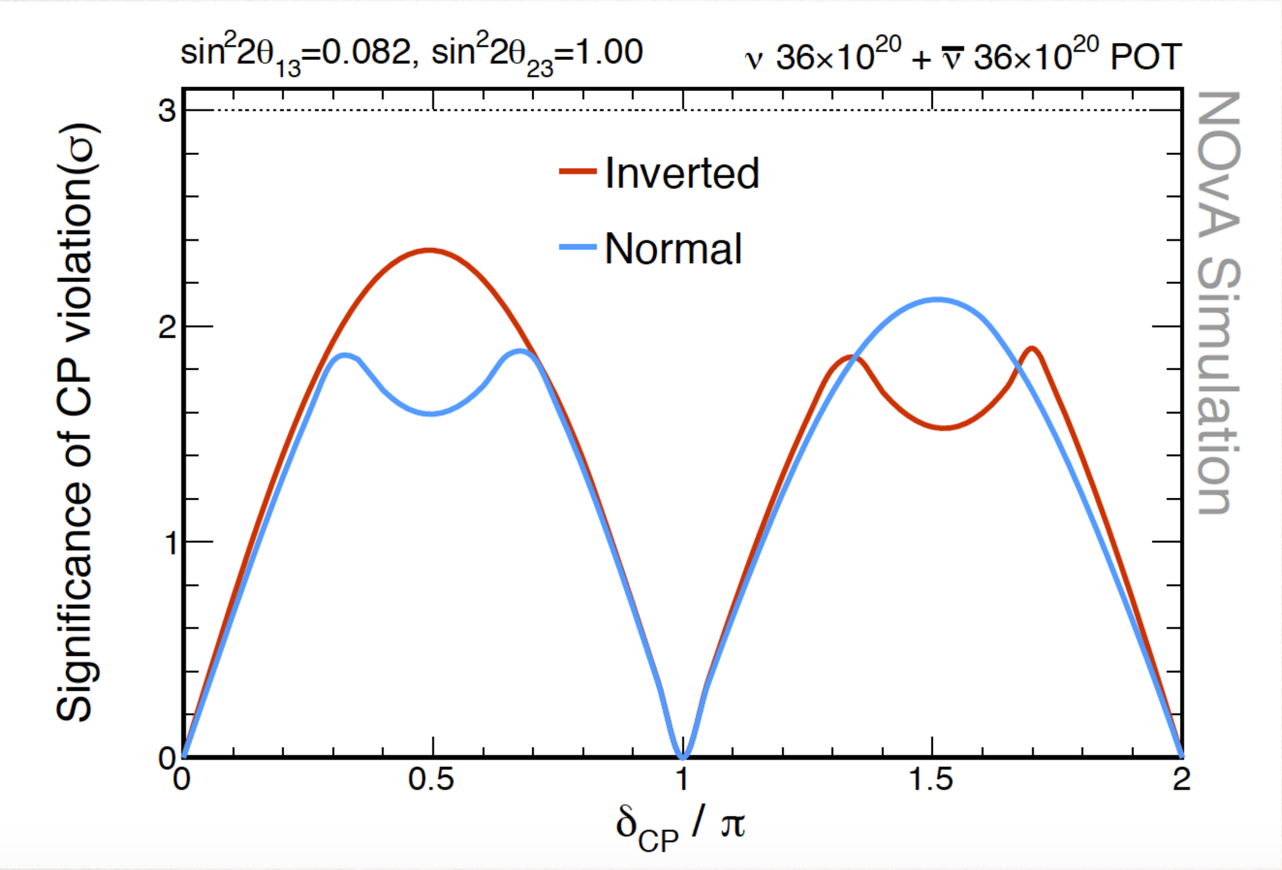
1σ contours

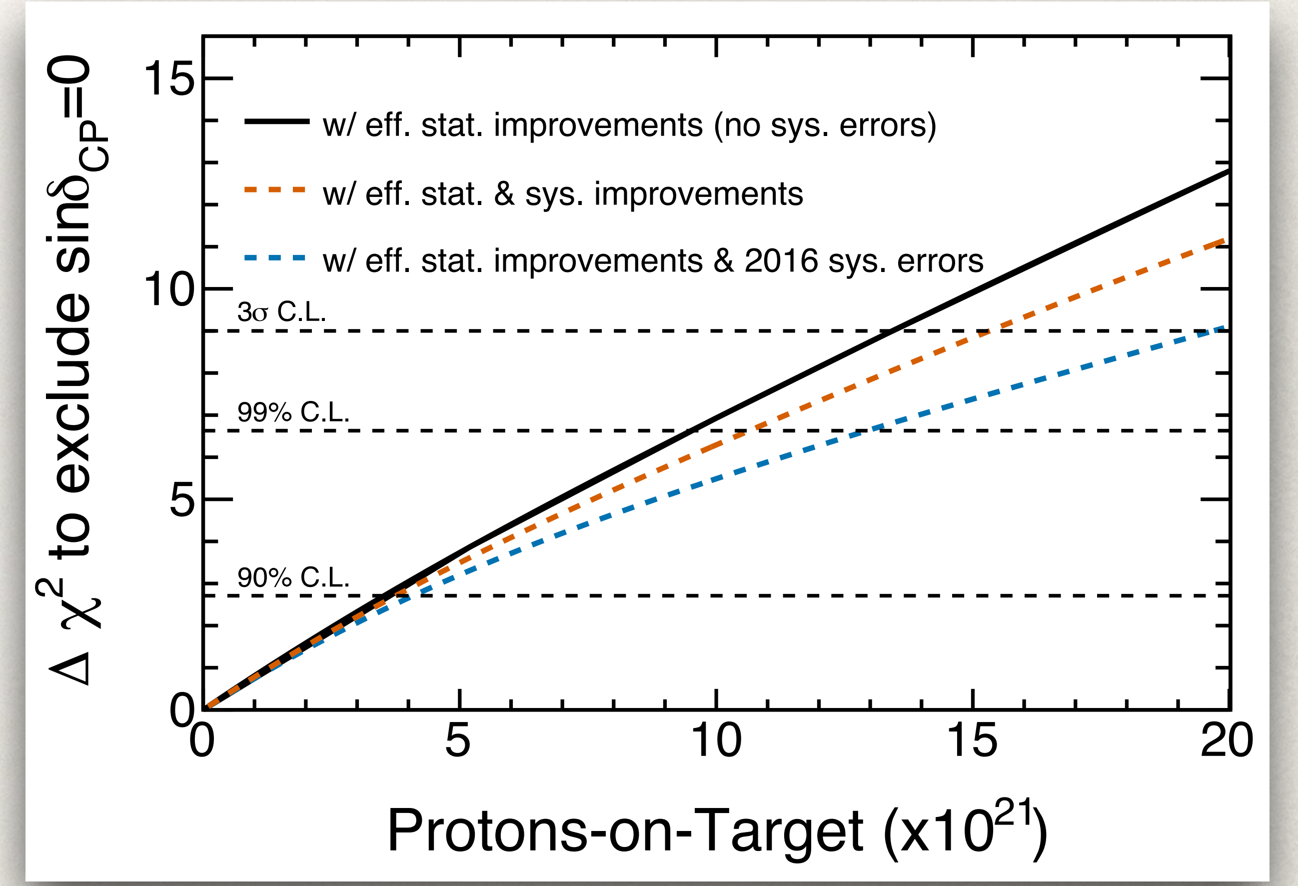


Prospects for CP violation

NOvA M. Sánchez, Neutrino'18

T2K-II Abe et al, 1609.04111



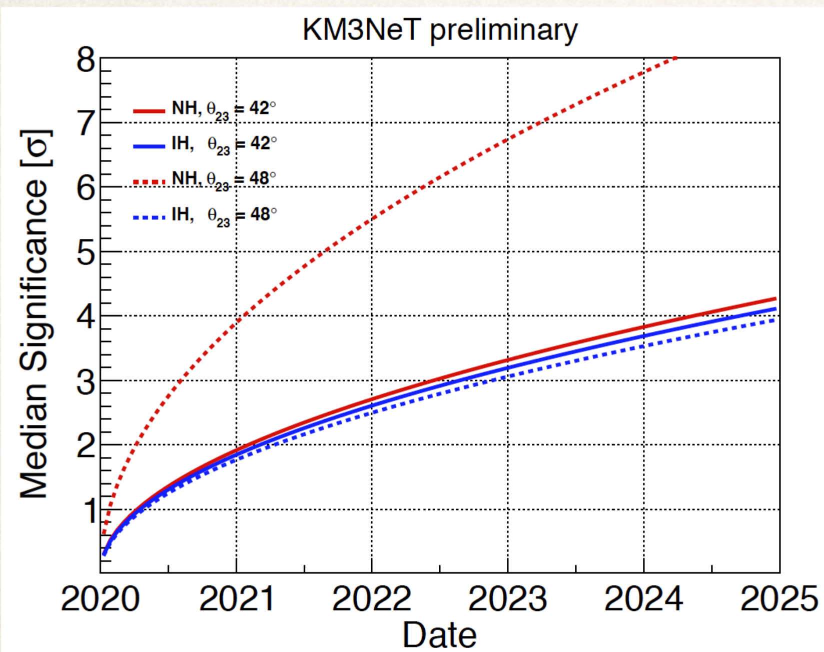


- by 2024: > 2σ sensitivity on CP violation at max CP violation (π/2 & 3π/2)
- by 2026 (20×10^{21} POT): > 3σ sensitivity on CP violation

Prospects for mass ordering

ORCA

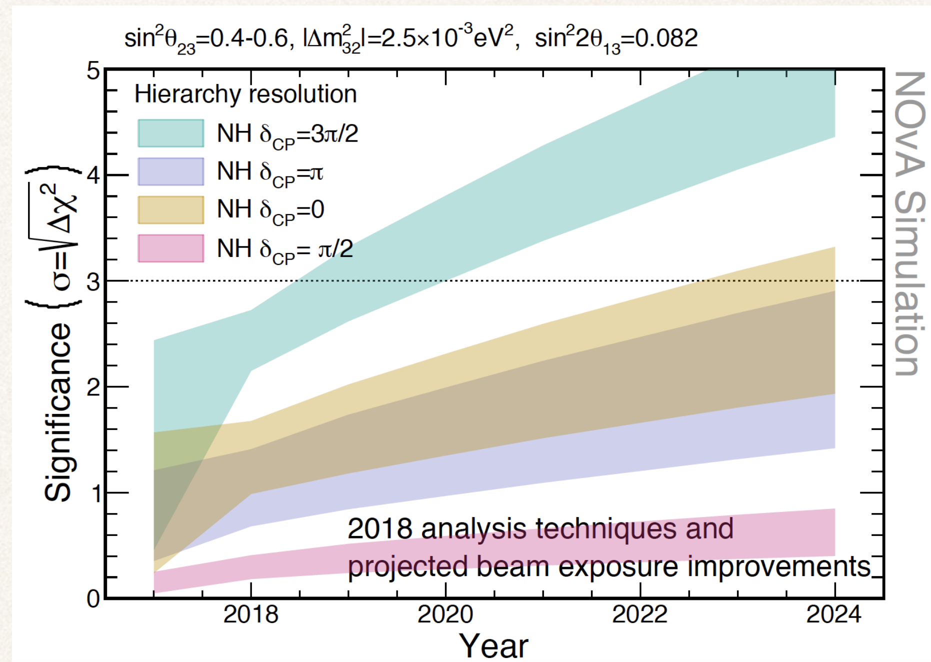
Adrian-Martinez et al, 1601.07459



- 2023: 3σ determination of MO

NOνA

M. Sánchez, Neutrino'18

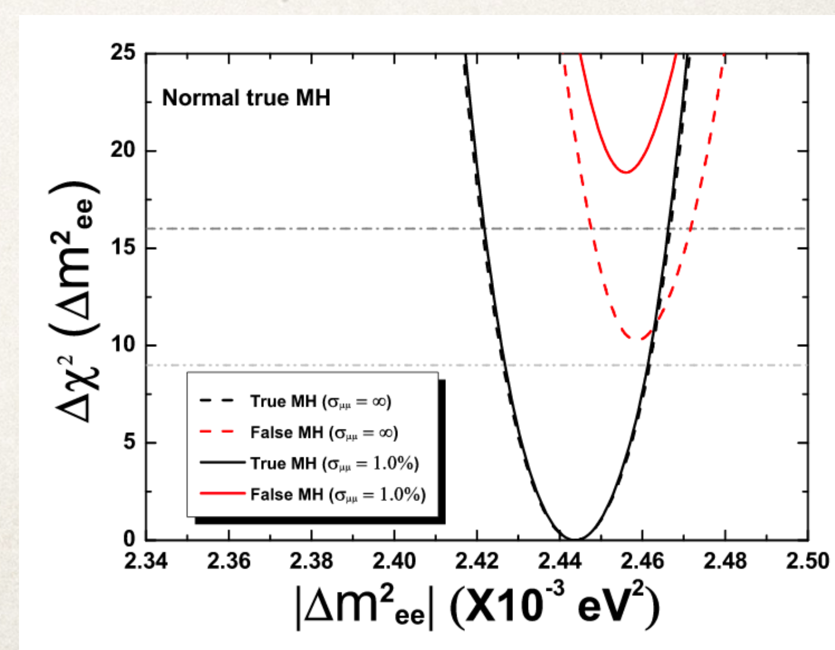


- 2020: 3σ sensitivity (NO and δ=3π/2)
- 2024: 3σ sensitivity for 30/50% of δ

JUNO

⇒ 3σ sensitivity on mass ordering after 6 years

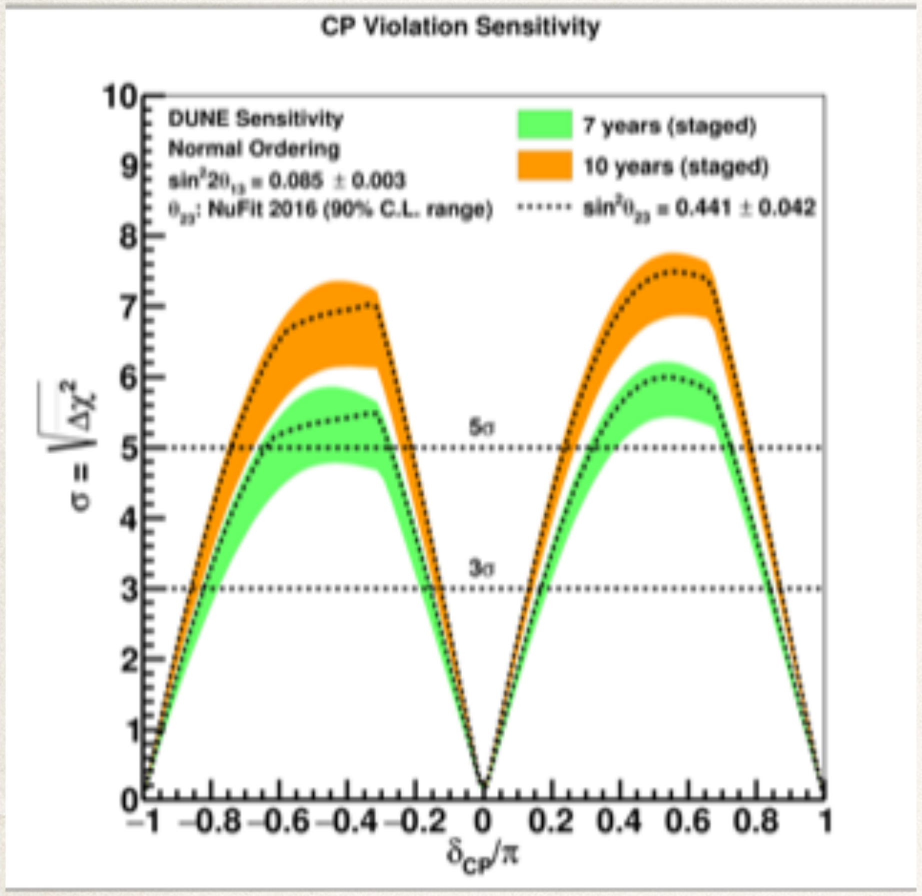
An et al, J. Phys. G 43 (2016) 030401



Next generation of ν experiments

DUNE

E. Worcester @ Neutrino'18



Next generation of ν experiments

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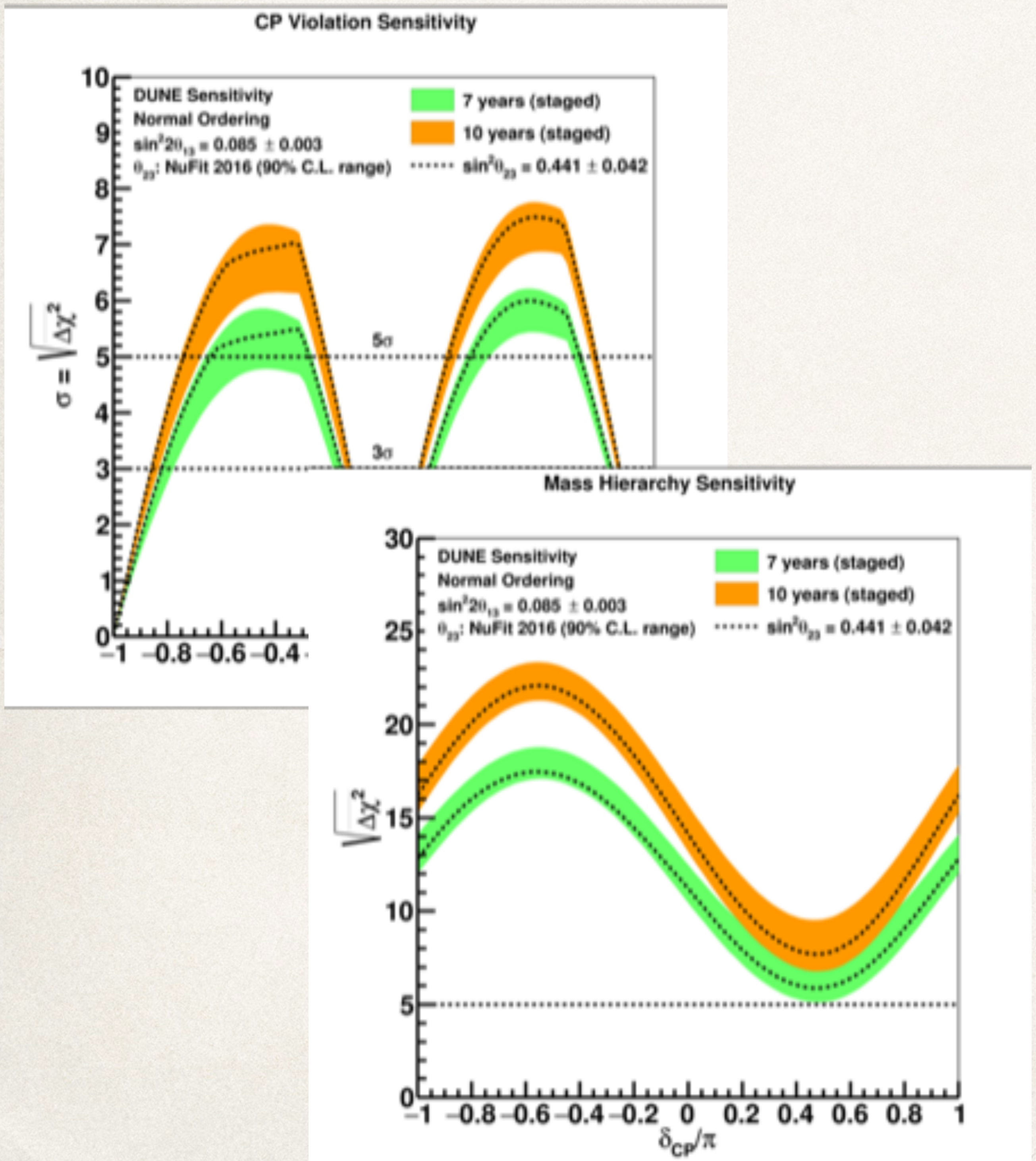
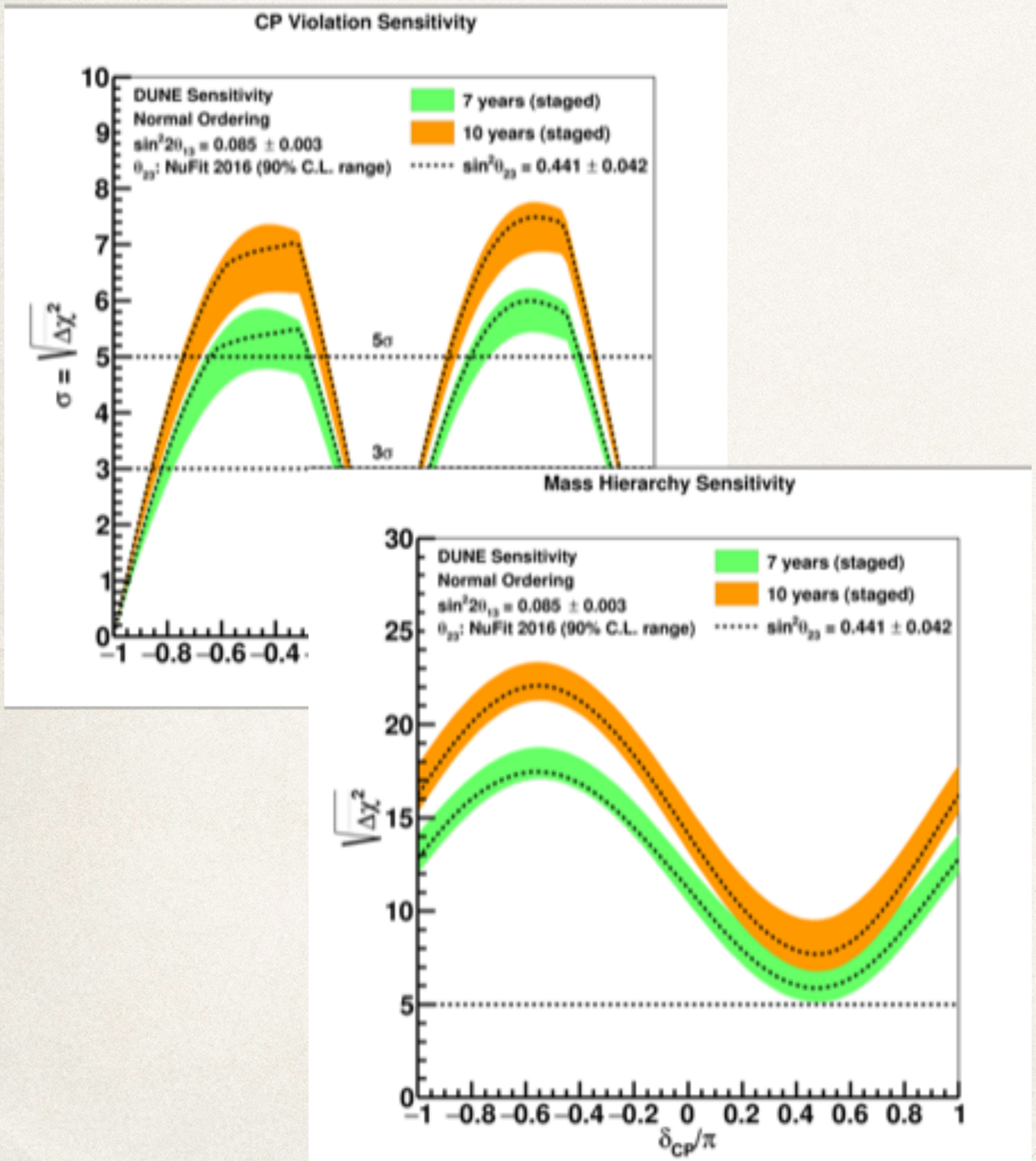


Next generation of ν experiments

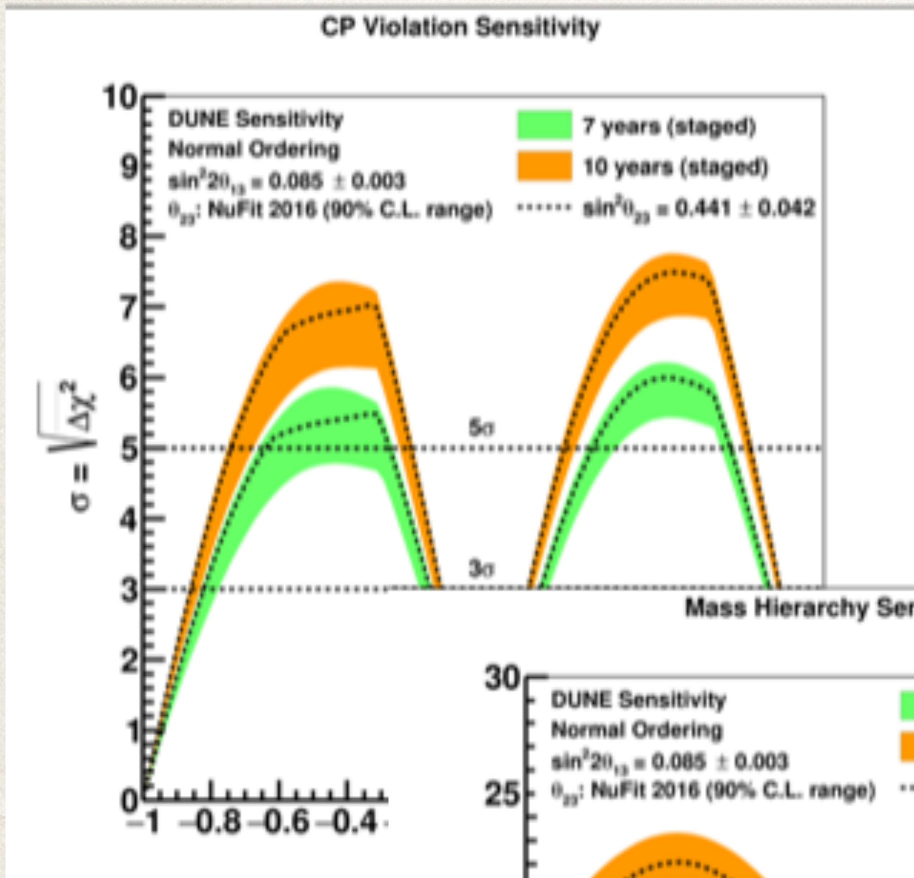
DUNE **E. Worcester @ Neutrino'18**

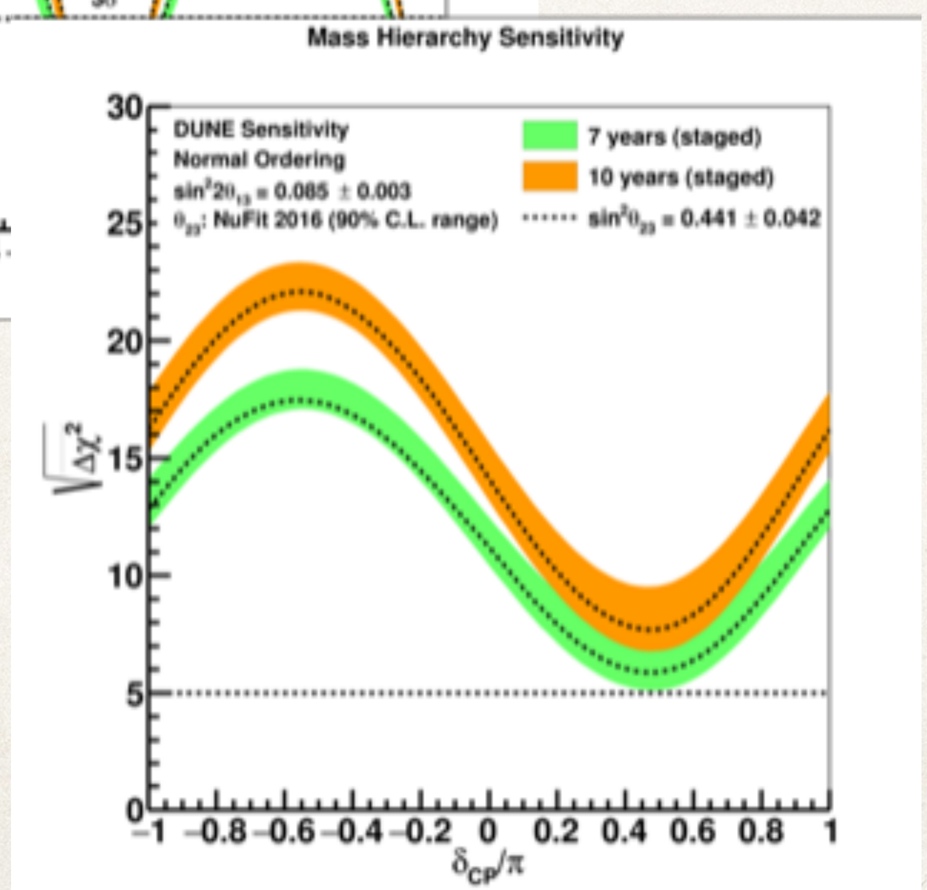
Hyper-Kamiokande **T. Kajita @ NOW2016**



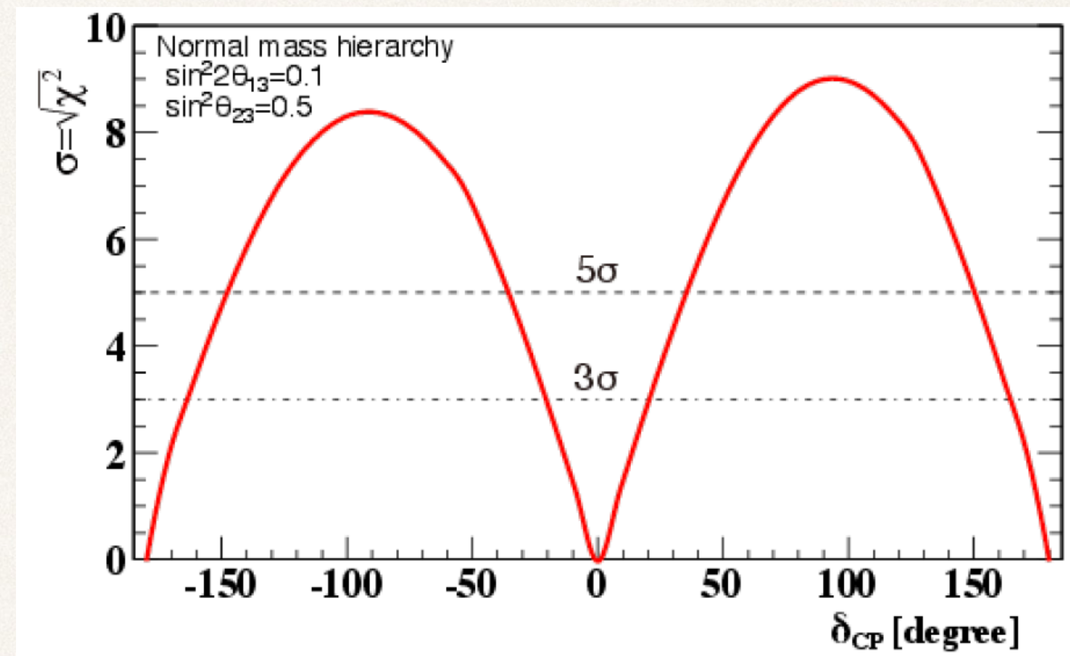
Next generation of ν experiments

DUNE **E. Worcester @ Neutrino'18**





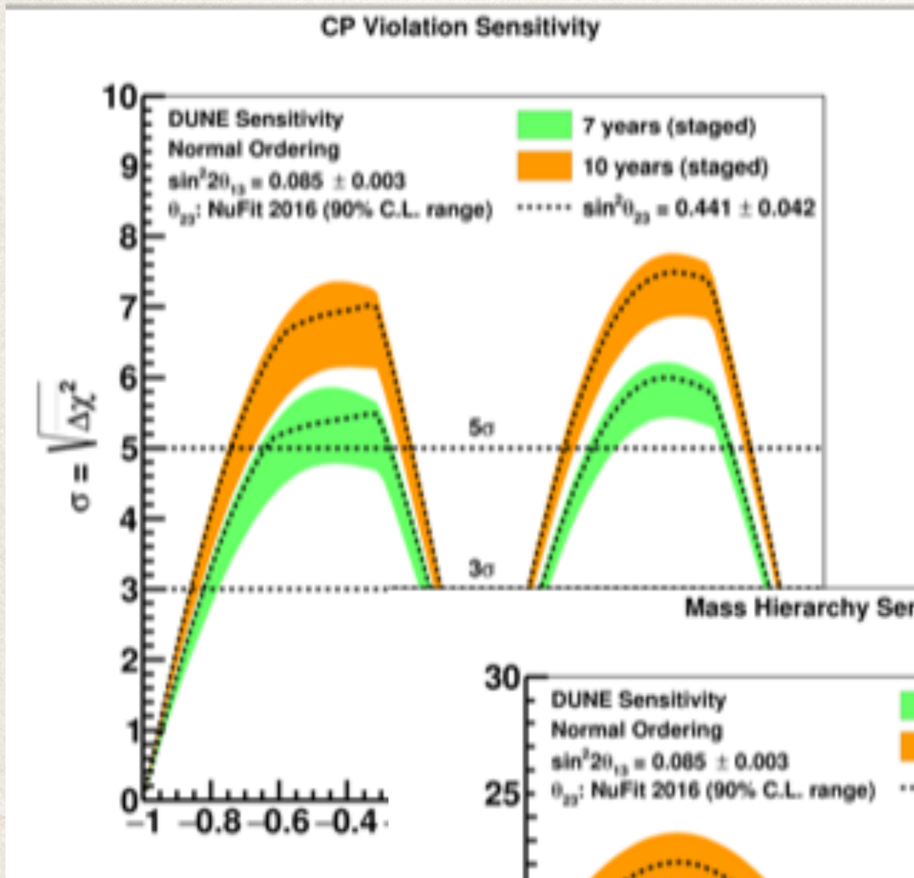
Hyper-Kamiokande **T. Kajita @ NOW2016**

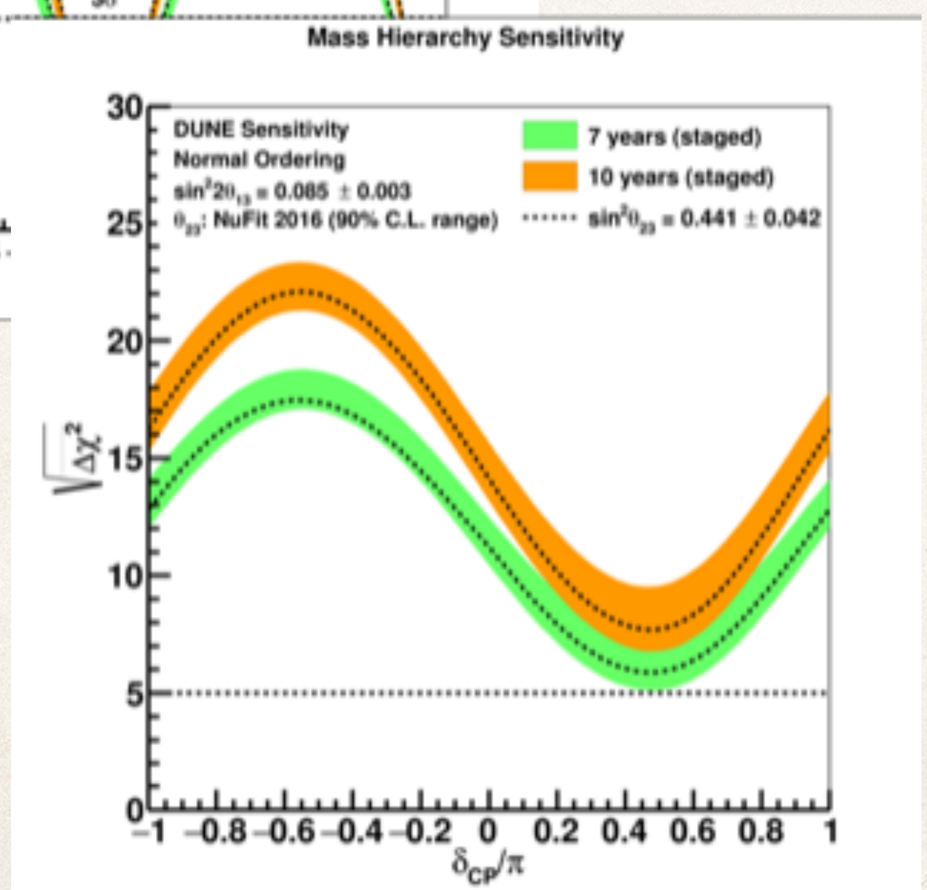


10 yr

Next generation of ν experiments

DUNE E. Worcester @ Neutrino'18





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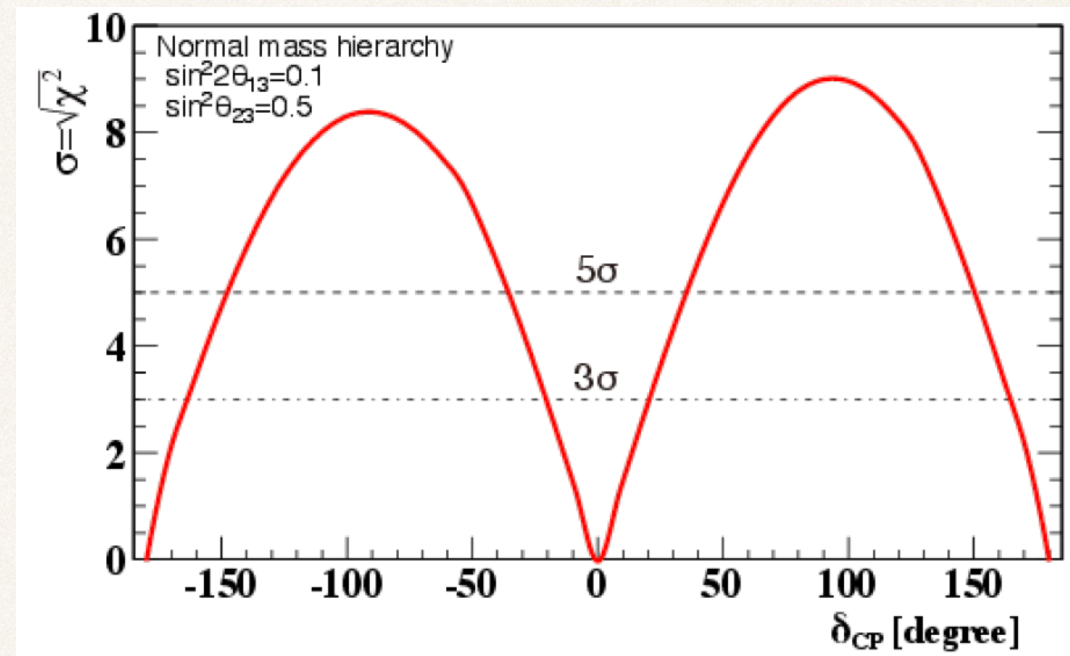
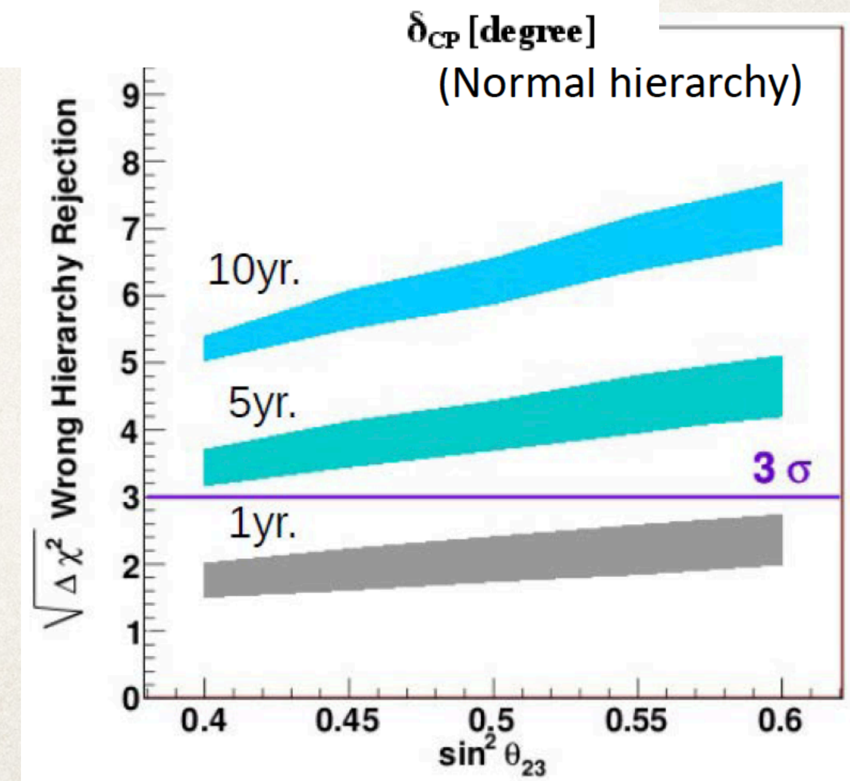
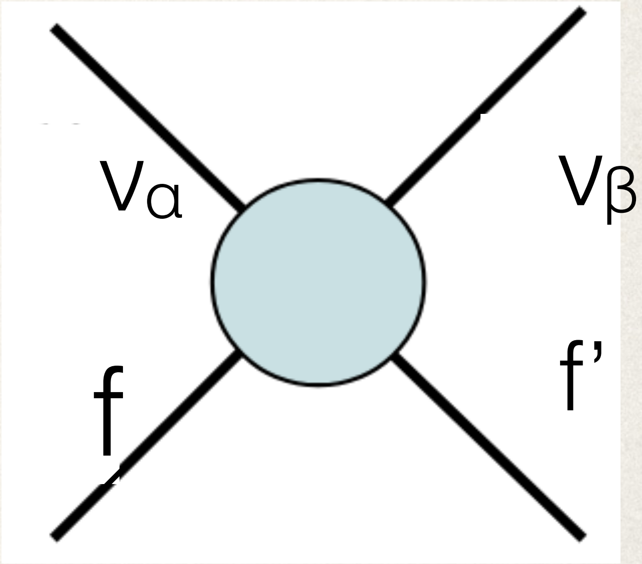


10 yr



Beyond the standard three-neutrino scenario

Non-Standard Interactions (NSI)



- NSI appear in **models of neutrino masses**

  ⇒ knowing the size of NSI could be very useful for neutrino model building

- NSI may affect the determination of oscillation parameters

⇒ precision measurements at current experiments

⇒ sensitivity reach of upcoming experiments (degeneracies and ambiguities)

CC-NSI: $$\mathcal{L}_{\rm CC-NSI} = -2\sqrt{2} G_F\, \epsilon^{f f' X}_{\alpha\beta}\, (\bar\nu_\alpha \gamma^\mu P_L \ell_\beta) \left(\bar f' \gamma_\mu P_X f\right)$$

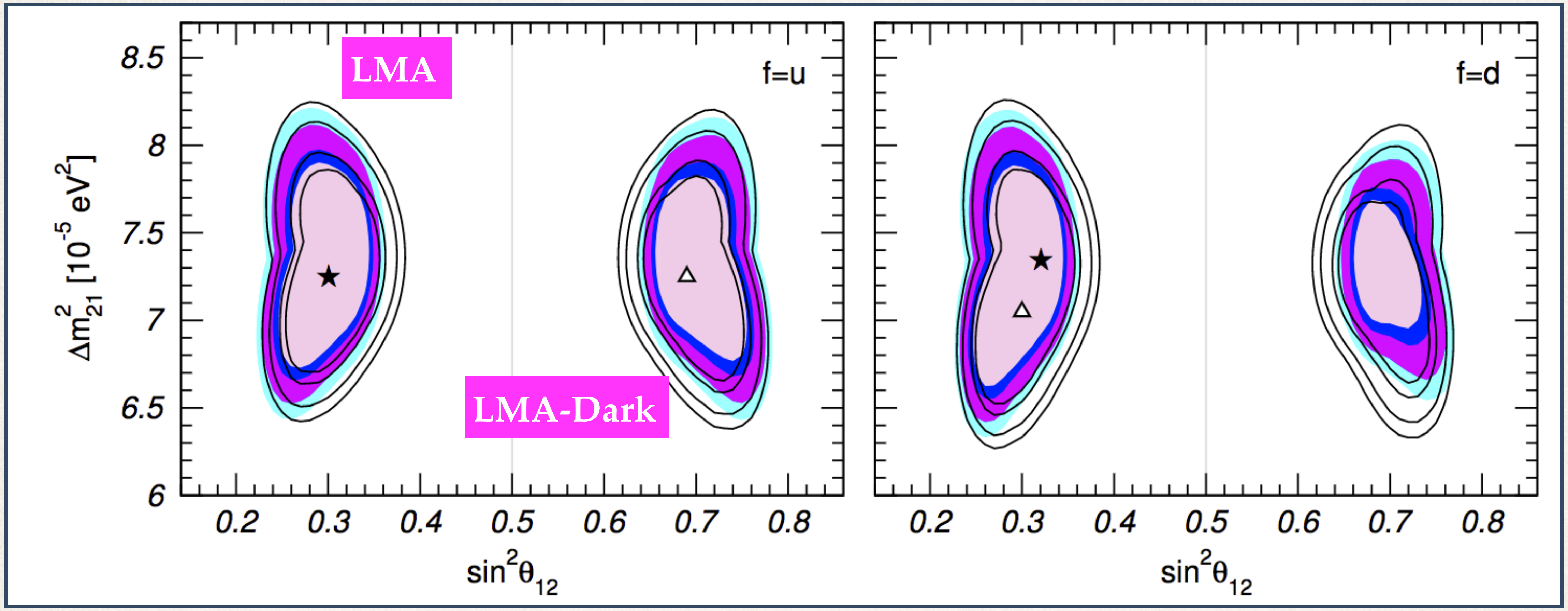
⇒ may affect neutrino **production** and **detection**

NC-NSI: $$\mathcal{L}_{\rm NC-NSI} = -2\sqrt{2} G_F\, \epsilon^{f X}_{\alpha\beta}\, (\bar\nu_\alpha \gamma^\mu P_L \nu_\beta) \left(\bar f \gamma_\mu P_X f\right)$$

⇒ mainly affecting neutrino **propagation** in matter

(but also detection, e.g., Super-K and Borexino)

NSI in the solar sector



Miranda et al, JHEP 2006

Gonzalez-Garcia et al, JHEP 2013

How to probe LMA-Dark?

⇒ combination with neutrino scattering experiments: CHARM, NuTeV

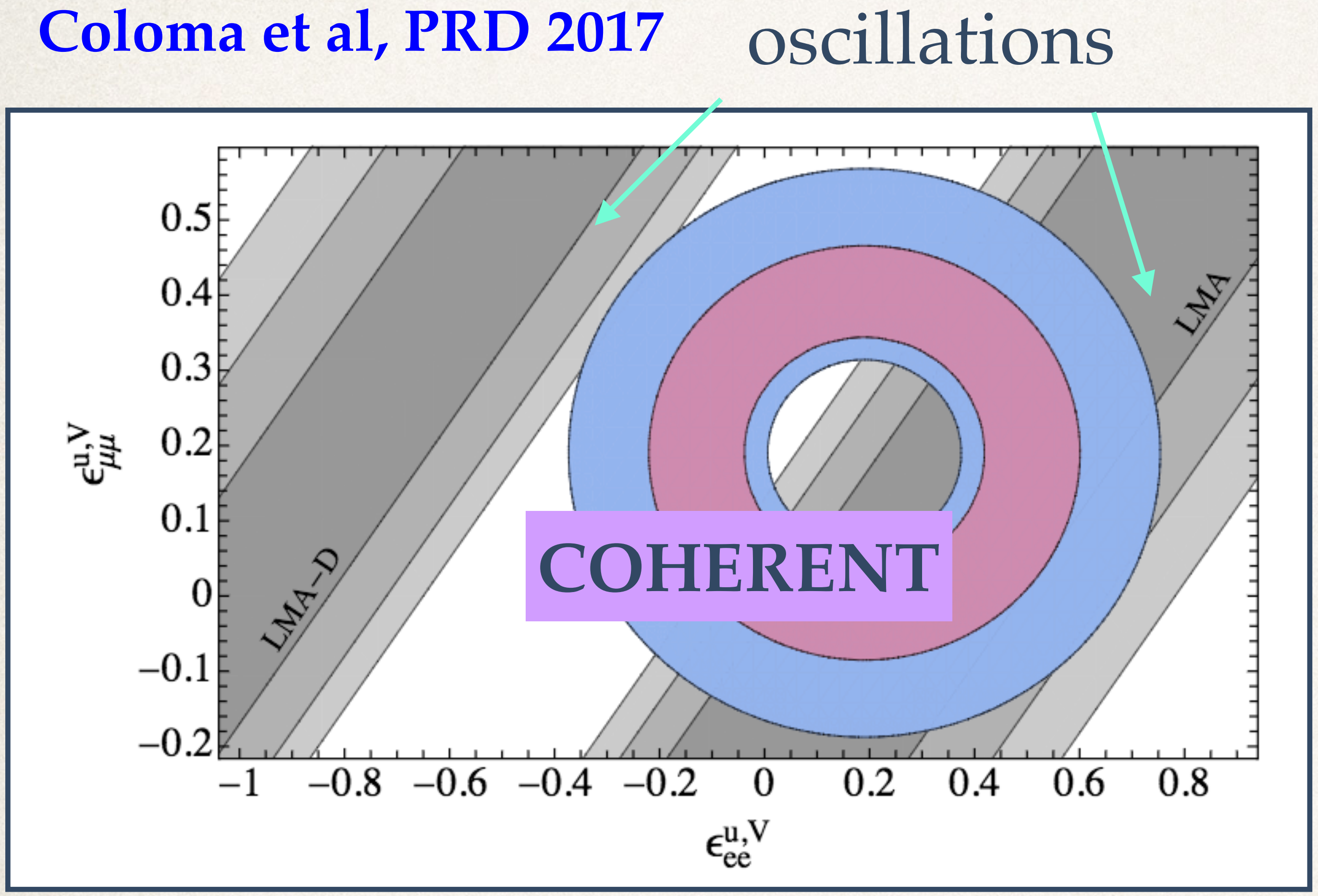
Escrihuela et al, PRD 2009, Coloma et al, JHEP 2017

⇒ combination with coherent neutrino-nucleus scattering

Coloma et al, PRD 2017

Impact of COHERENT results

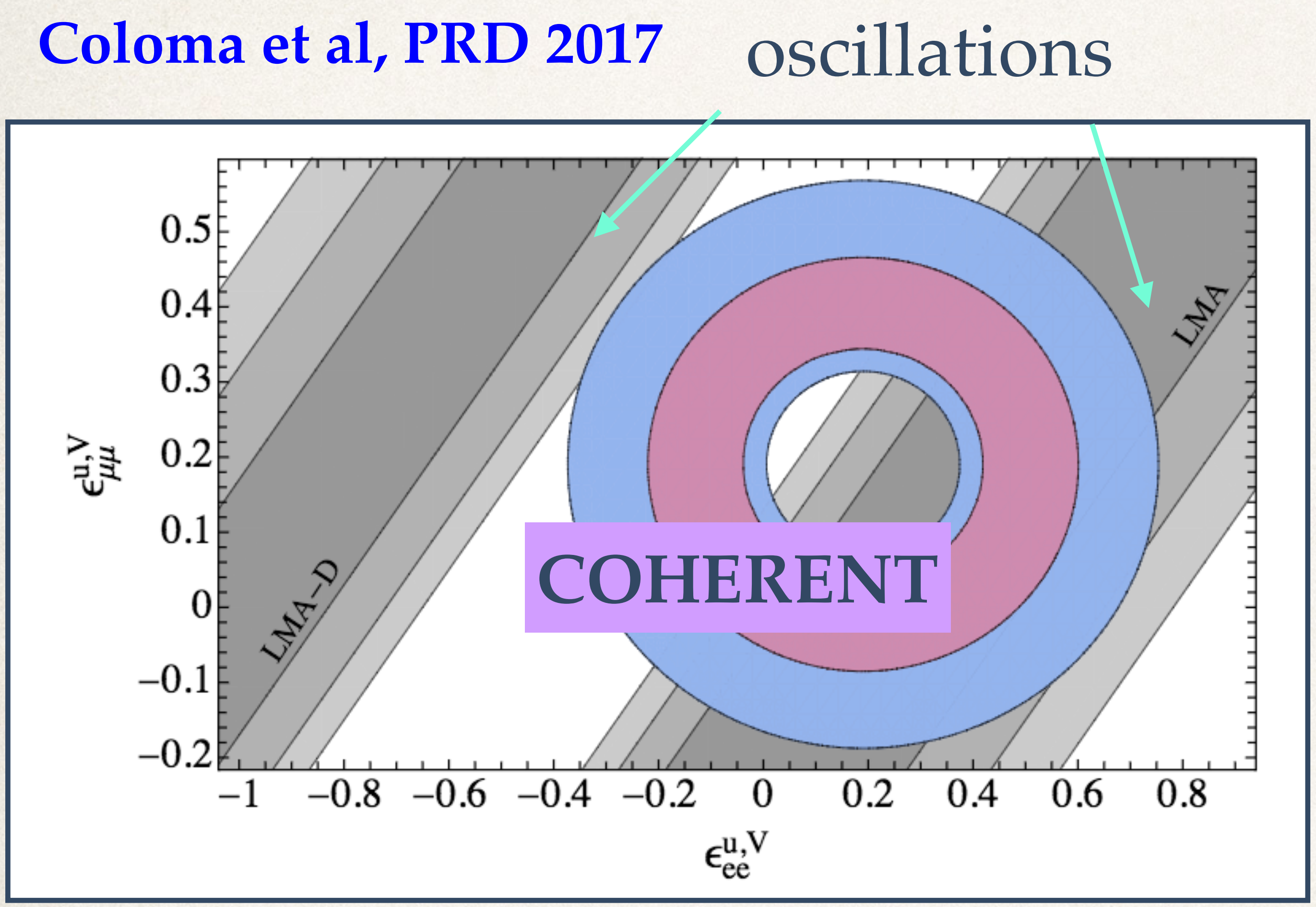
Coloma et al, PRD 2017



⇒ LMA-Dark excluded at 3σ

Impact of COHERENT results

Coloma et al, PRD 2017



⇒ LMA-Dark excluded at 3σ

However this can be relaxed if:

- NSI mediator lighter than 10 MeV

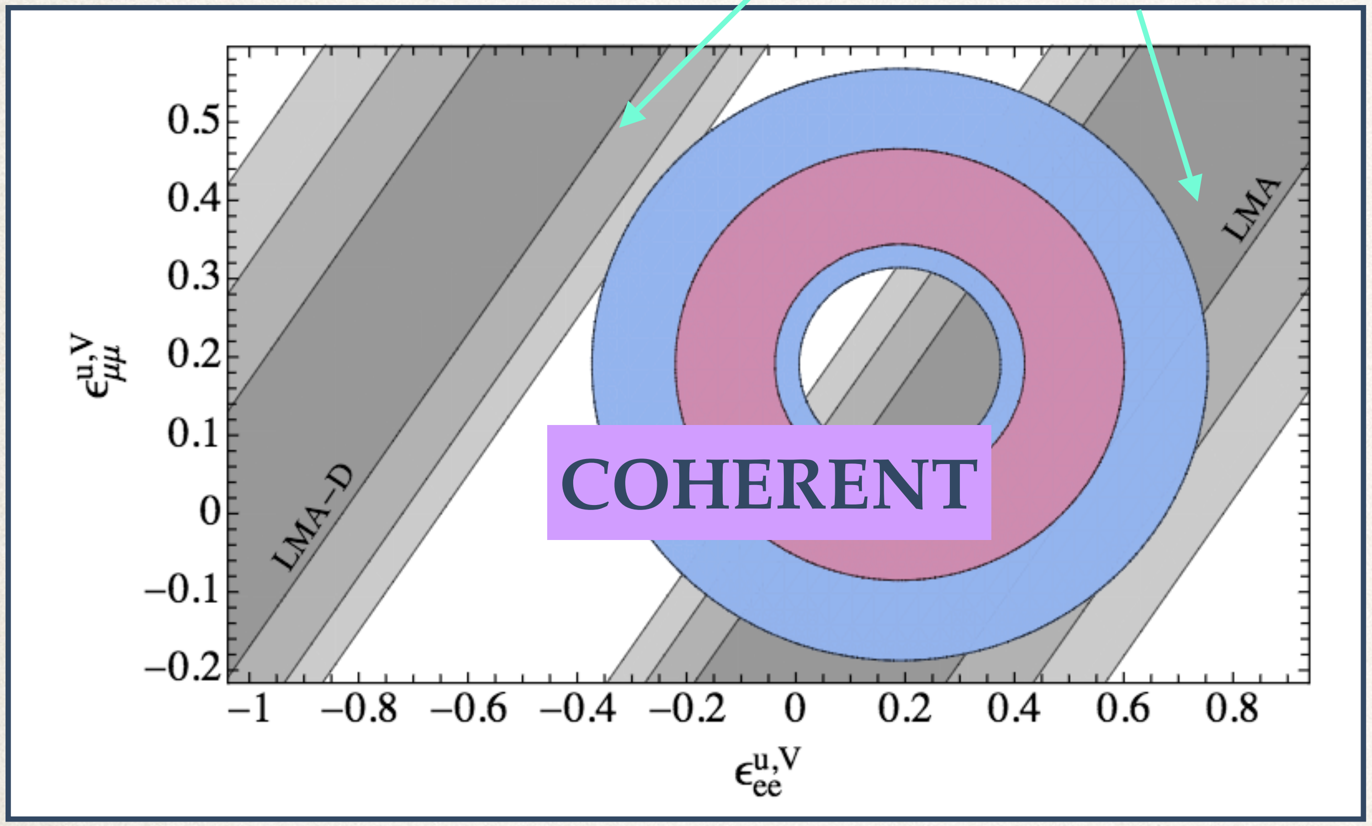
- degeneracies in ($\boldsymbol{\varepsilon}_d$, $\boldsymbol{\varepsilon}_u$)

Liao & Marfatia, PLB 2017

Impact of COHERENT results

Coloma et al, PRD 2017

oscillations



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Liao & Marfatia, PLB 2017

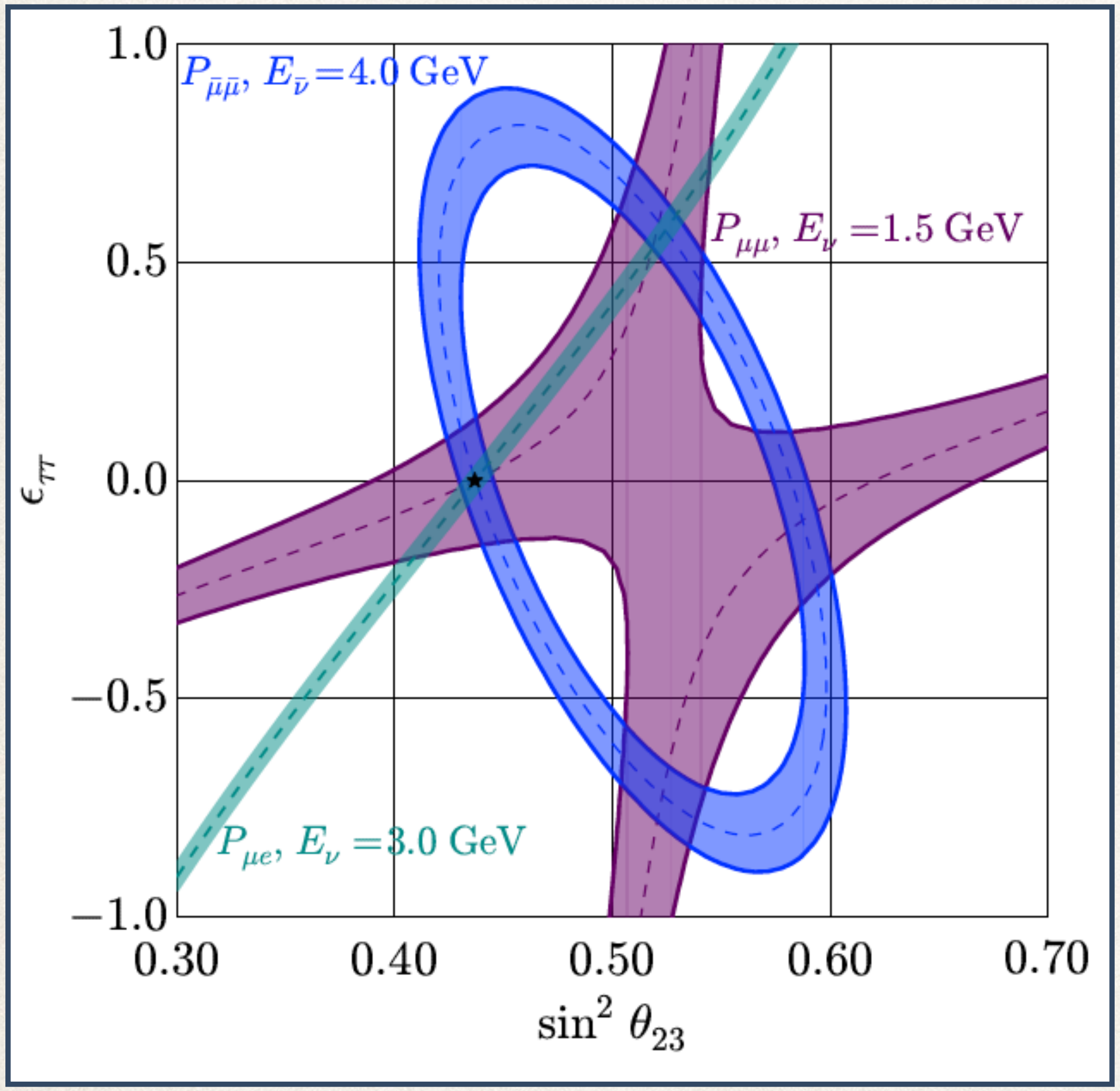
Global Analysis of Oscillation Data considering simultaneously NSI with *u* & *d* quarks

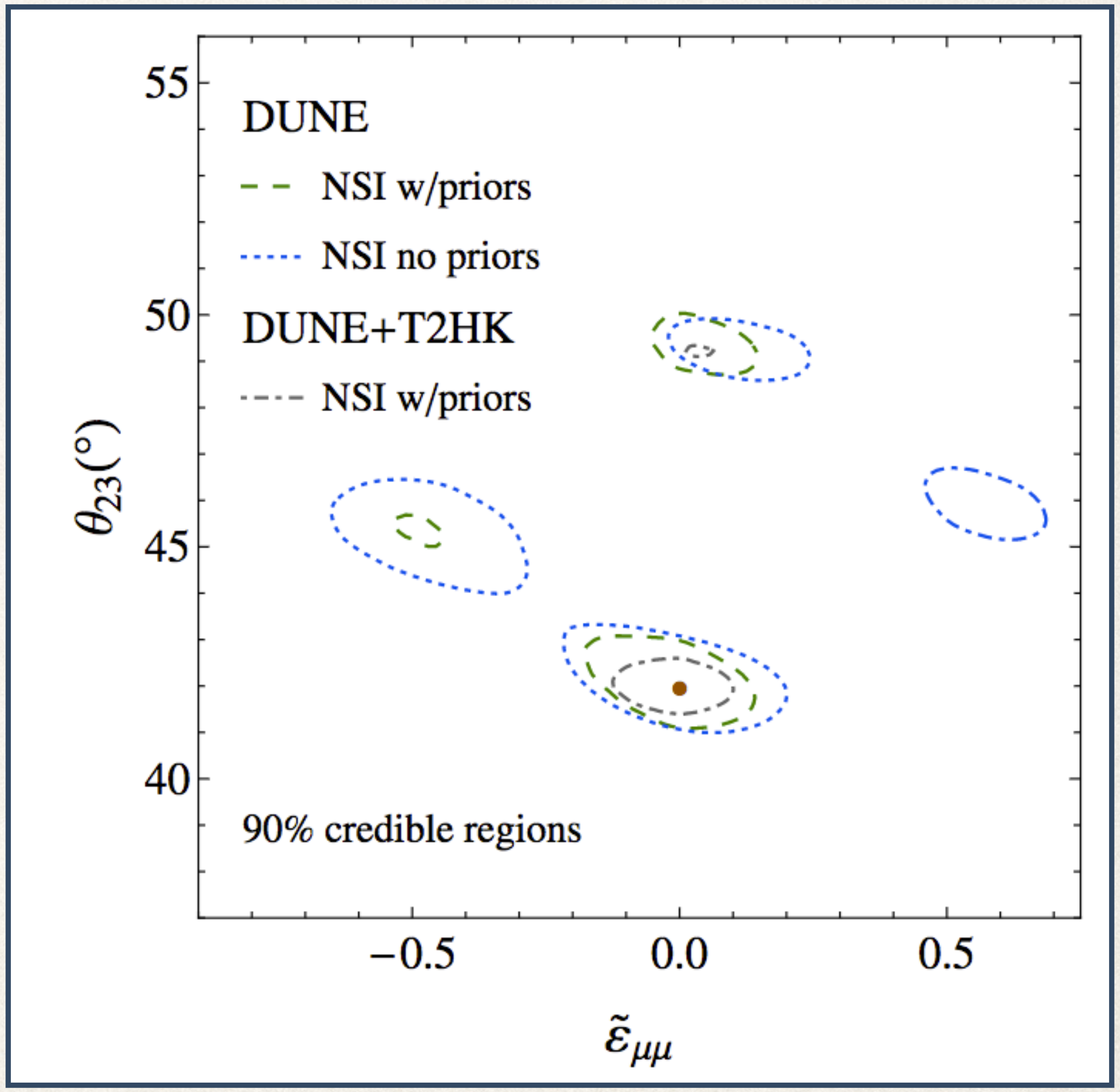
Esteban et al, JHEP 2018

⇒ LMA-D region remains allowed at the 3σ level for a given range of ratios of *u* and *d* NSI couplings

NSI at future LBL experiments

(θ_{23}-$\epsilon_{\tau\tau}$) degeneracy in DUNE





Gouvea and Kelly, NPB 2016

Coloma, JHEP 2016

Non-unitary light neutrino mixing

- Most models of neutrino masses include **new extra heavy states**

Ex: type I seesaw, inverse seesaw

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \qquad \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

- NxN mixing matrix with:

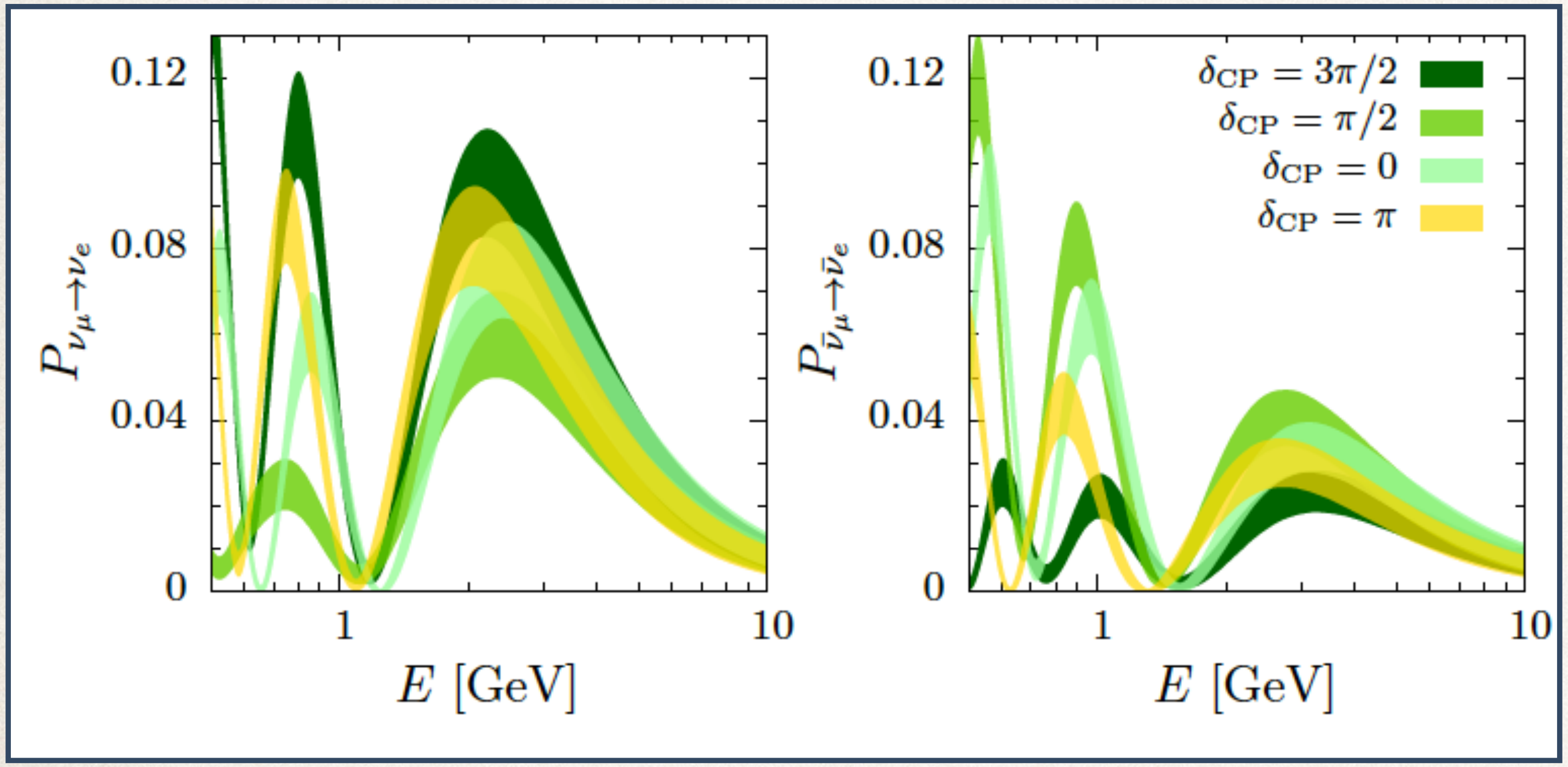
N(N-1)/2 mixing angles and (N-1)(N-2)/2 Dirac CP phases

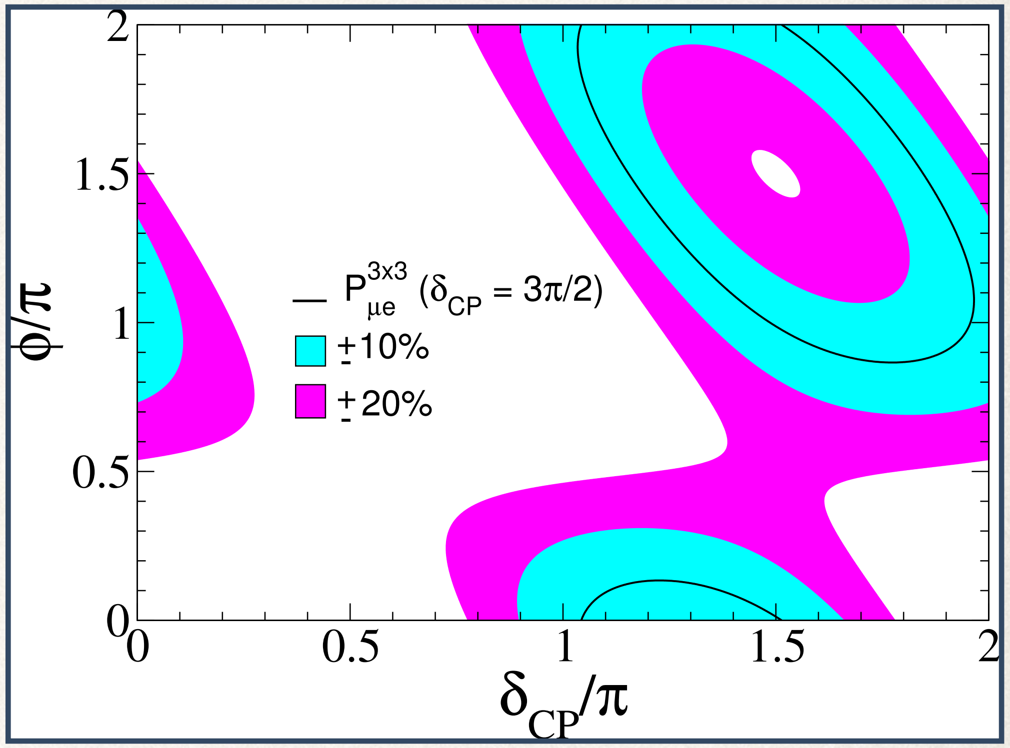
→ (3x3) light neutrino mixing matrix U is **non-unitary** in general

→ if U is non-unitary: 9 more parameters are needed to describe mixing: **6 new moduli + 3 new phases.**

NU neutrino oscillations in DUNE

The new phases will modify the standard oscillation picture in LBL experiments, such as DUNE



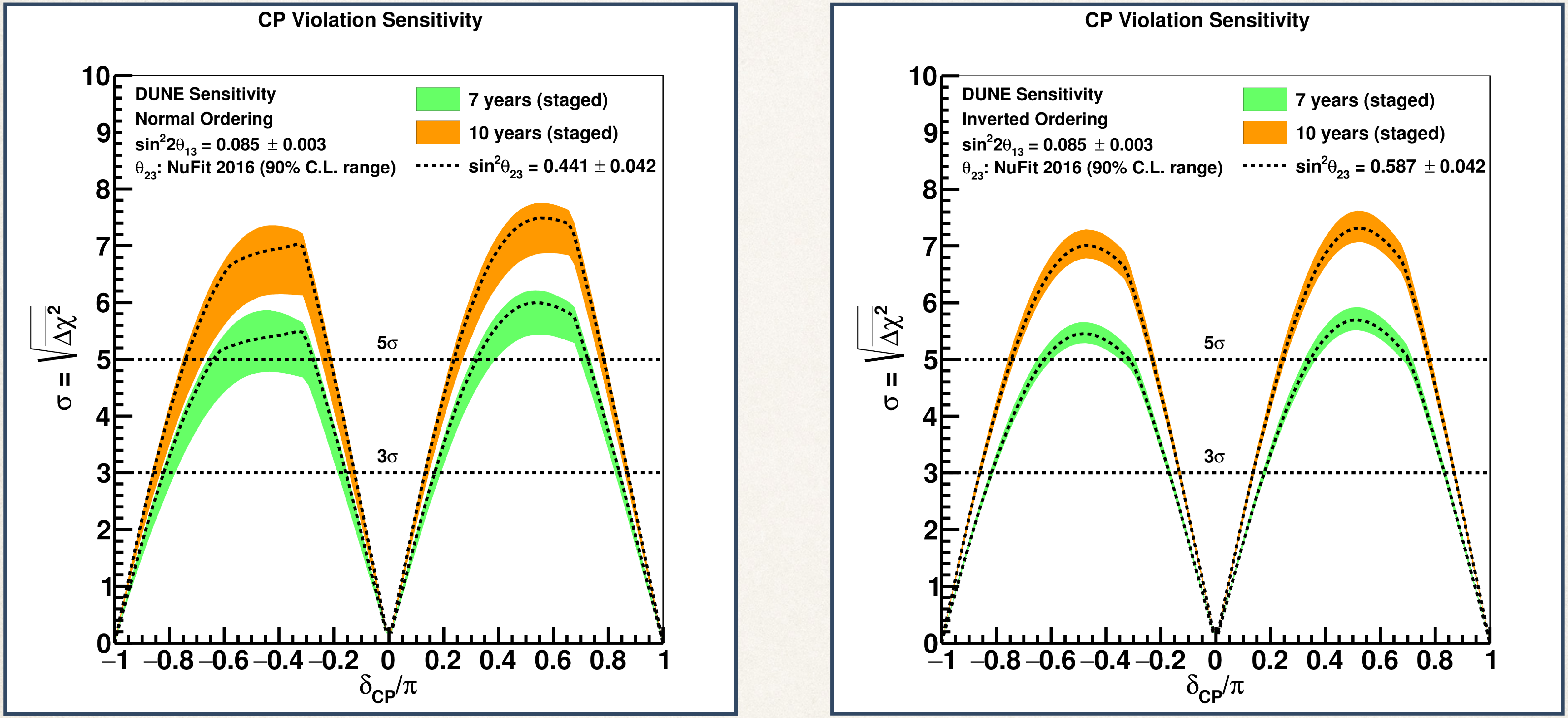


Escrihuela et al, NJP 2017

Miranda, MT, Valle, PRL 117 (2016)

→ (δ, ϕ) degeneracies in $P_{\mu e}$ for E≳ 3 GeV spoil sensitivity to δ

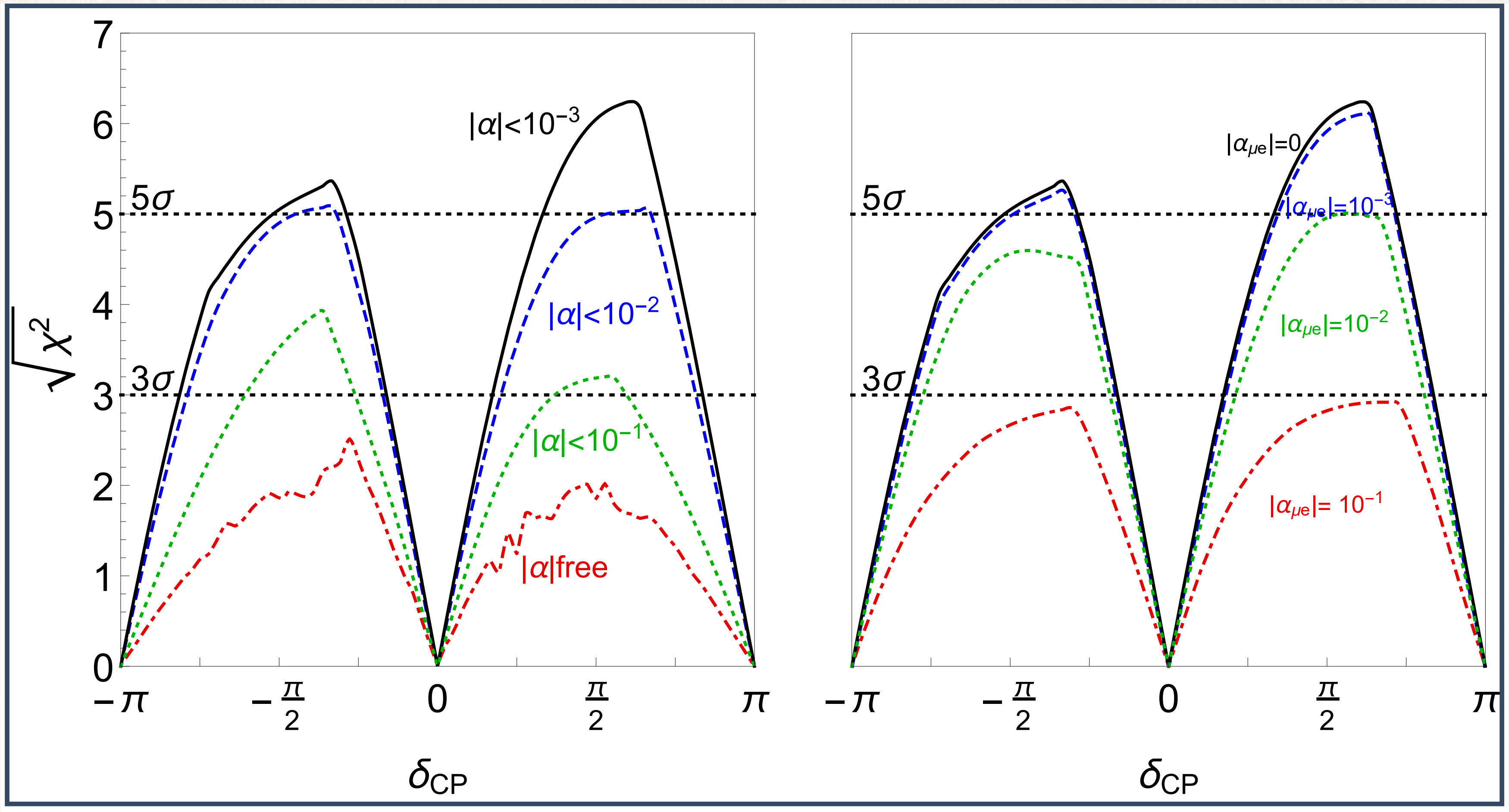
CP violation searches in DUNE



E. Worcester @ Neutrino'18

$> 5\sigma$ sensitivity for some fraction of δ_{CP}

DUNE CP sensitivity with NU



Courtesy of **E.Fernández-Martínez** (DUNE-BSM Working Group)

→ The sensitivity to CP violation might be spoiled in the absence of priors on NU

→ With priors based on current bounds (10^{-3}-10^{-2}), the effect is not less dramatic

Summary

- Current status of three-neutrino oscillation parameters:
  - precise and robust determinations for most of them (1.3-10%)
  - 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 affect previous δ and θ_{23} octant results

- Future prospects:
  - 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

  $\Rightarrow$ combined/global analyses may exploit complementarities
  $\Rightarrow$ sensitivities above 3σ from a single experiment: DUNE, Hyper-Kamiokande

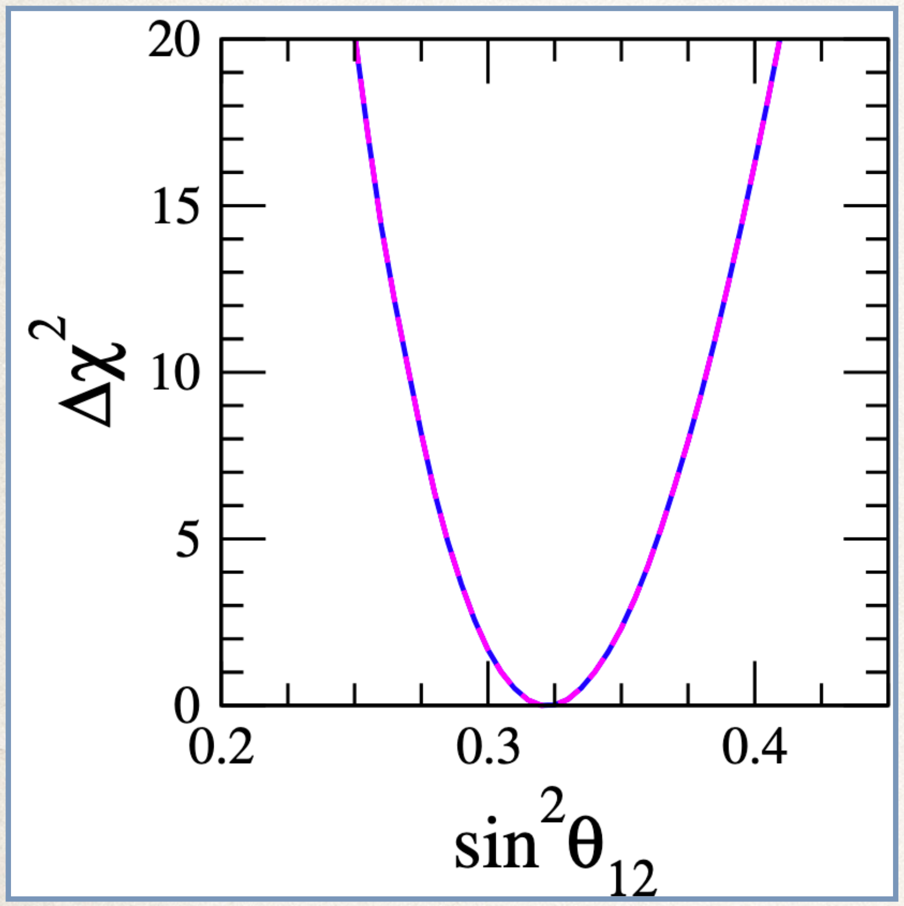
- New Physics BSM may affect our current description of 3-nu oscillations

Thank you!

Backup

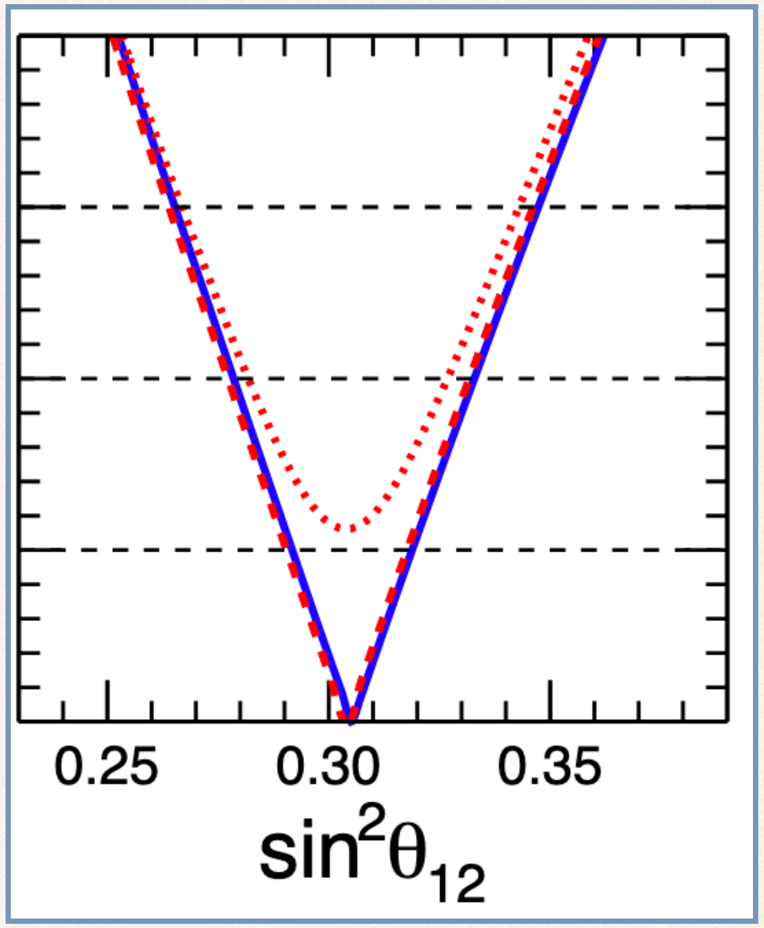
Solar mixing angle

$\Delta\chi^2$, Valencia [PLB 2018]



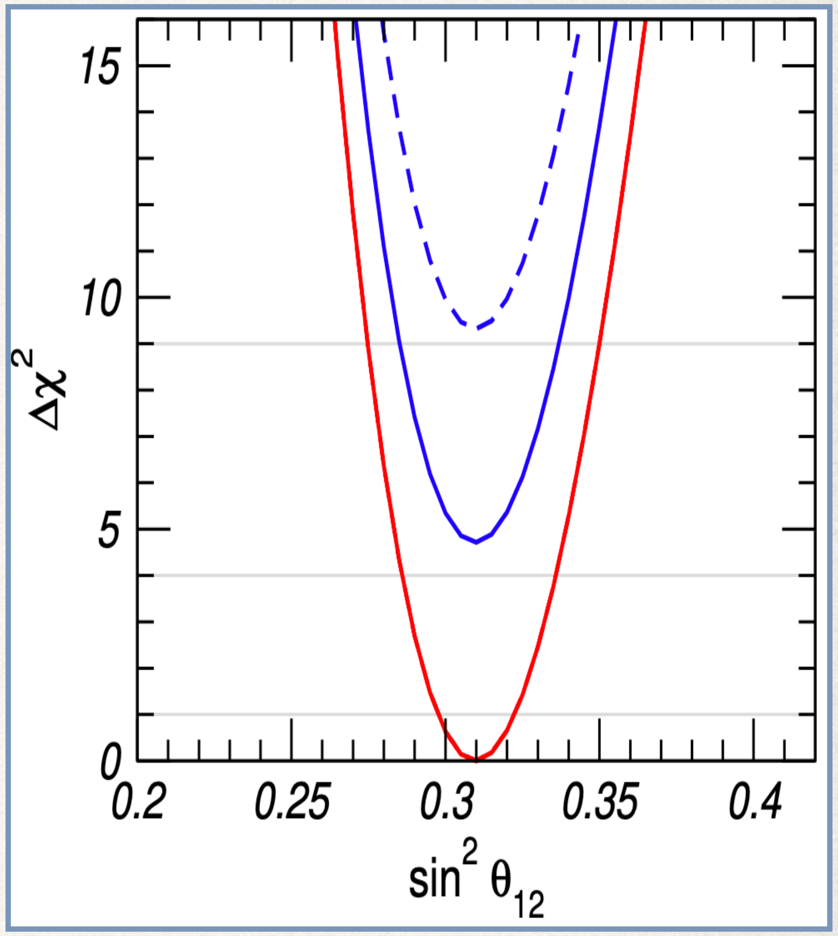
$\sin^2\theta_{12} = 0.320$ [0.273-0.379]

$N\sigma$, Bari [PPNP 2018]



$\sin^2\theta_{12} = 0.304$ [0.265-0.346]

$\Delta\chi^2$, NuFit v4.0 [JHEP 2019]

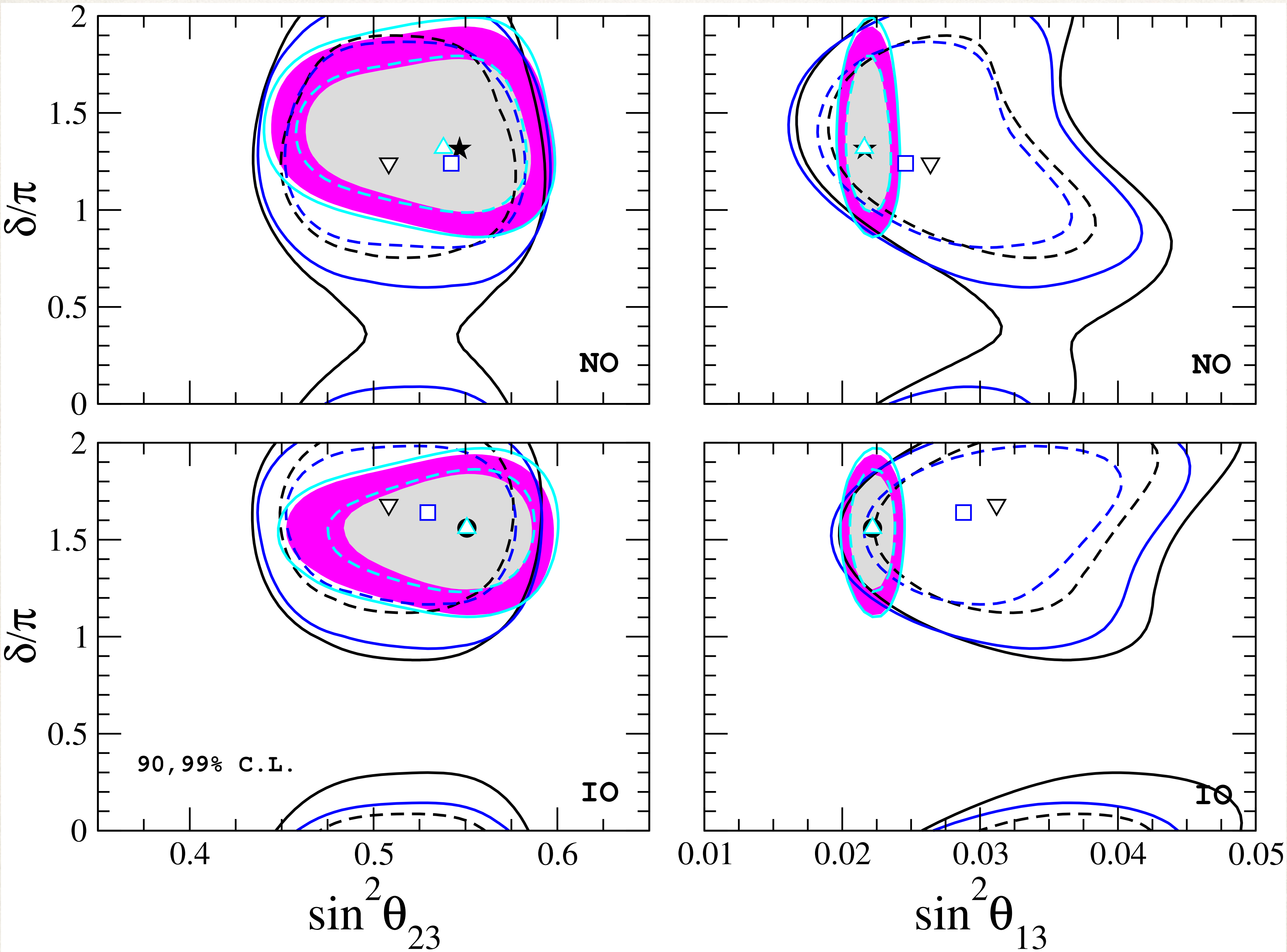


$\sin^2\theta_{12} = 0.310$ [0.275-0.350]

- Best fit point value and 3σ range, very sensitive to details solar and KamLAND analysis

Correlations θ_{23} - θ_{13} - δ

deSalas et al, PLB182 (2018) 633



LBL

LBL + SK

LBL + reactors

Global