Neutrino Physics

Mariam Tórtola
IFIC, CSIC/Universitat de València

XLIX International Meeting on Fundamental Physics

Benasque, 5-10 September 2022

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INSTITUT DE FÍSICA CORPUSCULAR

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Session 1

Neutrinos in the SM

- ✦ Main properties
- ✦ Neutrino mass in the SM

Neutrino oscillations

- ✦ Introduction & formalism
- ✦ Current status of ν oscillations
- ✦ Unknowns in the 3ν paradigm
- ✦ Future prospects

Session 2

Neutrino masses

- ✦ Current limits
- ✦ Neutrino mass models

Neutrino physics BSM

- ✦ Light sterile neutrinos
- ✦ Non-unitary neutrino mixing
- ✦ Non-standard interactions
- ✦ BSM searches with CEνNS

Neutrino Physics (I)

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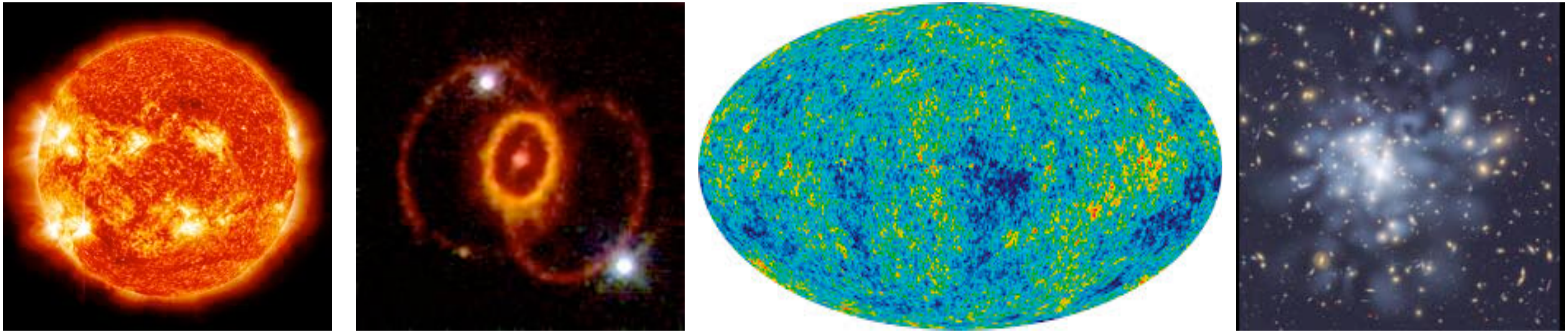
Why we care about neutrinos?

- They can probe environments that other techniques cannot: SN explosions, the core of the Sun,…
- Their role is crucial for the evolution of the universe (Big Bang Nucleosynthesis, structure formation)
- They could help explaining the matter-antimatter asymmetry of the Universe (leptogenesis mechanism)
- They could be a component of the dark matter of the universe.
- They provide the first evidence for physics beyond the SM!!!



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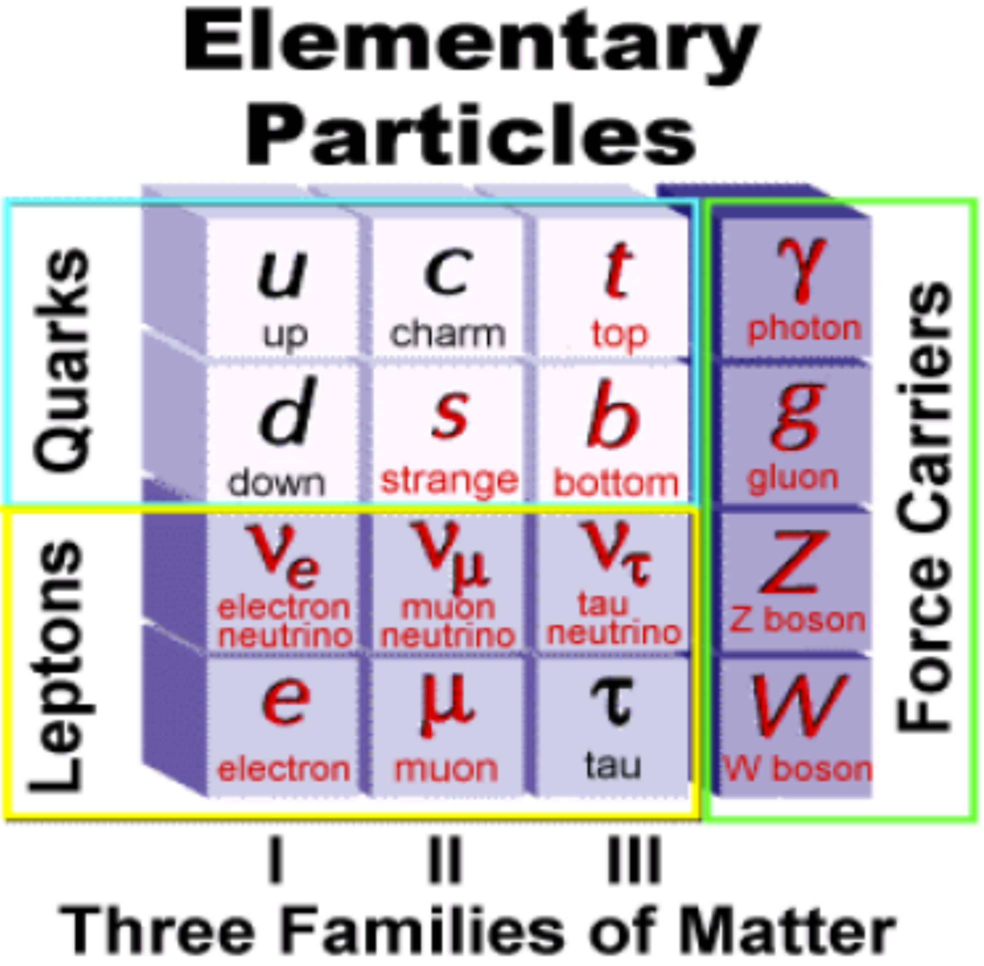
However: there are still many open questions in neutrino physics

Neutrinos in the Standard Model

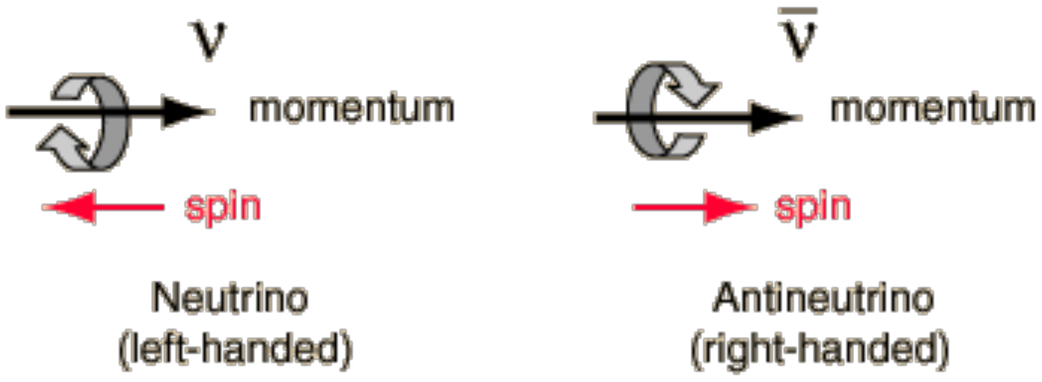


- Neutrinos come in 3 flavours, corresponding to the charged lepton associated
- Leptons are described as $SU(2)_L$ doublets

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

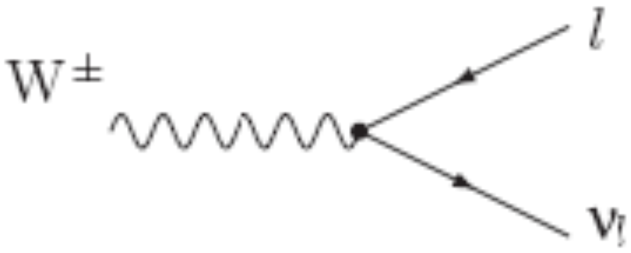
- Only two types of neutrinos have been observed in nature:
  - left-handed neutrino
  - right-handed antineutrino

[no SU(2) neutrino singlets in the SM]



Neutrino interactions in the SM

Charged Current (CC):



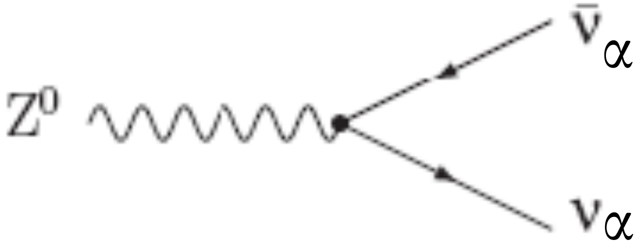
$$W^- \to l_\alpha^- + \overline{\nu}_\alpha$$

$$W^+ \to l_\alpha^+ + \nu_\alpha$$

$$(\alpha = e, \mu, \tau)$$

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}} \sum_\alpha \overline{\nu}_{\alpha L} \gamma^\mu l_{\alpha L} W_\mu + \text{h.c.}$$

Neutral Current (NC):



$$Z^0 \to \nu_\alpha \overline{\nu}_\alpha$$

$$\mathcal{L}_{\rm NC} = -\frac{g}{2\cos\theta_W} \sum_\alpha \overline{\nu}_{\alpha L} \gamma^\mu \nu_{\alpha L} Z^0_\mu$$

in the SM, only LH neutrinos and RH antineutrinos participate in weak interactions

- interactions conserve total Lepton Number L: $L(l^-) = L(\nu) = - L(l^+) = - L(\overline{\nu}) = 1$
- family lepton numbers L_e, L_μ, L_τ are also conserved (1998: nu oscill !!)

Fermion masses in the SM lagrangian

- ✦ In the SM, fermion masses appear in the lagrangian with terms like:

$$m\overline{\psi}\psi$$ → **Dirac mass term**

decomposing into its chiral states: $\psi \equiv \psi_L + \psi_R$

➡ $$m\overline{\psi}\psi = m\overline{\psi}_L\psi_R + m\overline{\psi}_R\psi_L$$

→ forbidden: not invariant under SU(2): it couples ψ_L with ψ_R (I_W=1/2)

→ solved by Higgs mechanism: after SSB, Dirac mass terms appear from Yukawa couplings:

$$\mathcal{L}_{\rm Yukawa} = Y\overline{\psi}_L\phi\psi_R + {\rm h.c.} \qquad \langle\phi^0\rangle = v$$

→ OK for most of particles but SM neutrino has only a L-chiral state (no ψ_R)

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What about a Majorana mass term??

Majorana neutrino mass

Majorana, ~1930

✦ We add a R-chiral field from a L-chiral field by charge conjugation:

$$\psi_R \equiv \psi_L^C = \hat{C}\overline{\psi}^T \qquad\qquad \hat{C} = i\gamma^2\gamma^0$$

→ the total neutrino field is: $\psi = \psi_L + \psi_R = \psi_L + \psi_L^C$ (2 degrees of freedom)

→ taking the charge conjugate: $\psi^C = (\psi_L + \psi_R)^C = \psi_L^C + \psi_L = \psi$

$$\psi = \nu = \nu_L + \nu_L^C$$

neutrino = antineutrino

Majorana mass term: $$-\mathcal{L}_M = \frac{1}{2} m \left(\overline{\nu_L^C} \nu_L + \overline{\nu_L} \nu_L^C \right)$$

Not invariant under U(1) transformations

However: this mass term not invariant under weak isospin (I_W=1)

→ solved with a Higgs triplet BUT it is not included in the SM.

→ solved with a dim-5 operator (Weinberg operator) BUT non-renormalizable

Neutrino mass in the SM

- ✦ Since the SM does not contain right-handed neutrinos: a Dirac mass term as for the rest of fermions is not allowed.
- ✦ The SM only contains one Higgs doublet: no Higgs triplet to build a Majorana mass term
- ✦ The SM is renomalizable and, therefore, dim-5 terms as the Weinberg operator are not allowed.

Neutrinos are strictly massless in the Standard Model!

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Neutrino oscillations

nobelprize.org

First indication of ν oscillations

1968: First observation of solar neutrinos by R. Davis in Homestake.

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

➡ 1/3 of the Standard Solar Model prediction !!

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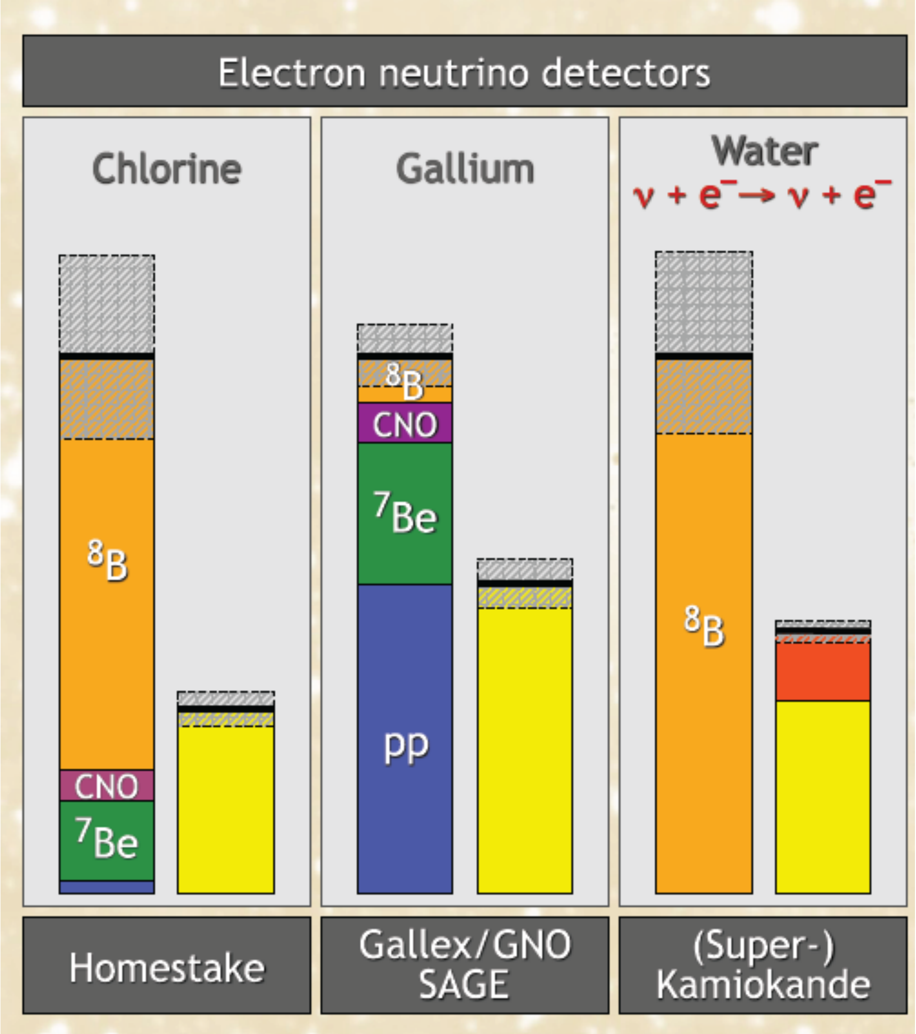

~30% ~50% ~40%

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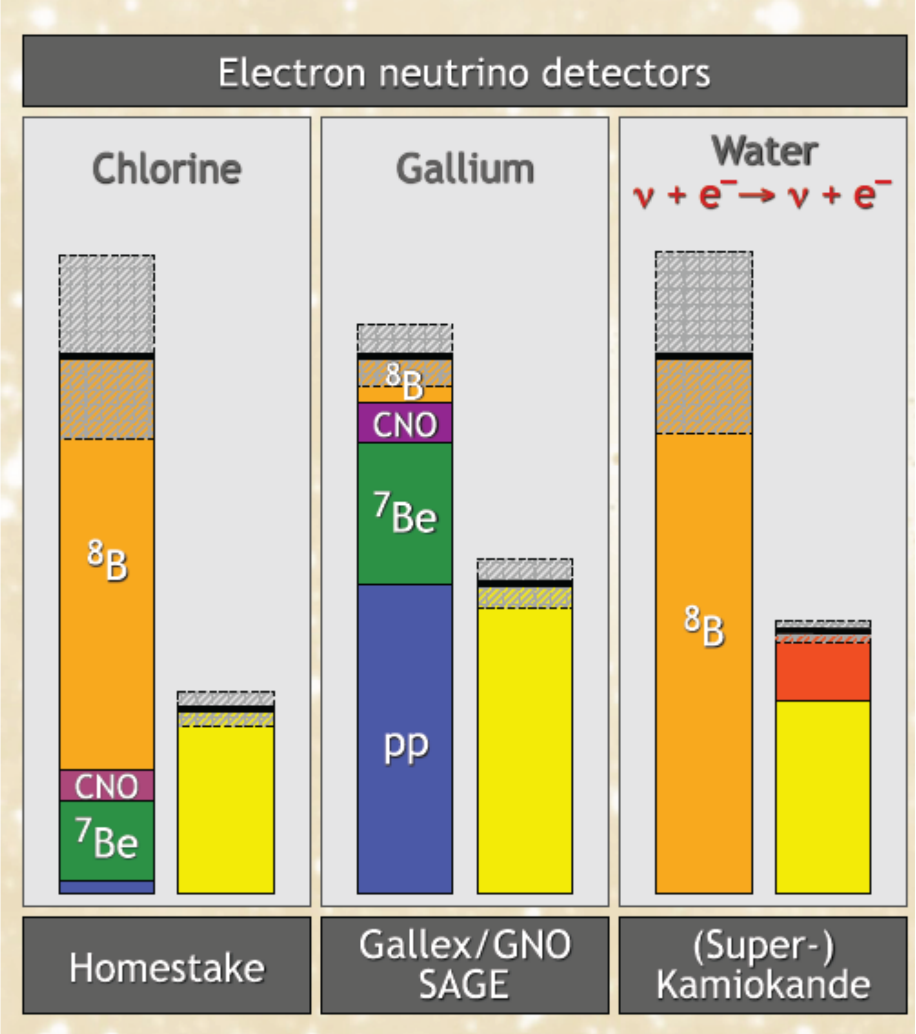

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→ something was happening to neutrinos

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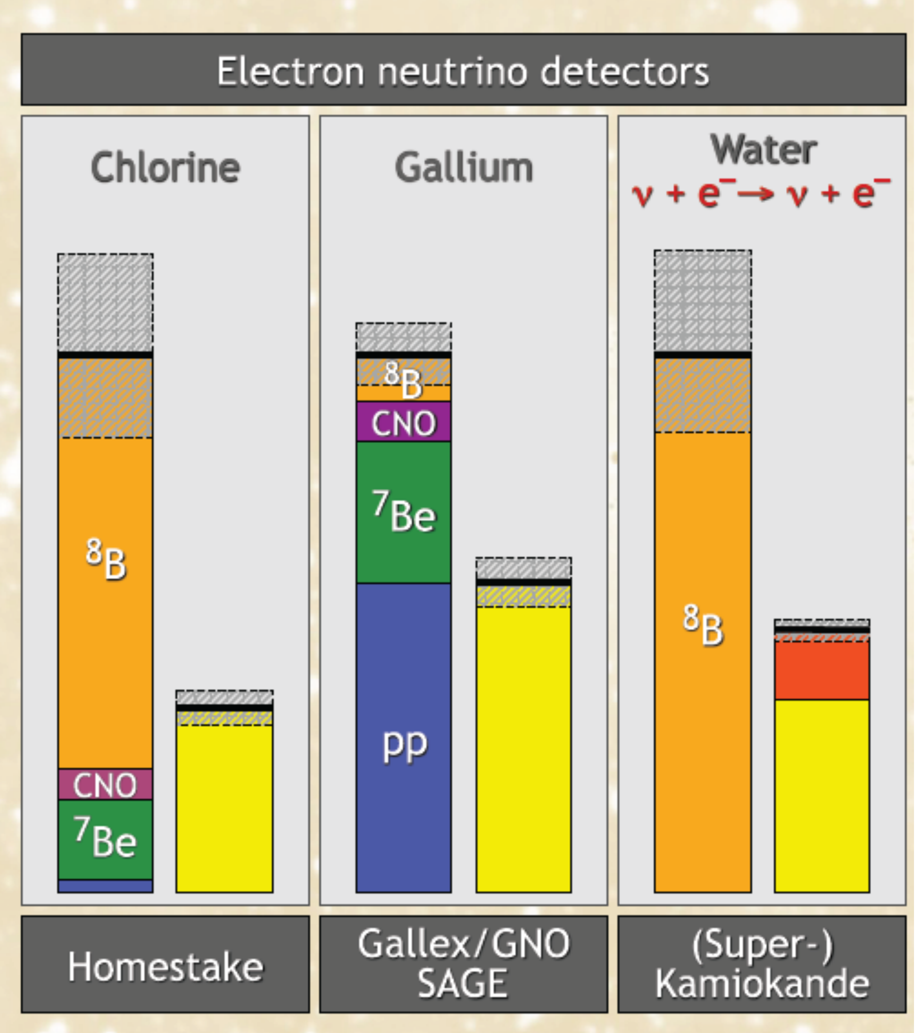
2002 Nobel Prize in Physics



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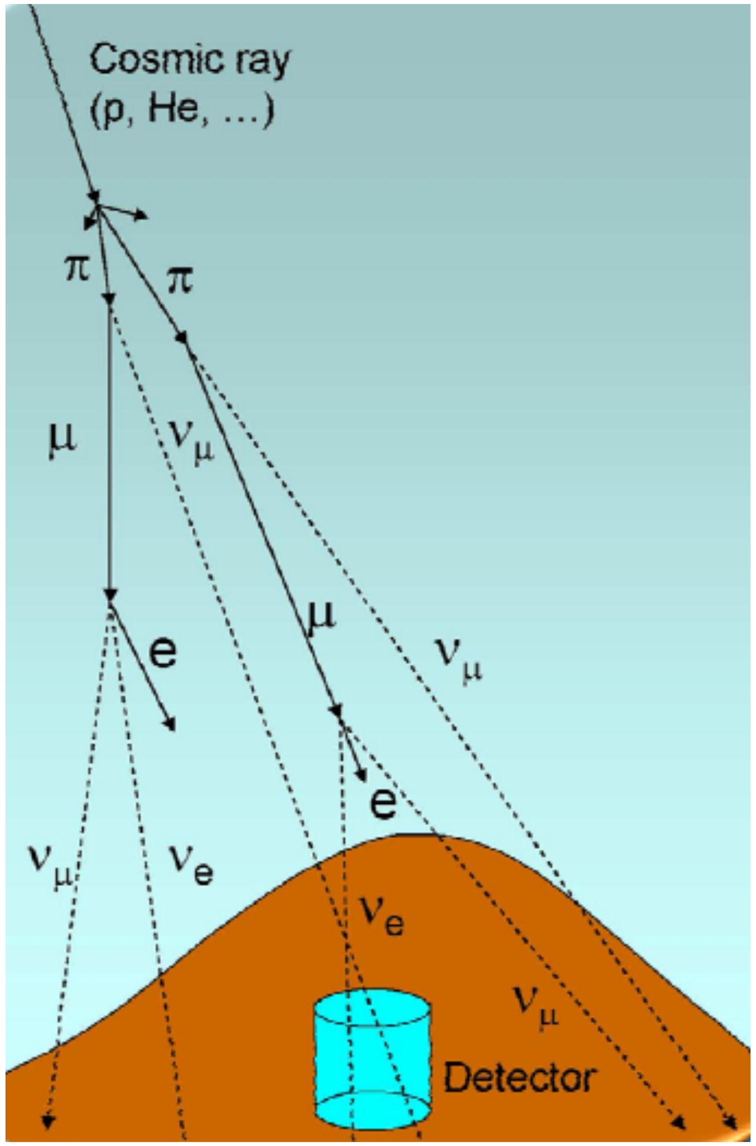
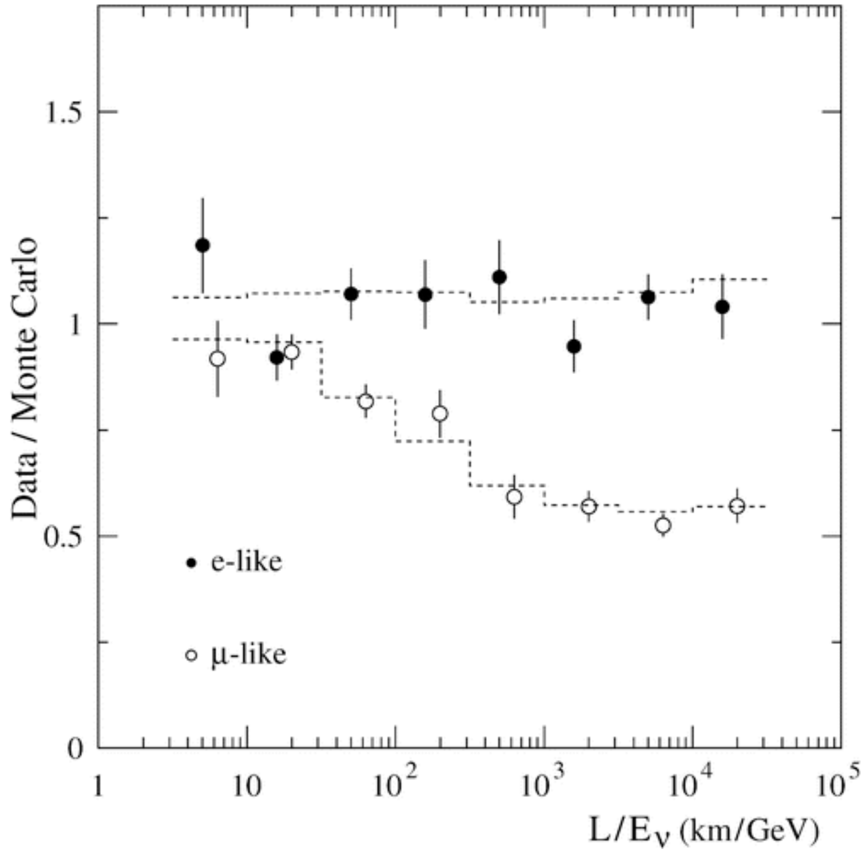
The atmospheric neutrino anomaly



1985: First indications of a deficit in the observed number of atmospheric ν_μ at the IMB experiment.

1994: Kamiokande finds the ν_μ deficit depends on the distance travelled by the neutrino and its energy.



1998: Discovery of atmospheric neutrino oscillations in Super-Kamiokande.

oscillation channel $\nu_\mu \to \nu_\tau$

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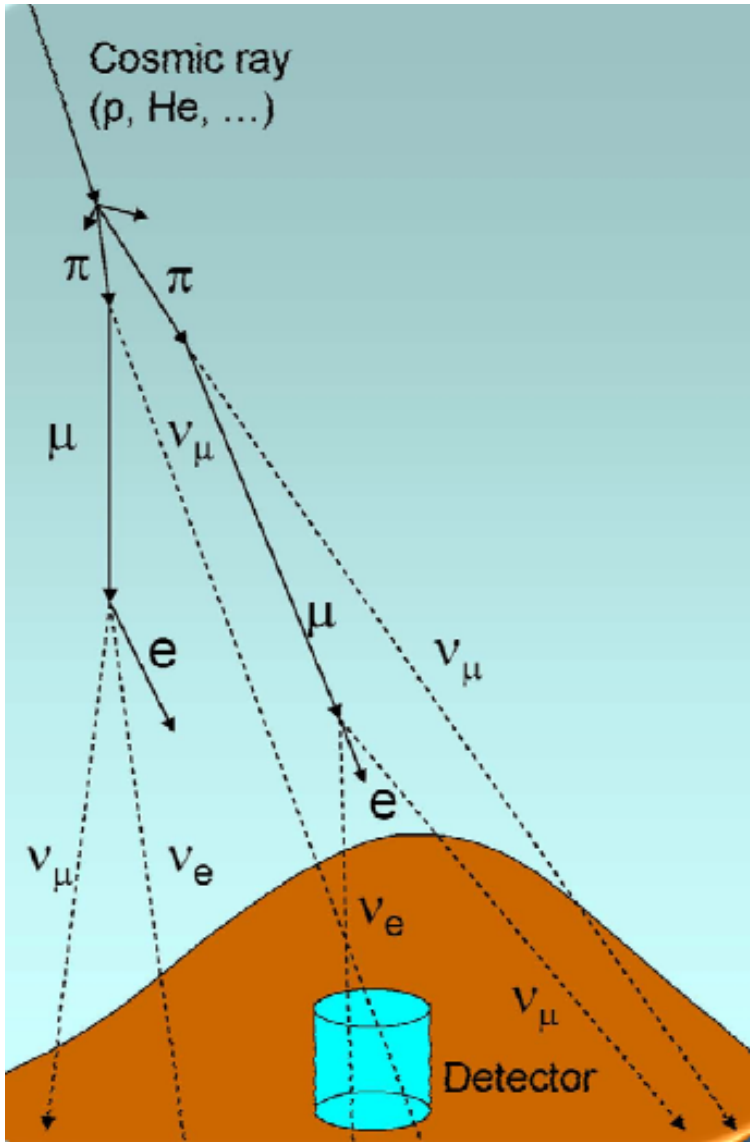

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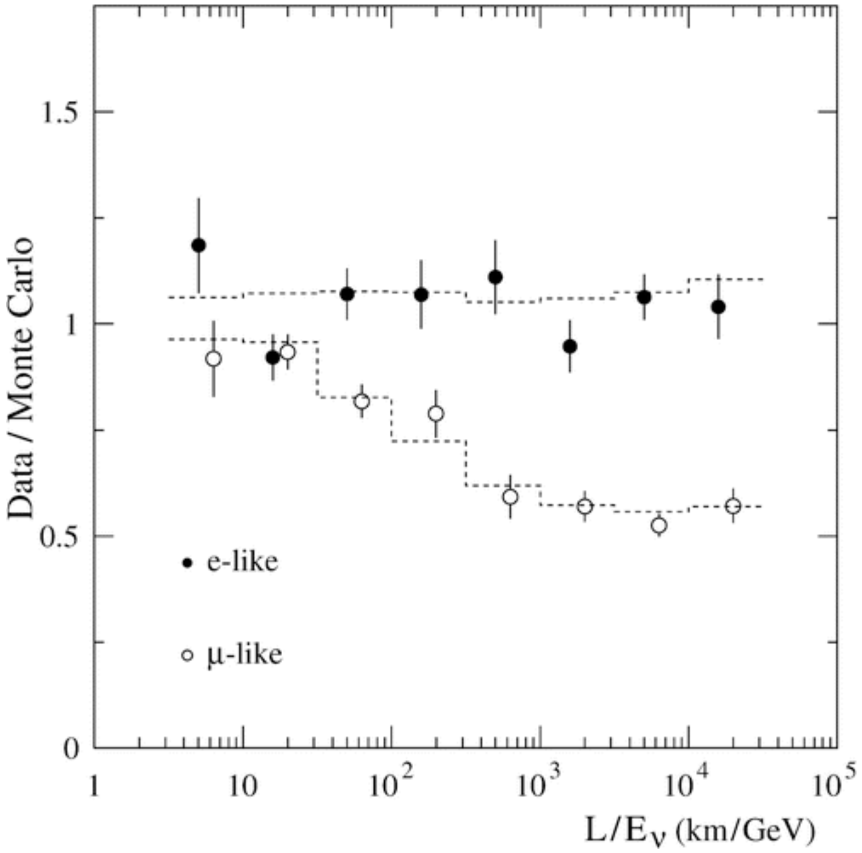

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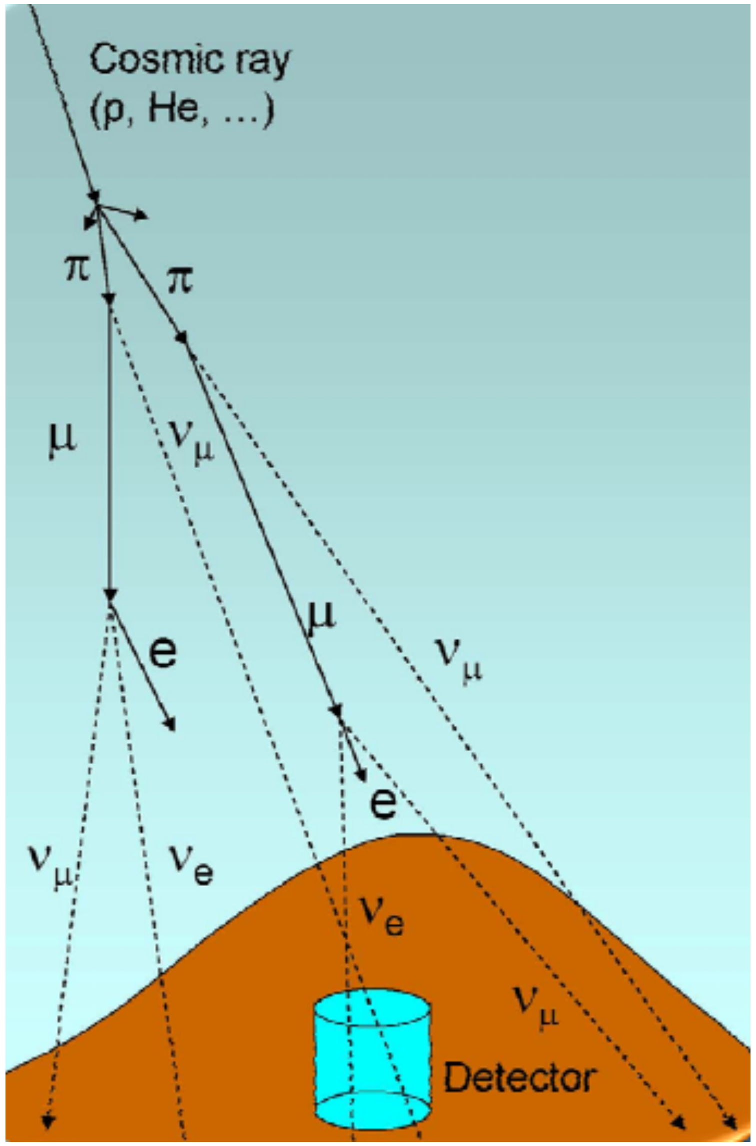

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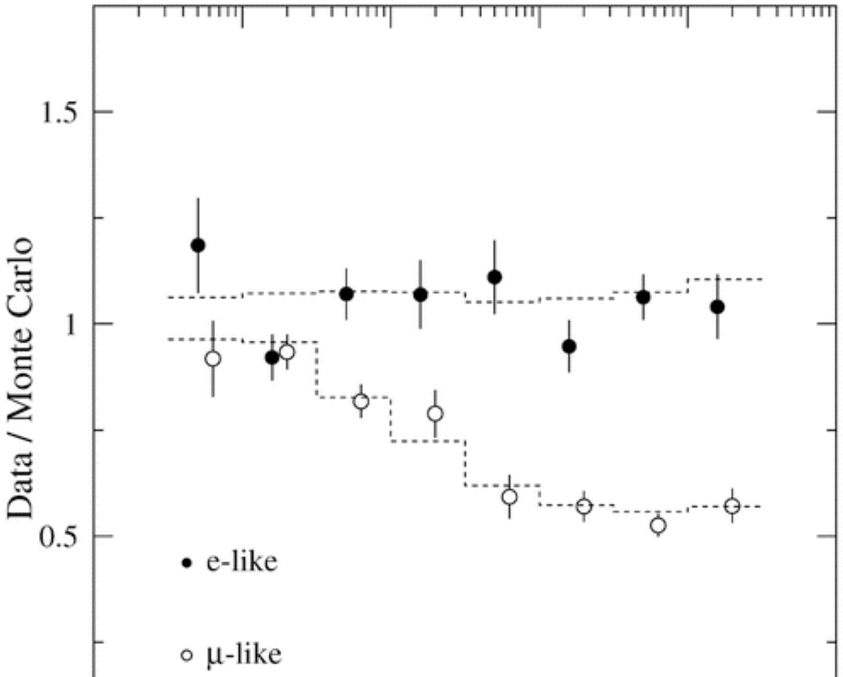
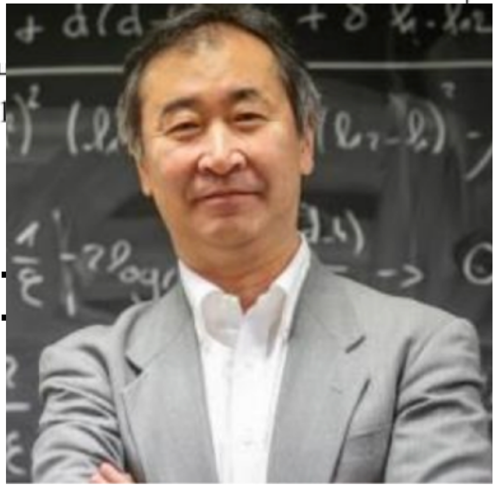


1998: Discovery of atmospheric neutrino oscillations in Super-



2015 Nobel Prize in Physics

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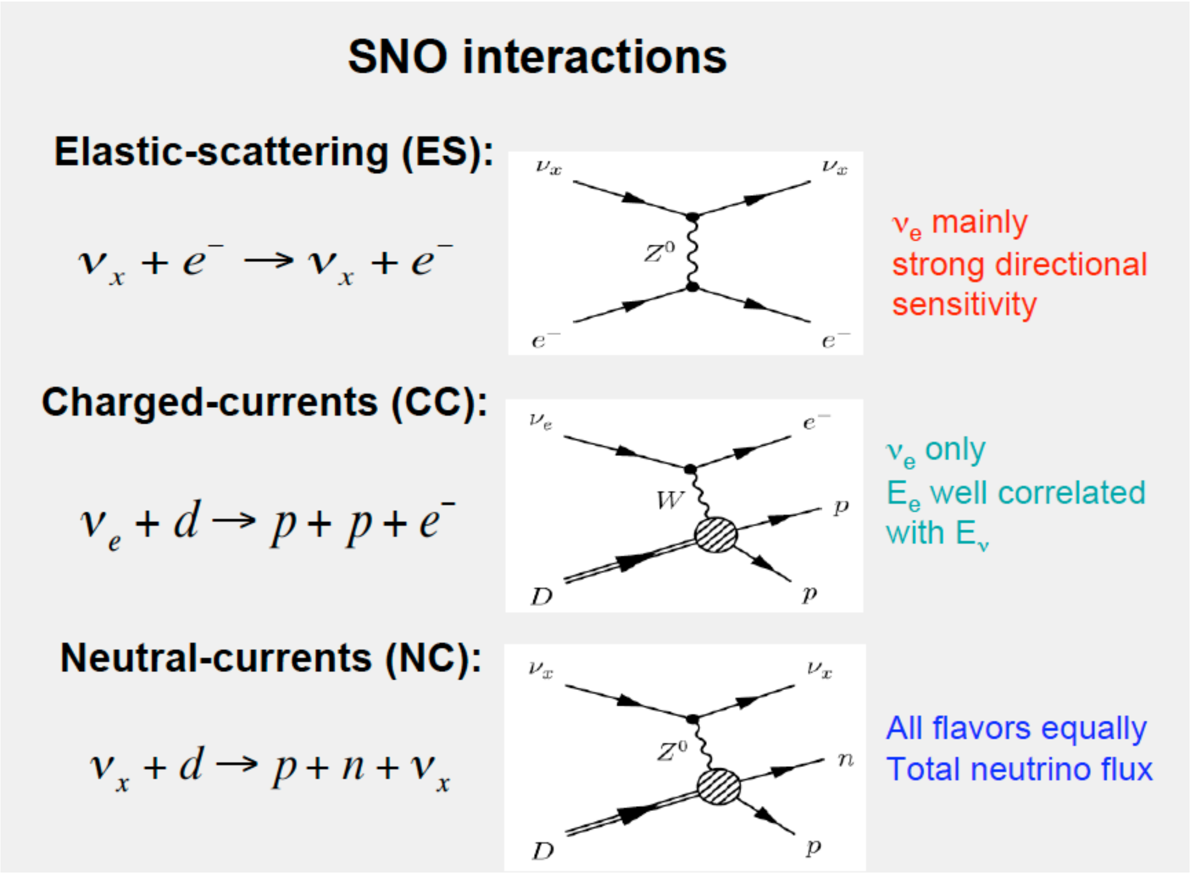
The Sudbury Neutrino Observatory

2001: Confirmation of flavor conversion in solar neutrinos in SNO.



SNO interactions

Elastic-scattering (ES):

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

ν_e mainly
strong directional sensitivity

Charged-currents (CC):

$$\nu_e + d \rightarrow p + p + e^-$$

ν_e only
E_e well correlated with E_ν

Neutral-currents (NC):

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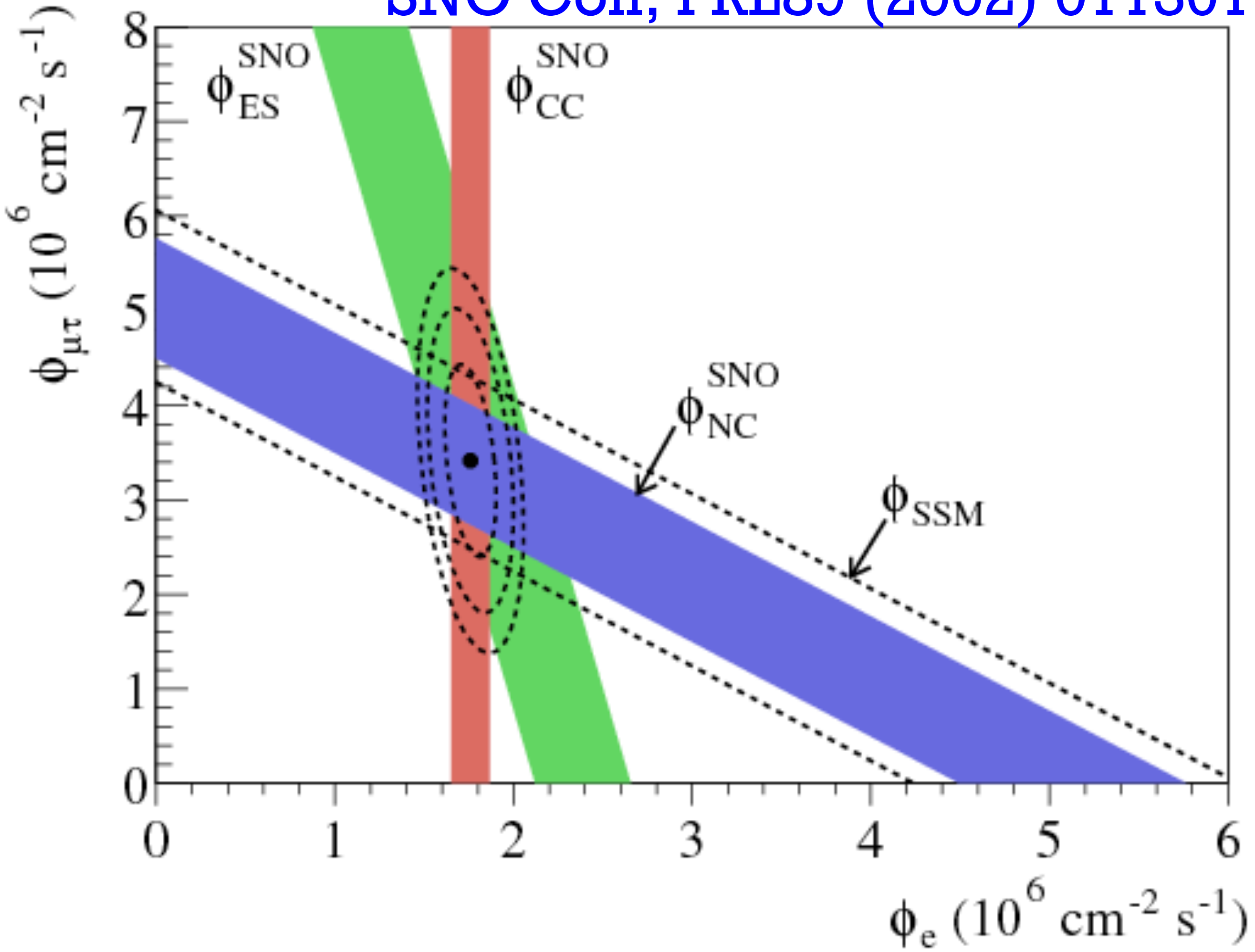
All flavors equally
Total neutrino flux

SNO Coll, PRL89 (2002) 011301



$$\frac{\phi_{\rm CC}^{\rm SNO}}{\phi_{\rm NC}^{\rm SNO}} = 0.301 \pm 0.033$$

→ 30% of solar neutrinos are detected as ν_e

$$\phi_{\rm NC}^{\rm SNO} \simeq \phi_{^8{\rm B}}^{\rm SSM}$$

→ conversion $\nu_e \rightarrow \nu_{\mu\tau}$

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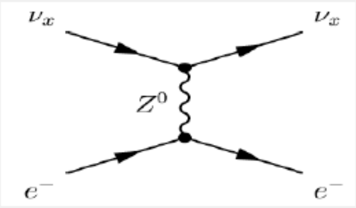

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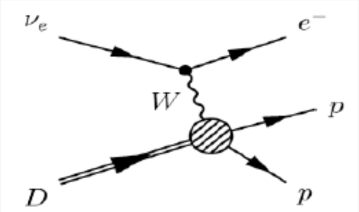

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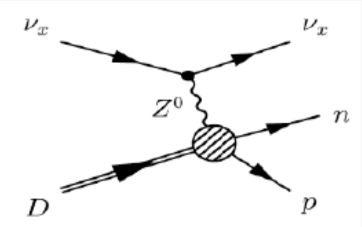

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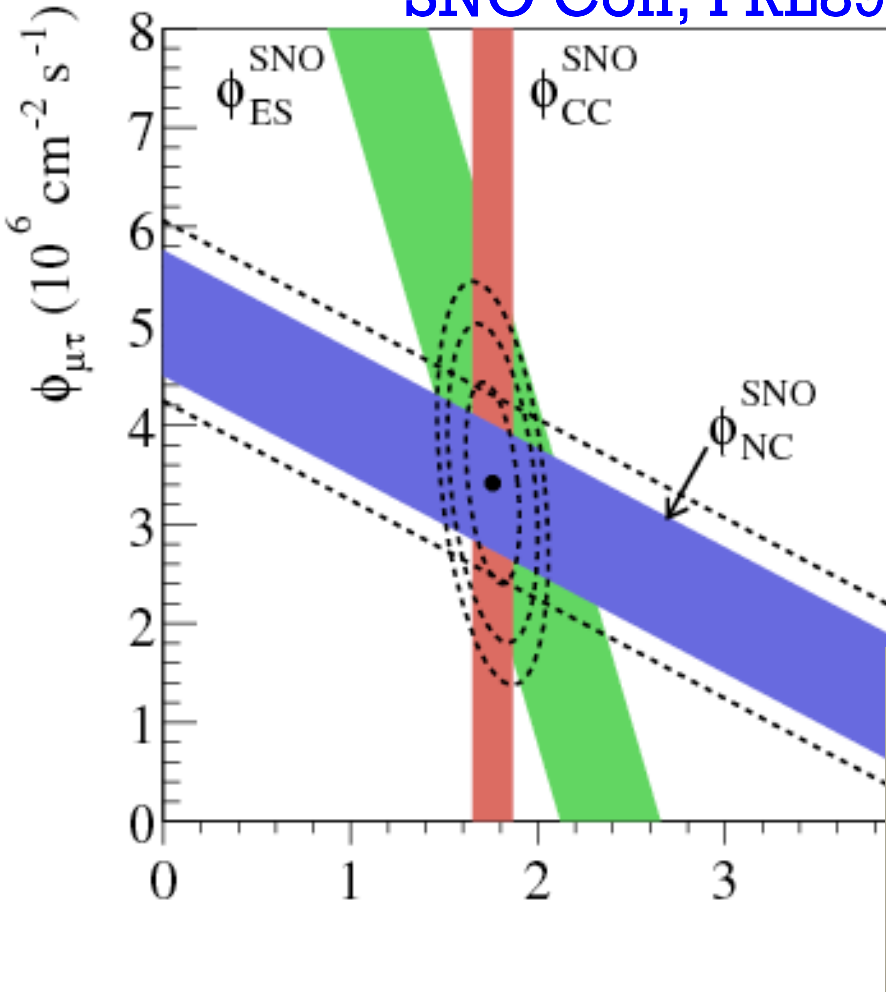

2015 Nobel Prize in Physics

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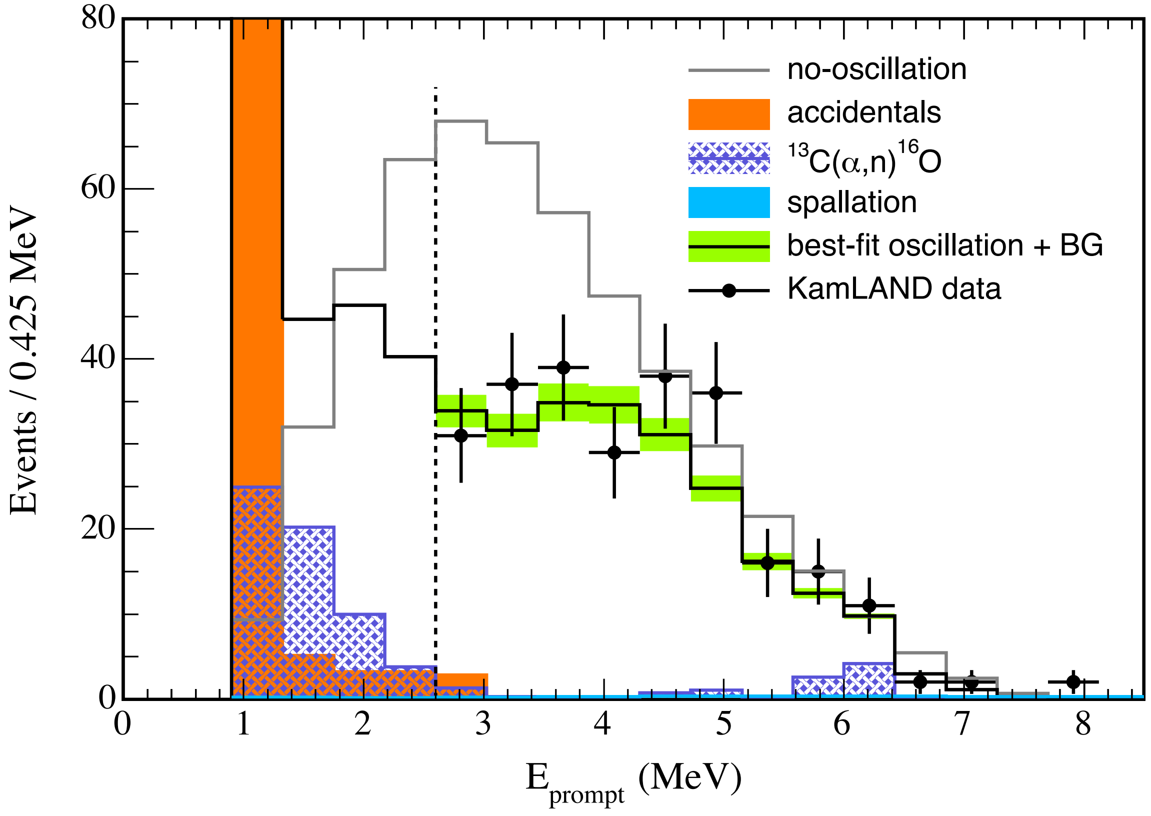
Other important results

2002: The reactor experiment KamLAND observed neutrino oscillations consistent with the solar anomaly.



KamLAND Coll, PRL 90 (2003) 021802

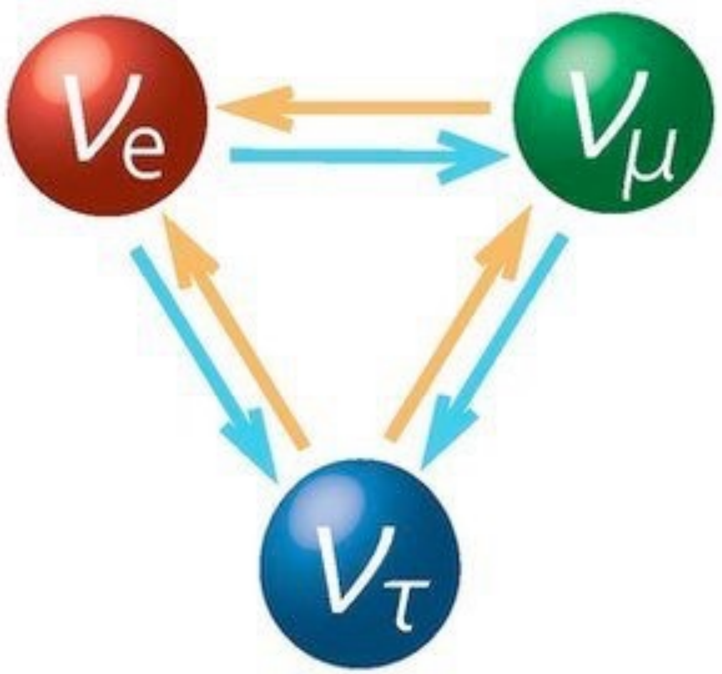
2002: Results of the accelerator experiment K2K consistent with ν_μ oscillations as in the atmospheric anomaly (MINOS, T2K, NOvA).

2011: $\nu_\mu \to \nu_e$ oscillations observed in long-baseline accelerator experiments: first hint for a non-zero θ_{13}.

2011: Double Chooz confirmed reactor antineutrino oscillations in a baseline of ~1 km: first measurement of θ_{13}. (Daya Bay, RENO)

neutrino oscillations have been observed in solar, atmospheric, reactor and accelerator neutrino experiments.

Neutrino oscillations: formalism



Neutrino mixing

- Mixing described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

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- For Majorana neutrinos, the mass term is not invariant under global phse transformations: only N phases can be eliminated from U.

→ N(N-1)/2 **physical phases:** (N-1)(N-2)/2 Dirac phases → effect in ν oscil.

(N-1) Majorana phases → relevant for 0νββ

Neutrino mixing

- 2-neutrino mixing depends on 1 angle only (+1 Majorana phase)

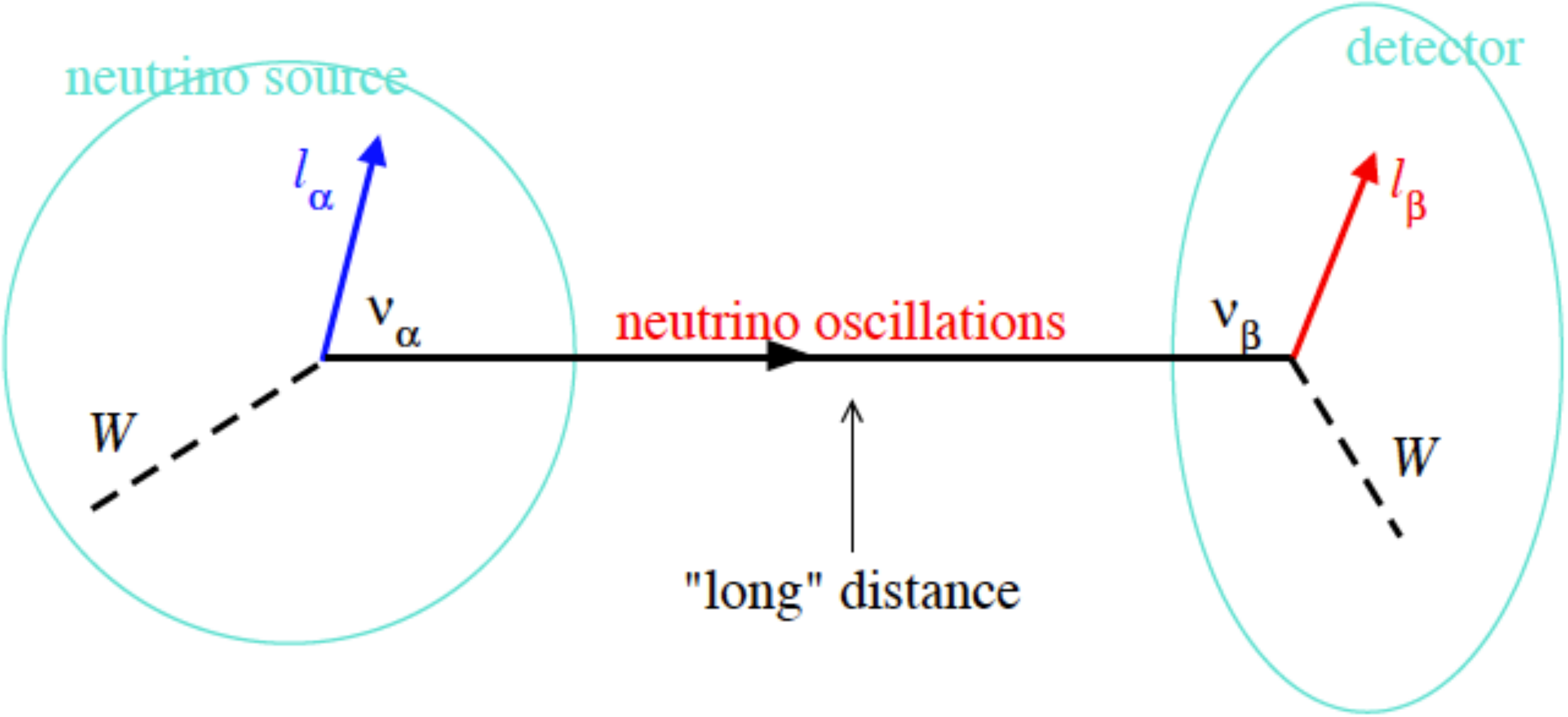
$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- 3-neutrino mixing is described by 3 angles and 1 Dirac (+2 Majorana) CP violating phases.

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric + LBL reactor + LBL solar + KamLAND

Neutrino oscillations picture



Production

$$|\nu_\alpha\rangle = \sum_j U^*_{\alpha j}|\nu_j\rangle$$

coherent superposition
of massive states

Propagation

$$\nu_j : e^{-i\frac{m_j^2 L}{2E}}$$

different propagation
phases change ν_j
composition

Detection

$$\langle\nu_\beta| = \sum_j \langle\nu_j|U_{\beta j}$$

projection over
flavour eigenstates

Neutrino oscillation probability

Neutrino oscillation amplitude:

detection production

$$\mathcal{A}_{\nu_\alpha\to\nu_\beta} = \langle\nu_\beta(t)|\nu_\alpha(0)\rangle = \sum_j \langle\nu_\beta|\nu_j(t)\rangle\langle\nu_j(t)|\nu_j(0)\rangle\langle\nu_j(0)|\nu_\alpha\rangle$$

propagation

$$= \sum_j U_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U^*_{\alpha j}$$

Neutrino oscillation probability:

$$P_{\nu_\alpha\to\nu_\beta} = \left|\sum_j U_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U^*_{\alpha j}\right|^2$$

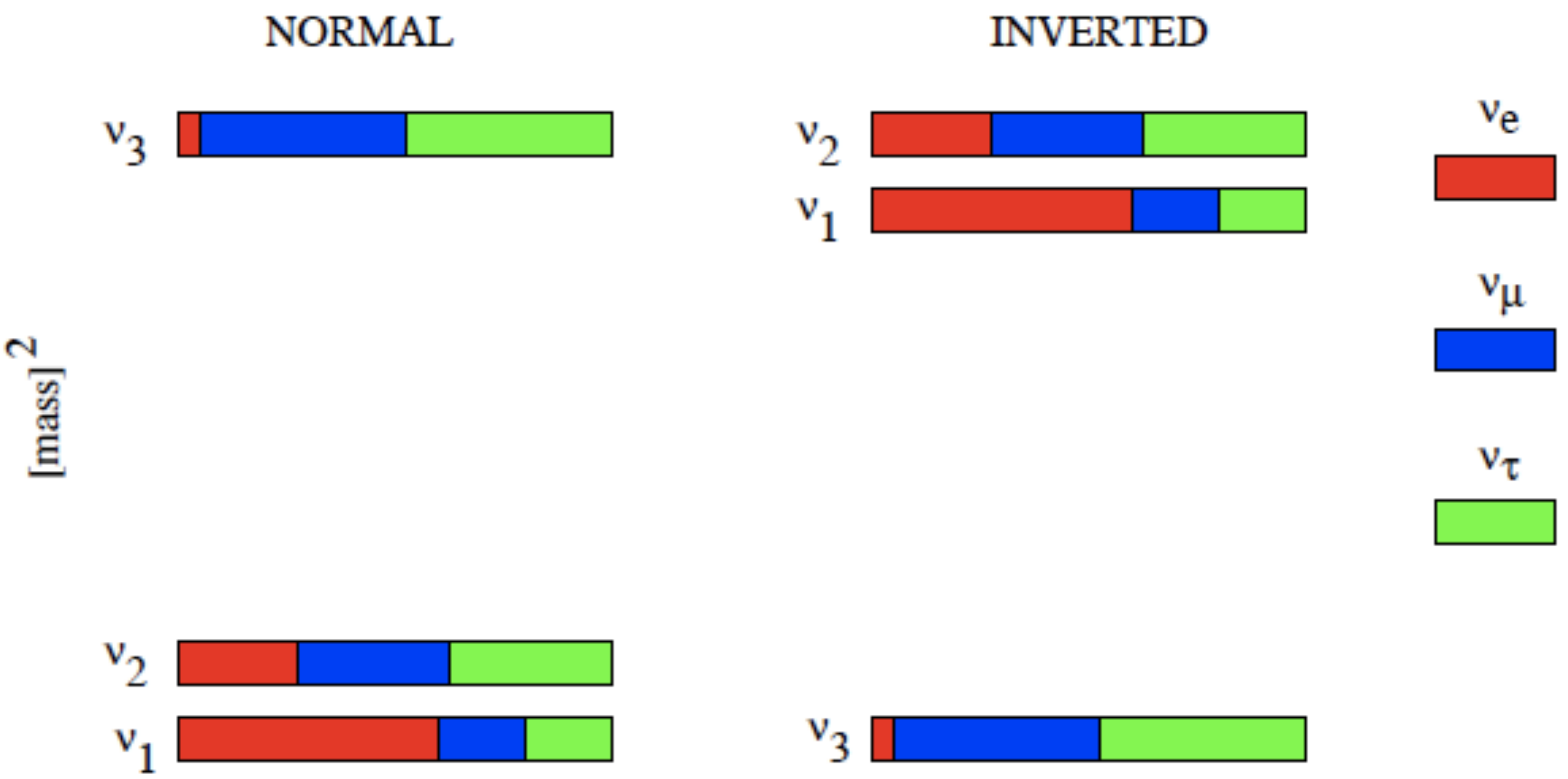
$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re\left(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}\right)\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) +$$

$$+\,2\sum_{i>j} Im\left(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}\right)\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

Two possible mass orderings

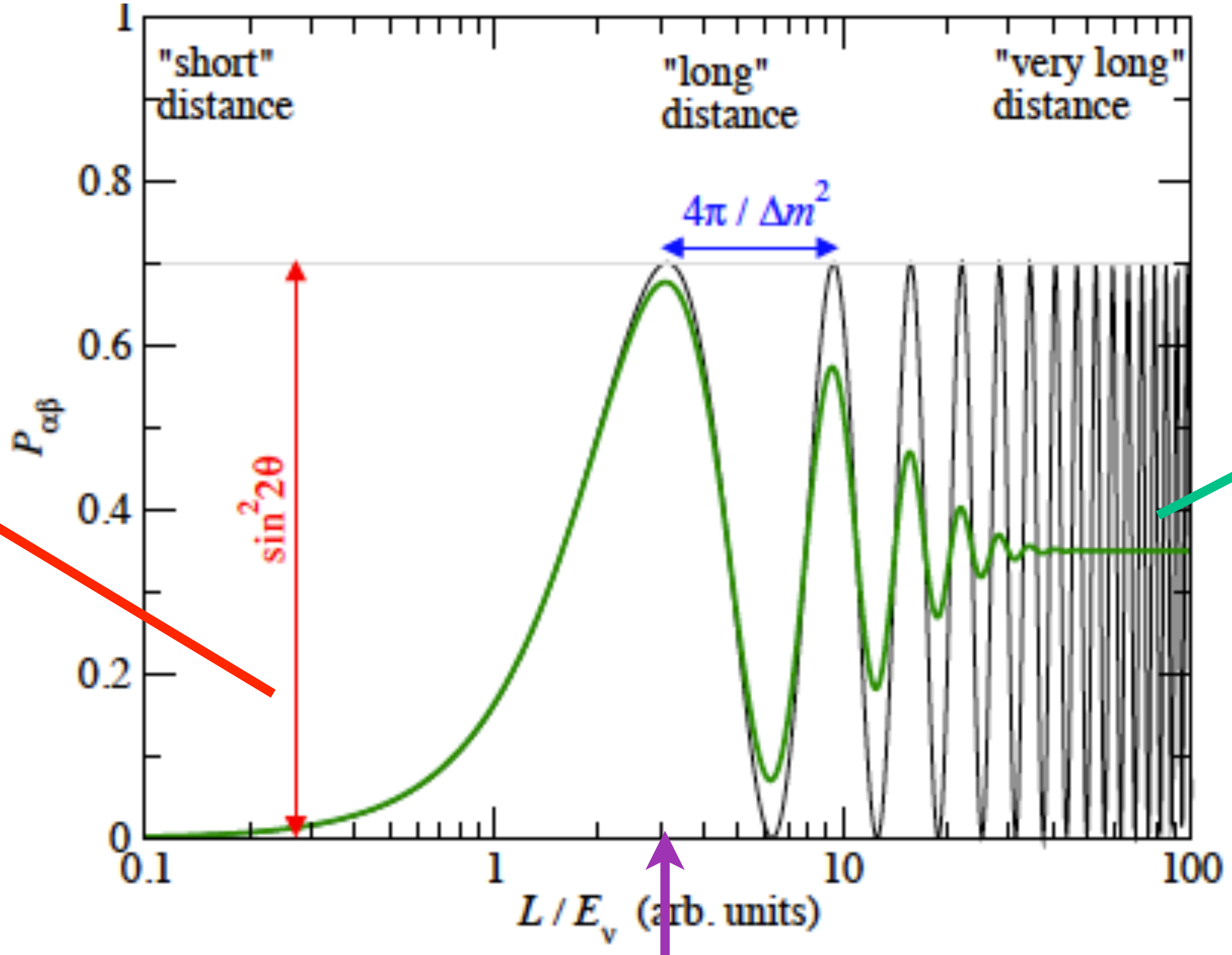
- Δm^2_{21} : solar + KamLAND (positive)
- Δm^2_{31} : atmospheric + LBL accelerator + SBL reactor (sign?)



$\Delta m^2_{31} > 0$ $\Delta m^2_{31} < 0$

2-neutrino oscillation probability

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



oscillation amplitude

averaged oscillations

oscillation length:

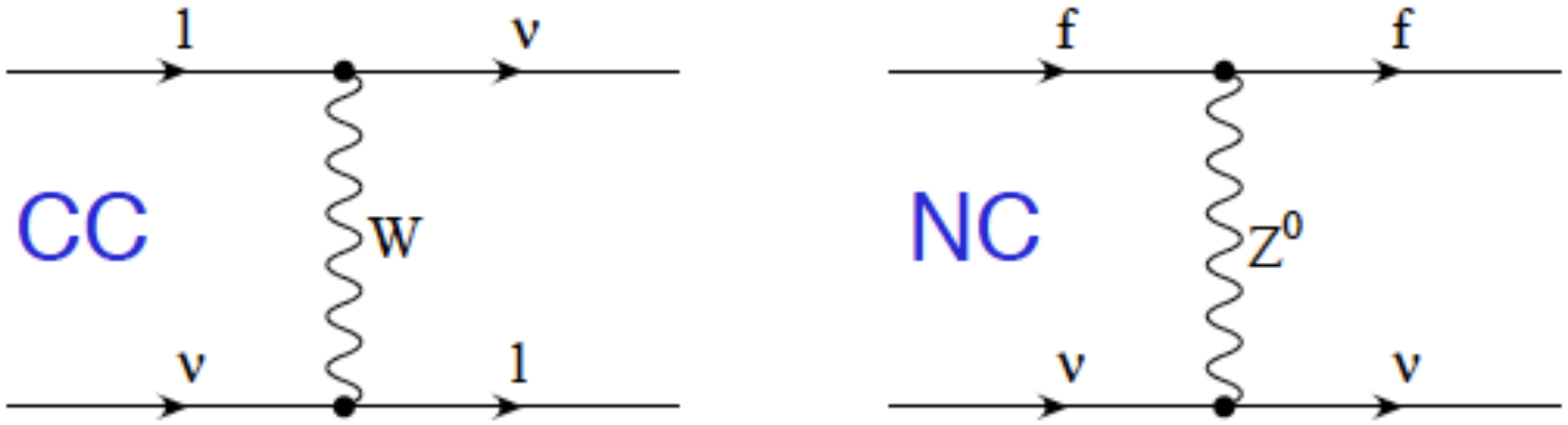
$$L_{\rm osc} = \frac{4\pi E}{\Delta m^2}$$

first oscillation maximum:

Matter effects on neutrino oscillations

✦When neutrinos pass trough matter, the interactions with the particles in the medium induce an **effective potential** for the neutrinos.

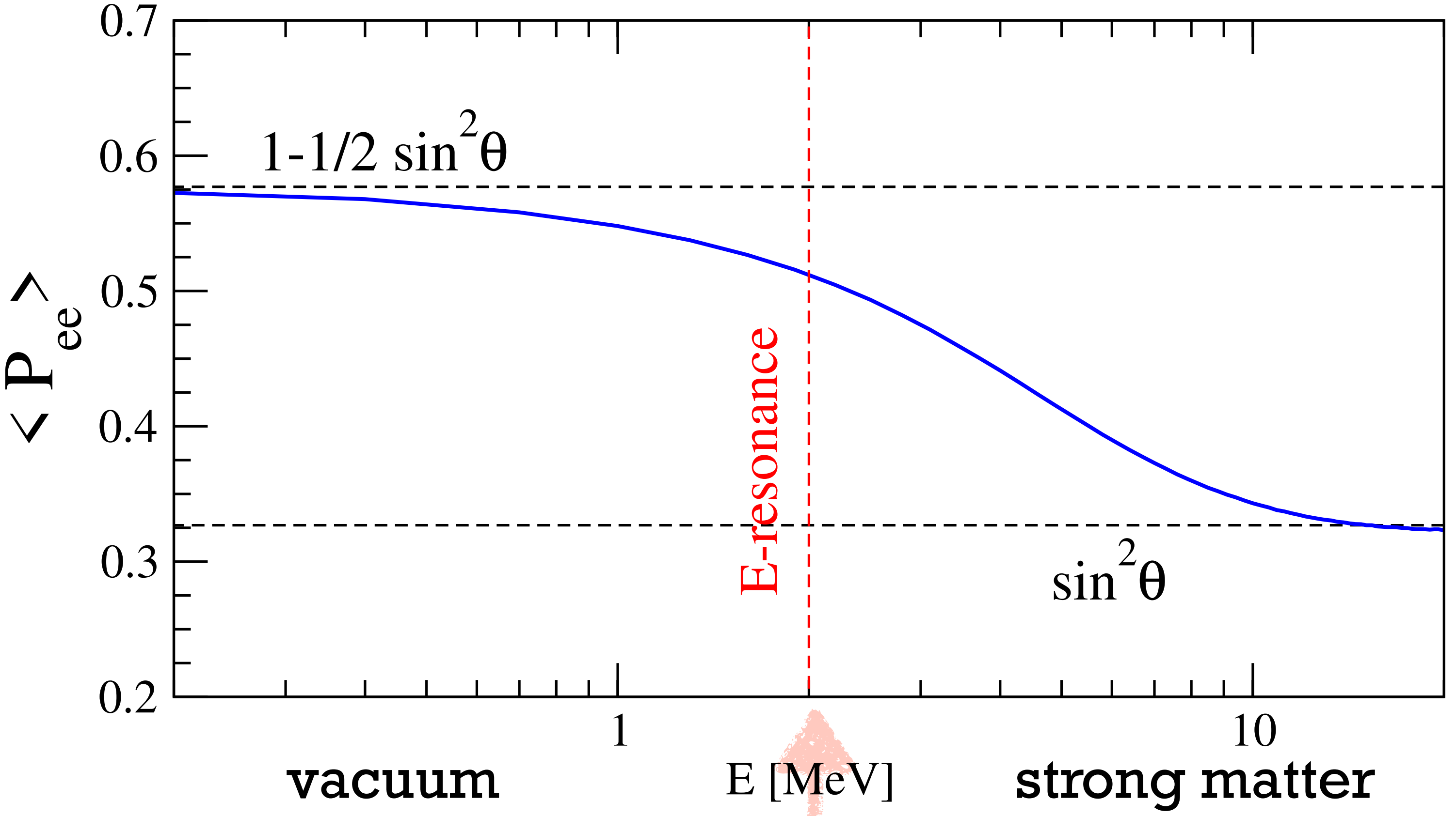
[→ the coherent forward scattering amplitude leads to an index of refraction for neutrinos. **L. Wolfenstein, 1978**]



→ modifies the **mixing between flavor states and mass eigenstates** as well as the eigenvalues of the Hamiltonian, leading to a different oscillation probability with respect to vacuum oscillations.

Matter effects in solar neutrinos

- Electron neutrino survival probability (MSW effect)

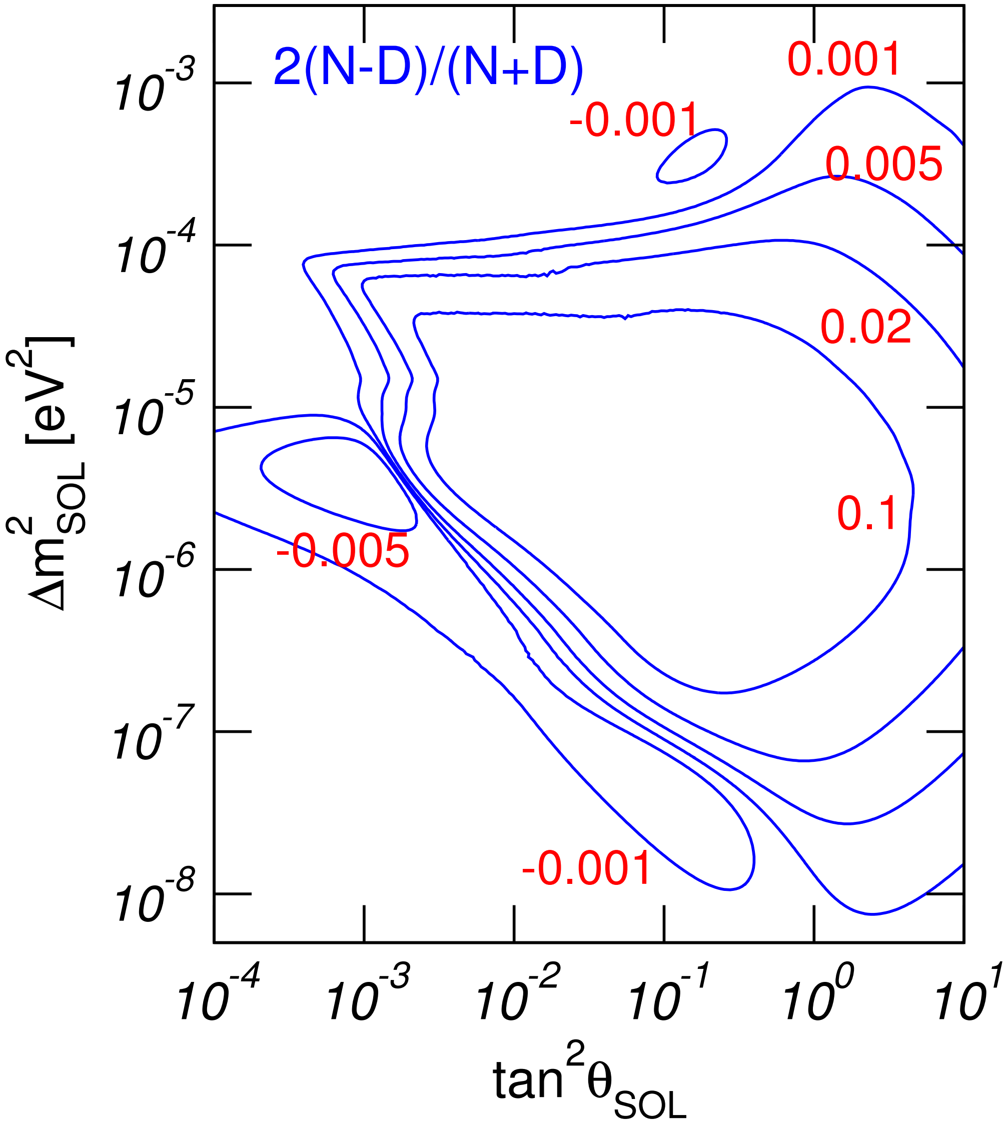


vacuum regime

strong matter effect regime

MSW resonance

- Day-night effect

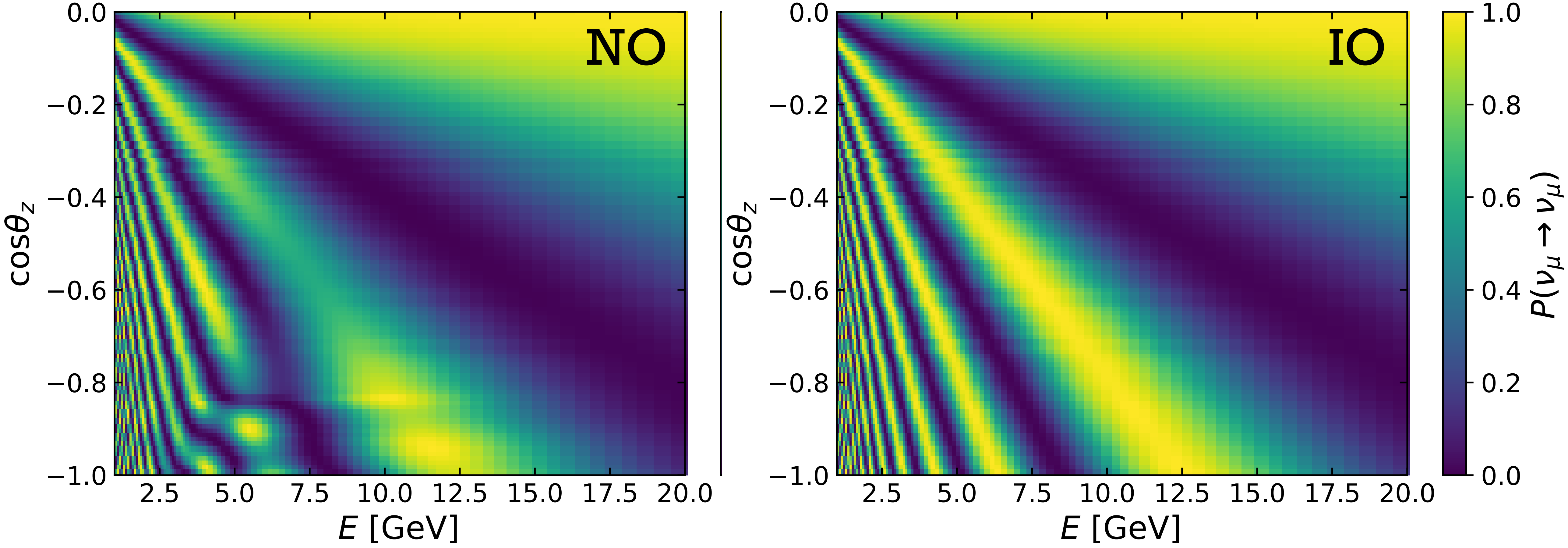


$$\phi_{\rm ND} \simeq 3.3\%$$

[Super-Kamiokande Coll, 2016]

Matter effects in atmospheric ν's

- ✦ They are harder to observe since they depend on θ_{13}
- ✦ Matter effects are sensitive to the mass ordering: NO vs IO

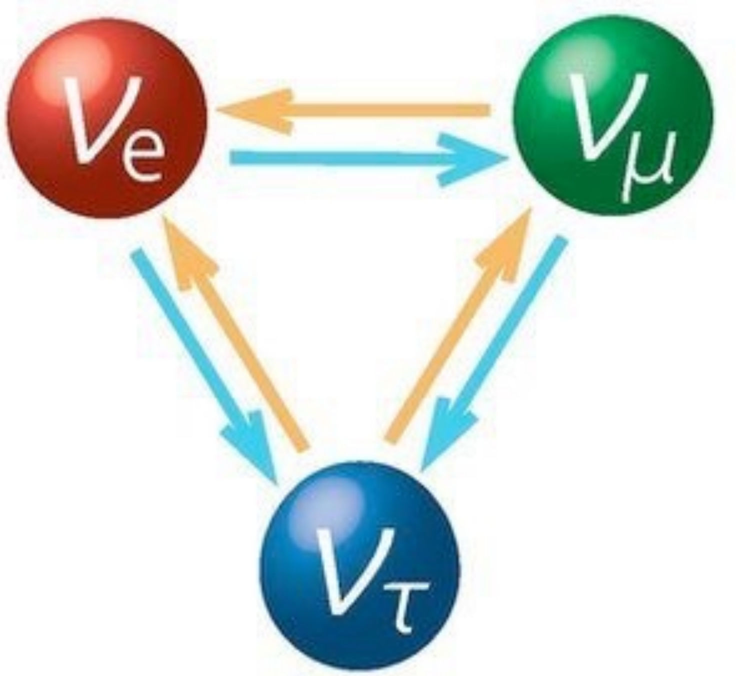


de Salas et al, Front.Astron.Space Sci. 5 (2018) 36

At E~ 3-8 GeV: MSW resonance for neutrinos and NO mass spectrum.

For antineutrinos ⟹ the resonance appears in IO

Neutrino oscillations: experimental results



The three-flavour ν picture

neutrino mixing

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

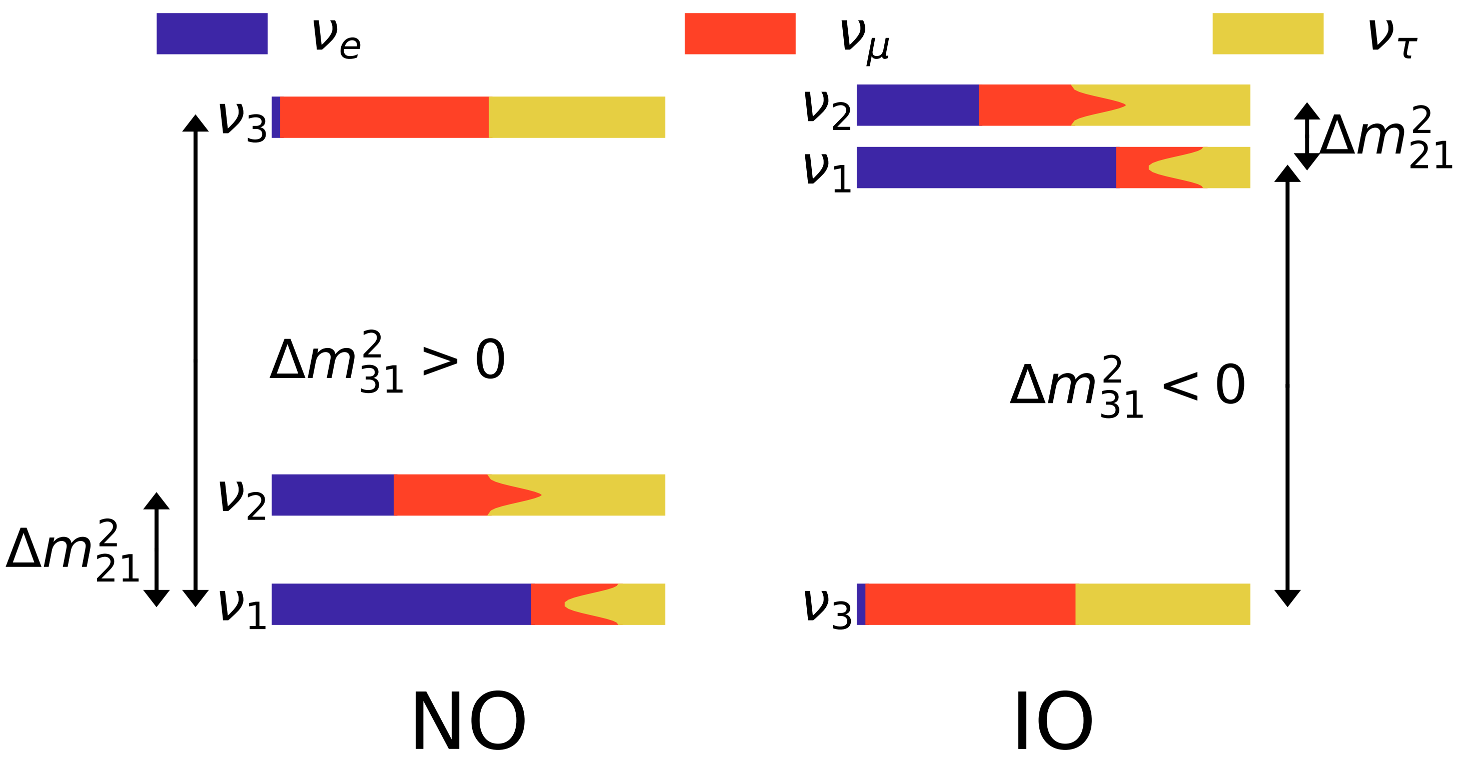
- ✓ 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- ✓ 3 CP phases: 1 Dirac + 2 Majorana
- ✓ 3 masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

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

neutrino mass spectrum



Experimental data

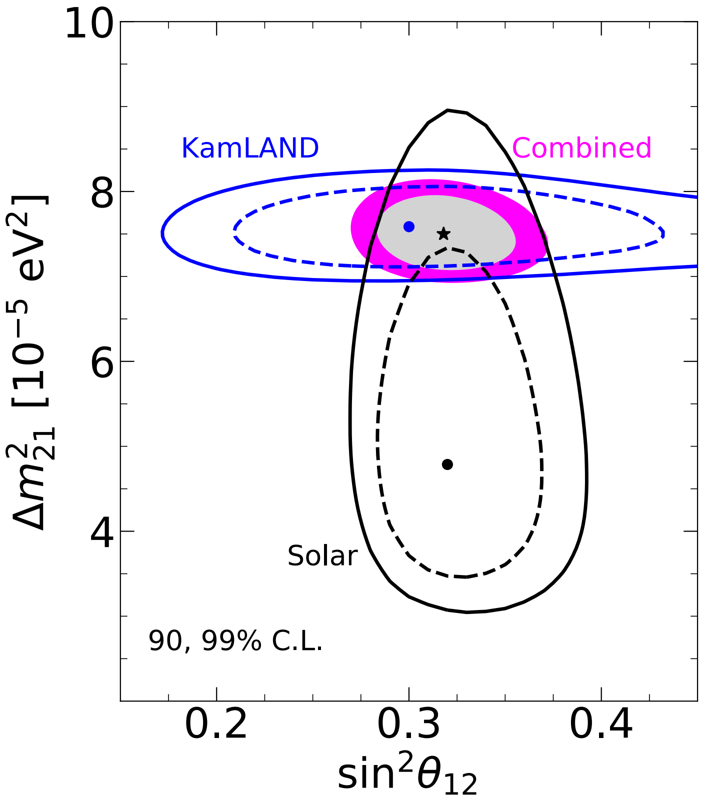
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]

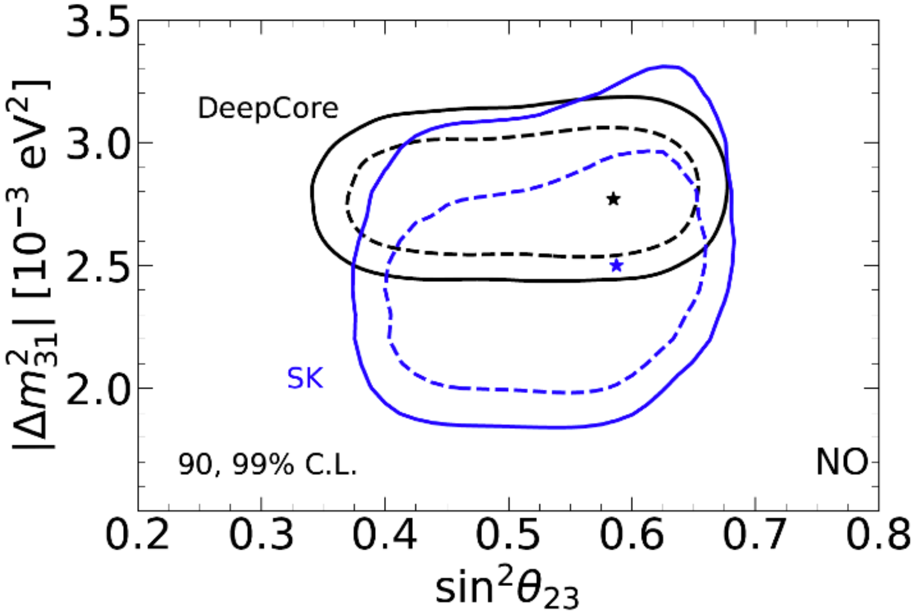
solar sector

Cl, Ga, SK

SNO, Borexino

KamLAND





atmospheric results

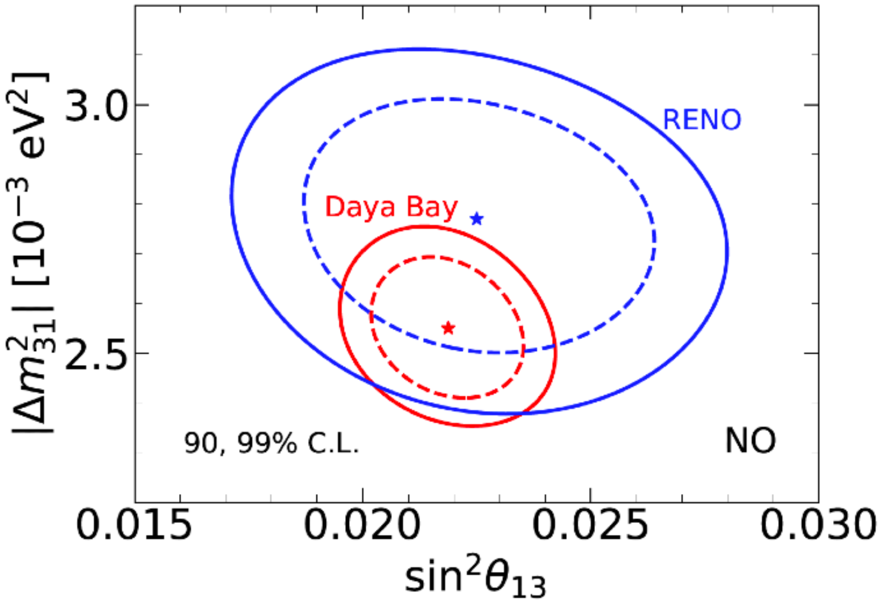
Super-K

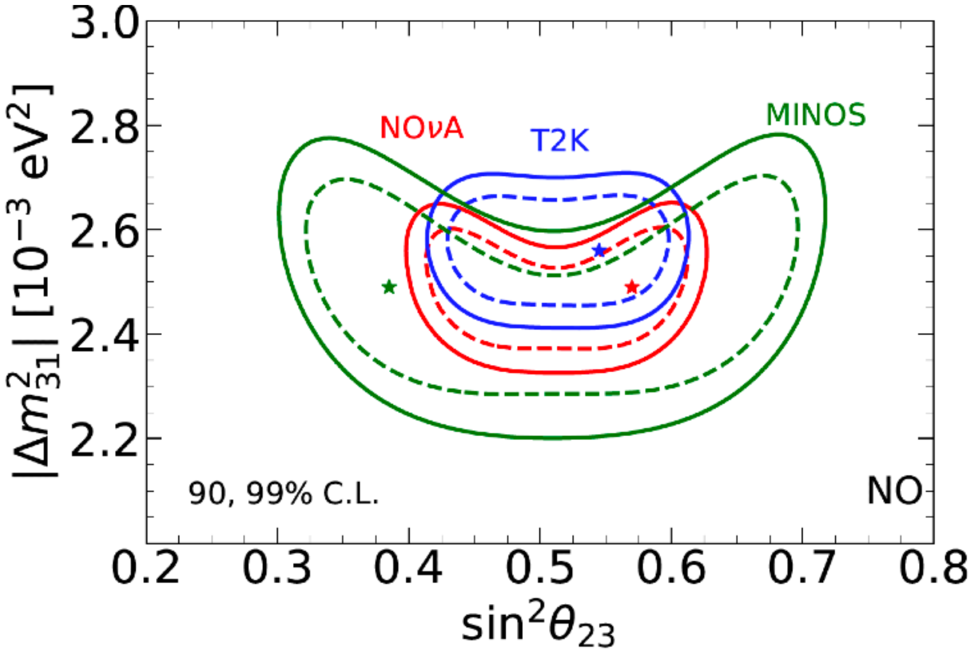
IC-DeepCore

SBL reactors

Daya Bay

RENO





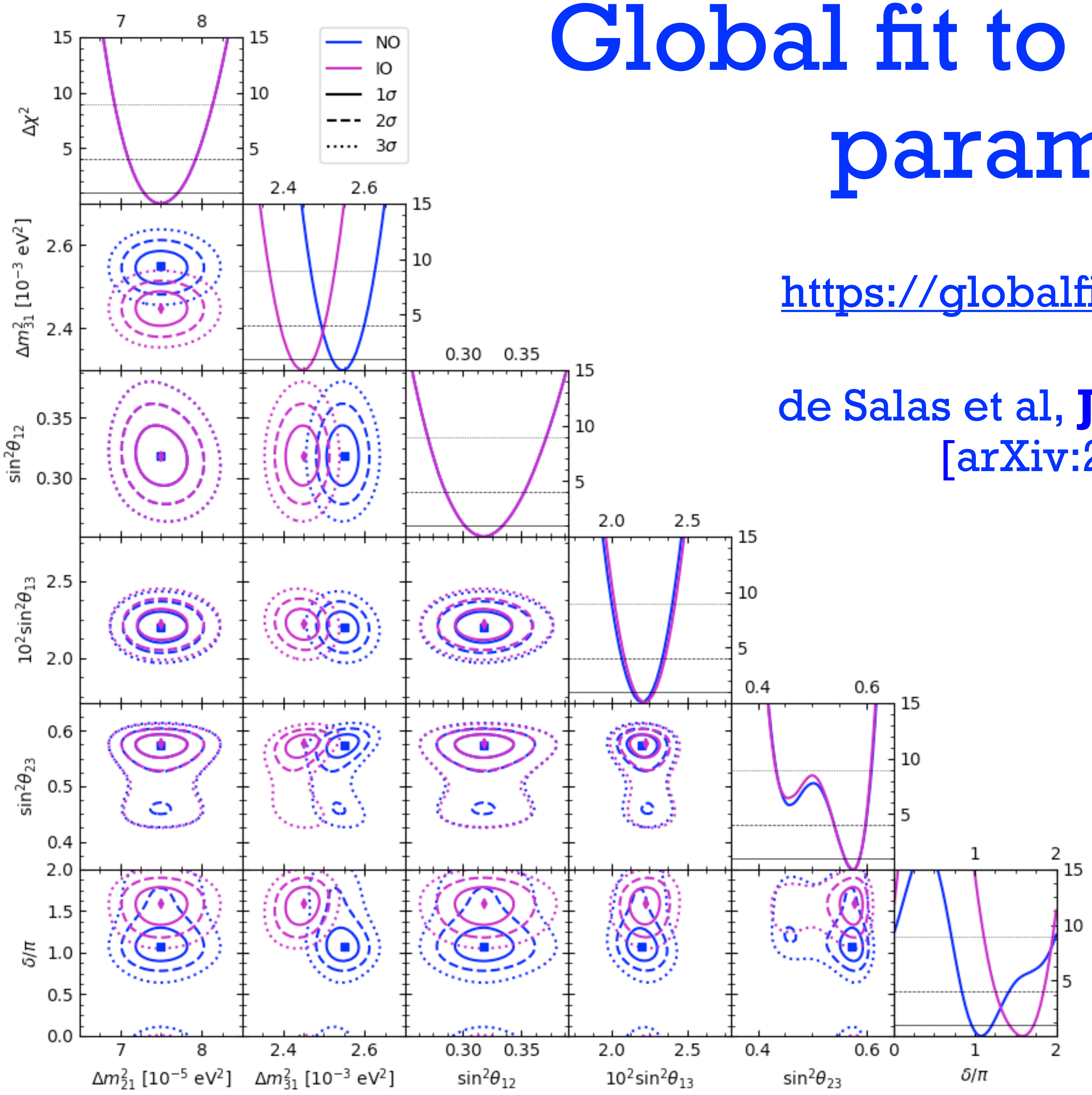
LBL experiments

MINOS

T2K

NOvA

Global fit to ν oscillation parameters



https://globalfit.astroparticles.es/

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]

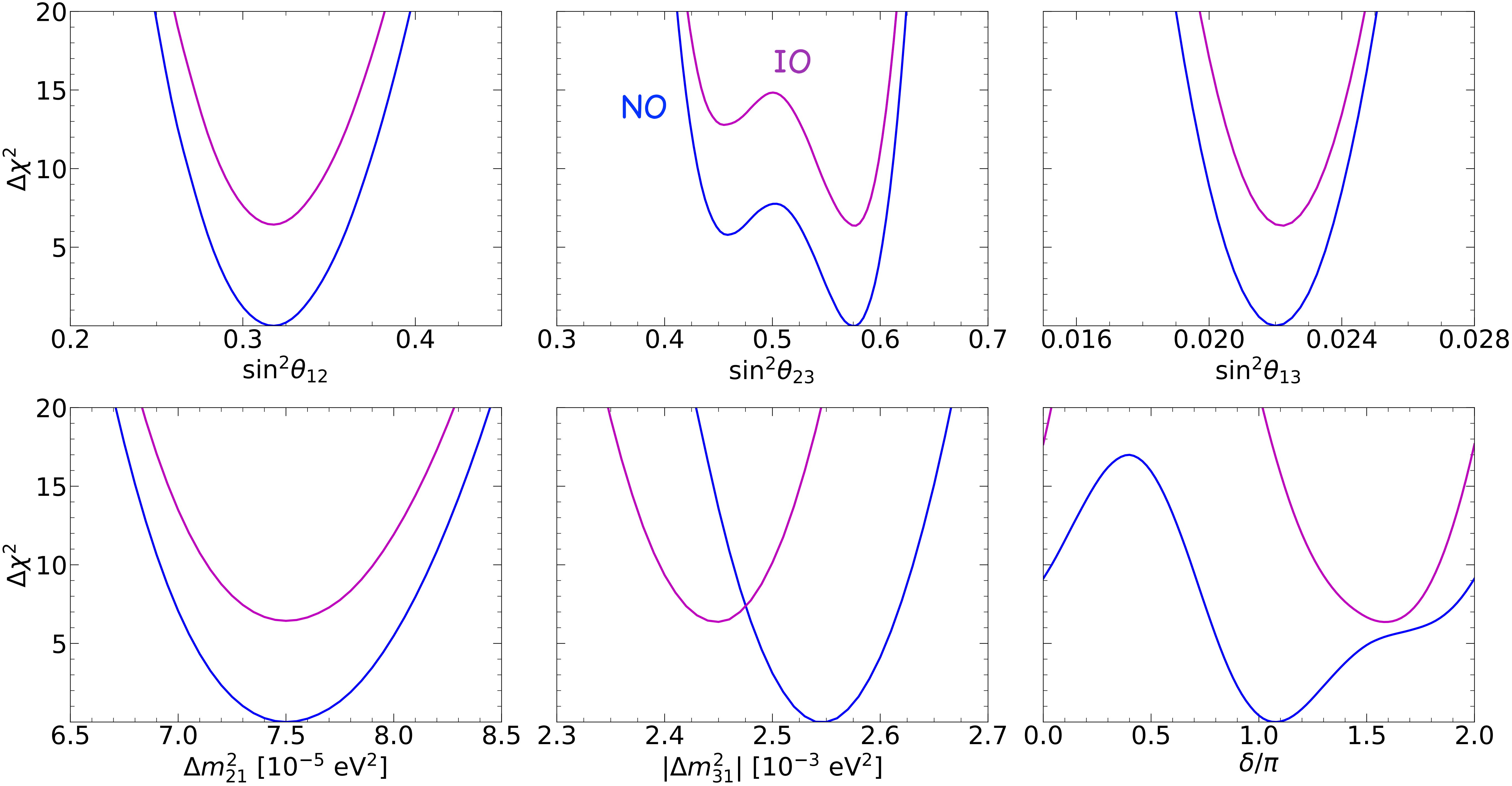
See also NuFIT and Bari group analyses

https://globalfit.astroparticles.es/

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

Global fit to ν oscillation parameters

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



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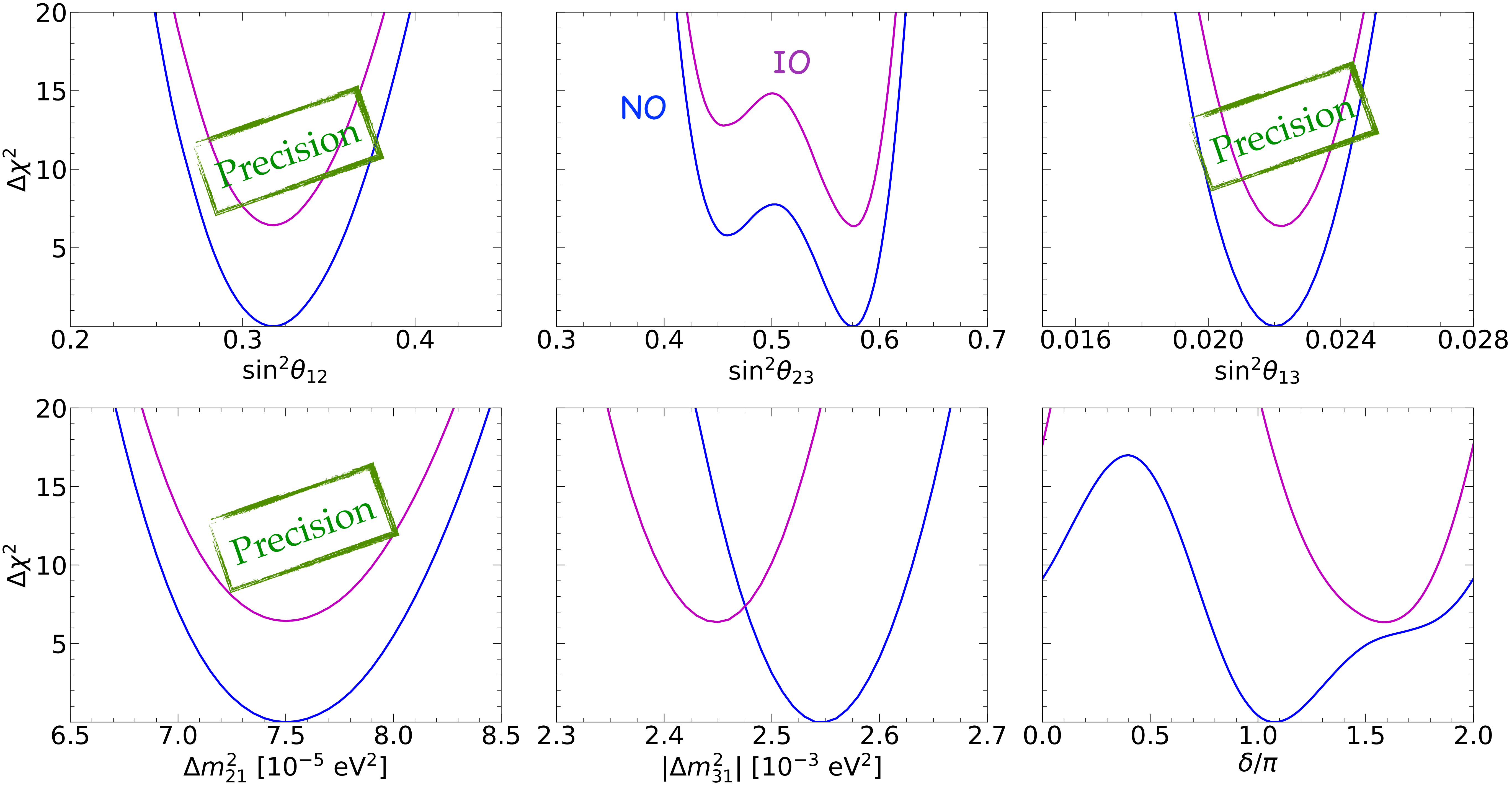

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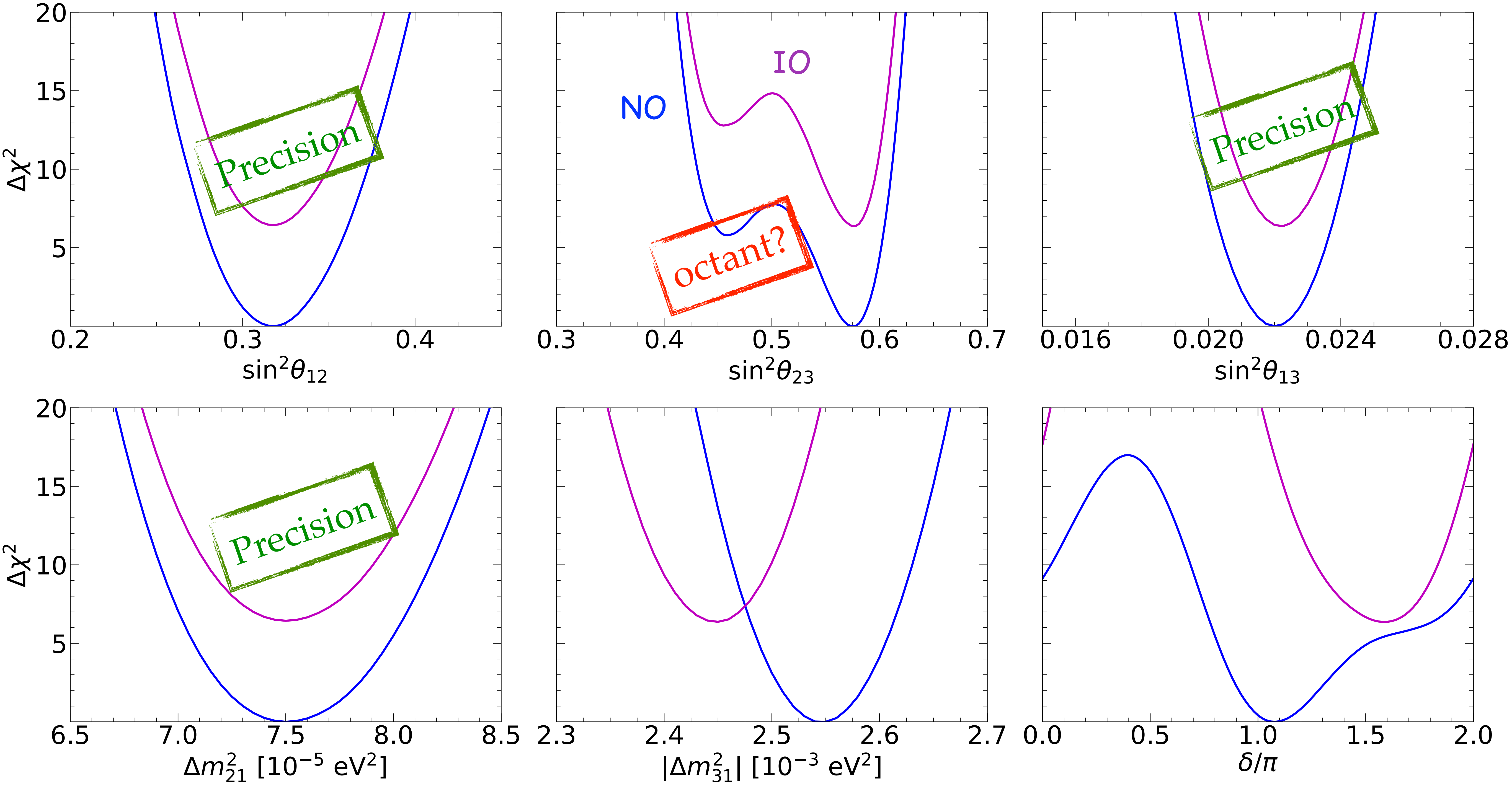

Global fit to ν oscillation parameters

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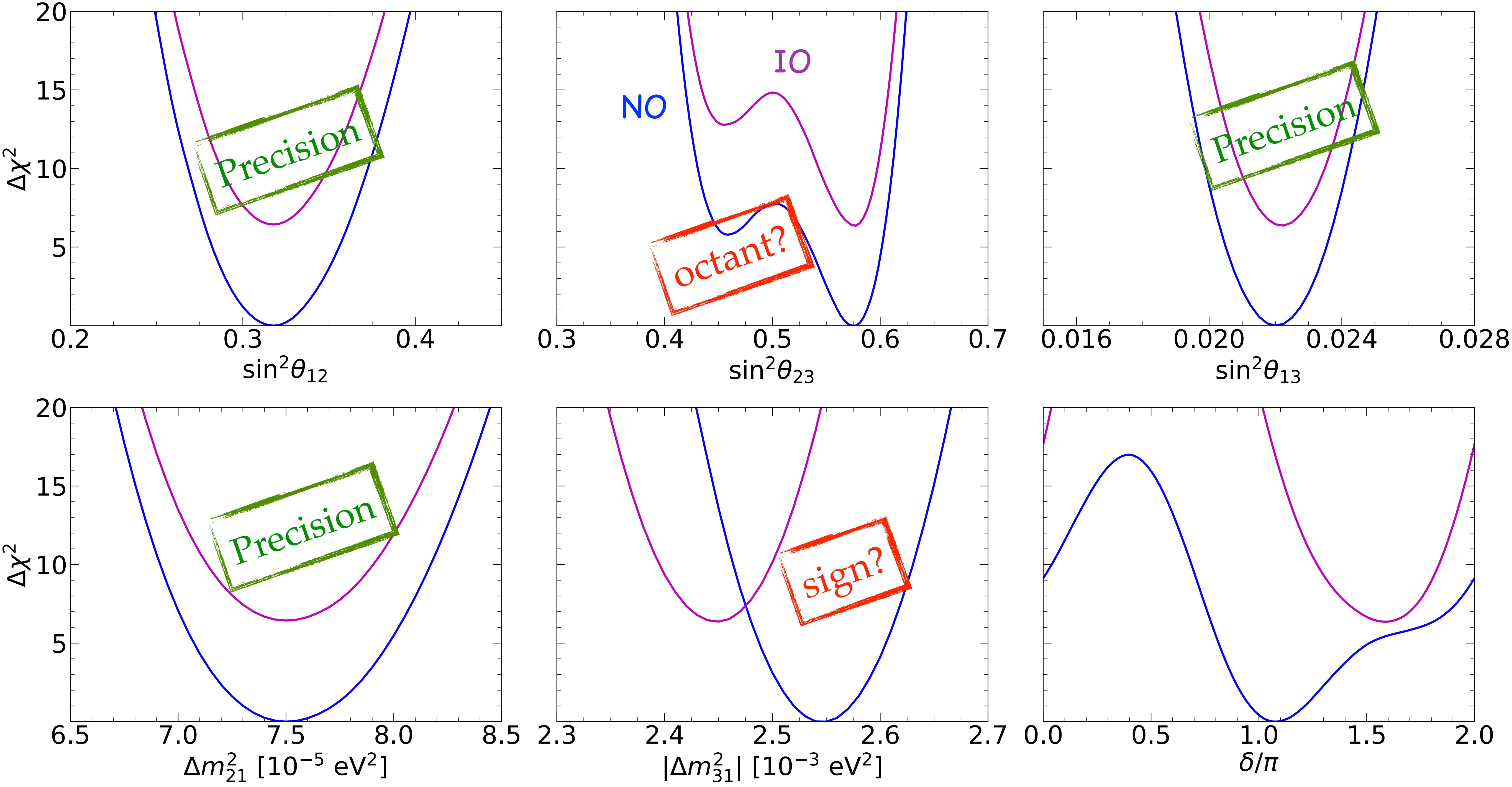
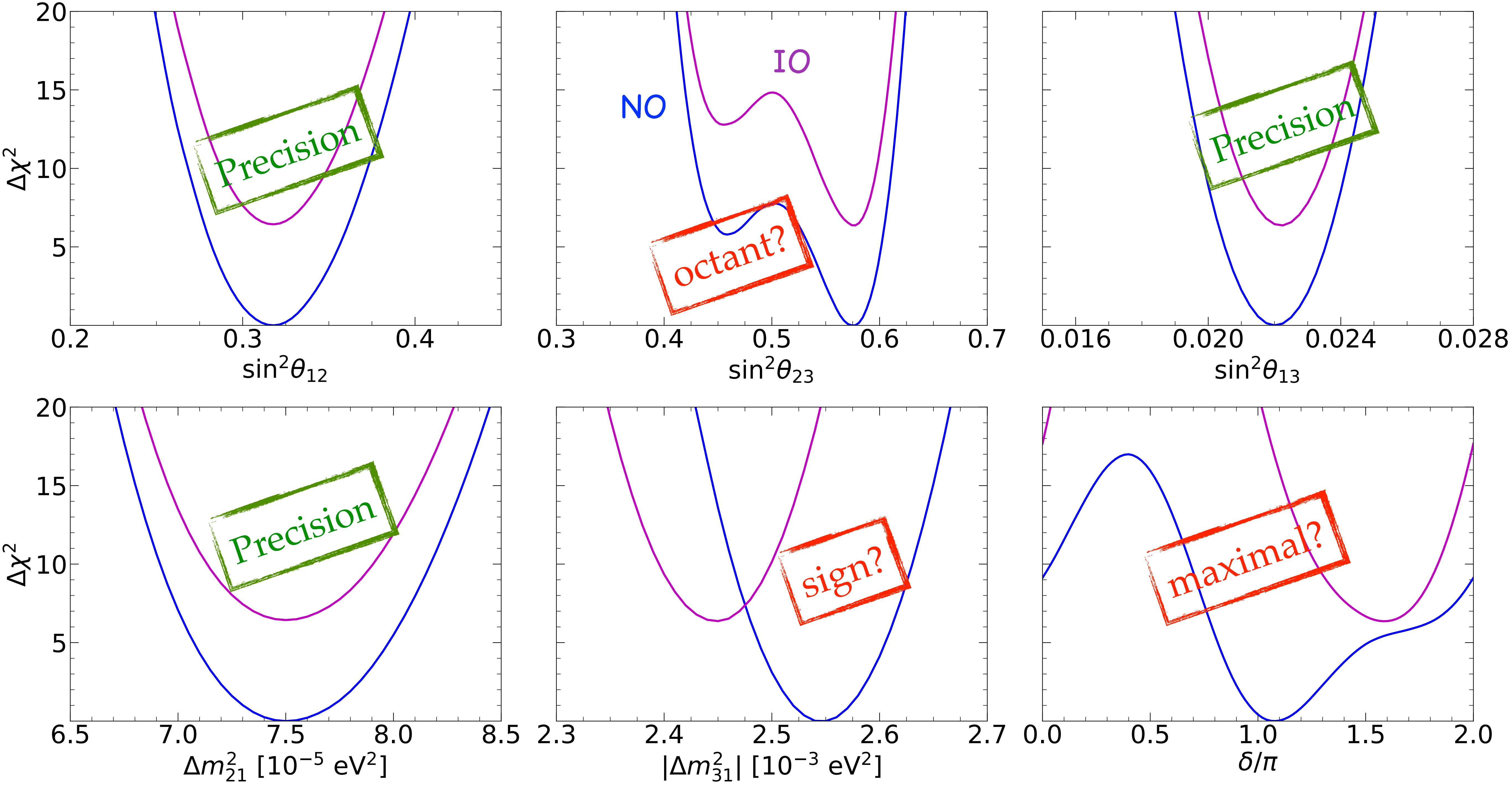


Global fit to ν oscillation parameters

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



Global fit to ν oscillation parameters

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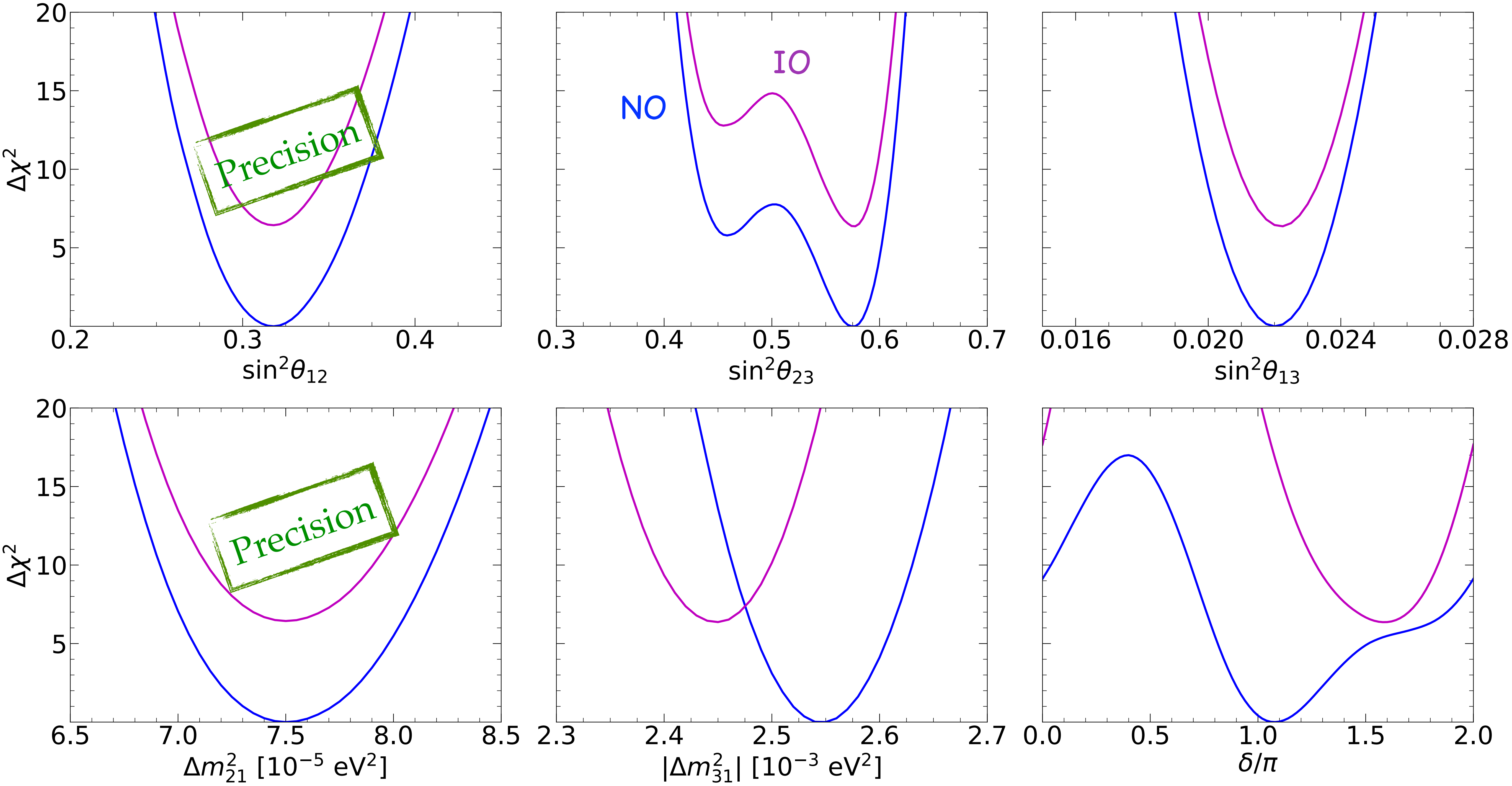
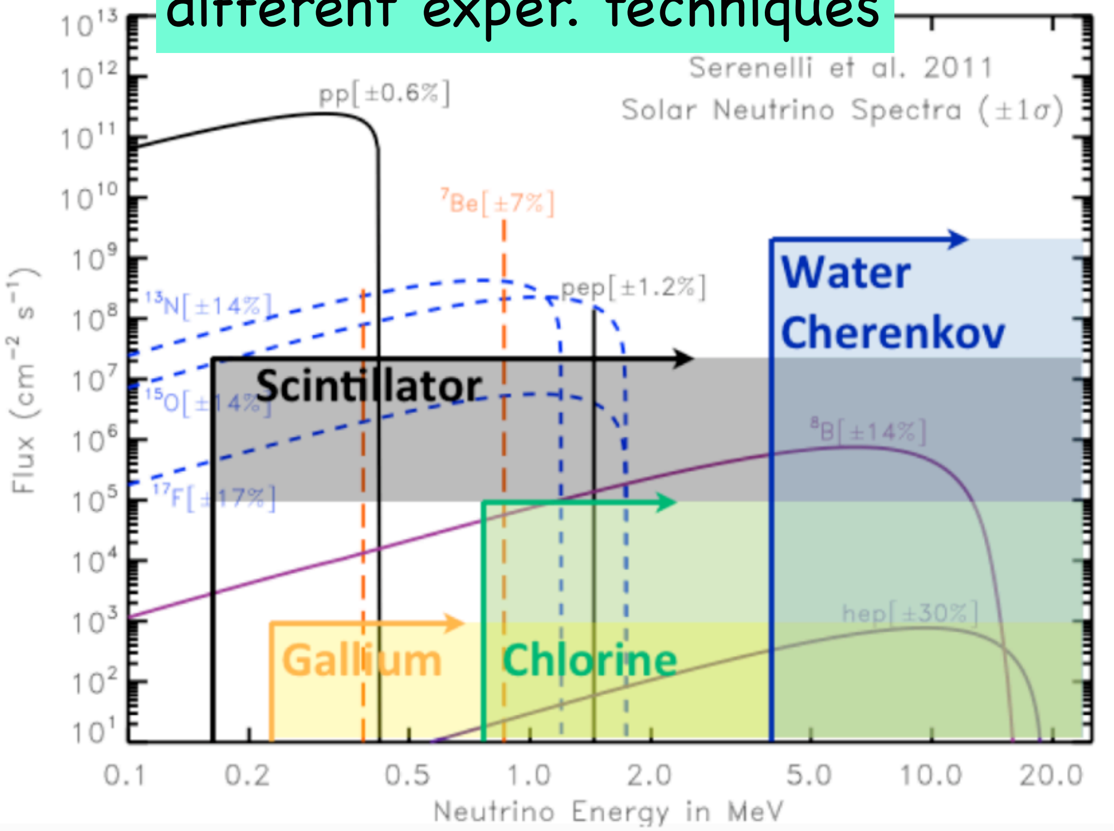


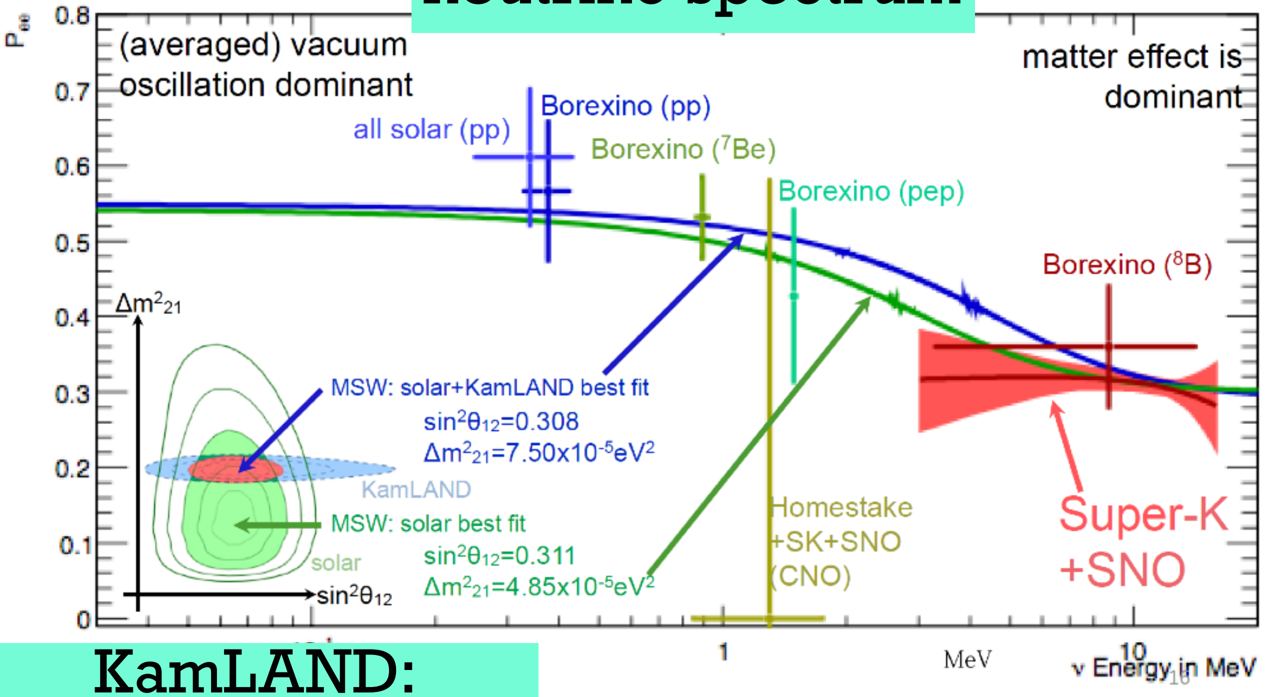
The solar neutrino sector

Solar experiments have measured neutrino disappearance for ~ 50 years

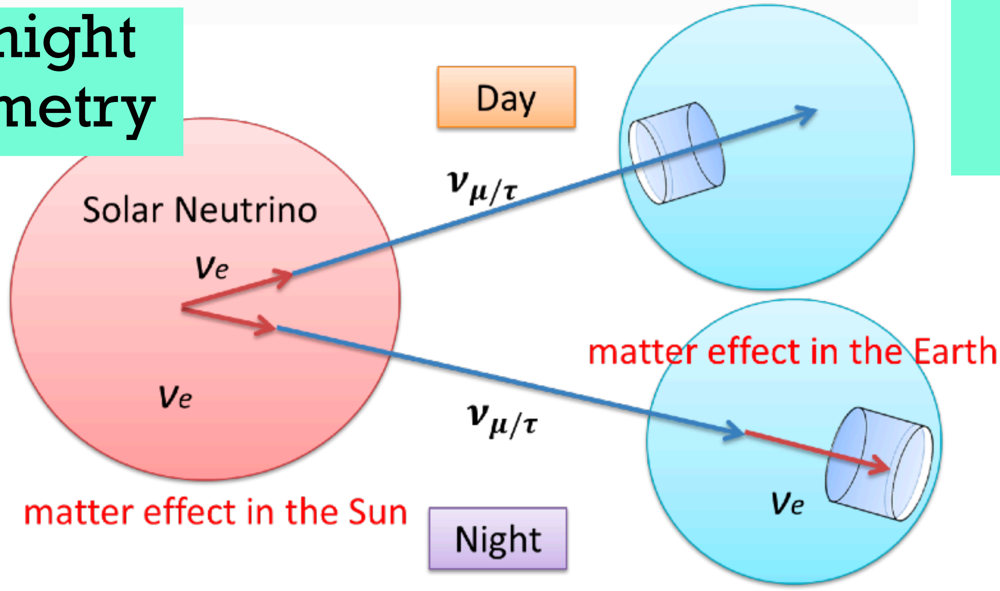
different exper. techniques



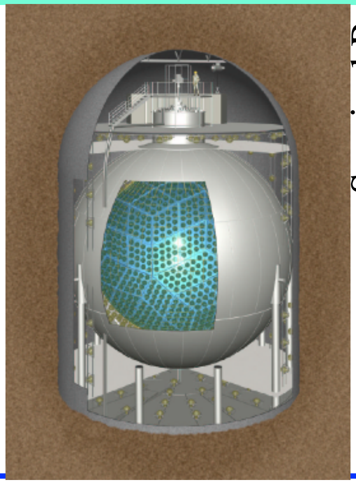
neutrino spectrum

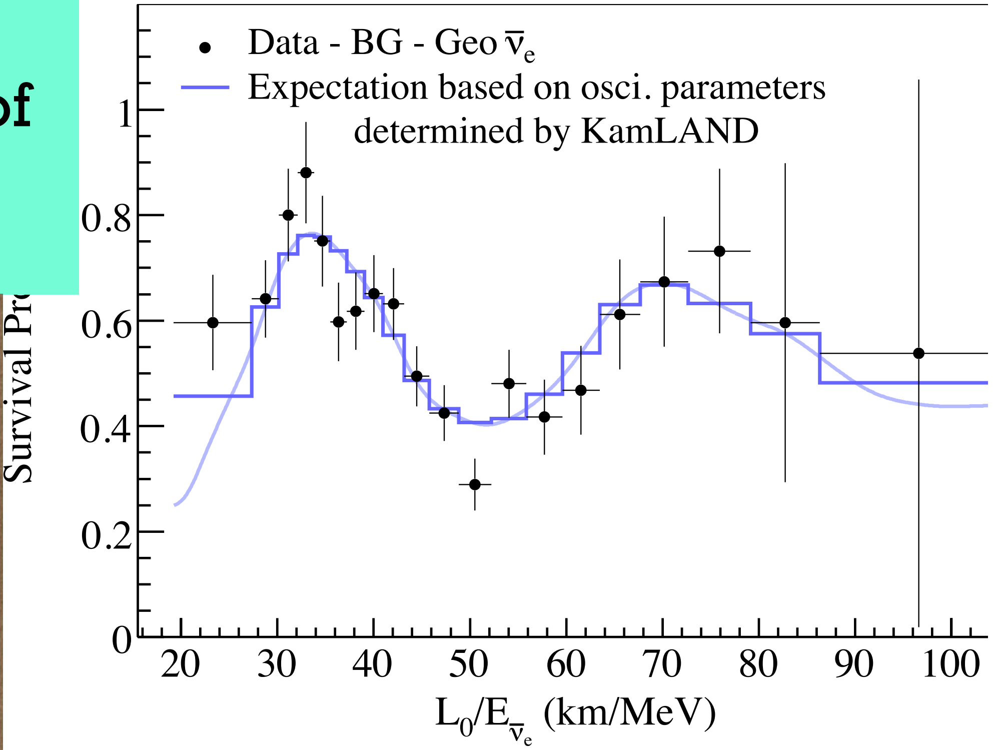


day/night asymmetry

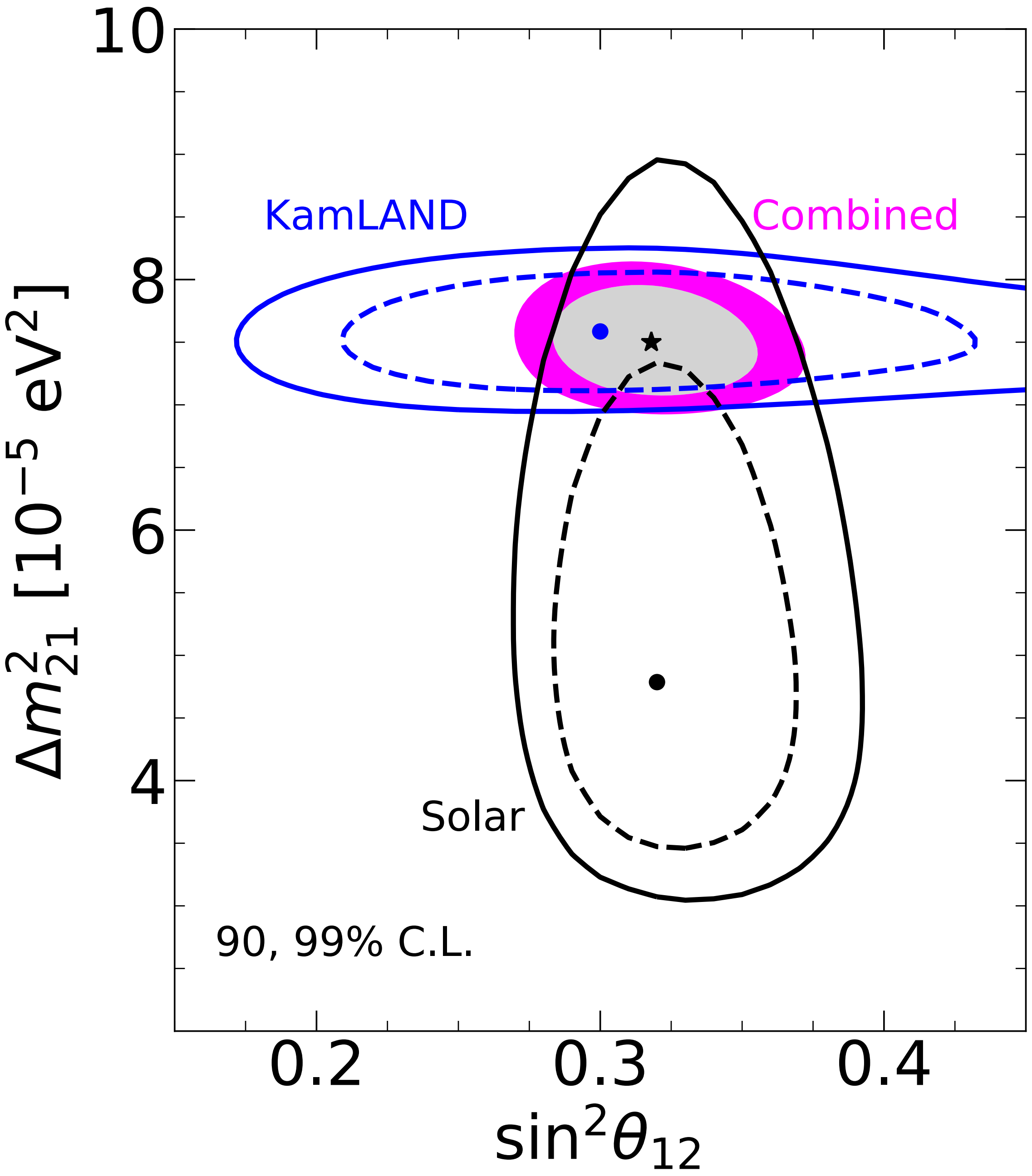


KamLAND: precise measurement of oscillation frequency





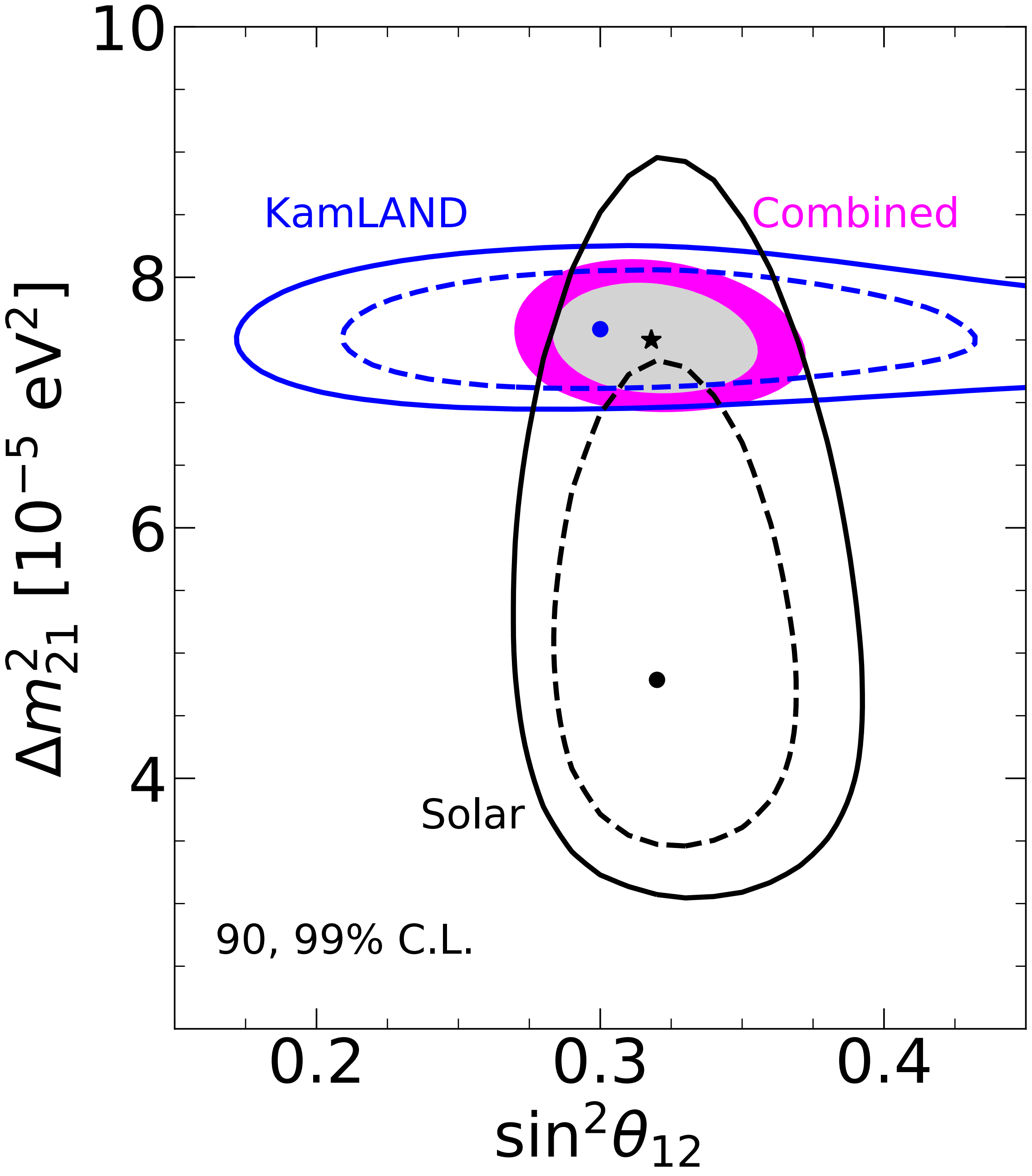
The solar sector



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

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

The solar sector



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

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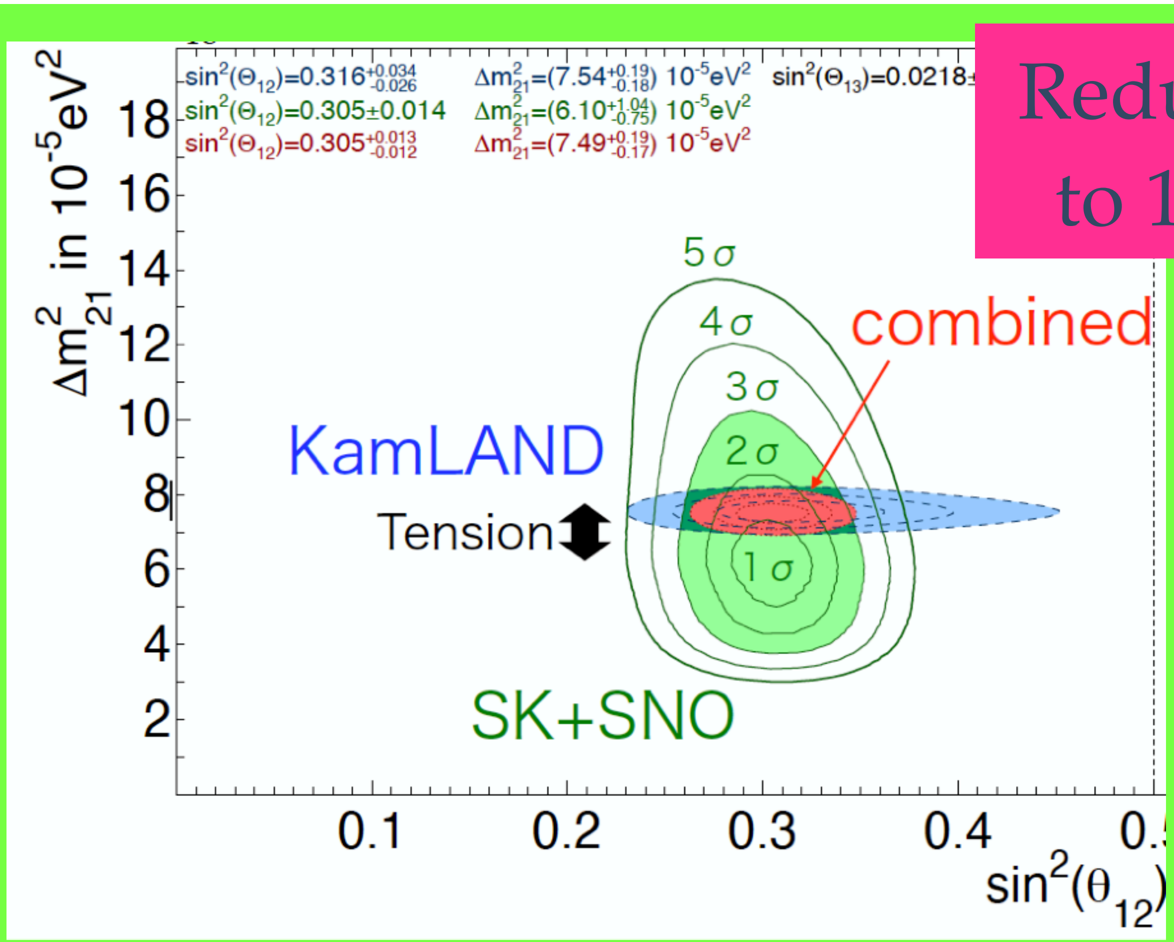


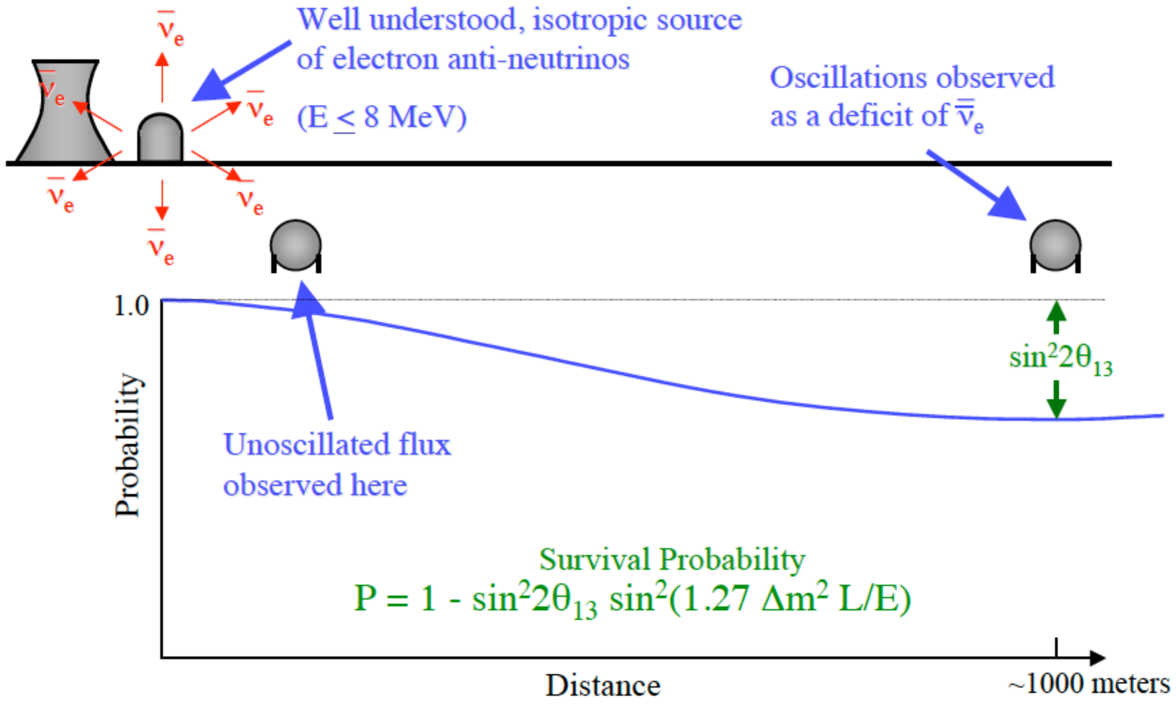
Reduced to 1.5σ

Y. Koshio, Neutrino-2022

The reactor sector

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

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



Well understood, isotropic source of electron anti-neutrinos (E $\leq$ 8 MeV)

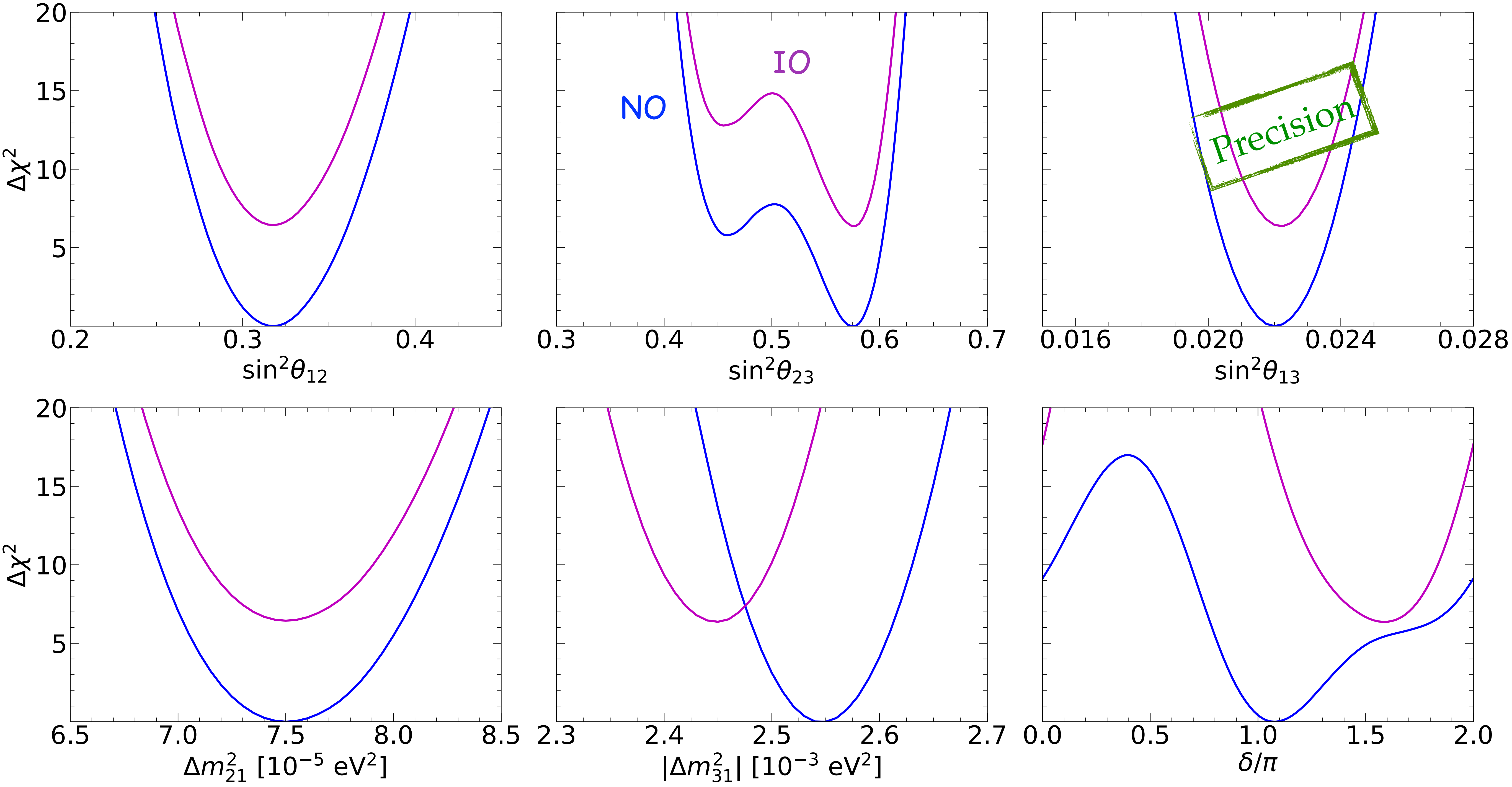
Oscillations observed as a deficit of $\bar{\nu}_e$

Unoscillated flux observed here

Survival Probability
$P = 1 - \sin^2 2\theta_{13} \sin^2(1.27\, \Delta m^2\, L/E)$

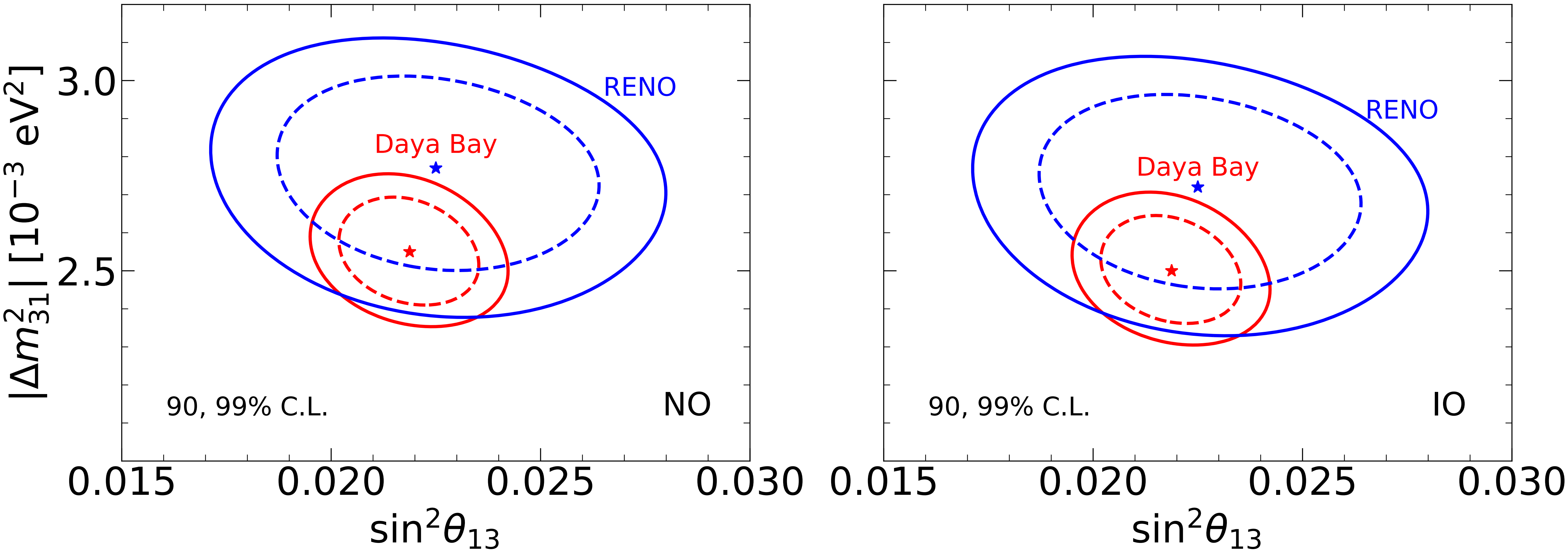
Global fit to ν oscillation parameters

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



The reactor sector

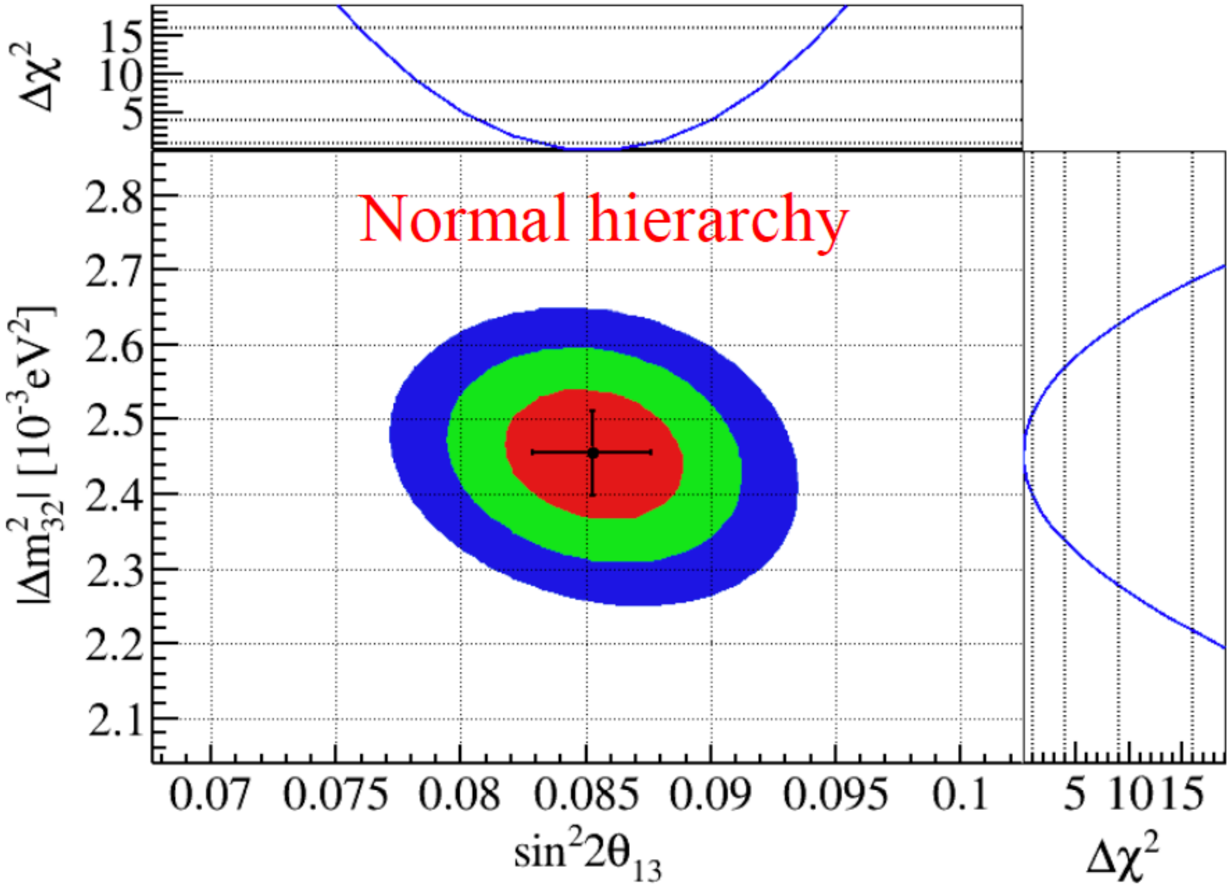
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]

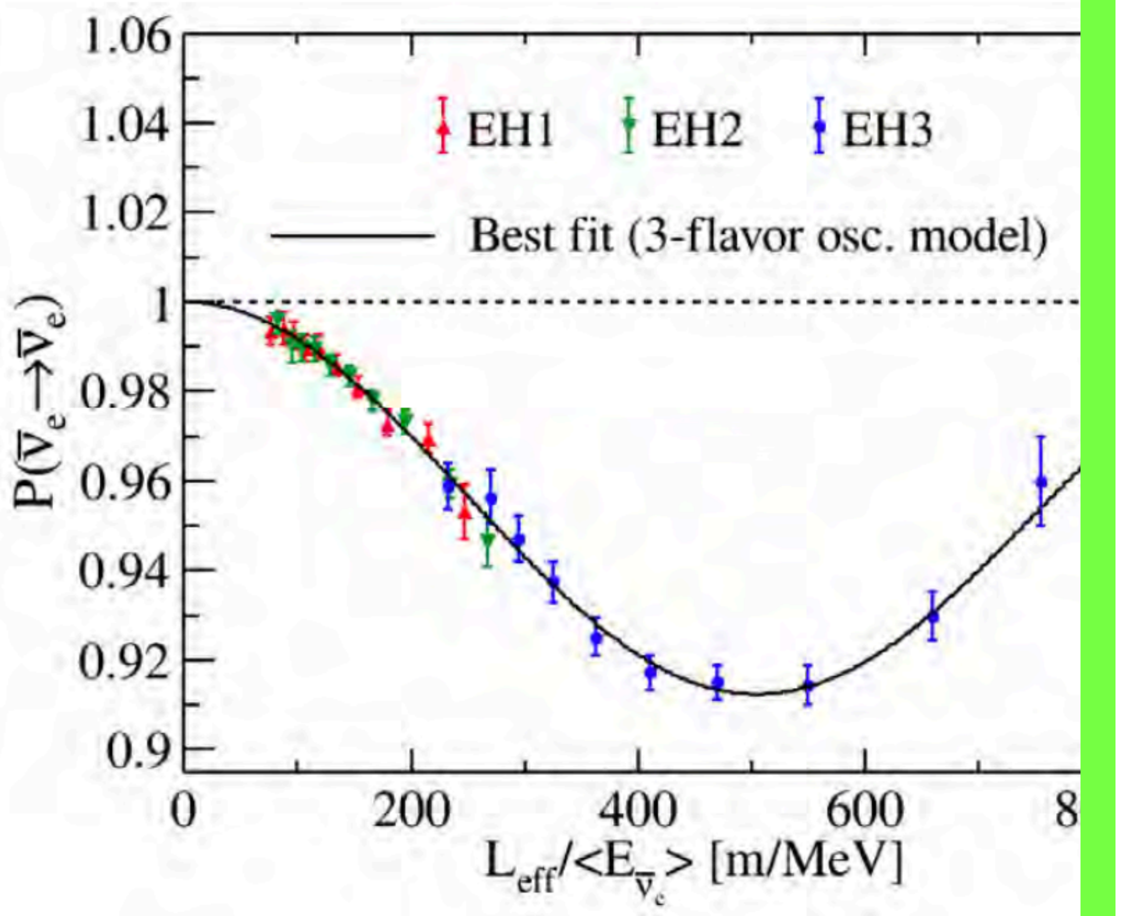


- Daya Bay: 1958-day data: $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$ (3.4%)
- RENO: 2900-day data: $\sin^2 2\theta_{13} = 0.0892 \pm 0.0063$ (7%)

Precision dominated by Daya Bay

The reactor sector





Best-fit results: $\chi^2/\text{ndf} = 559/518$

$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$ (2.8% precision)

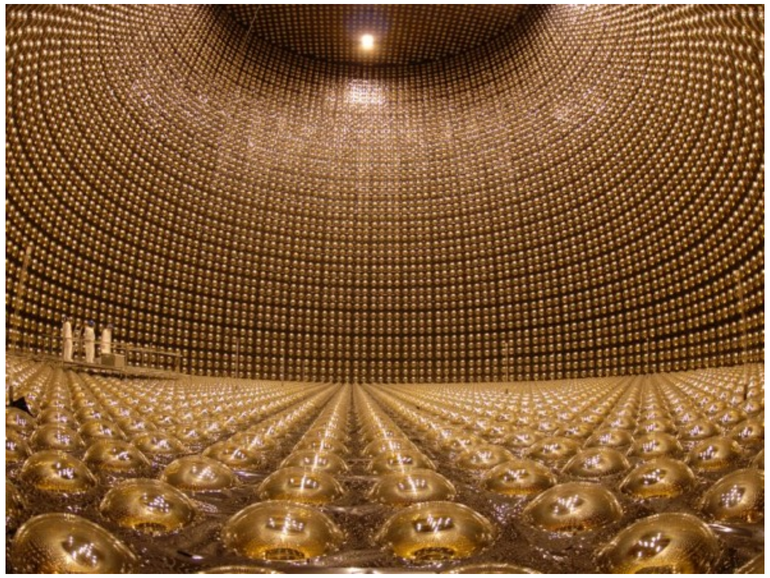
Daya Bay: 3158-day data

K. Luk, Neutrino-2022

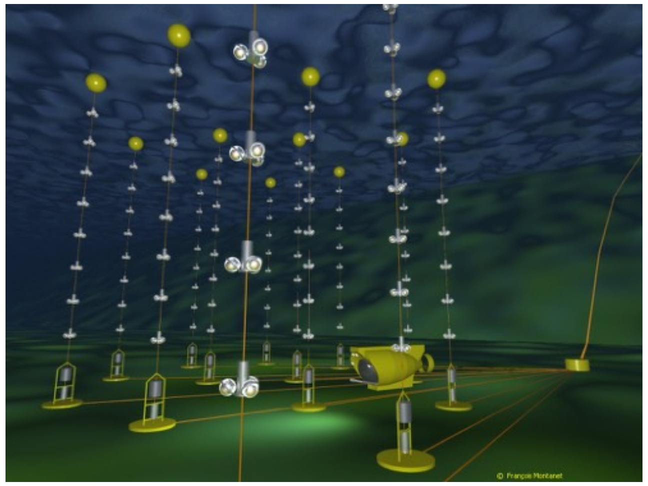
The atmospheric sector

Atmospheric experiments

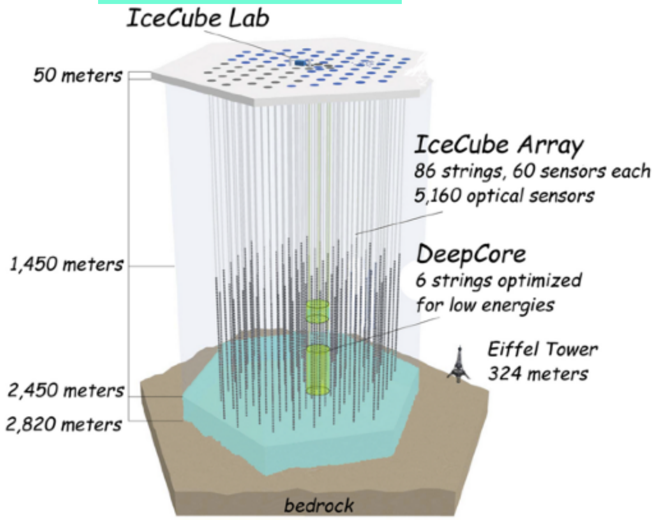
Super-Kamiokande



ANTARES

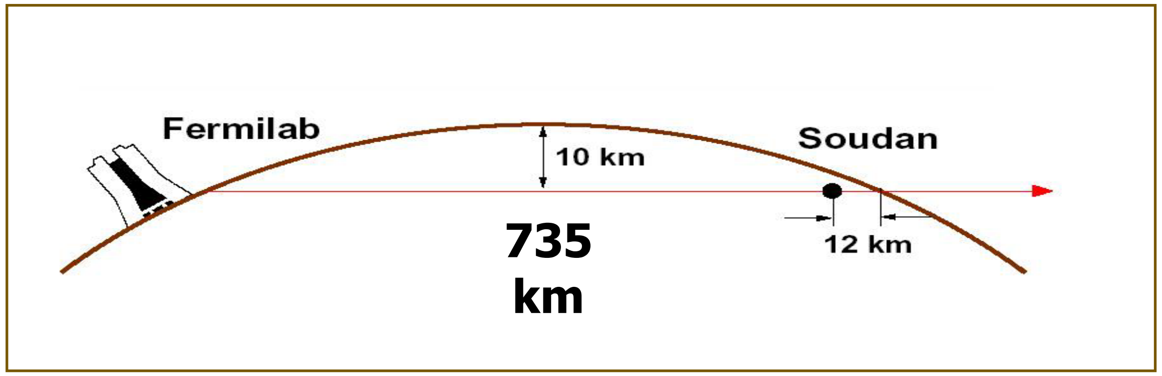


IceCube

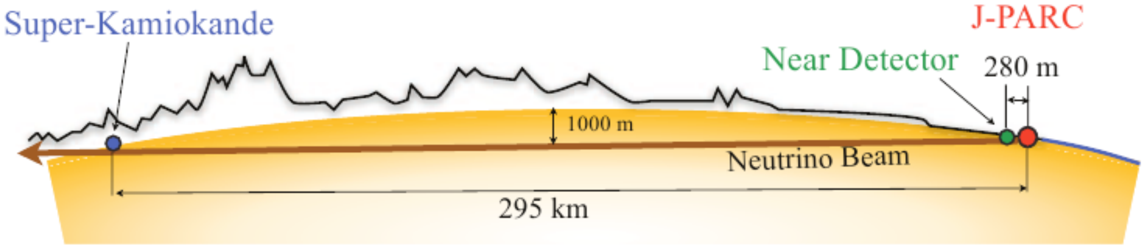


Accelerator long-baseline experiments

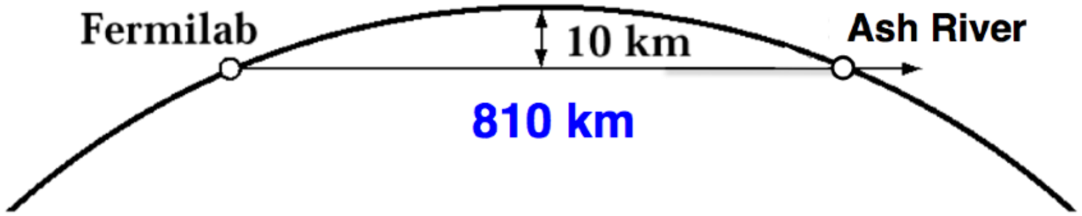
MINOS



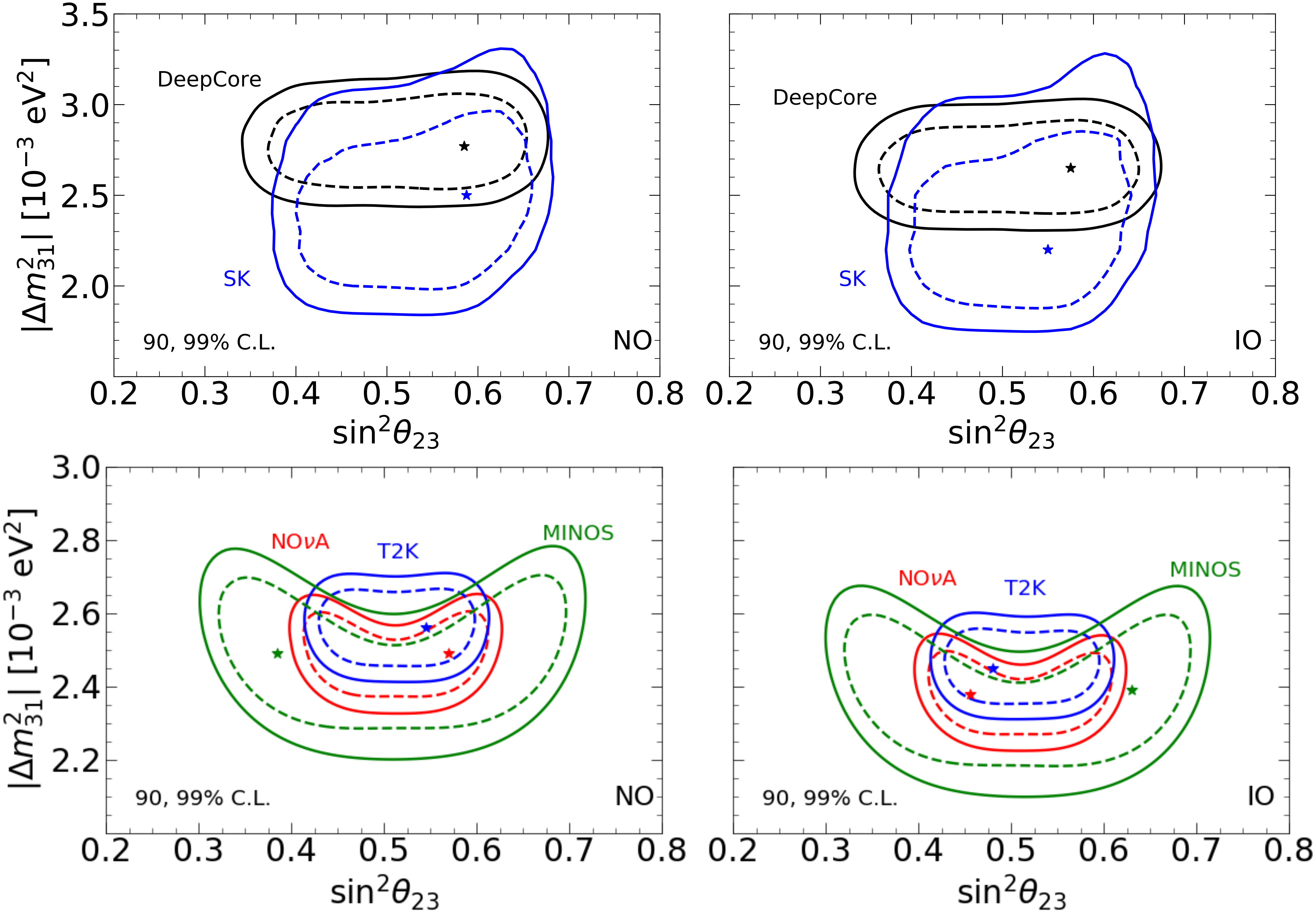
T2K



NOvA

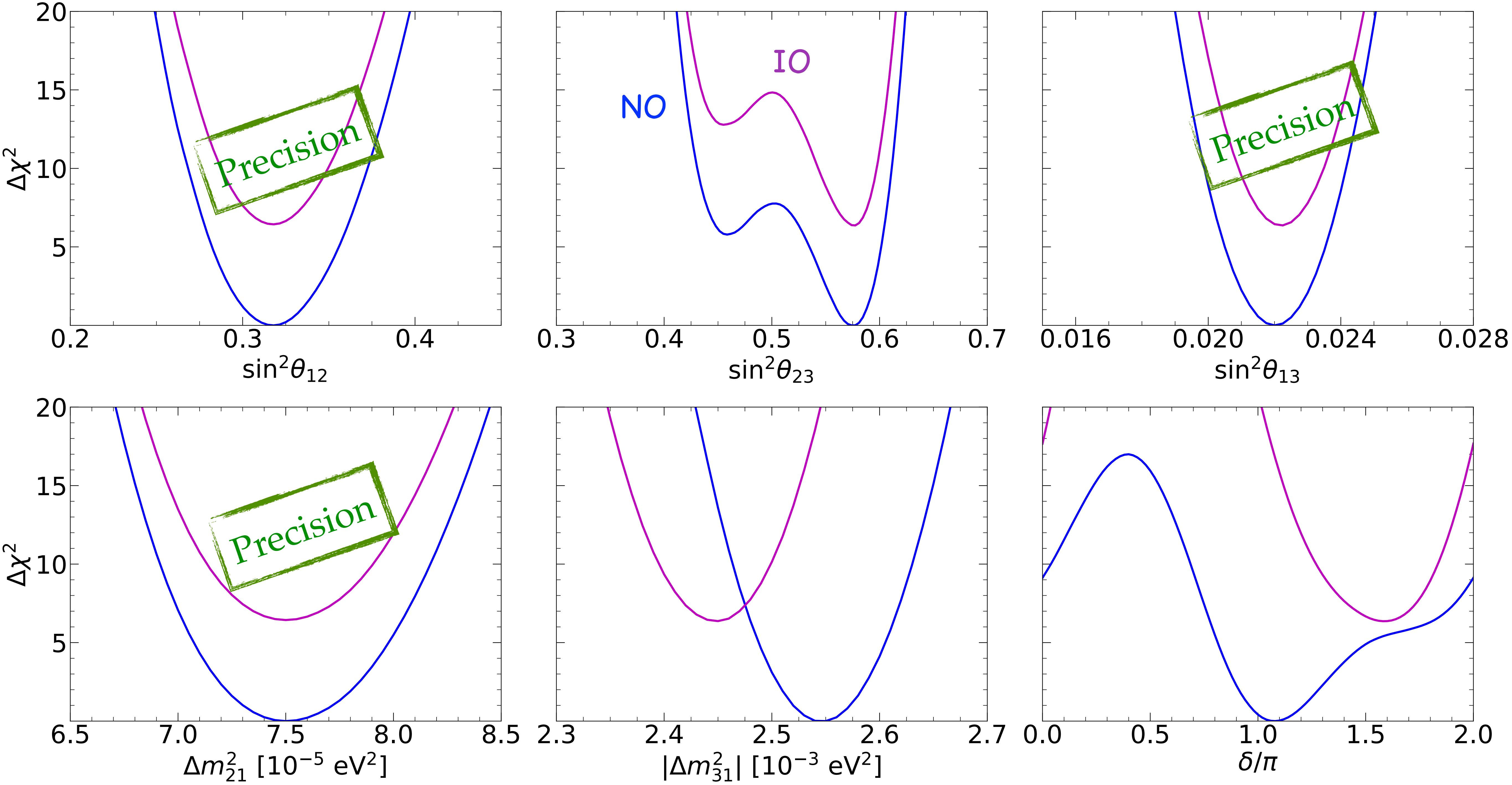


The atmospheric sector



Global fit to ν oscillation parameters

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



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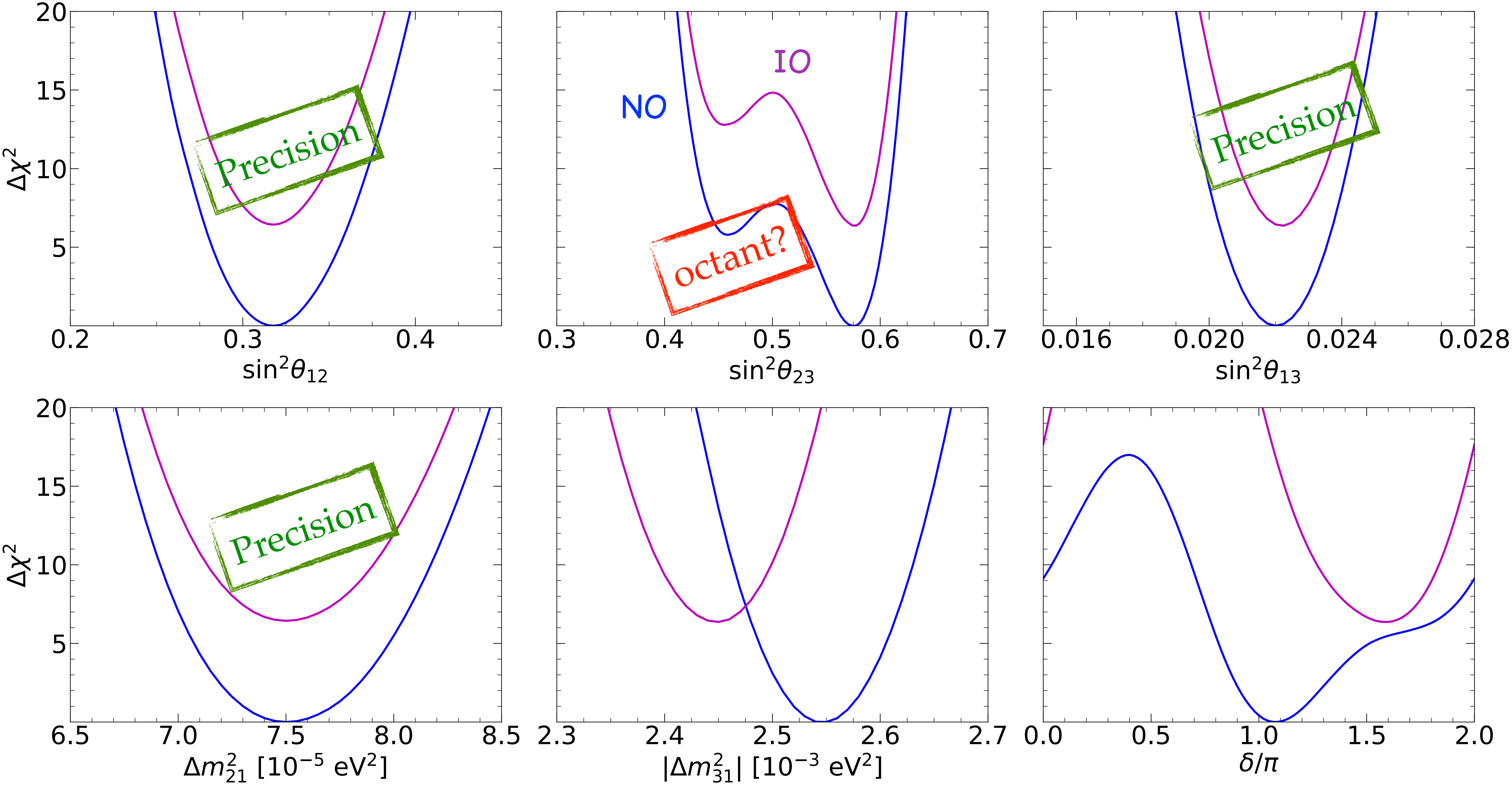
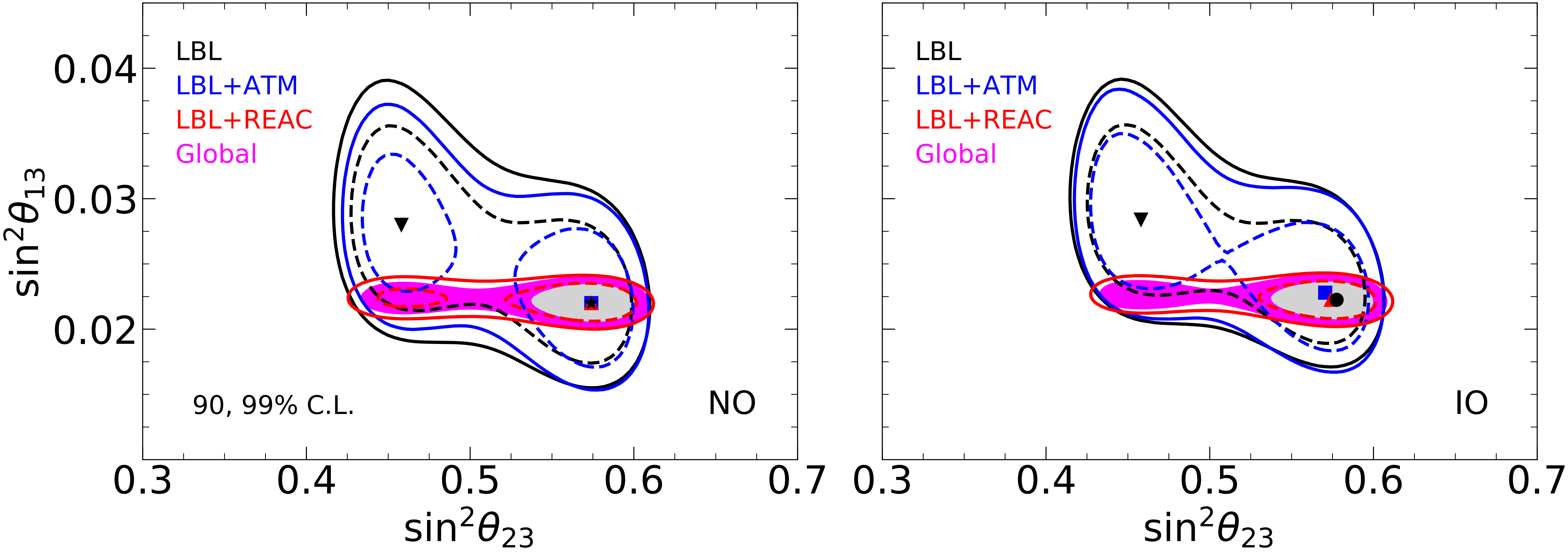


The octant of θ_{23}

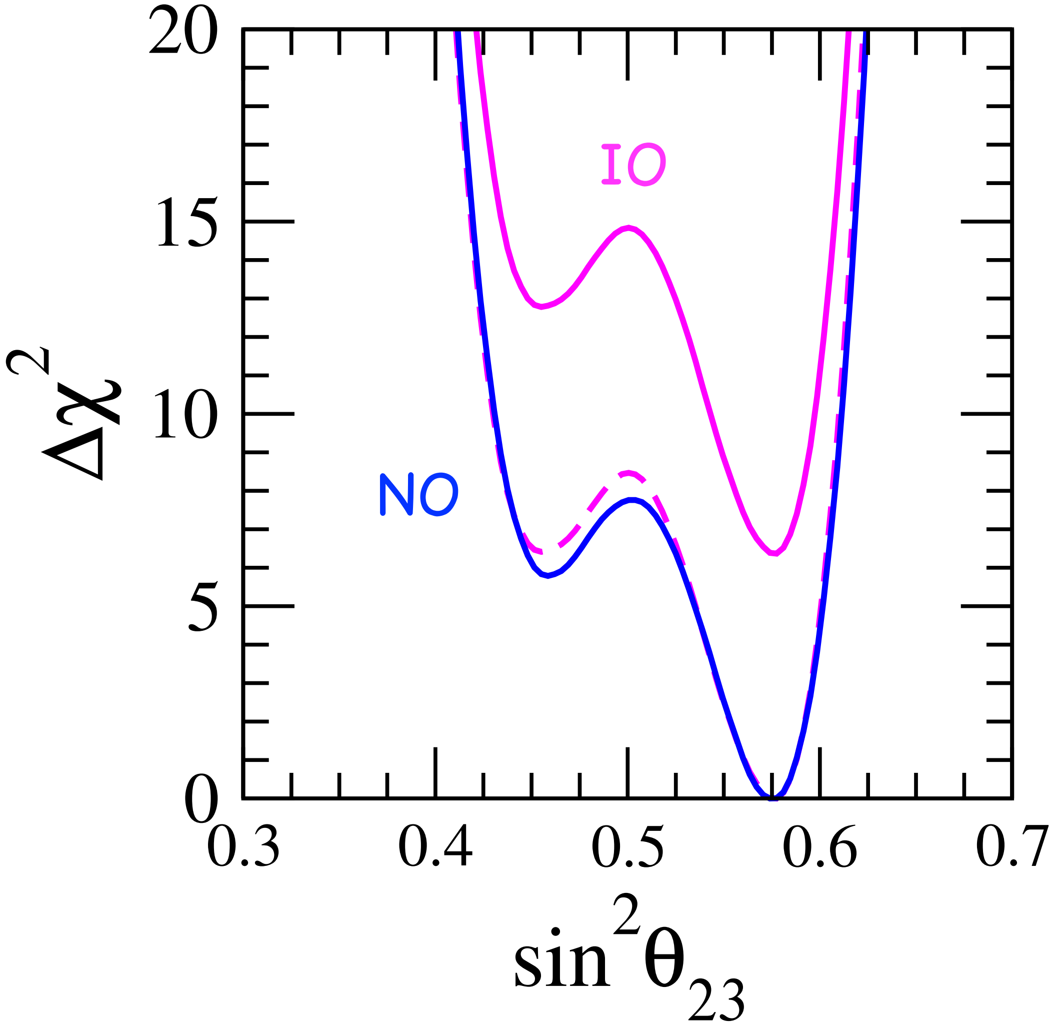
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



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

The octant of θ_{23}

de Salas et al, JHEP 02 (2021) 071

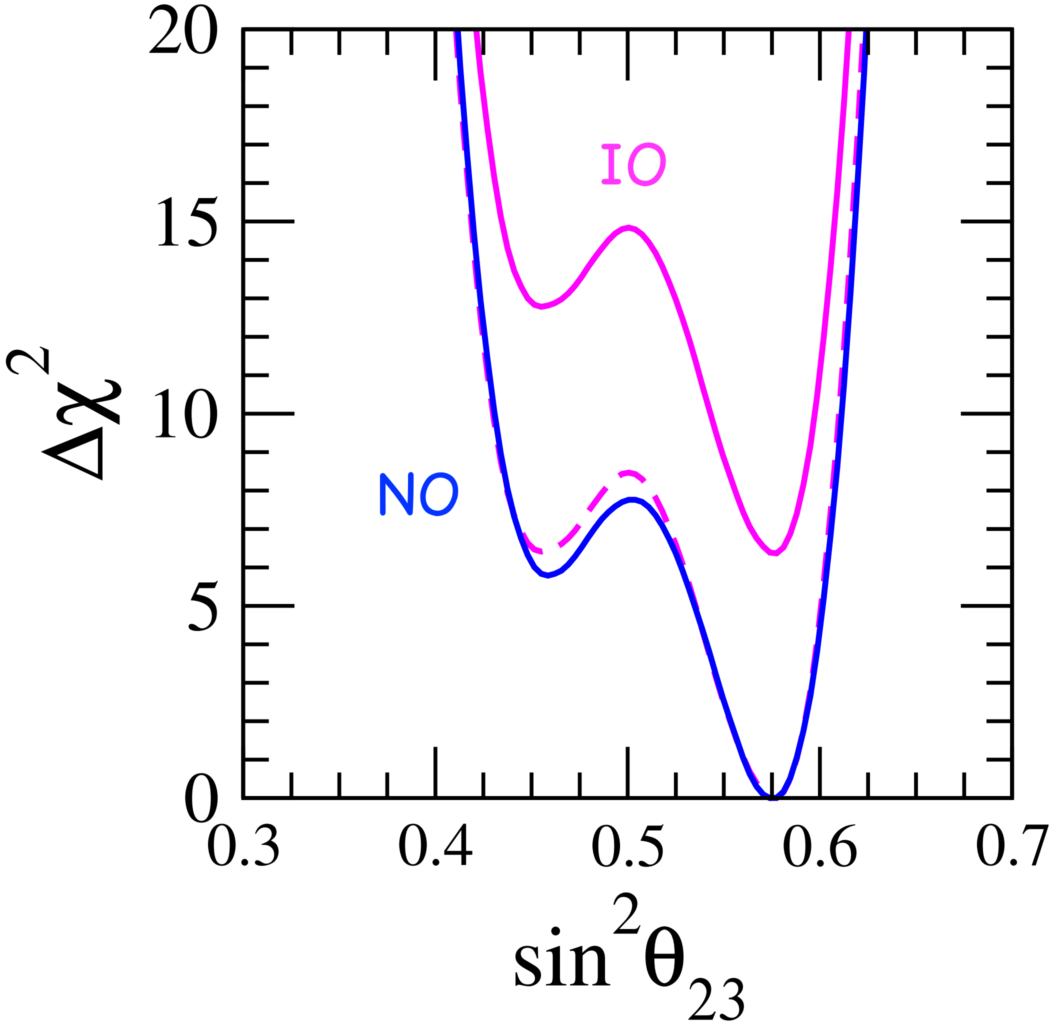


Values at the 1st octant disfavored

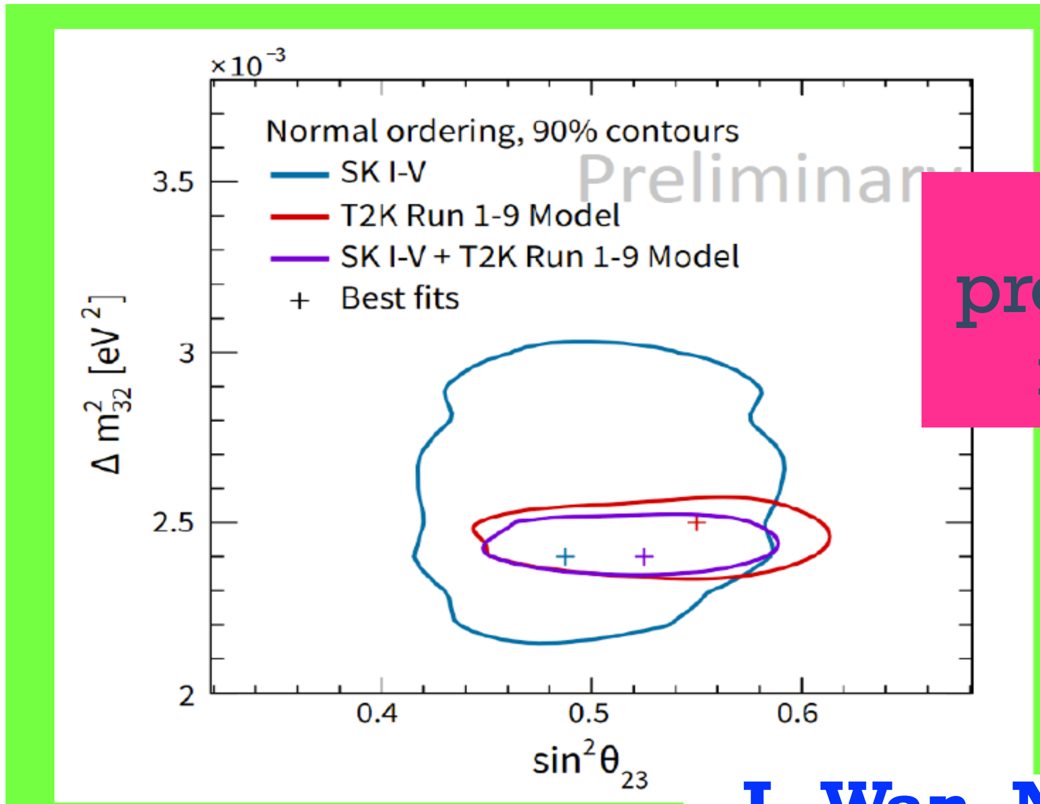
with $\Delta\chi^2 \geq 5.8$ (6.4) for NO (IO)

The octant of θ_{23}

de Salas et al, JHEP 02 (2021) 071

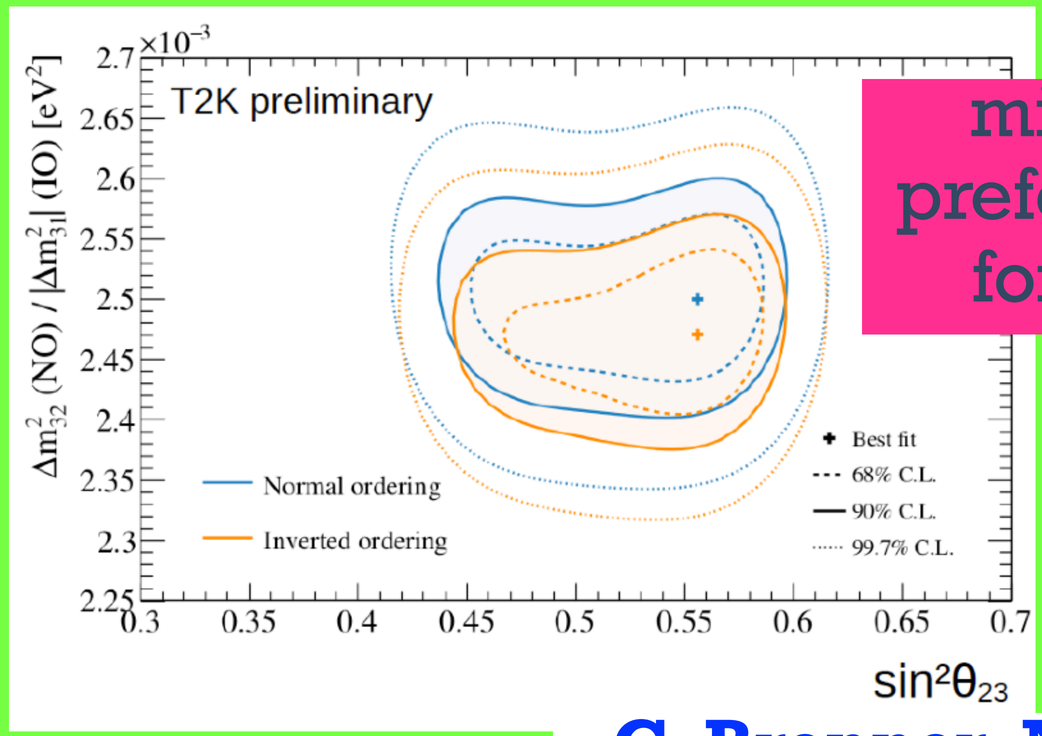


Values at the 1st octant disfavored with $\Delta\chi^2 \geq 5.8$ (6.4) for NO (IO)



slight preference for LO

L. Wan, Nu 2022

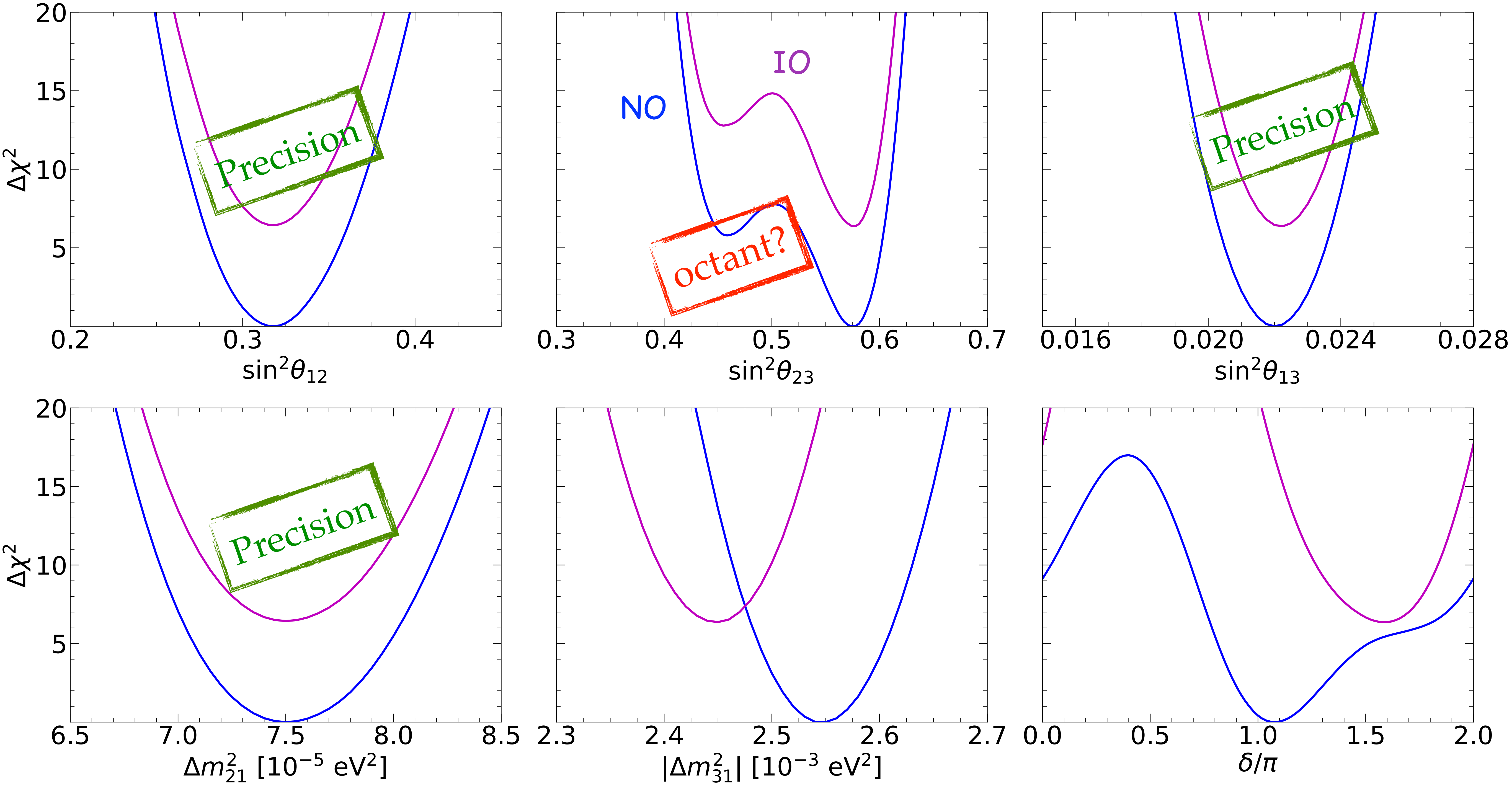


milder preference for UO

C. Bronner, Nu 2022

Global fit to ν oscillation parameters

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



Global fit to ν oscillation parameters

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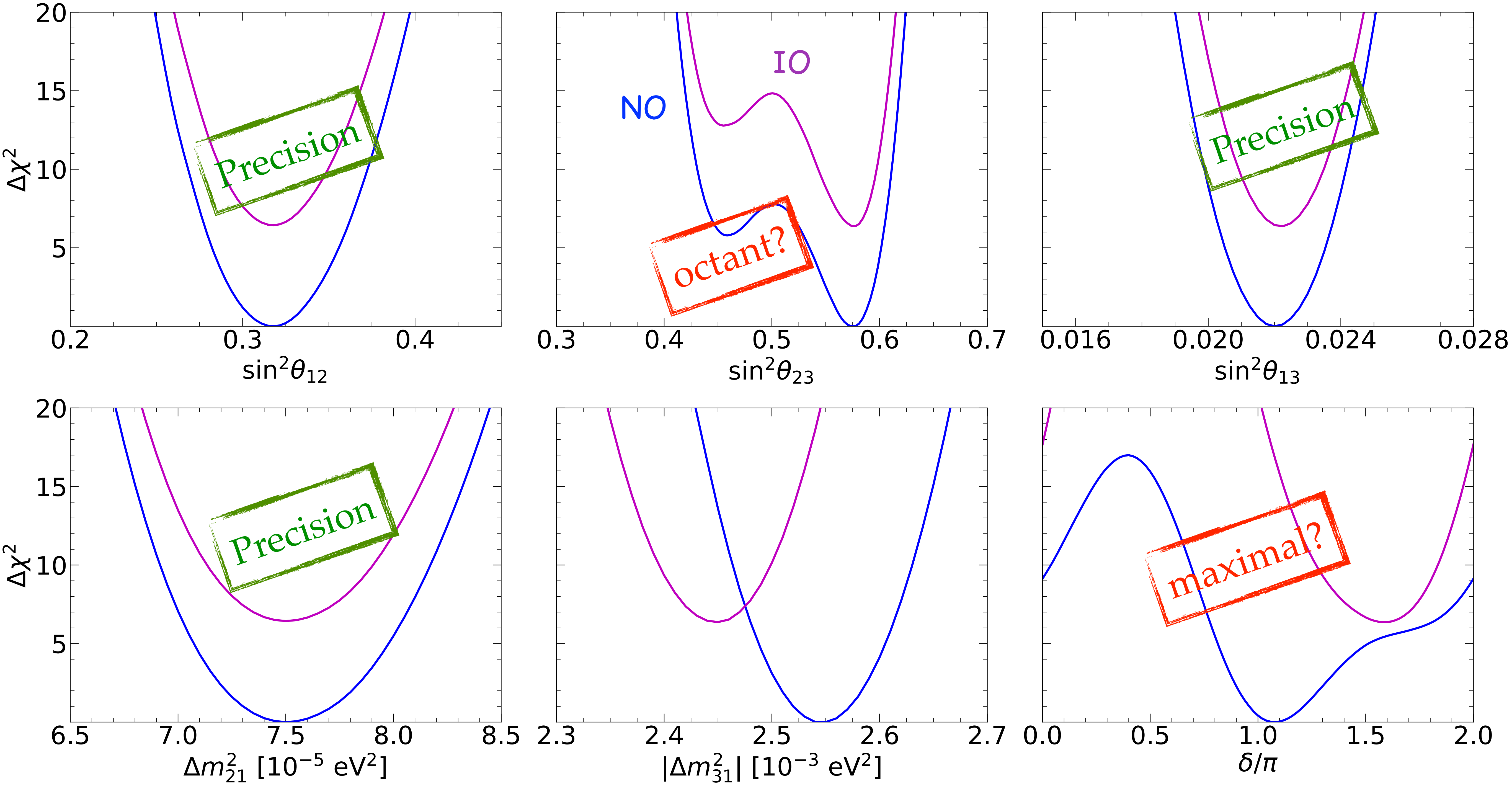
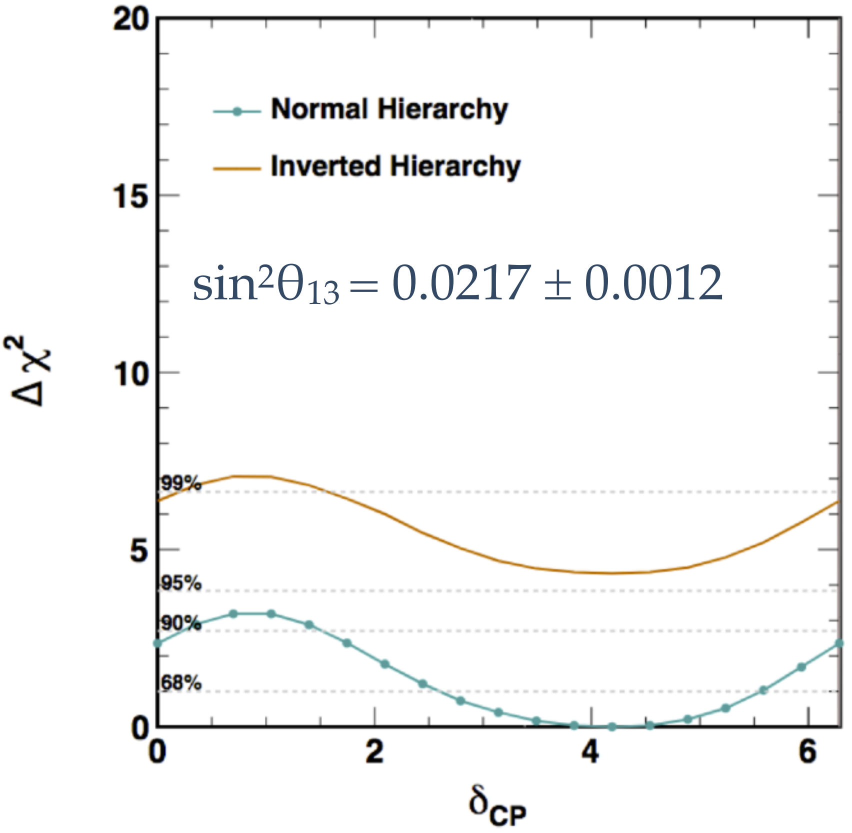


The CP phase

Super-Kamiokande (atm)



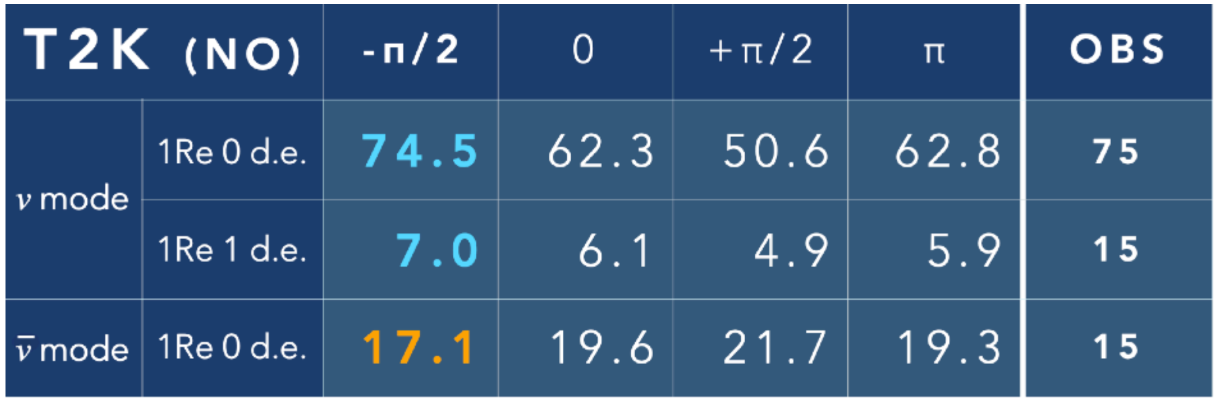
- ✦ δ_{BF} = 1.5π (1.2π) for NO (IO)
- ✦ preference driven by sub-GeV e-like samples

SK Collab. PRD97 (2018)

T2K

H. Tanaka, TAUP 2019

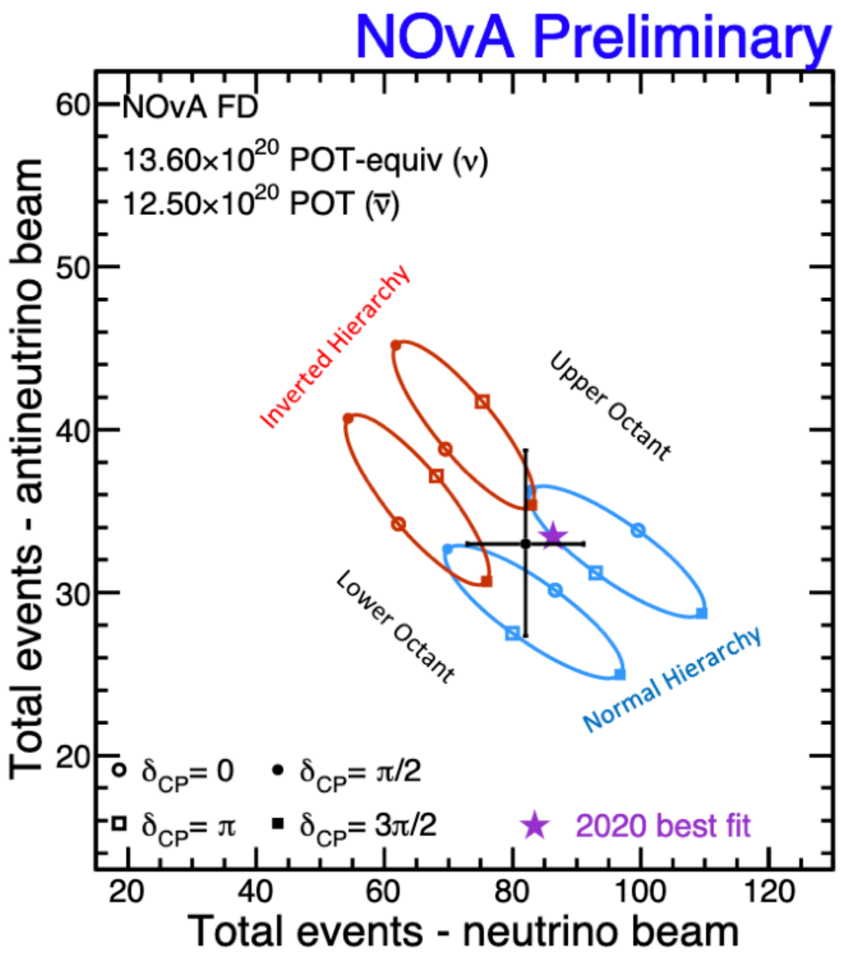
$\delta_{BF} \simeq 3\pi/2$ due to better agreement with observed ν_e and ν_e events



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

NOvA

P Vahle, TAUP 2021



The CP phase

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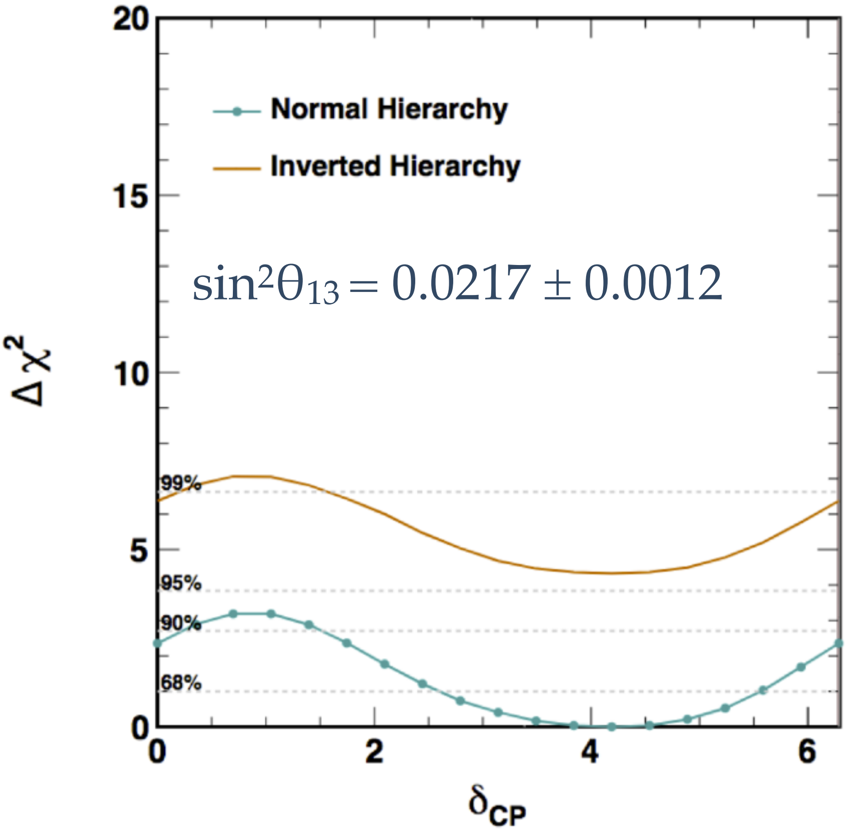
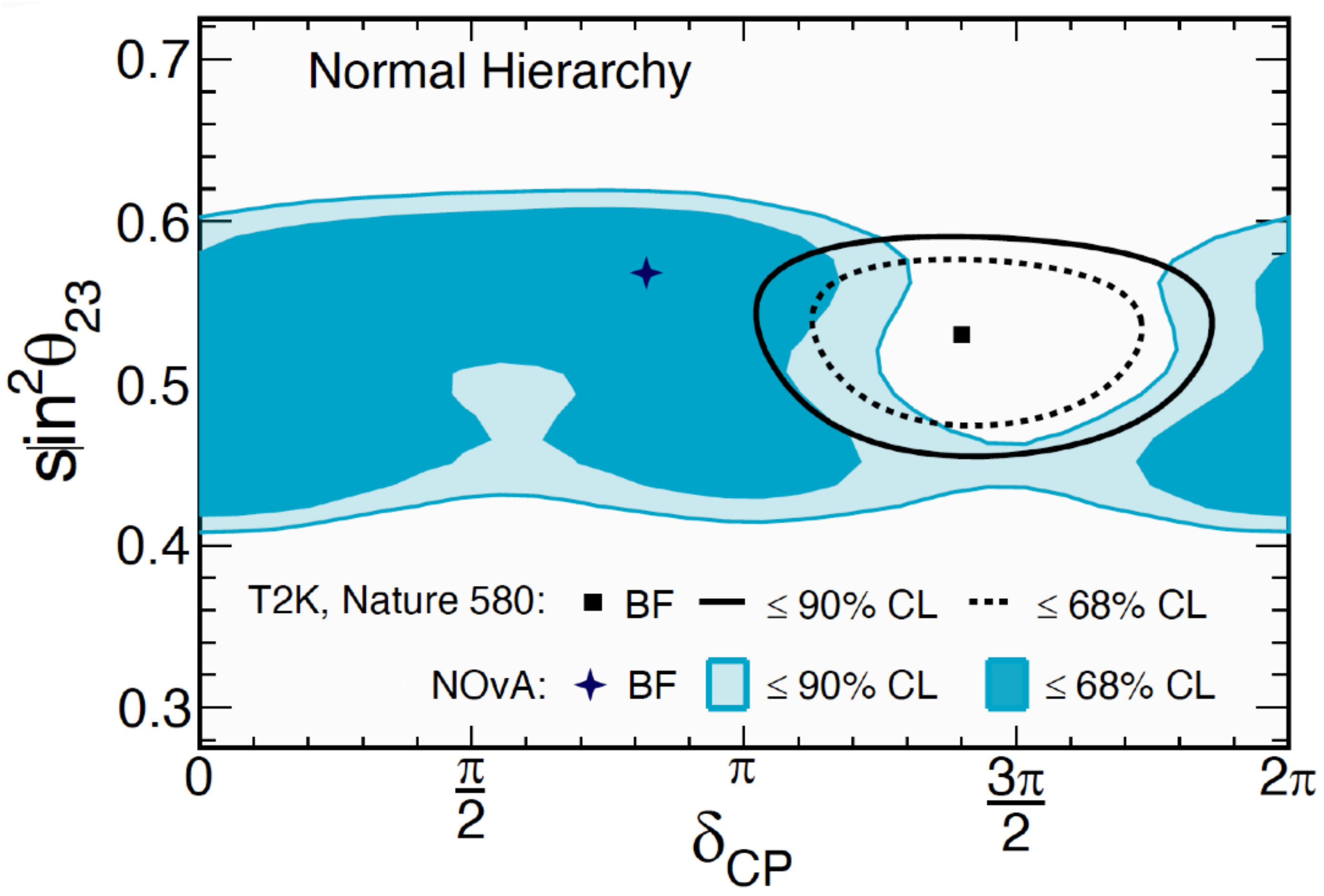


- $\delta_{BF} = 1.5\pi\ (1.2\pi)$ for NO (IO)
- preference driven by sub-GeV e-like samples

SK Collab. PRD97 (2018)

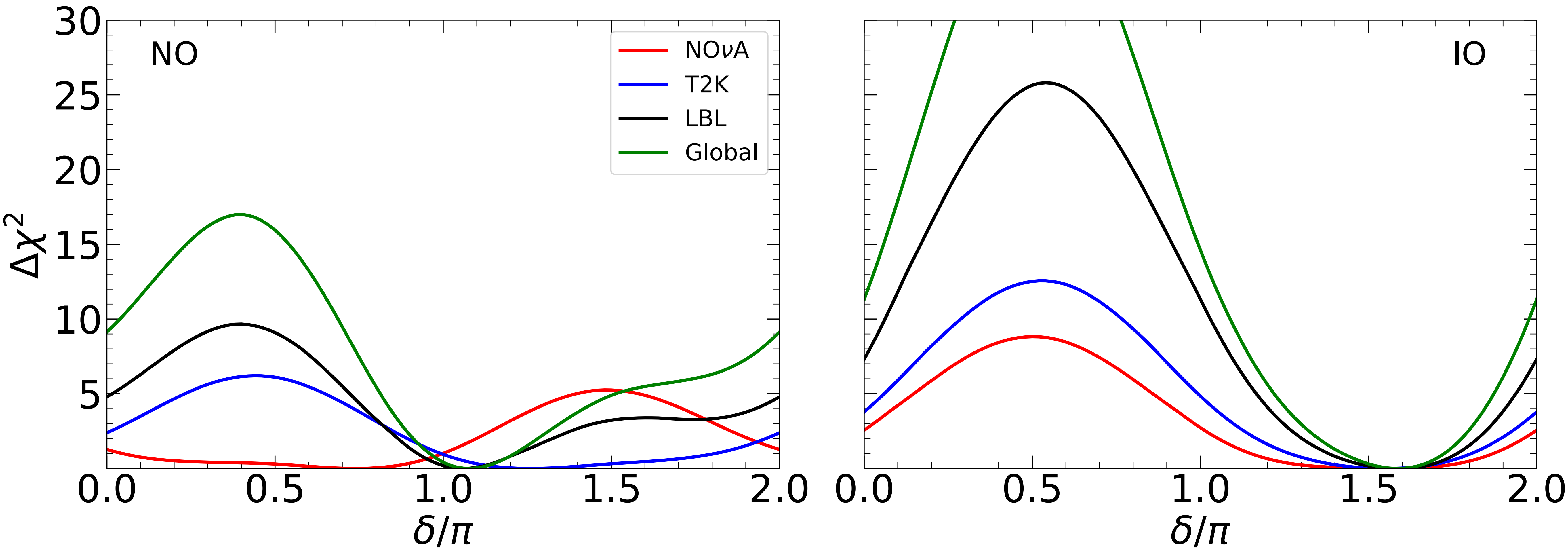
Slight tension between T2K and NOvA results for NO



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

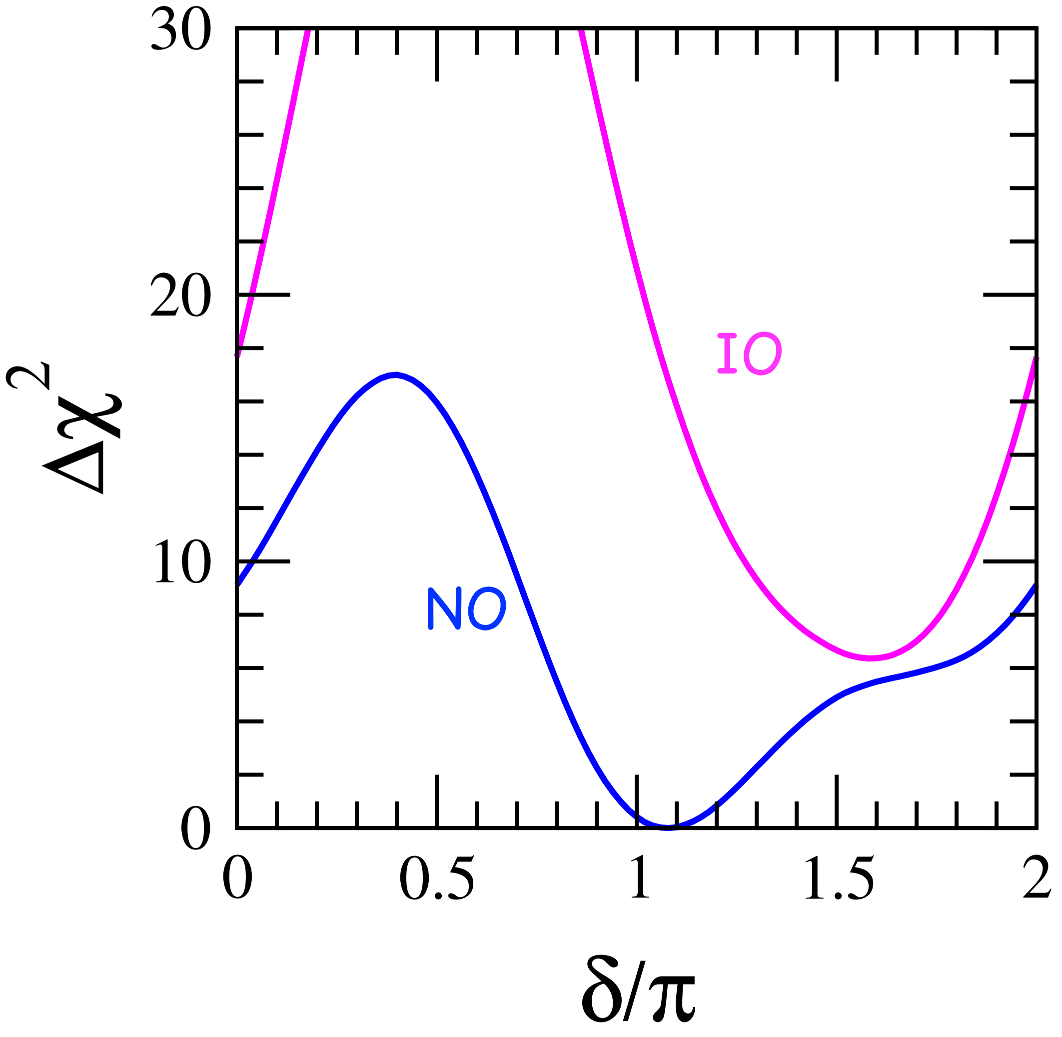
  $\delta_{BF} = 1.08\pi$; $\delta = \pi/2$ (0) disfavored at 4.0σ (3.0σ); $\delta = 3\pi/2$ with $\Delta\chi^2 = 4.9$

- IO: all experiments prefer $\delta \approx 3\pi/2$

  $\delta_{BF} = 1.58\pi$; $\delta = \pi/2$ (π) disfavored at 6.2σ (3.8σ);

The CP phase

de Salas et al, JHEP 02 (2021) 071

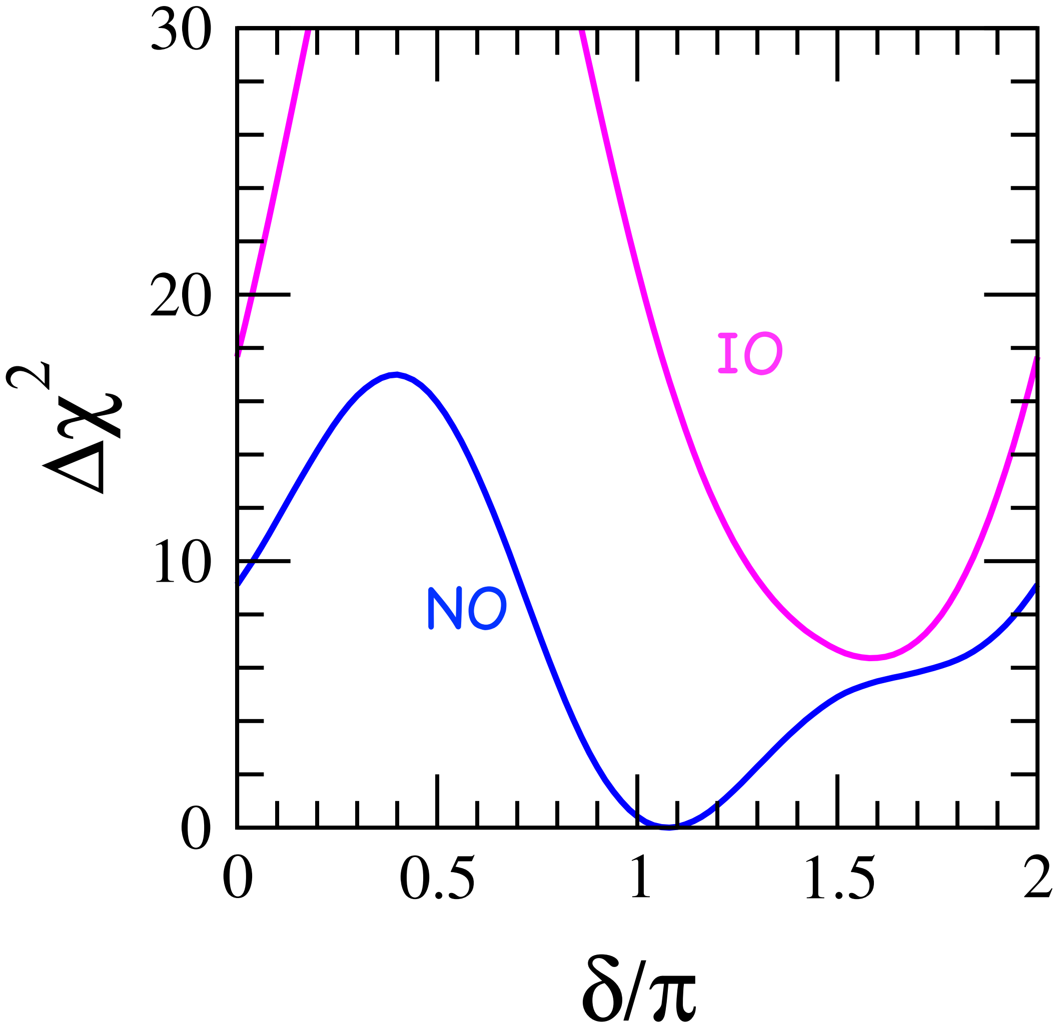


NO: δ_{BF} = 1.08π (NOvA-T2K tension)
δ= π/2 (0) disfavored at 4.0σ (3.0σ)

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

The CP phase

de Salas et al, JHEP 02 (2021) 071



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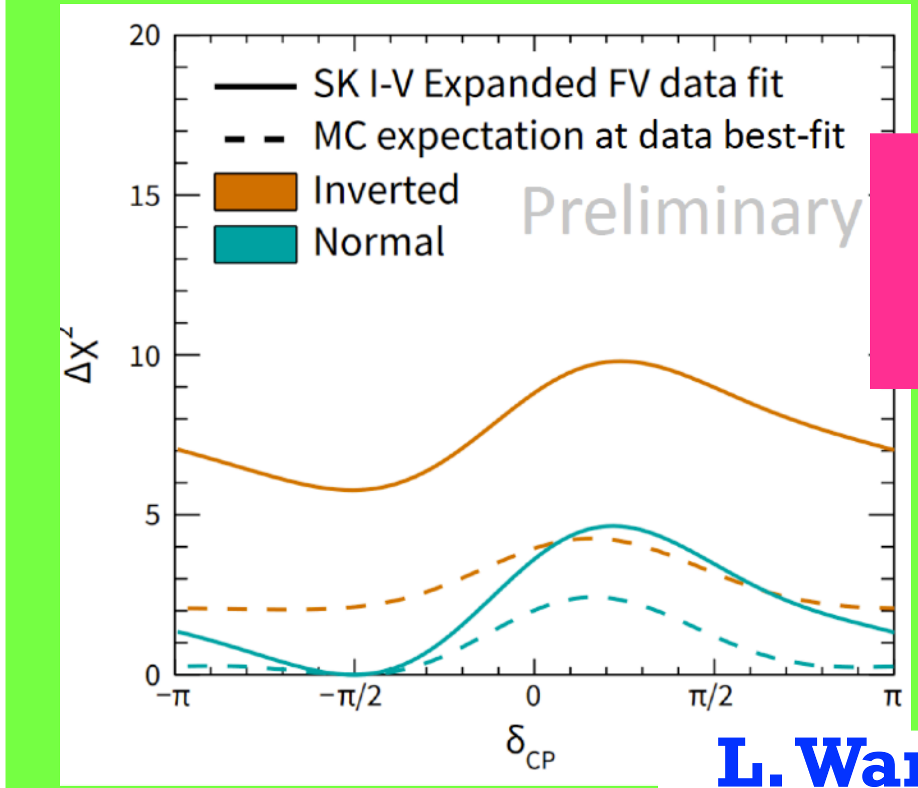
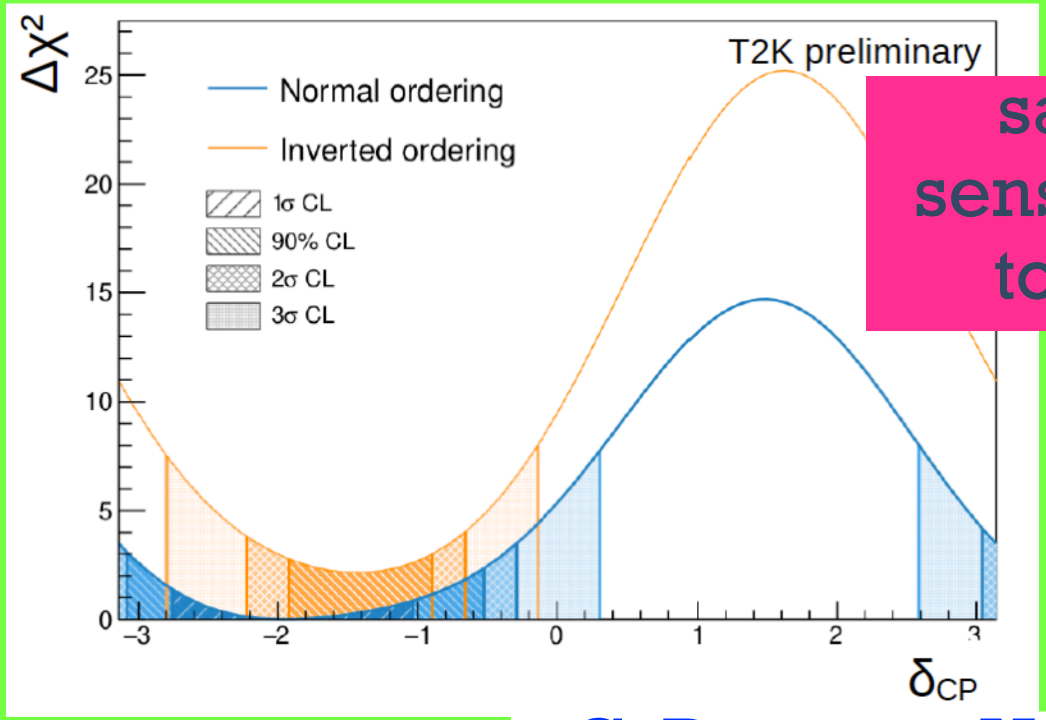
IO: δ_{BF} = 1.58π ;
δ= π/2 (π) disfavored at 6.2σ (3.8σ)



improved sensitivity to δ_{CP}

L. Wan, Nu 2022

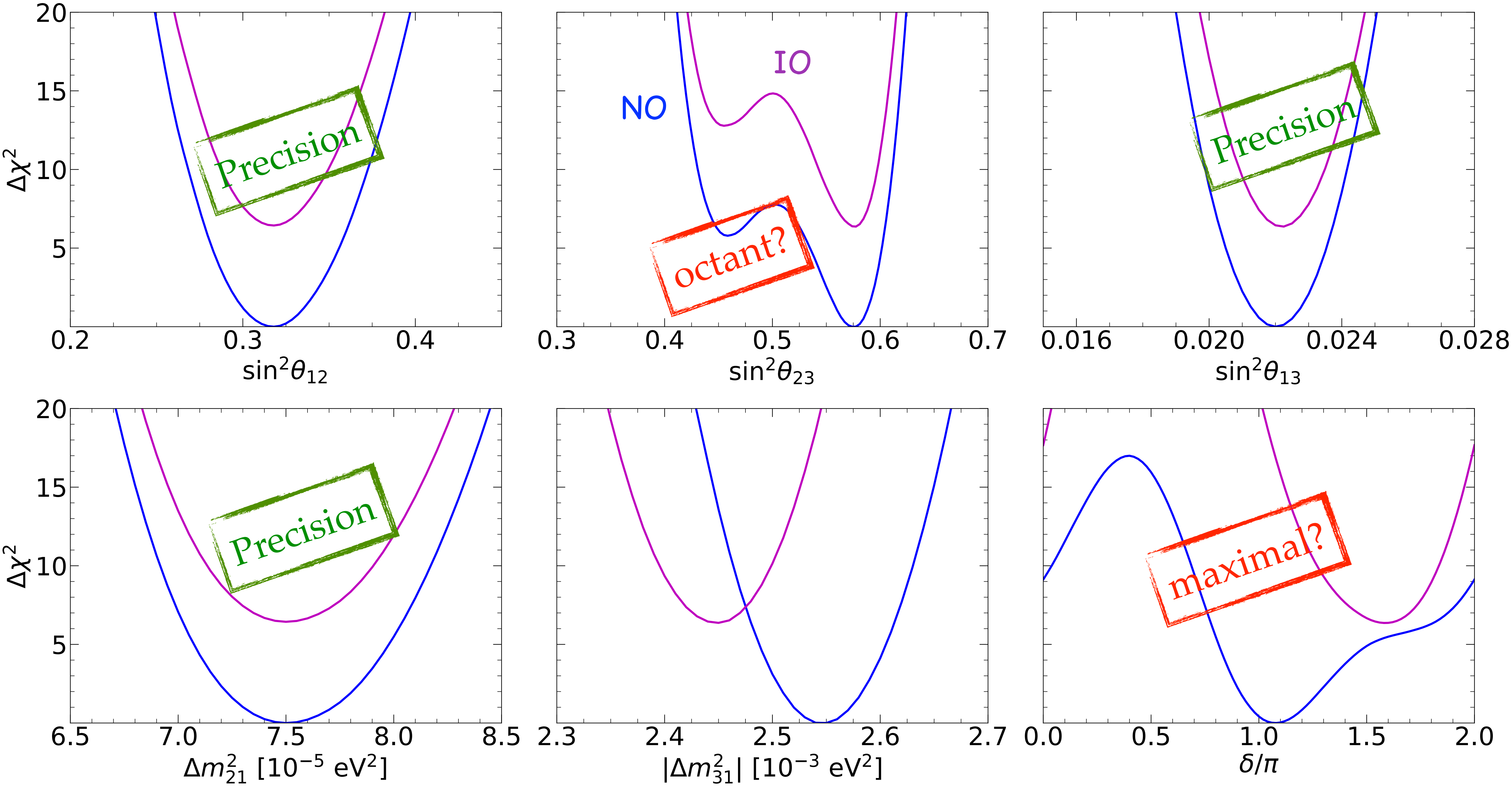


same sensitivity to δ_{CP}

C. Bronner, Nu 2022

Global fit to ν oscillation parameters

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



Global fit to ν oscillation parameters

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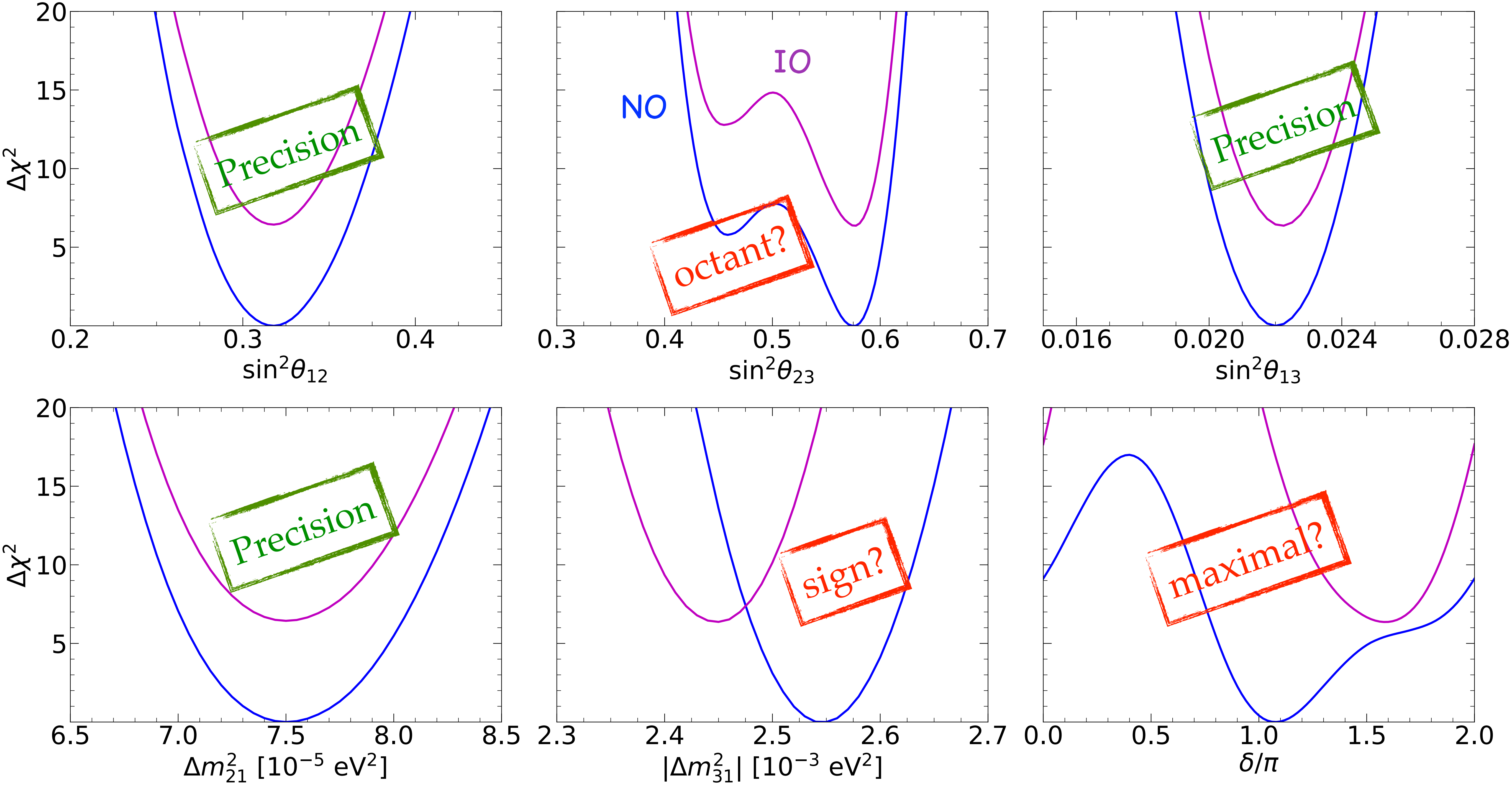
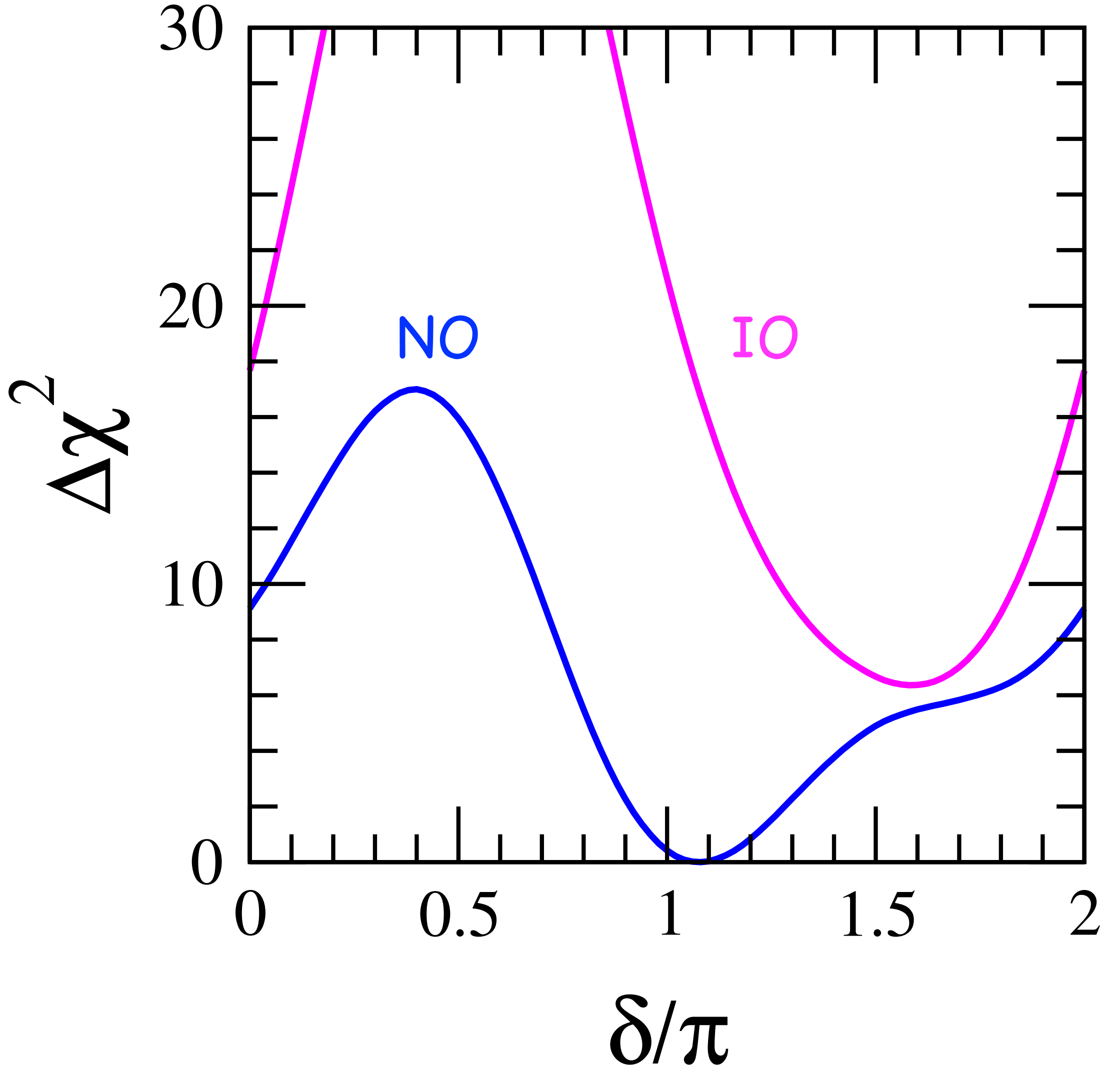


The mass ordering

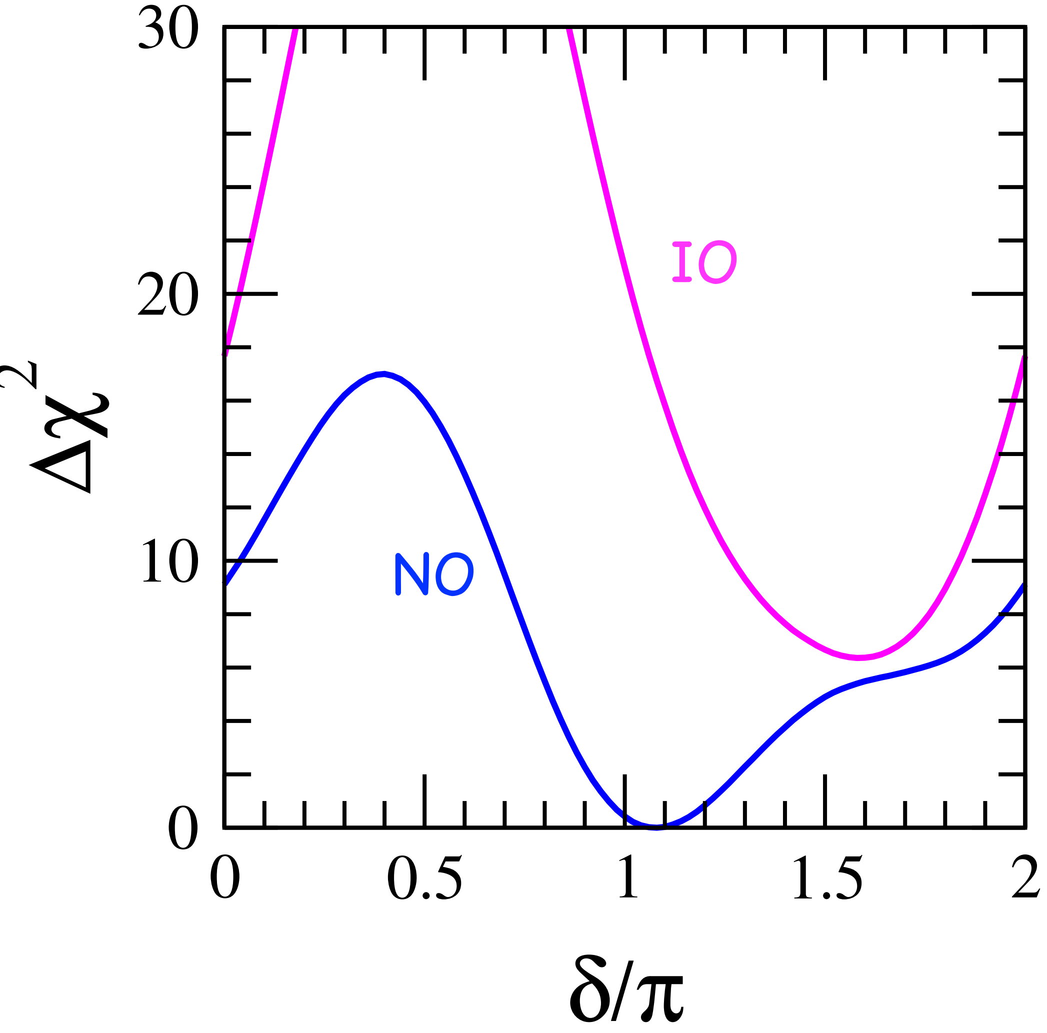
- ✦ T2K and NOvA separate analyses prefer NO with $\Delta\chi^2 \approx 0.4$
- ✦ T2K + NOvA combined prefer IO with $\Delta\chi^2 \approx 2.4$ (tension in δ for NO)
- ✦ LBL + REAC prefer NO with $\Delta\chi^2 \approx 1.4$ (tension in Δm^2_{31} measurement in IO)
- ✦ Atmos. sensitivity: Super-K ($\Delta\chi^2 \approx 3.5$) and DeepCore ($\Delta\chi^2 \approx 1.0$)
- ✦ Global fit: $\Delta\chi^2 = 6.4$ → 2.5σ preference for NO



de Salas et al, JHEP 02 (2021) 071

The mass ordering

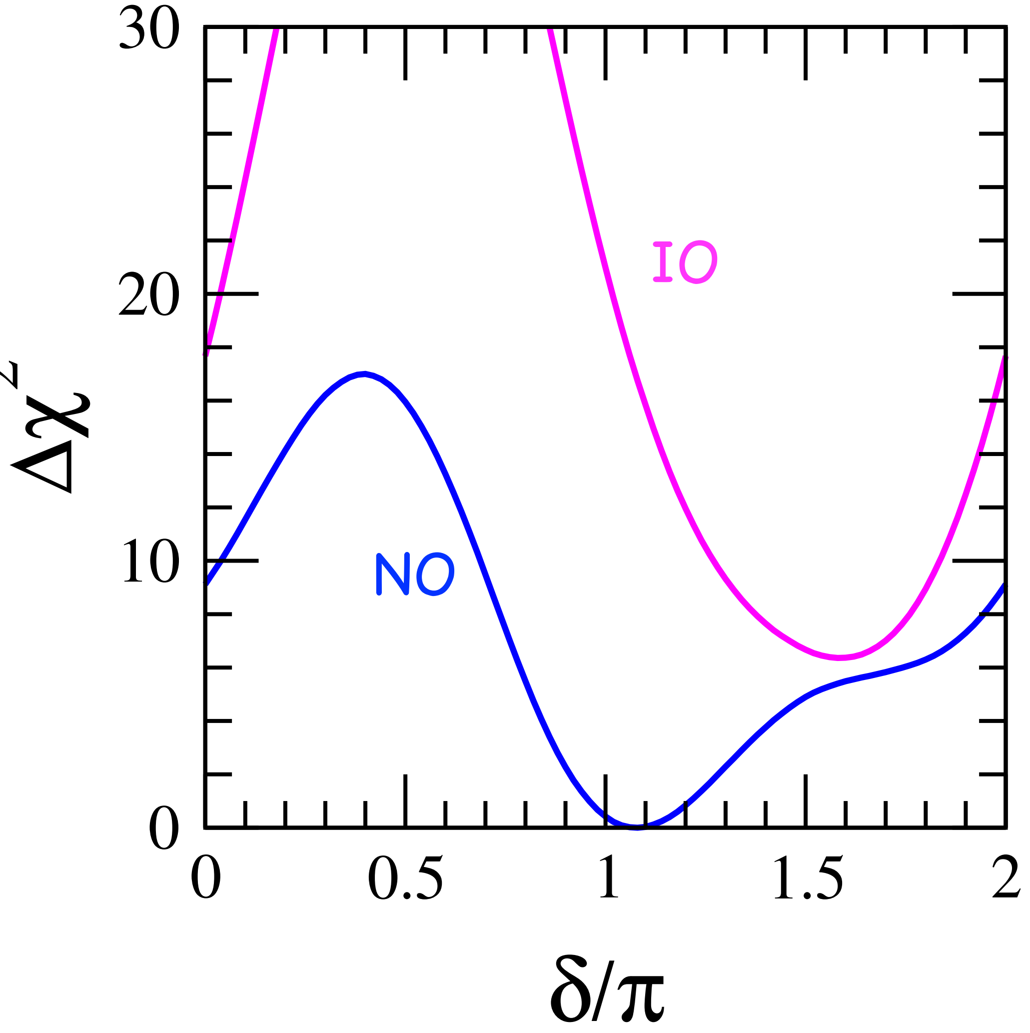
de Salas et al, JHEP 02 (2021) 071



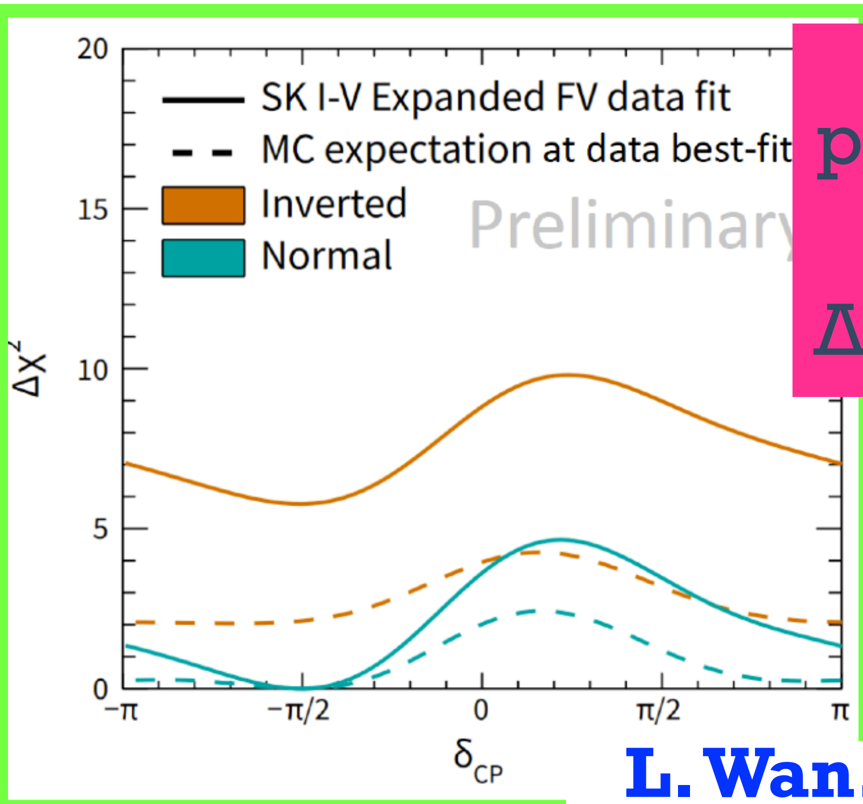
2.5σ preference for NO

The mass ordering

de Salas et al, JHEP 02 (2021) 071



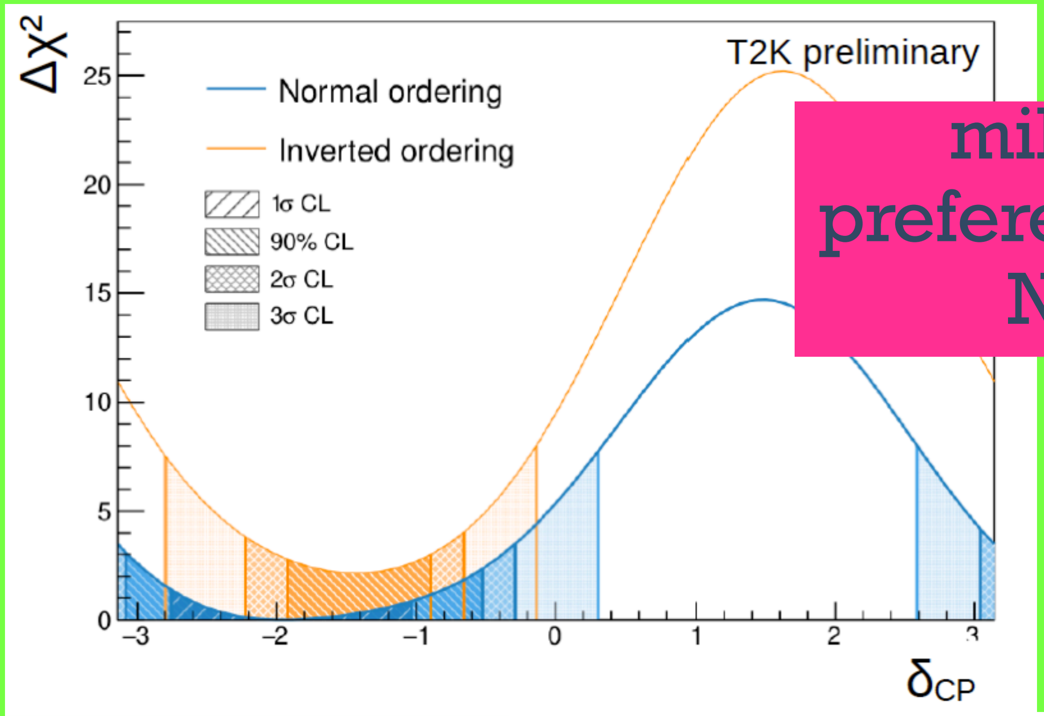
2.5σ preference for NO



higher preference for NO:

$\Delta\chi^2 = 3.5 \rightarrow 5.8$

L. Wan, Nu 2022



milder preference for NO

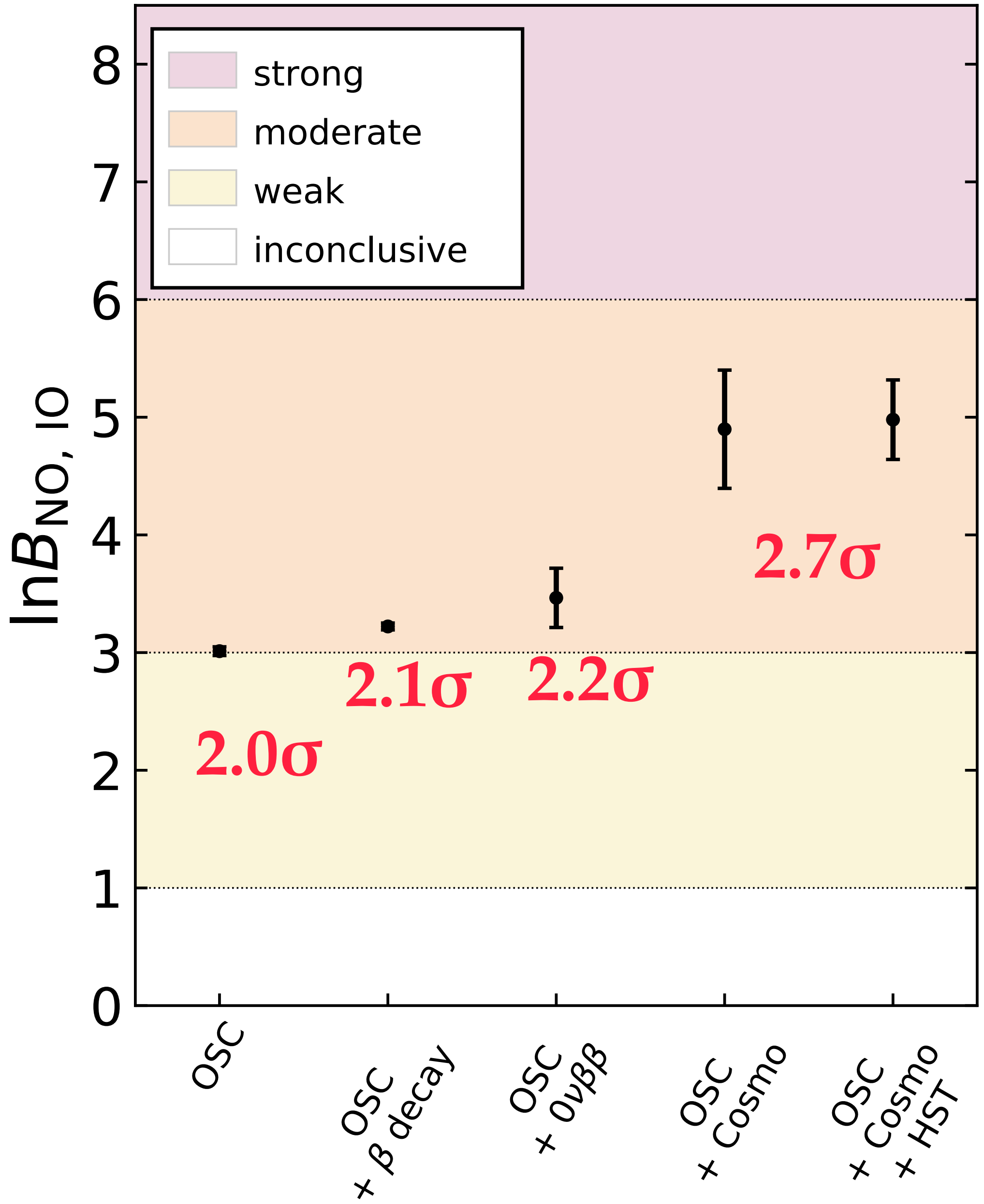
C. Bronner, Nu 2022

Other inputs for mass ordering?

Experimental sensitivity to neutrino masses:

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

de Salas et al, JHEP 02 (2021) 071



Results from the combined bayesian analysis:

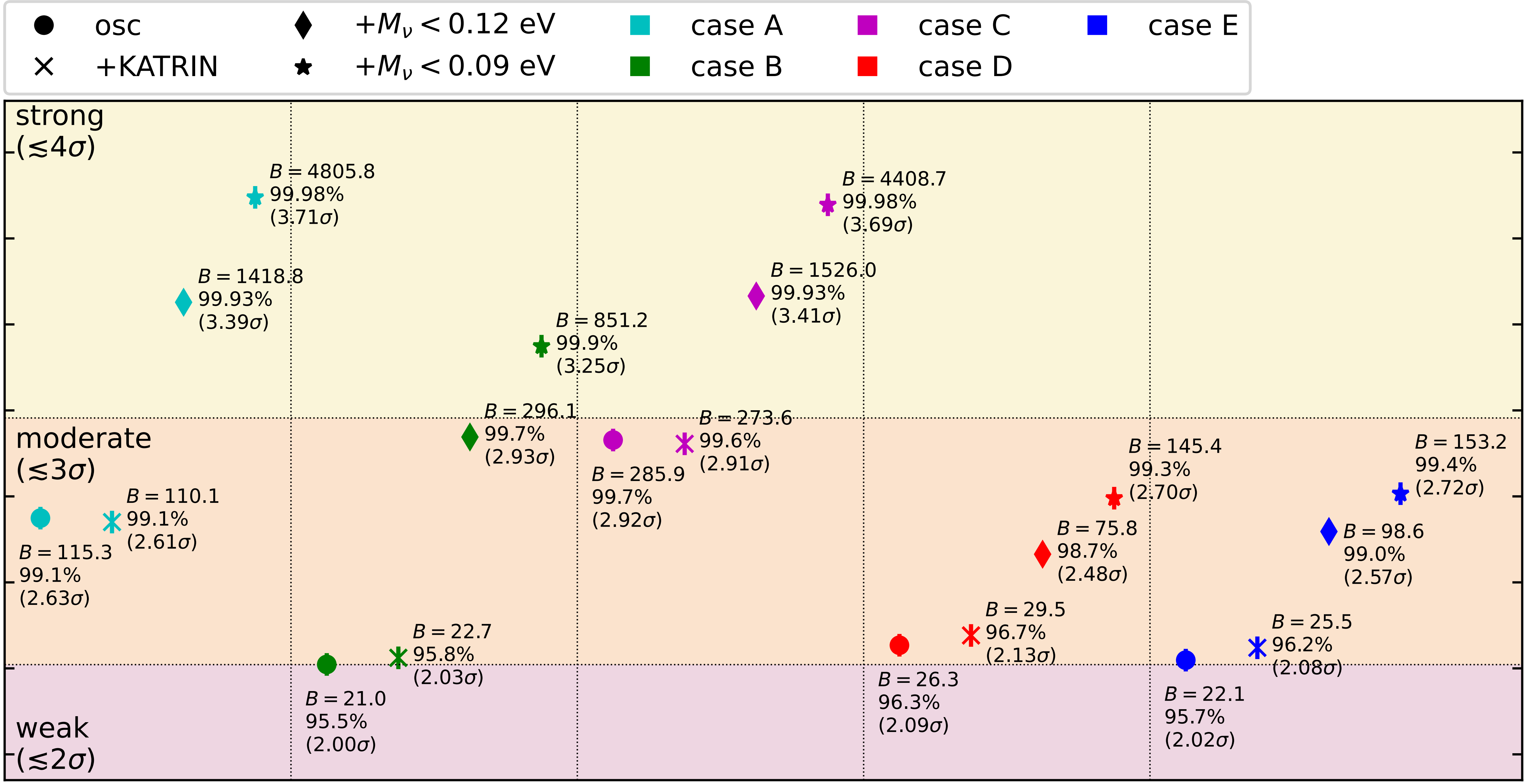
⇒ weak/moderate preference for NO driven by oscillation data (2.0σ)

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

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

Preference for NO (with OSC)

Gariazzo et al, 2205.02195



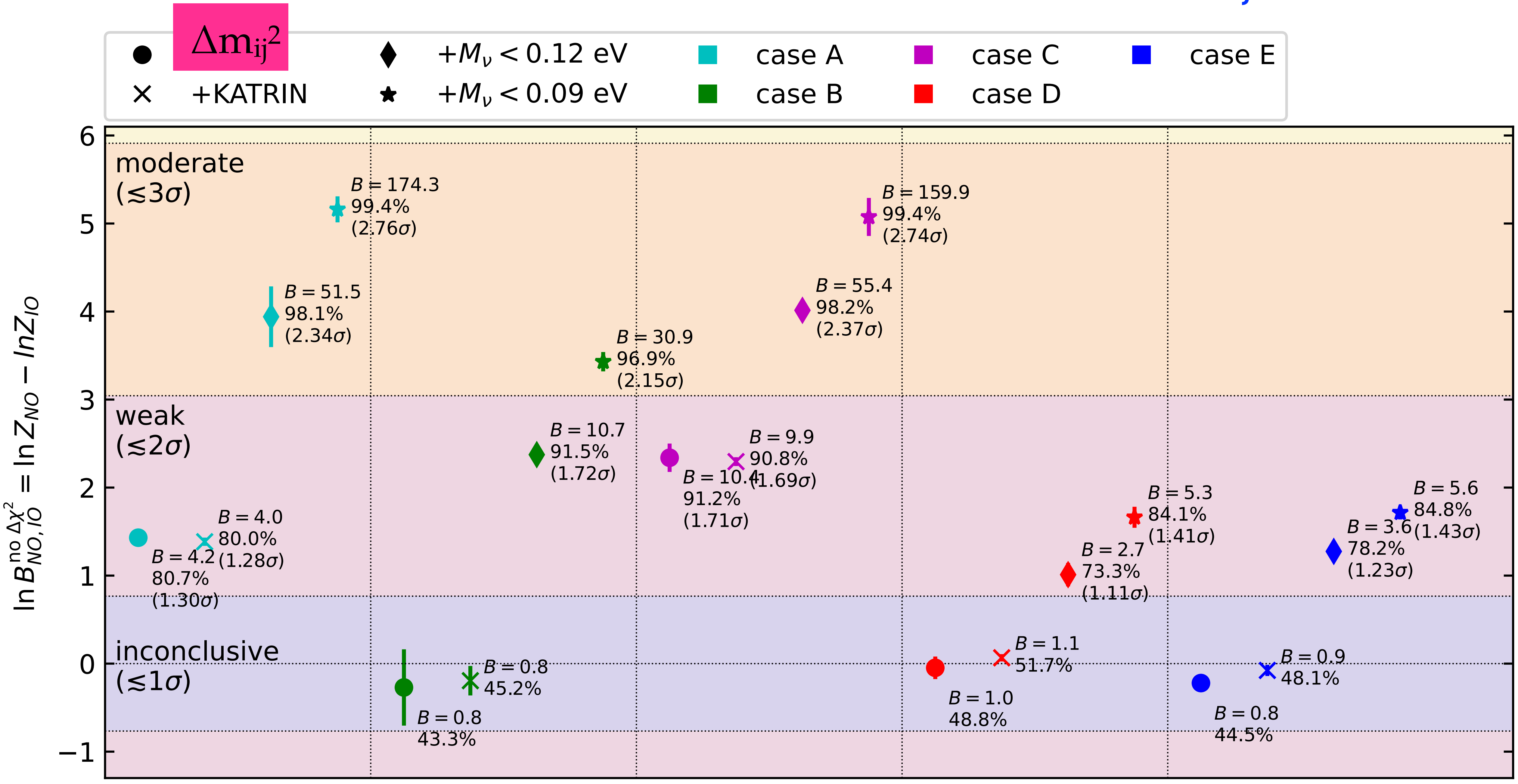
log m_i (gauss) | m_i | log m_i | log m_0 (m_0) | Σm

independent prior on the 3 masses

+ priors on Δm^2_{ij}

Preference for NO (without OSC)

Gariazzo et al, 2205.02195



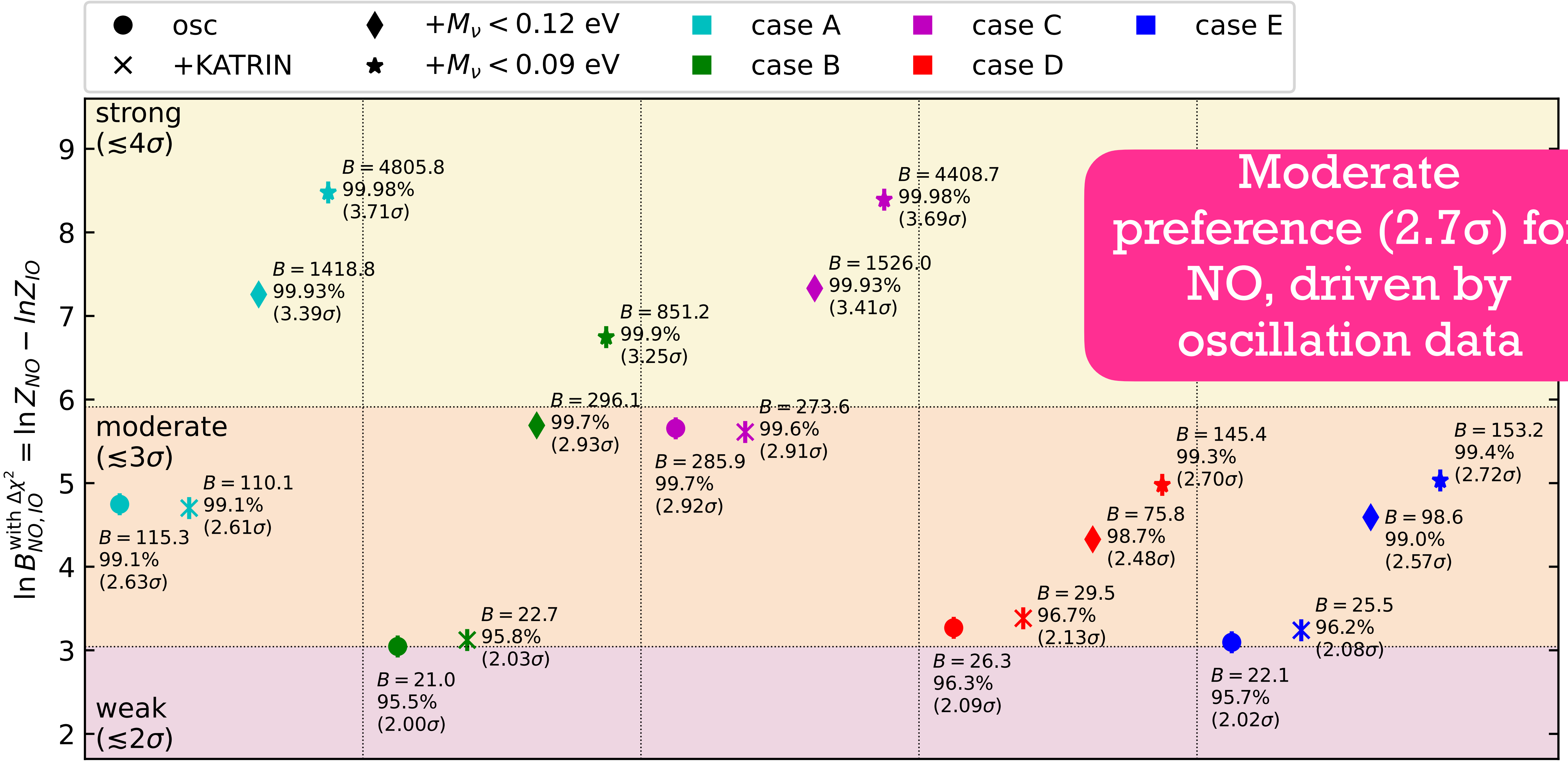
$\log m_i$ (gauss) m_i $\log m_i$ $\log m_0$ (m_0) Σm

independent prior on the 3 masses

+ priors on Δm^2_{ij}

Preference for NO (with OSC)

Gariazzo et al, 2205.02195



Moderate preference (2.7σ) for NO, driven by oscillation data

log m_i (gauss) m_i log m_i log m_0 (m_0) Σm

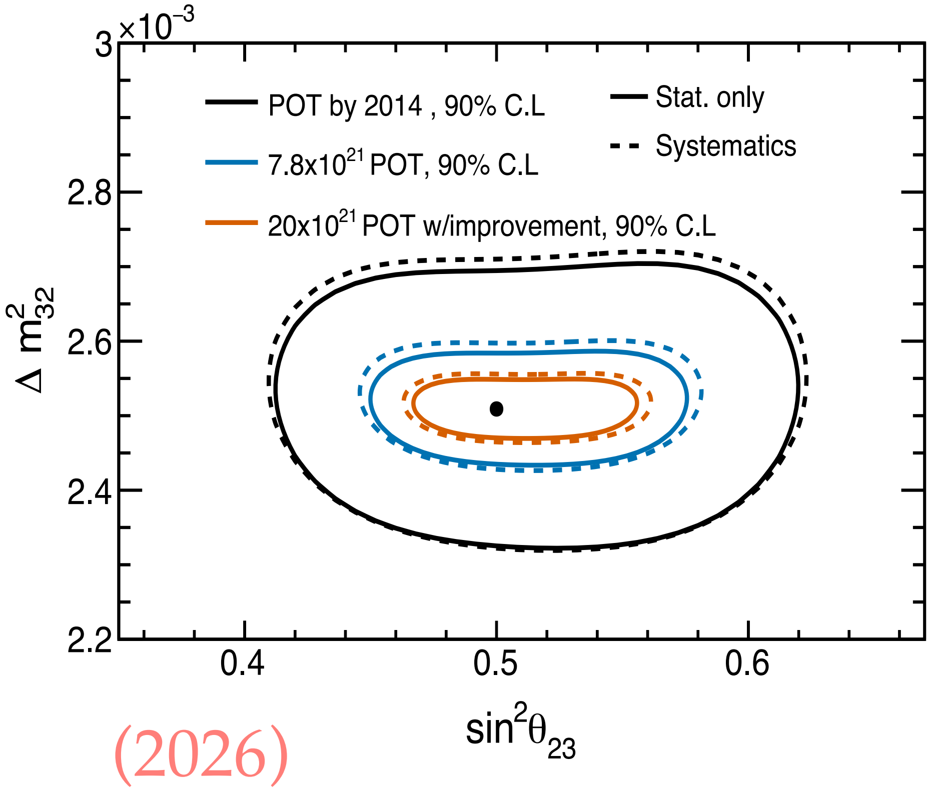
independent prior on the 3 masses

+ priors on Δm^2_{ij}

Future prospects in neutrino oscillations

Prospects for precision

T2K **Abe et al, 1609.04111**

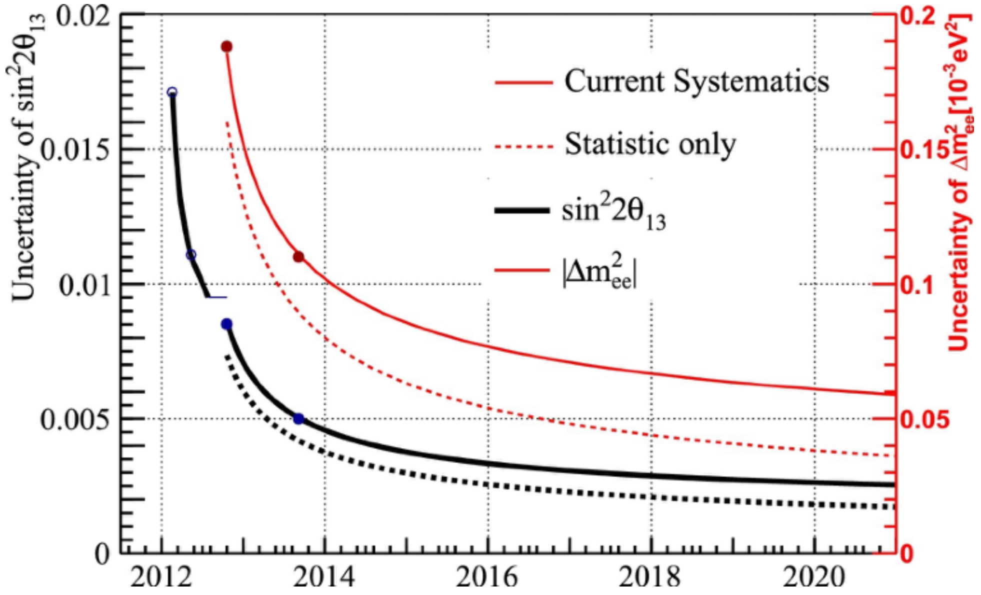


(2026)

~1% precision on Δm^2_{32}

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

DayaBay

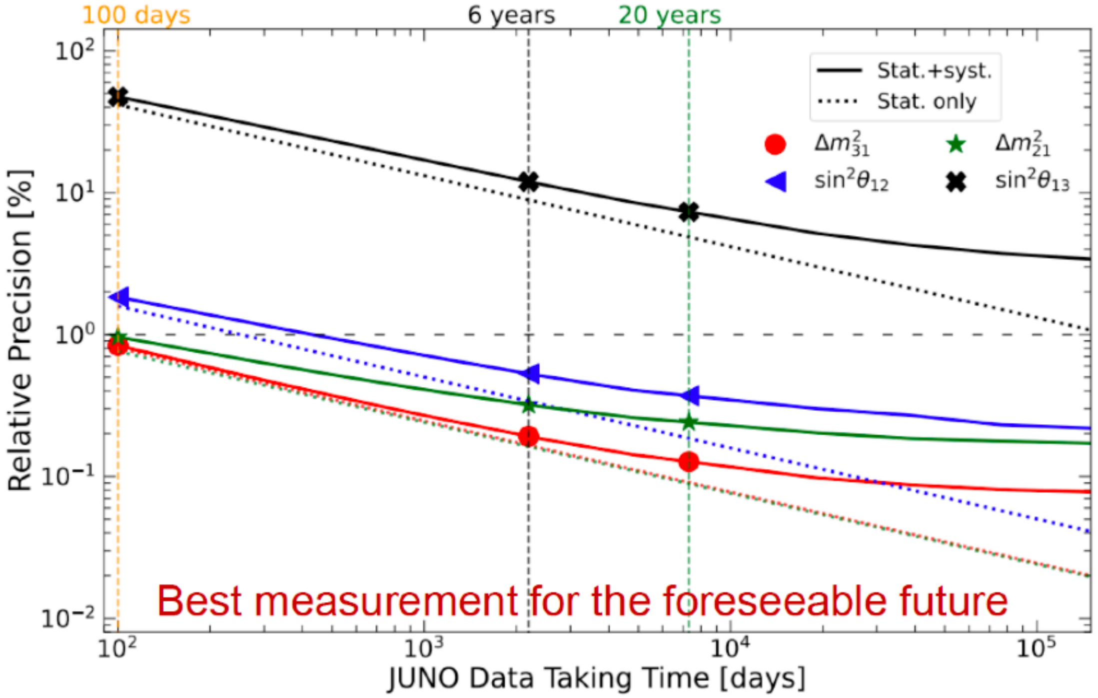


Cao and Luk, 1605.01502

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

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

JUNO (also SNO+)



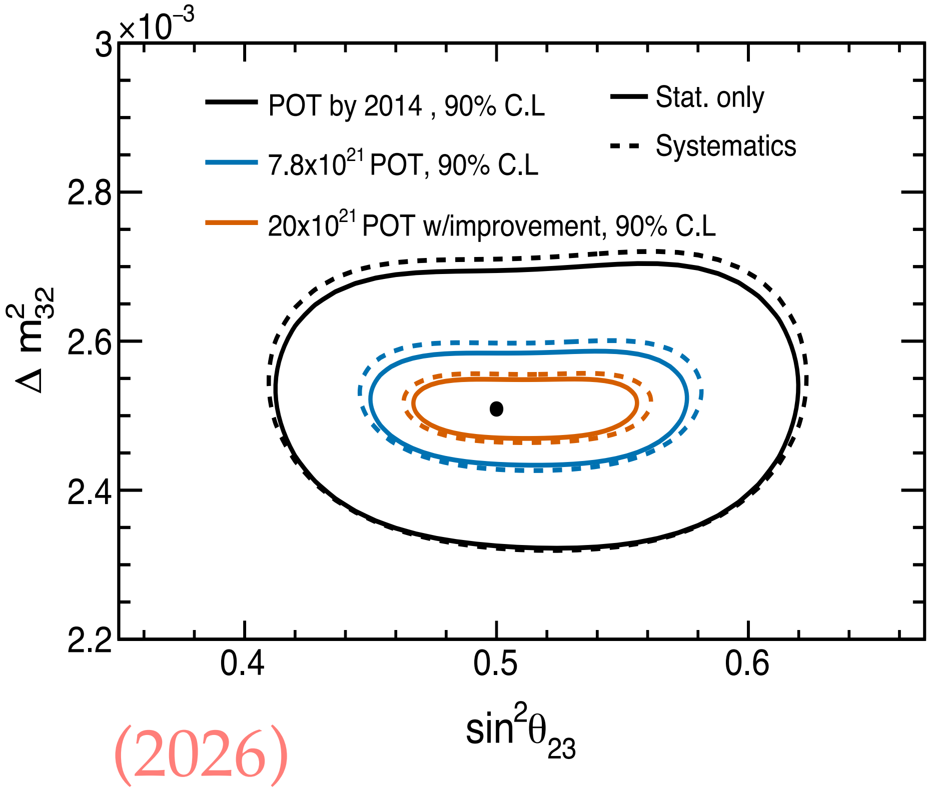
6 years:

< 0.5% precision on $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$

J. Zhao, Neutrino 2022

Prospects for precision

T2K **Abe et al, 1609.04111**



(2026)

~1% precision on Δm^2_{32}

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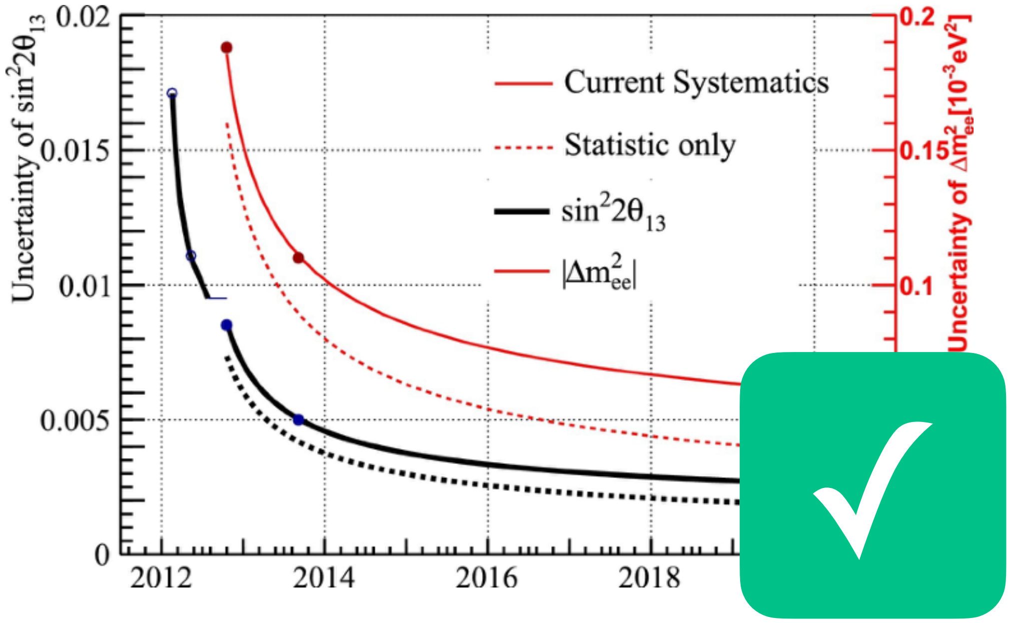
DayaBay



Cao and Luk, 1605.01502

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

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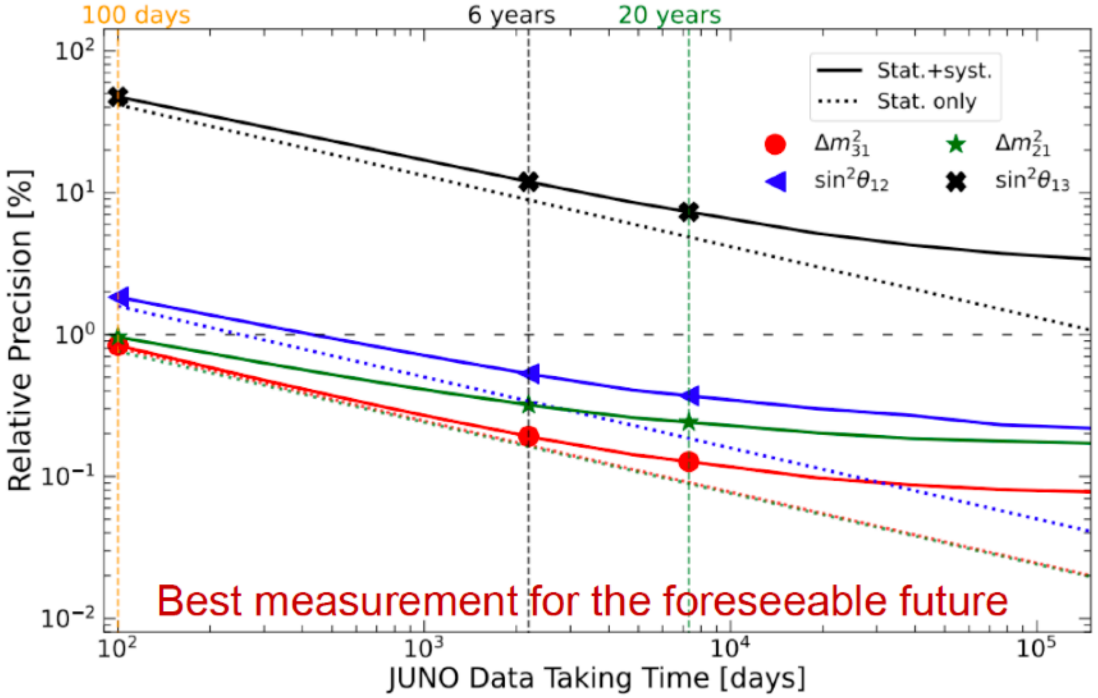


6 years:

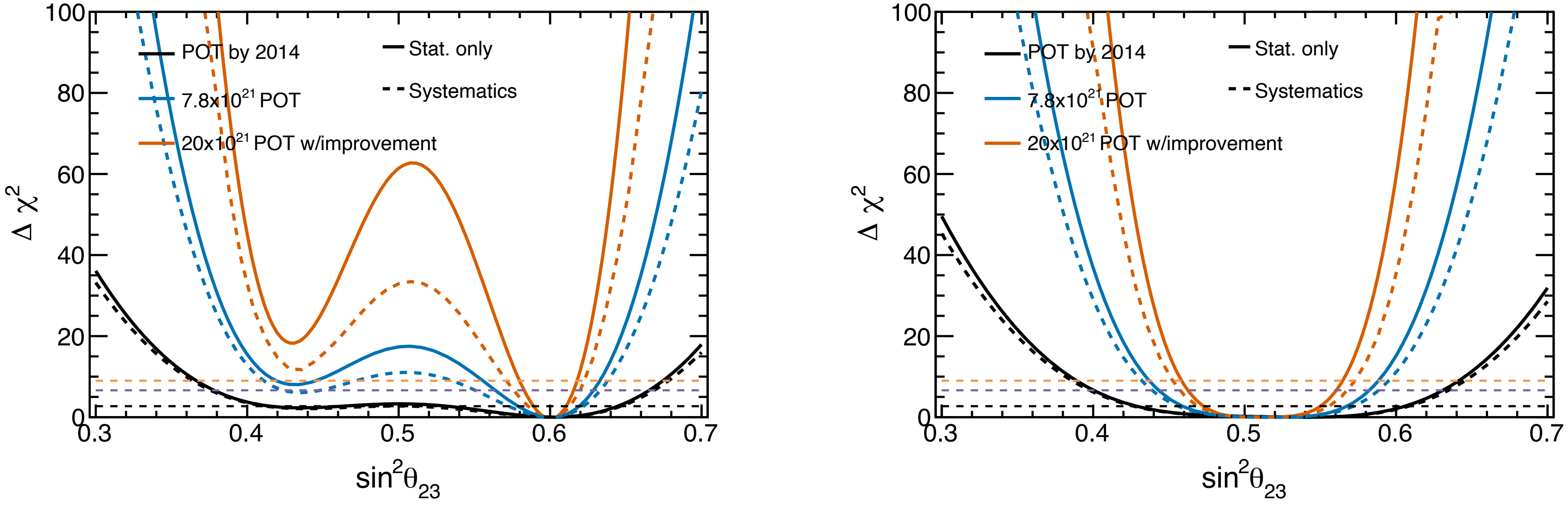
< 0.5% precision on $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$

J. Zhao, Neutrino 2022

Prospects for atmospheric octant

T2K

Abe et al, 1609.04111



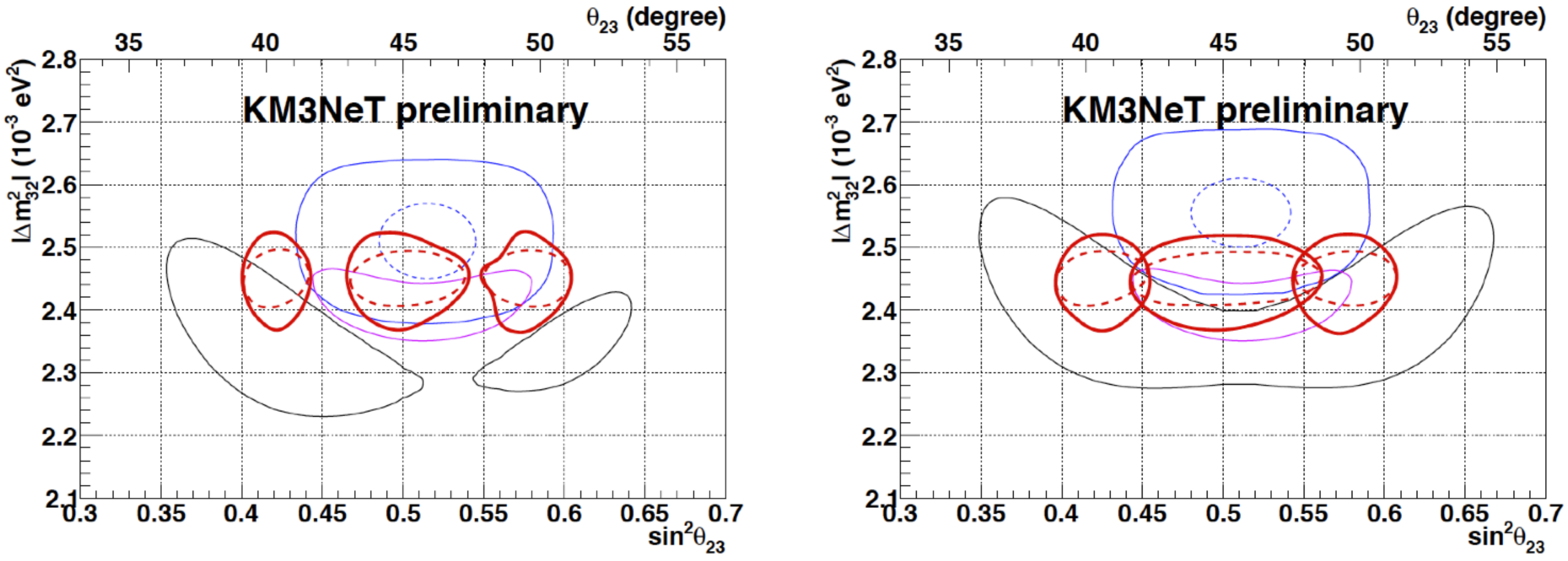
octant degeneracy can be resolved at ≳ 3σ for $\sin^2\theta_{23}$=0.60, 0.43

ORCA

Adrian-Martinez et al, 1601.07459

3 years of data

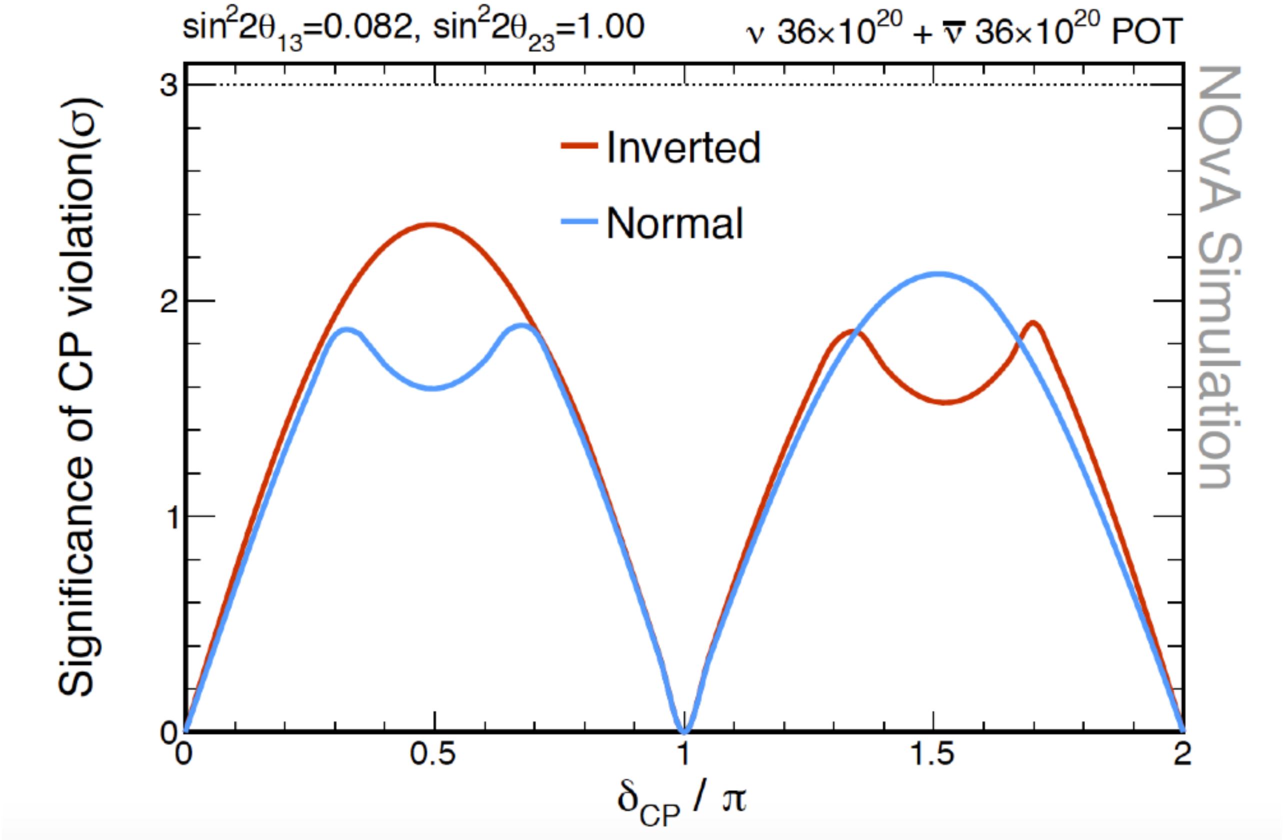
1σ contours

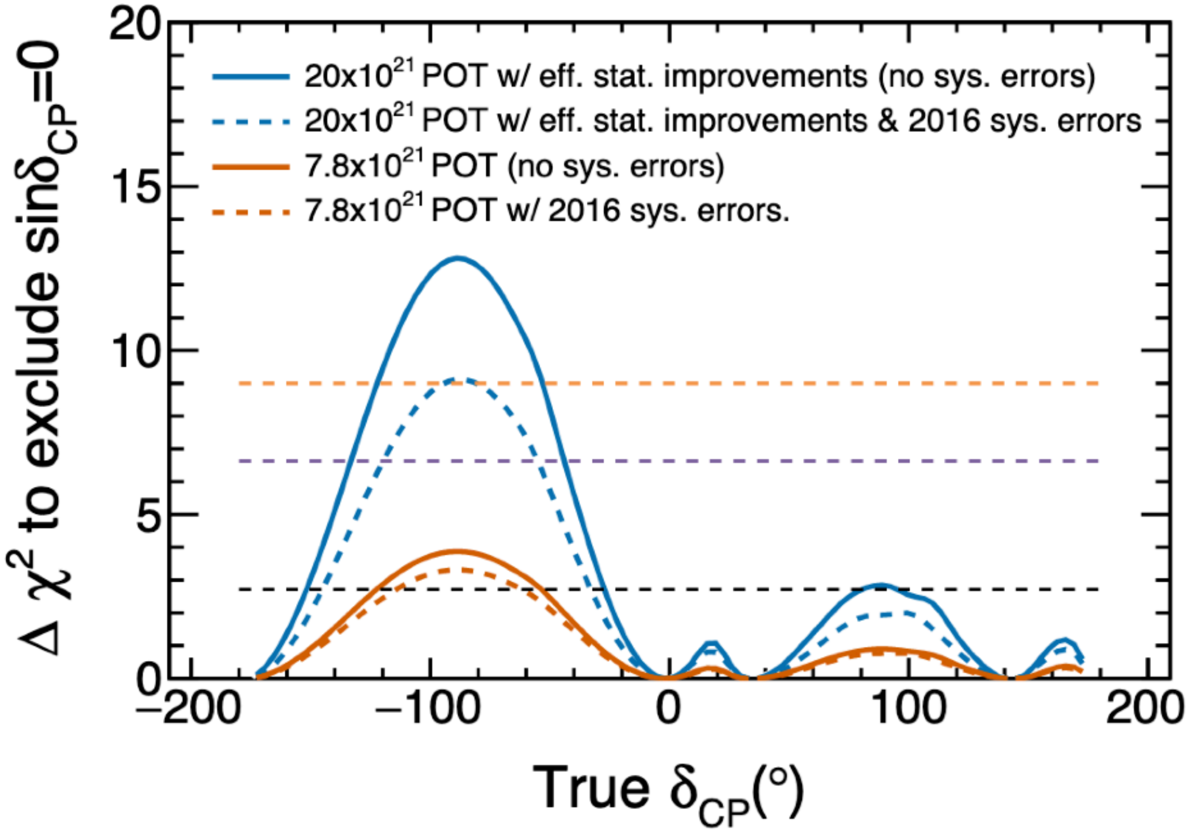


Prospects for CP violation

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

T2K **Abe et al, 1609.04111**



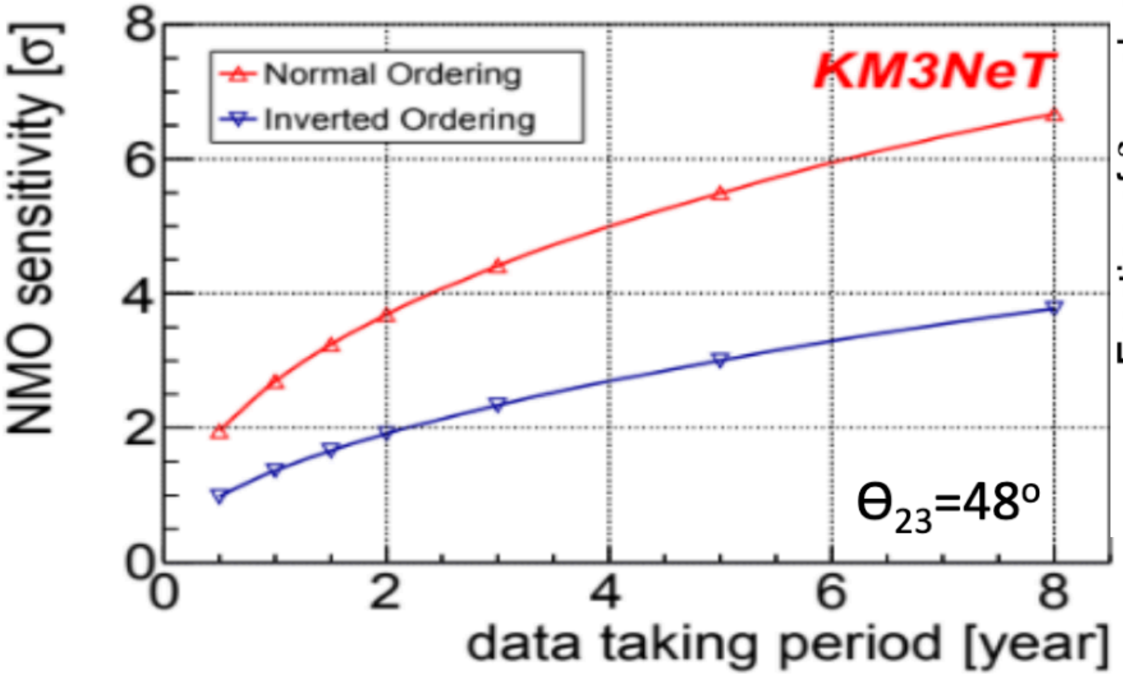


- ✦by 2026 (60-70 x 10^{20} POT):
  ~ 2σ sensitivity on CP violation at max CP violation (π/2 & 3π/2)

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

Prospects for mass ordering

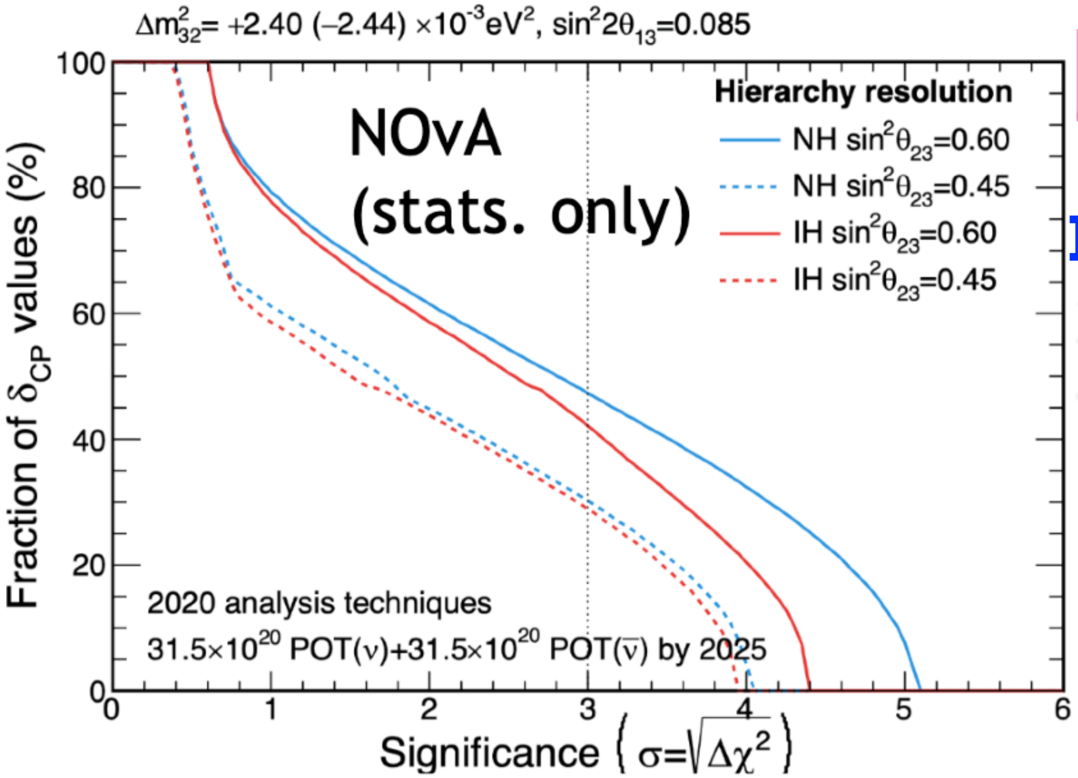
ORCA



- ✦ 3σ determination of MO in 4-5 yr

A. Heijboer, Neutrino 2022

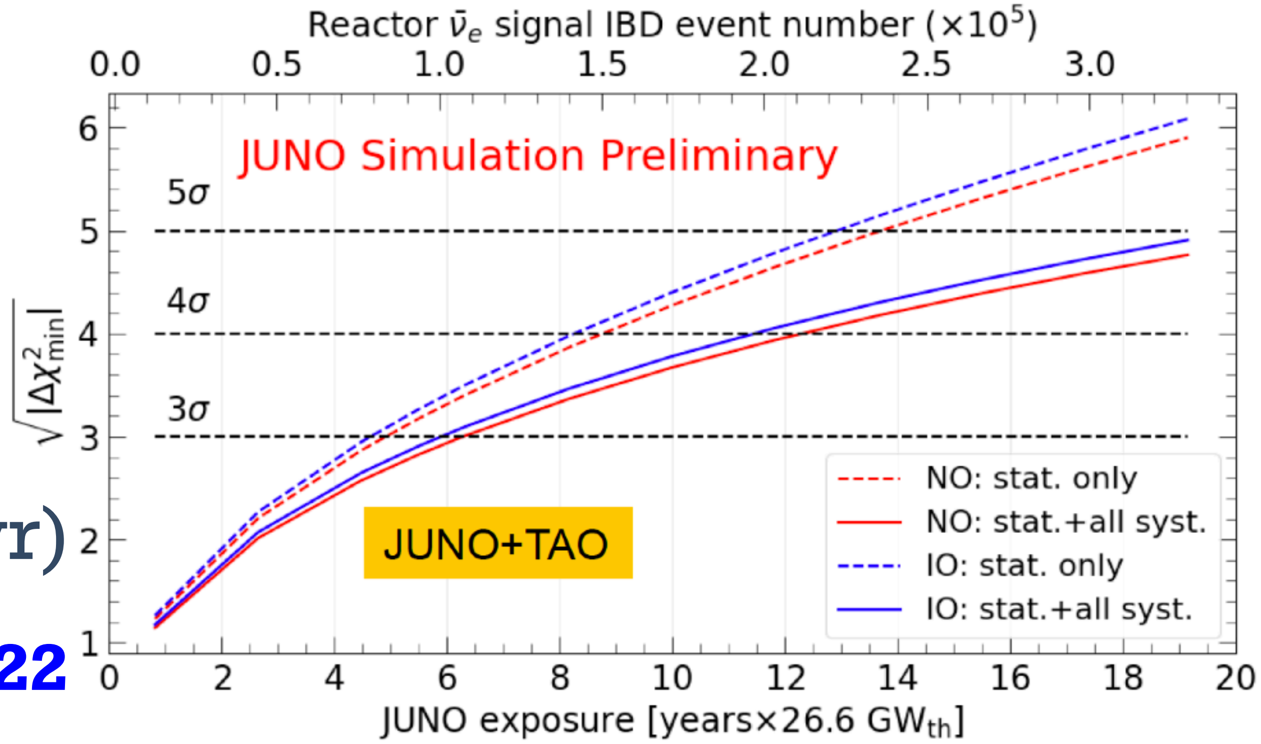
NOvA



P. Vahle, TAUP'21

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

JUNO

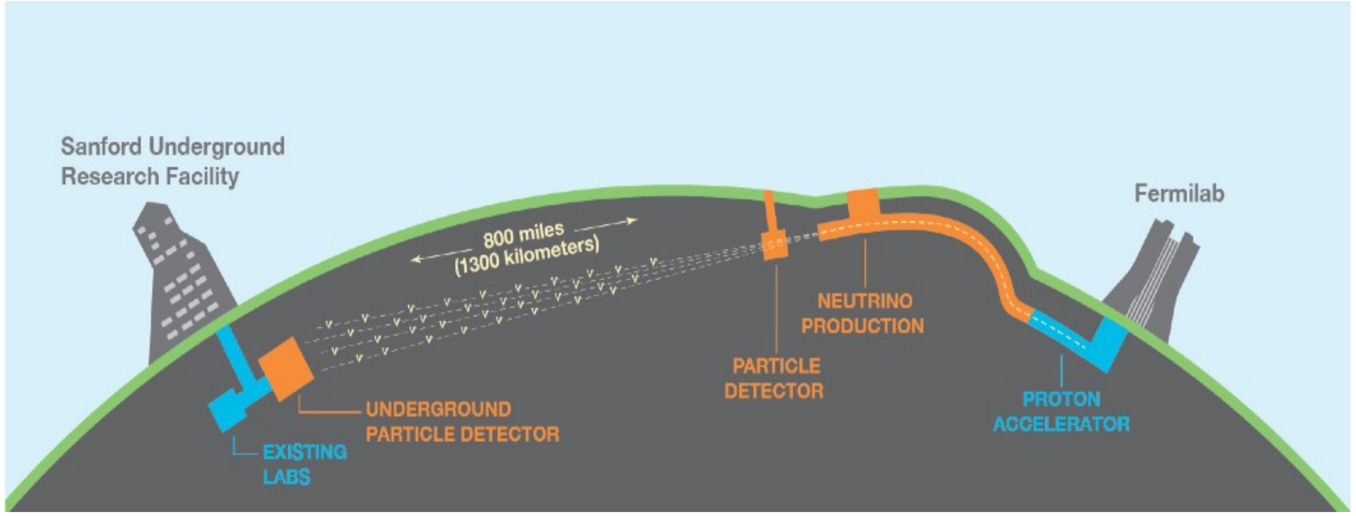


- ✦ 3σ sensitivity (6 yr)

J. Zhao, Neutrino 2022

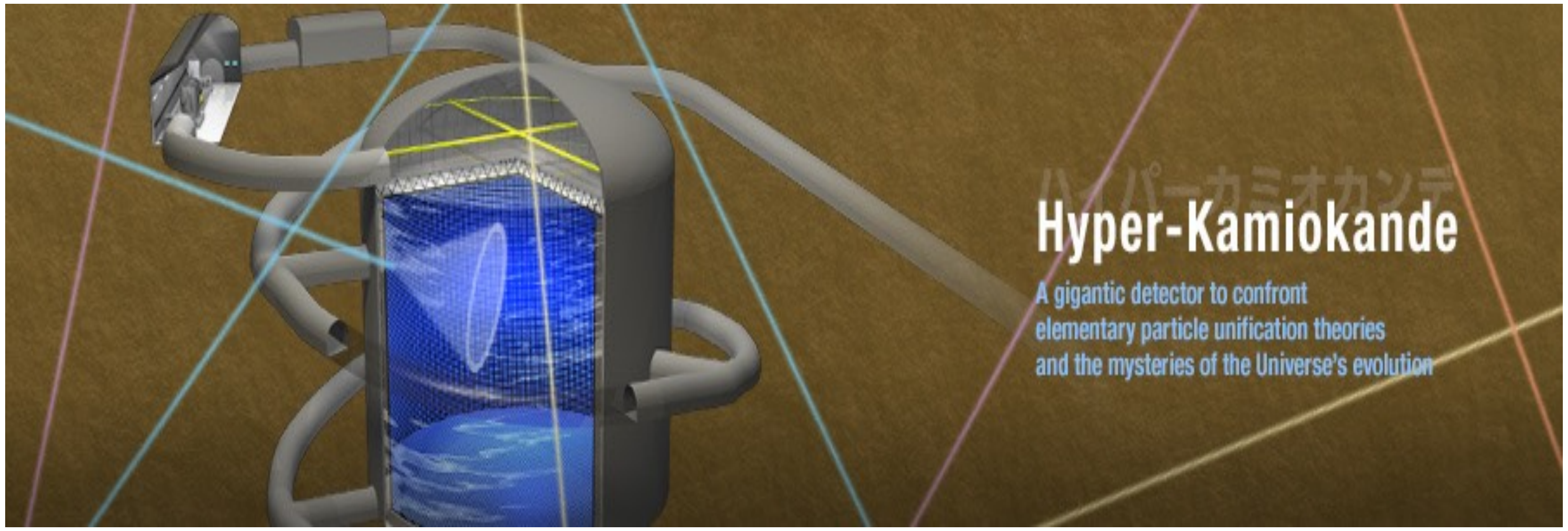
Next generation of ν experiments

DUNE



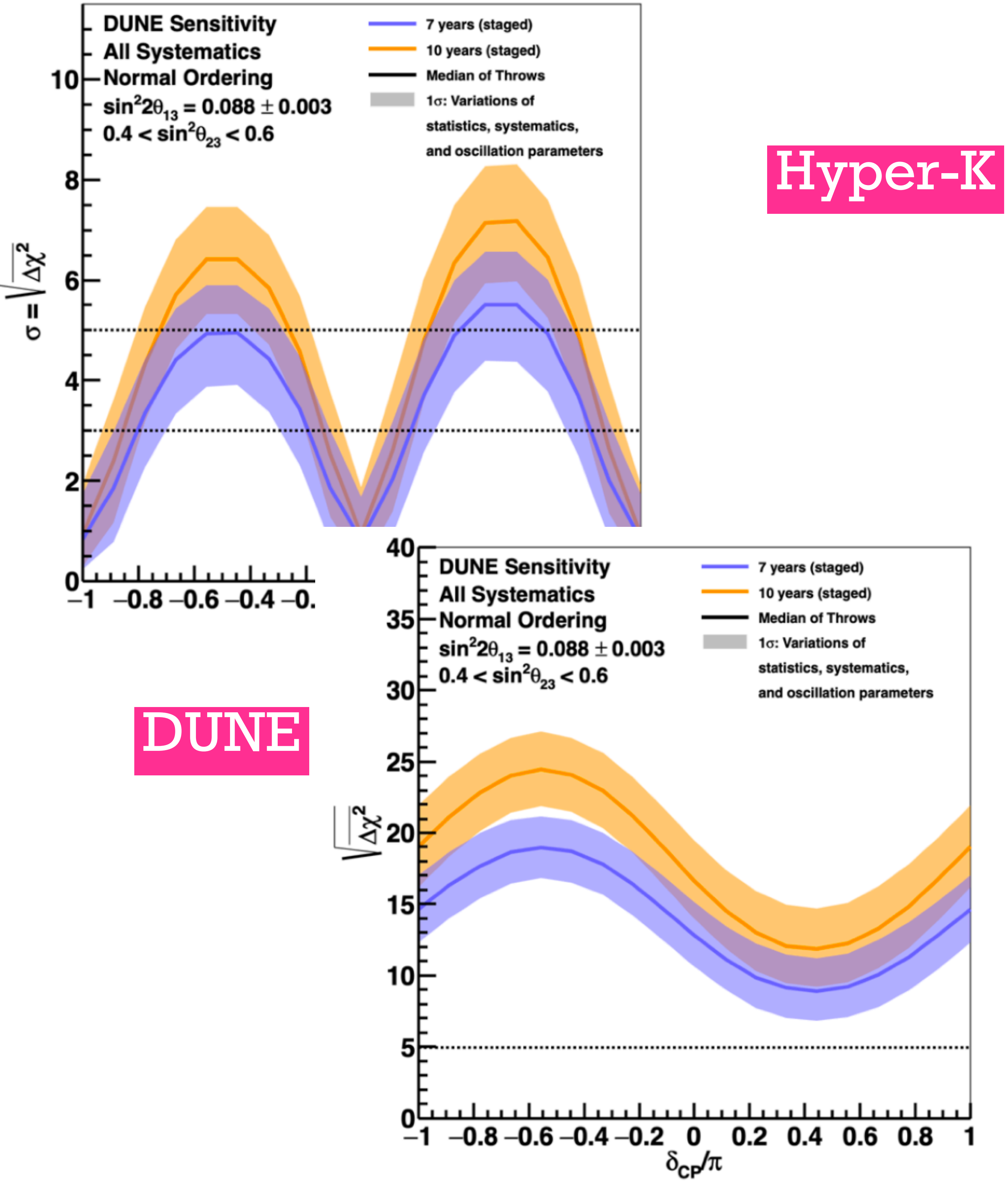
- 1.2 MW wide-band beam from FNAL to SURF (1300km)
- 4x10 kt Liquid Argon TPCs
- capability to probe 2nd oscillation max
- great sensitivity to mass ordering

Hyper-Kamiokande



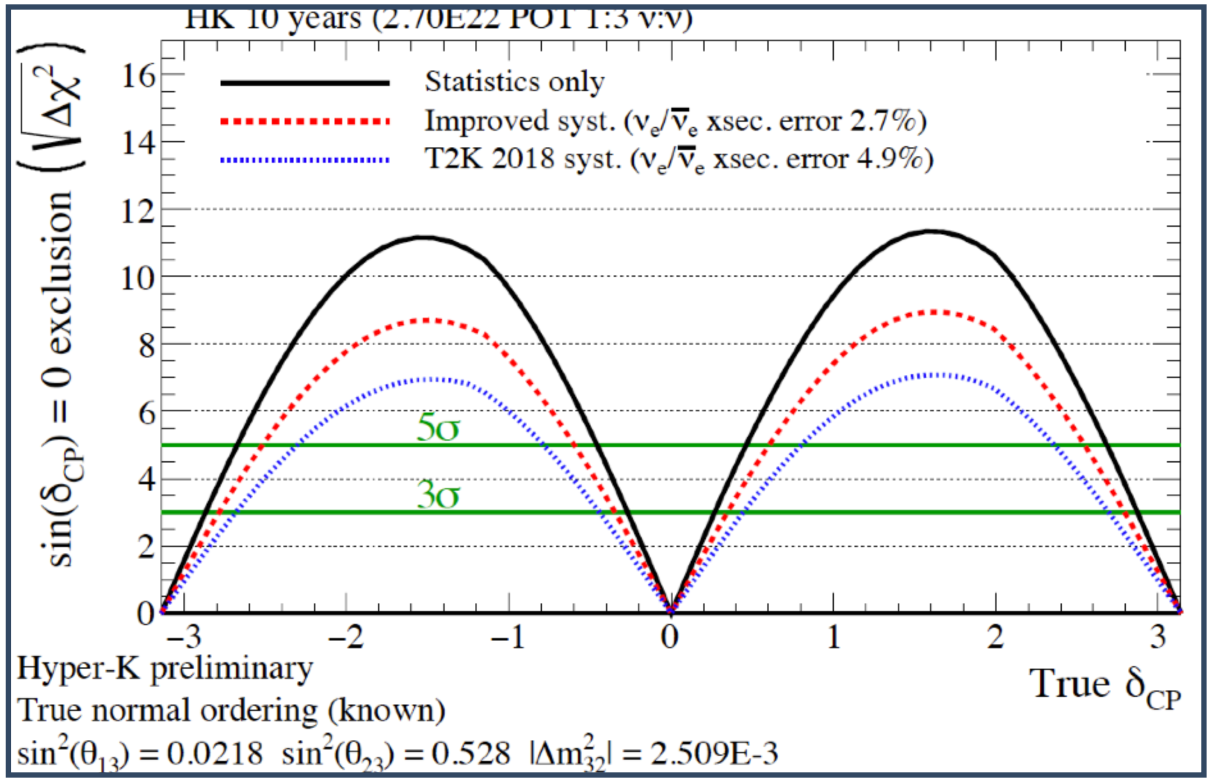
- 188 kton water Cherenkov
- T2HK: great sensitivity to δ_{CP}
- T2HKK (1100km) will have similar sensitivities as DUNE

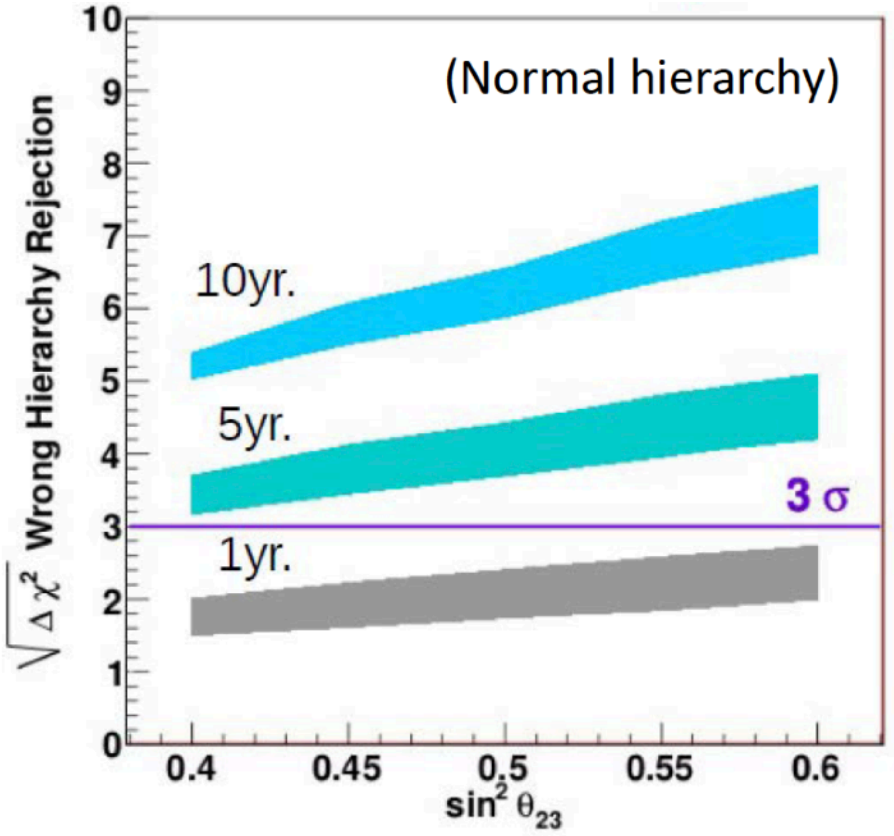
Next generation of ν experiments



DUNE

Hyper-K





Summary (Part I)

✦ Neutrino oscillations is a well-established phenomenon, observed in atmospheric, solar, reactor and accelerator neutrino experiments.

✦ Current status of three-neutrino oscillation parameters:

✓ very precise and robust determinations for most of them (1.3-10%)

✓ preference for $\theta_{23} > 45°$, 1st octant value disfavoured with $\Delta\chi^2 \geq 5.8$ (6.4)

✓ $\delta_{BF} = 1.08\pi$ (1.58π) for NO (IO) ; $\delta = \pi/2$ disfavored at 4.0σ (6.2σ)

✓ 2.5σ hint for normal ordering from atmospheric, LBL and reactor data

✓ sensitivity on mass ordering driven by oscillation data so far.

✦ New results presented in Neutrino 2022:

✓ Daya Bay achieved expected final sensitivity on $\sin^2 2\theta_{13}$

✓ Small changes expected in CP violation, atmospheric octant and mass ordering

✦ By 2025/2026:

✓ oscillation parameters will be measured with 0.6-3% precision

✓ θ_{23} octant can be resolved at more than 3σ (for some values)

✓ 2-3σ sensitivity to CP violation at NOvA and T2K

✓ 3σ sensitivity to MO from reactor, accelerator and nu-telescopes

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