Global fits of neutrino oscillation parameters and open questions in neutrino physics

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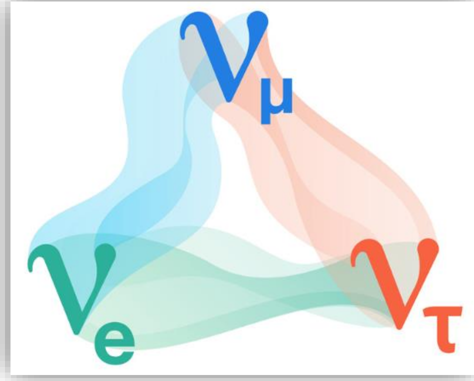
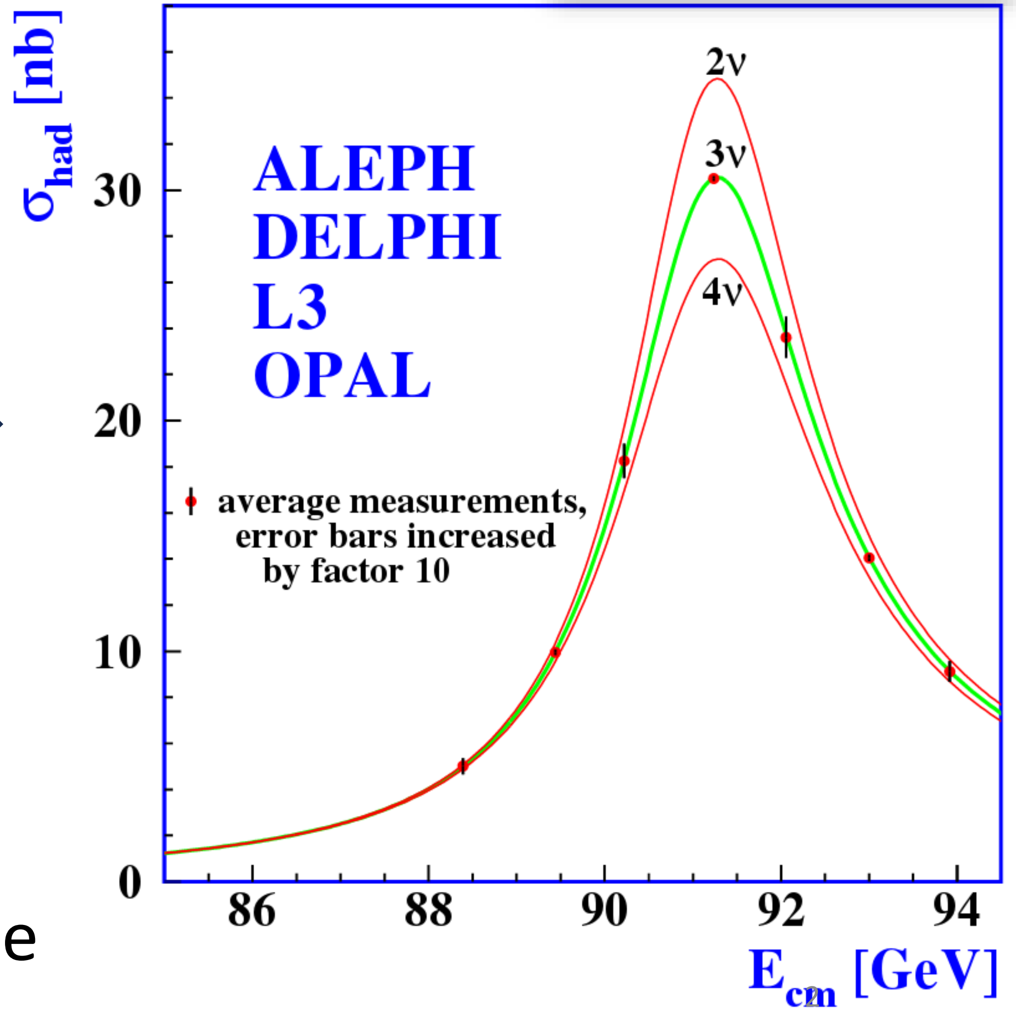
42nd International Symposium on Physics in Collision (PIC2023)

¿What do we know about the neutrino?



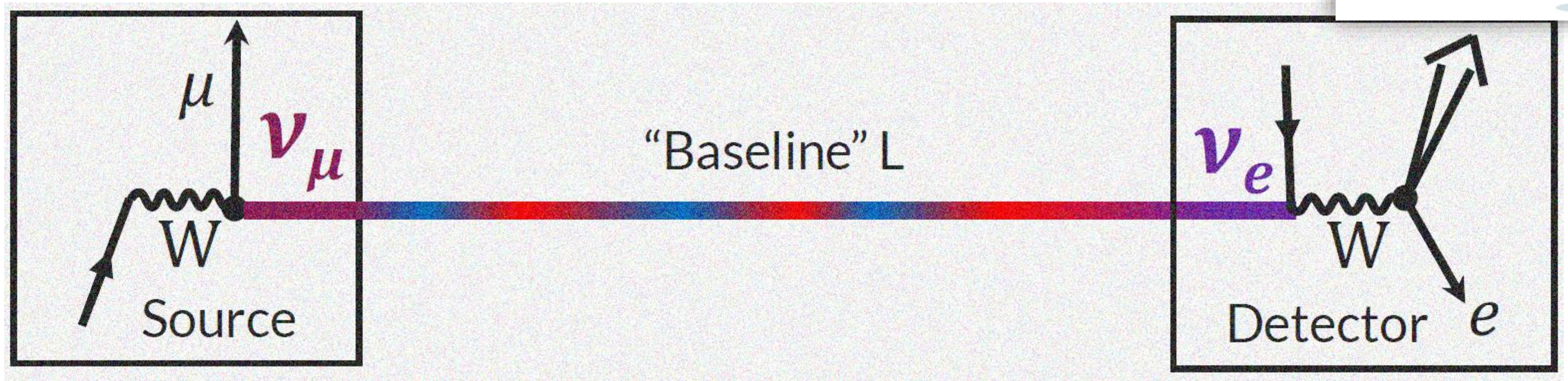
- It is a fundamental particle, a fermion
- Has no electric charge
- Interacts mainly through the **weak interaction**

Comes in **three flavors**, associated to each charged lepton (e, μ, τ)



- *Changes its flavor* during propagation
  Explained by **neutrino oscillations**
  - Has a tiny but non-zero mass
- Most abundant massive particle in the Universe

Neutrino oscillations ‘in a Nutshell’



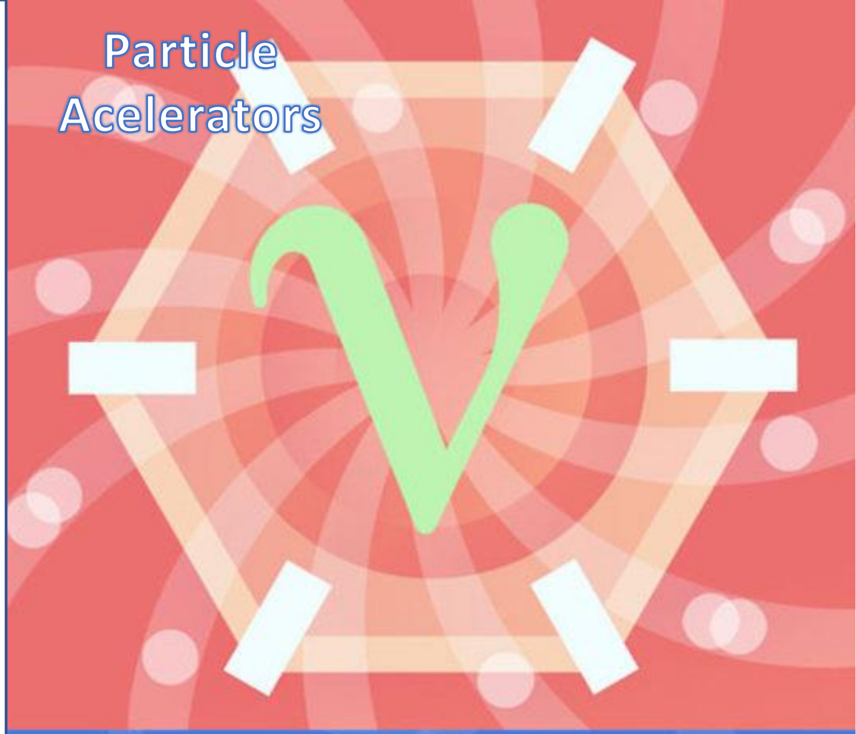
$$P_{\alpha\beta}^{2\nu} = sin^2(2\,\theta_{mix})sin^2(\phi_{osc})$$

$\phi_{osc} \propto \frac{\Delta m^2[eV^2]L[km]}{Energy[GeV]}$ & $\boldsymbol{sin^2\theta_{mix}^{max} = 0.5}$

- $m_j^2 - m_k^2 \equiv \boldsymbol{\Delta m^2}$ Sensitivity range, depends on Baseline/Energy
- So far, two Δm^2’s found in Nature: $\boldsymbol{\Delta m_{sol}^2}$ (KamLAND) & $\boldsymbol{\Delta m_{atm}^2}$ (SK)

Non-zero neutrino masses, a discovery recognized -> **Physics Nobel Prize (2015)**

Neutrino Sources



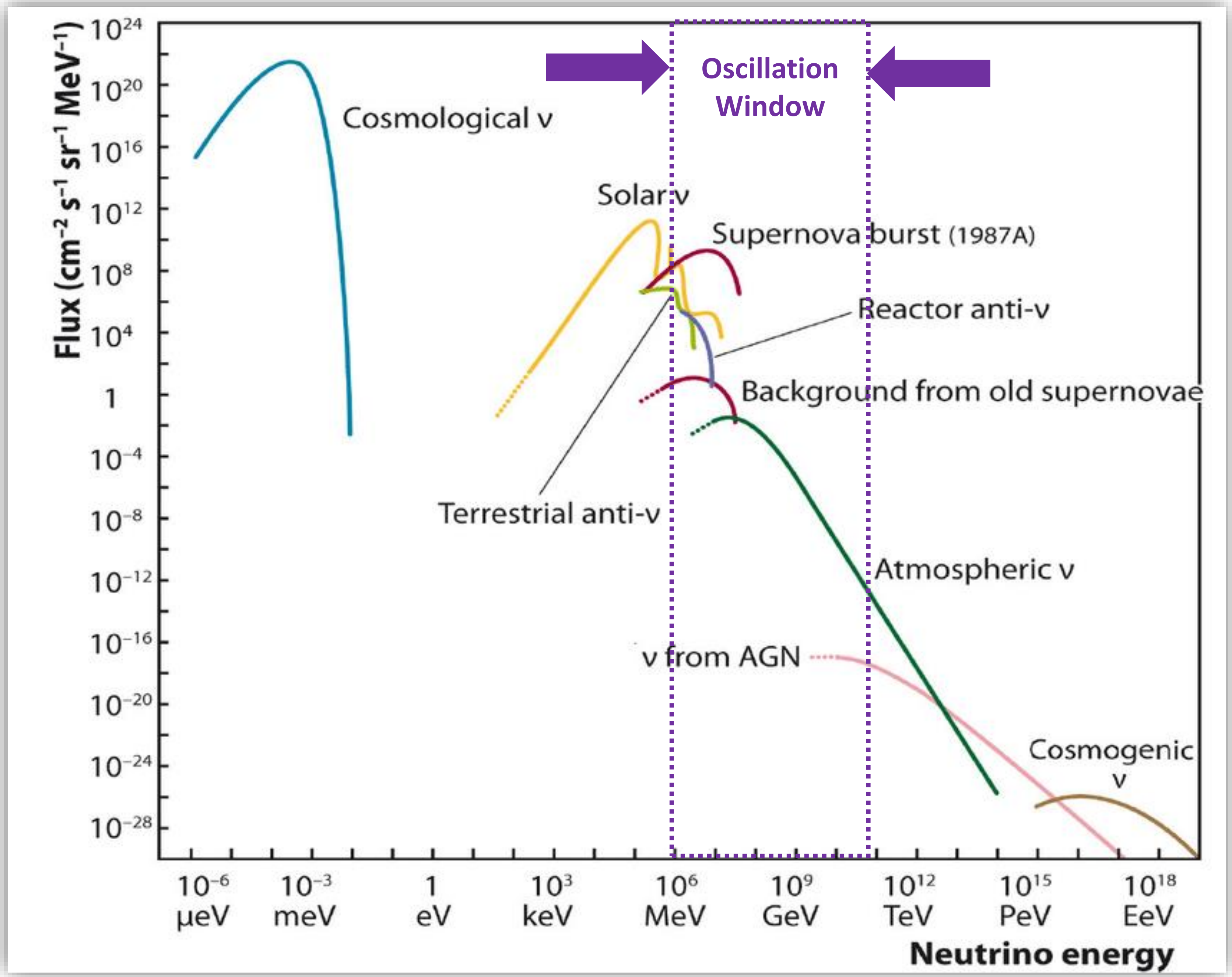
www.symmetrymagazine.org

Neutrino Sources

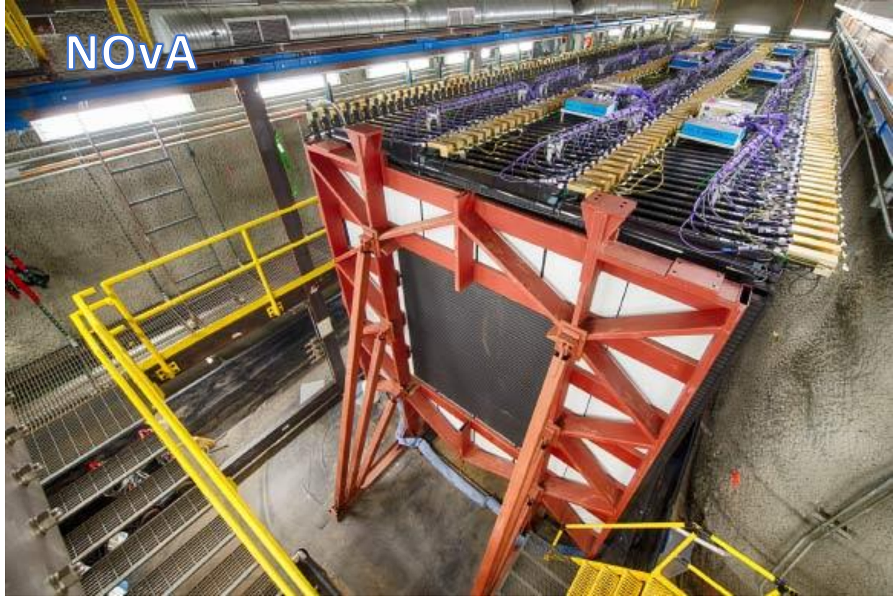
Oscillation Energy Window :
 ~1 MeV -- ~100 GeVs

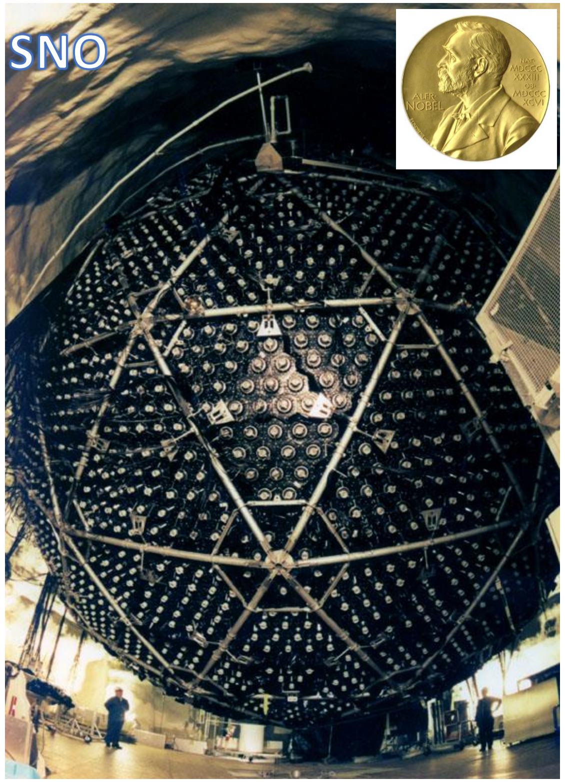
- Solar
- Atmospheric
- Reactor

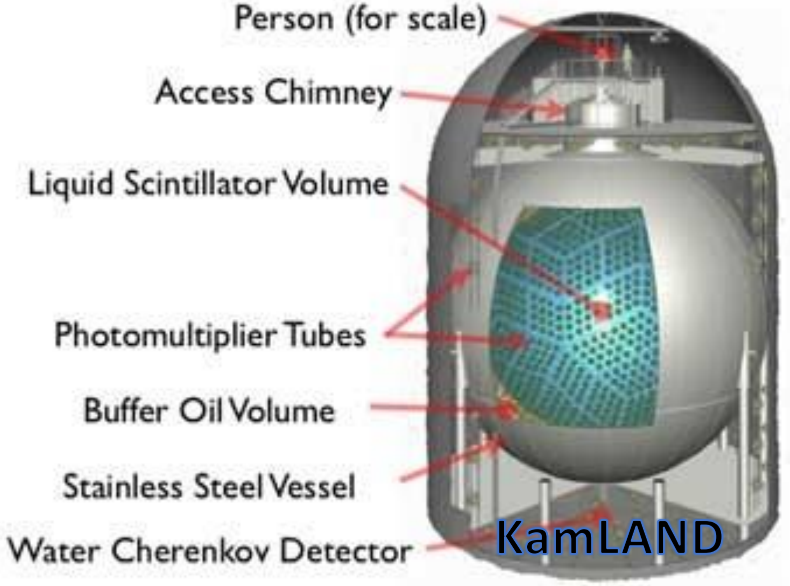
¿Why if it is there so many neutrinos are so hard to detect?

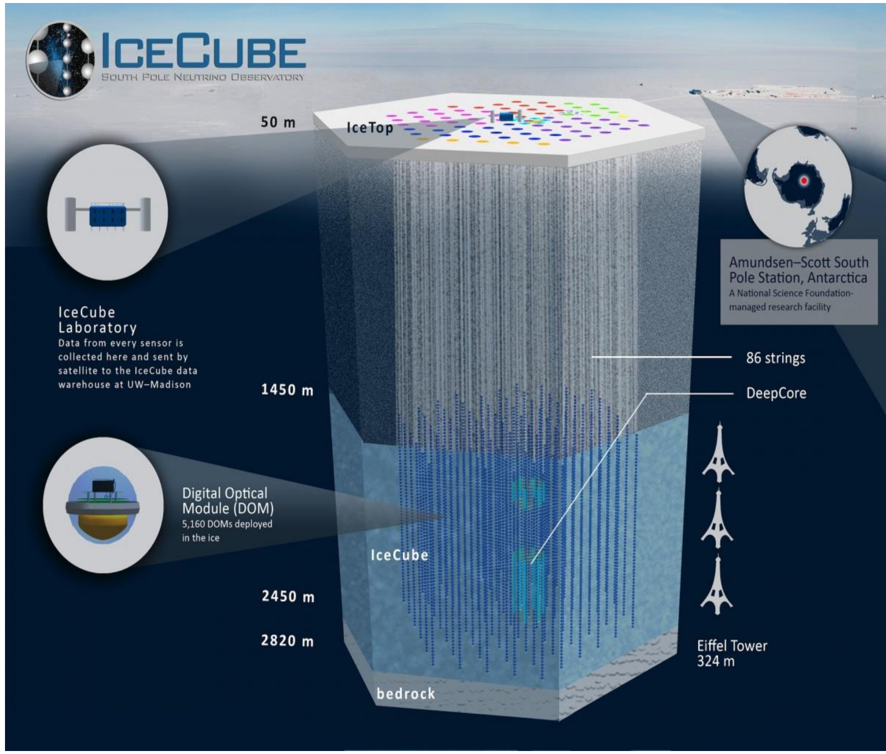


Some neutrino detectors









Three-active neutrino framework

$$|\nu_\alpha\rangle = \sum_{k=1}^{3} U_{\alpha k}^{*} \, |\nu_k\rangle$$

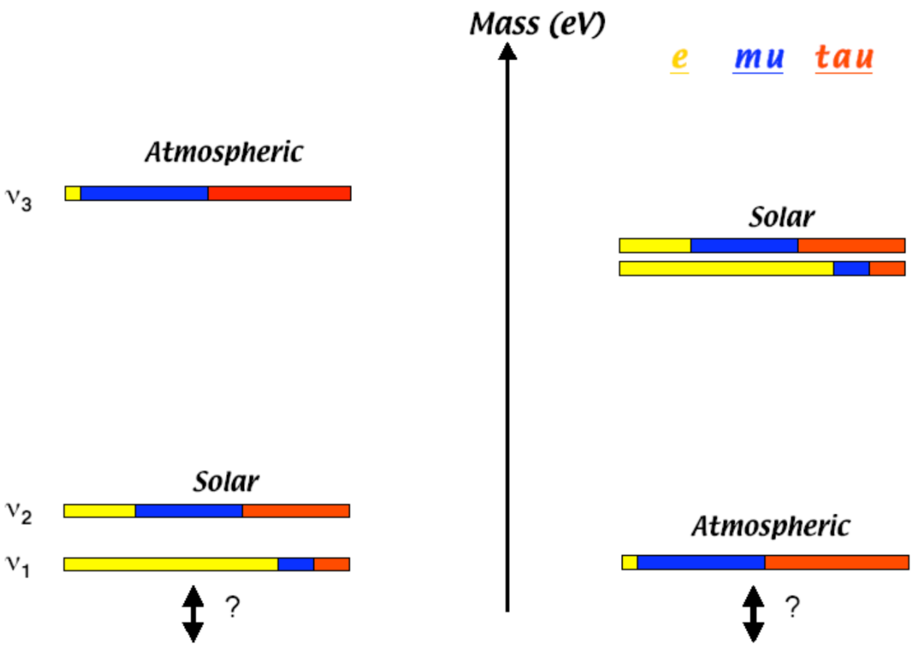
Atm.—Solar Interference

$$U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\text{Atmospheric}} \overbrace{\underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{\text{Reactor}}}^{\text{Atm.—Solar Interference}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Solar}}$$

- Three mixing angles (θ_{ij})
- One CP-Violating phase (δ)

- Two mass-squared differences (Δm_{k1}^2)

Two possible mass orderings
Normal (L), Inverted (R)



Neutrino oscillations are NOT sensitive to:

- Majorana CP-Violating phases (If Majorana neutrinos)
  - Previous talk ($0\nu\beta\beta$)
- Absolute neutrino mass (m_0)
  - End point of β-decay (direct)
  - Cosmology (indirect)

Attend **Caroline Rodenbeck's Talk** on Friday

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Neutrino Osc. Experiments (by their `source`)

Neutrino Experiment=Source+Detector, separated the CORRECT baseline

Solar

Homestake, GALLEX/GNO, SAGE, Borexino

SuperKamikande (SK), SNO

KamLAND (LBL reactor)

Attend **Xuefeng Ding's Talk** on Friday

Atmospheric

SuperKamiokande (SK)

IceCube DeepCore (DC)

Accelerator (LBL)

K2K, MINOS

T2K, NOvA

Reactor (km)

Daya Bay

RENO

- Tunable `source` or that **can be characterized**
- Multip `detectors` (**ND**, FD)

Attend **Mario Acero's Talk** to follow

Attend **Pedro Ochoa's Talk** on Wednesday

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Neutrino Oscillation Channels

Two Δm^2's found in Nature: $\boldsymbol{\Delta m^2_{21} = \Delta m^2_{sol}}$ & $|\boldsymbol{\Delta m^2_{31}}| \propto \boldsymbol{\Delta m^2_{atm}}$

	Channel	Experiment	Main	Other
$\boldsymbol{\Delta m^2_{sol}}$	$\nu_e \to \nu_x$	Solar: SK, SNO, et. al	θ_{12}	Δm^2_{21}, θ_{13}
	$\bar{\nu}_e \to \bar{\nu}_e$	Reactor: KamLAND	Δm^2_{21}	θ_{12}, θ_{13}
$\boldsymbol{\Delta m^2_{atm}}$	$\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$	Atmospheric: SK, IceCube (DC)	θ_{23},Δm^2_{31}	θ_{13}, δ
	$\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)$	LBL: T2K(MINOS,NOvA)	θ_{13}, δ	θ_{23}
	$\nu_\mu(\bar{\nu}_\mu) \to \nu_\mu(\bar{\nu}_\mu)$	LBL: T2K(MINOS,NOvA)	Δm^2_{31}, θ_{23}	
	$\bar{\nu}_e \to \bar{\nu}_e$	Reactors: RENO,Daya Bay	θ_{13}, Δm^2_{31}	θ_{12}

No single experiment is sensitive to ALL parameters, so **we need global-fits**:

- To find the **parameters allowed by the data** taken at Neutrino Oscillation Experiments
- To account for **correlations between parameters**

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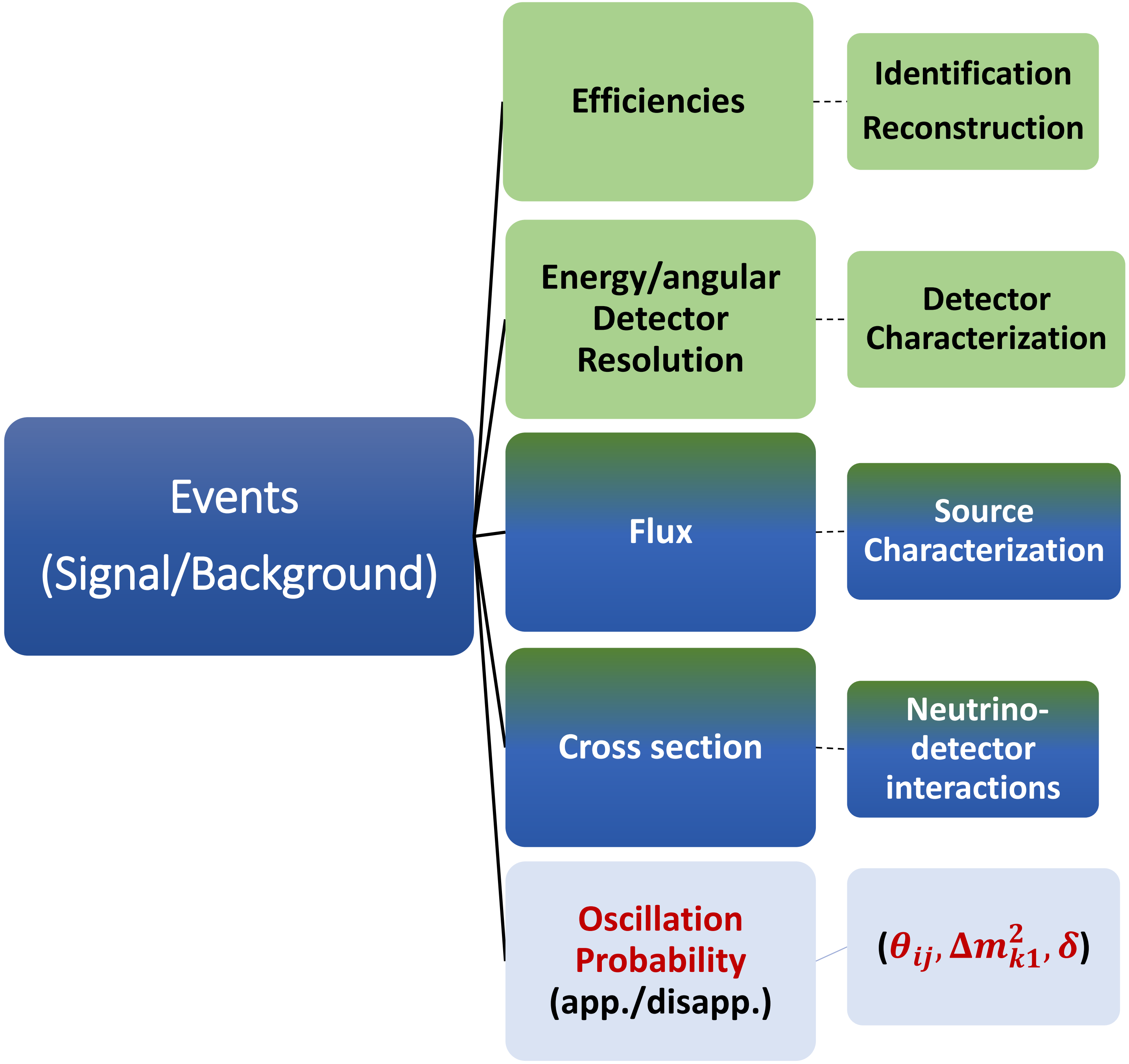
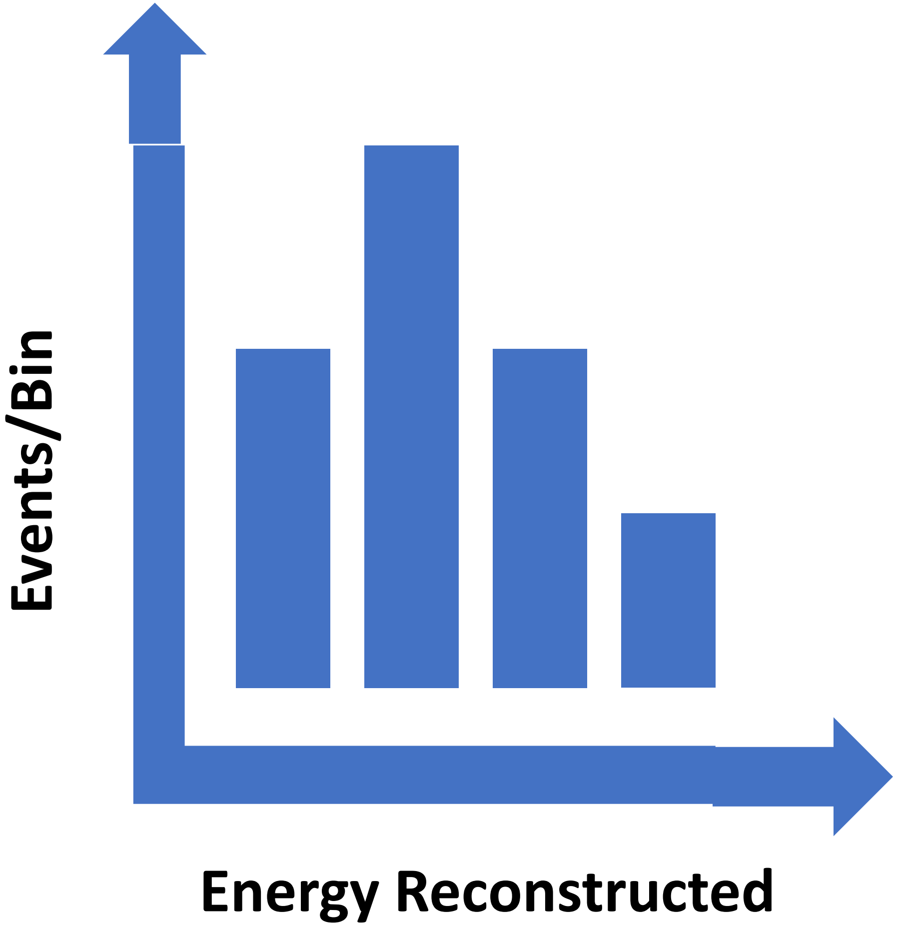
The Modeling

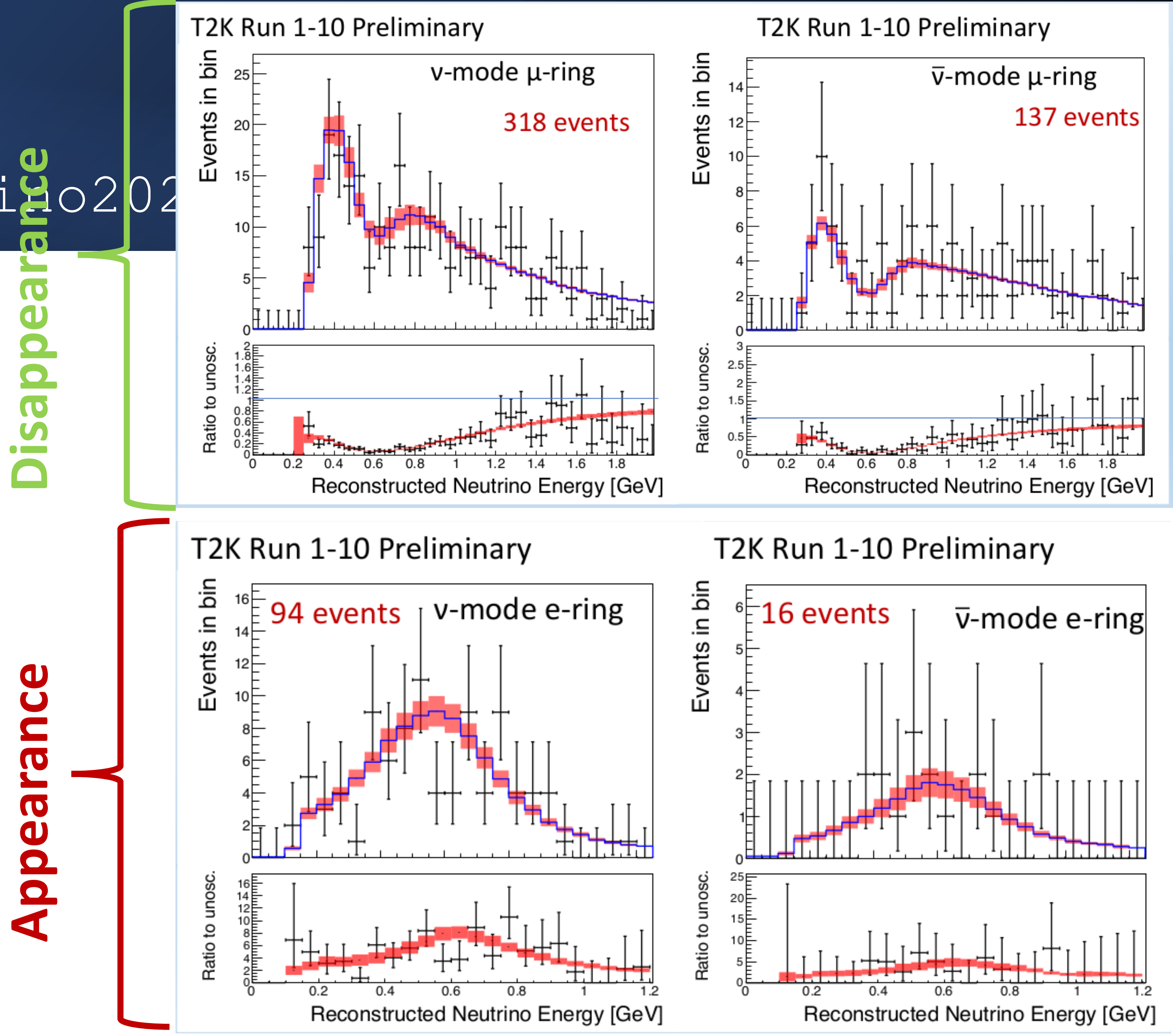
Calculation of neutrino events at a given

Detector



Example of a Data set: T2K @neutrino202





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Then ‘new’ data sets considered in the latest update (after neutrino2020)

https://globalfit.astroparticles.es/

2020 global reassessment of the neutrino oscillation picture

P.F. de Salas,[a] D.V. Forero,[b] S. Gariazzo,[c,d] P. Martínez-Miravé,[c,e] O. Mena,[c] C.A. Ternes,[c,d] M. Tórtola[c,e] and J.W.F. Valle[c]

Solar

- ‘Latest’ results: from the three phases

Atmospheric

- IceCube DeepCore: 3-years of data. Addition of track-like, shower-like events included (events from ~6000 to ~20000)

Reactor

- Daya Bay: 1958 days
- RENO: 2900 days

LBL

- T2K: 19.7×10^{20} POT (19.7×10^{20} POT), 318 ν_μ & 94 ν_e (137 $\overline{\nu_\mu}$ & 16 $\overline{\nu_e}$) -> previous slide
- NOvA: 13.6×10^{20} POT (12.5×10^{20} POT), 211 ν_μ & 82 ν_e (105 $\overline{\nu_\mu}$ & 33 $\overline{\nu_e}$)

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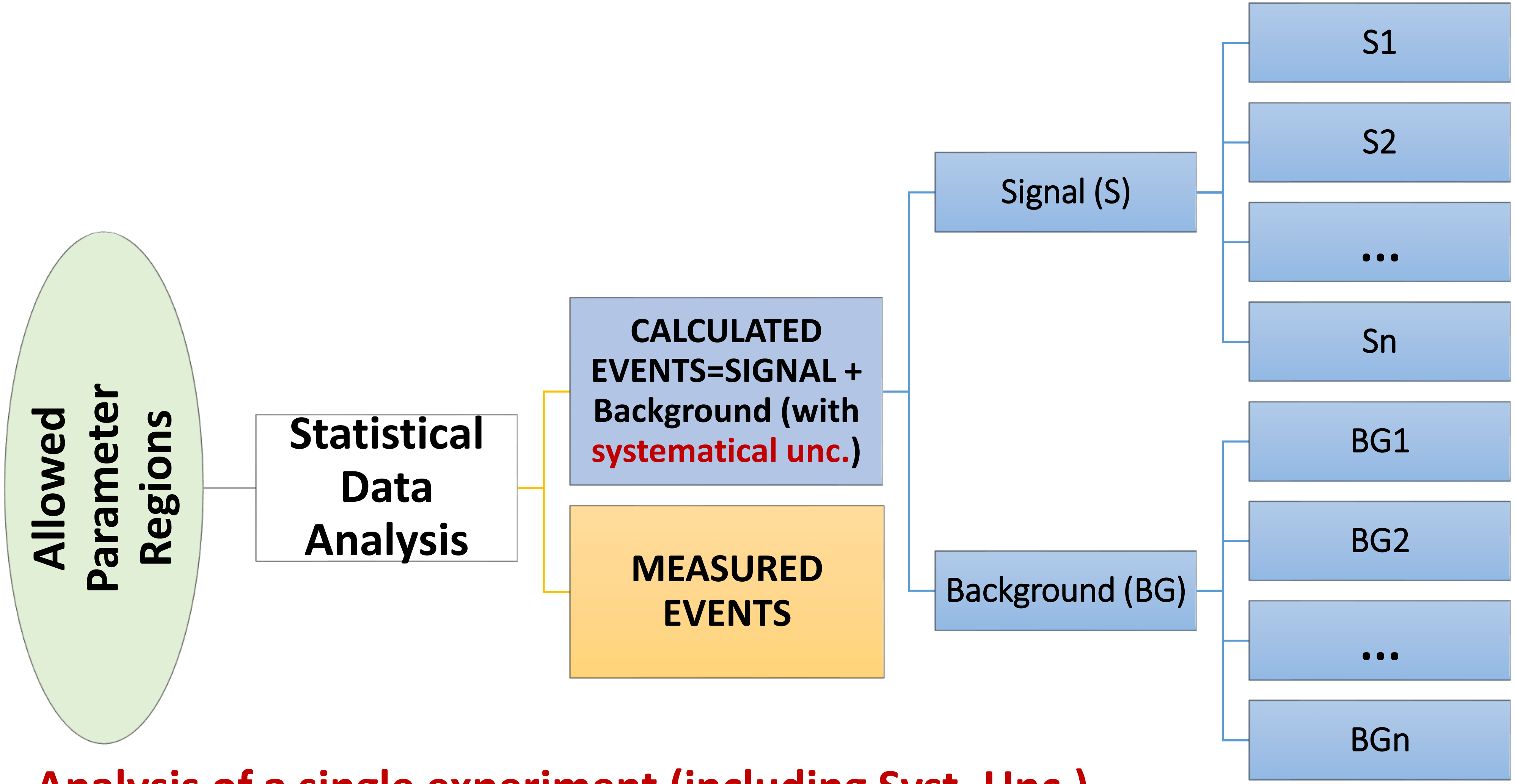
Statistical Data Analysis



Analysis of a single experiment (including Syst. Unc.)

Partial Fit results, Solar and Atmospheric sectors

https://globalfit.astroparticles.es/

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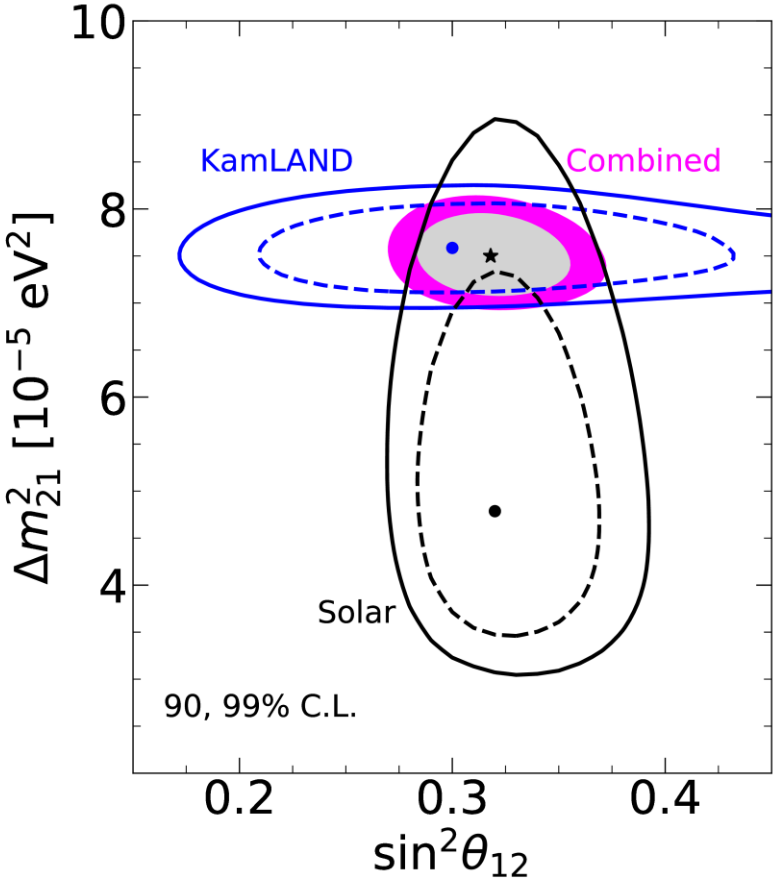
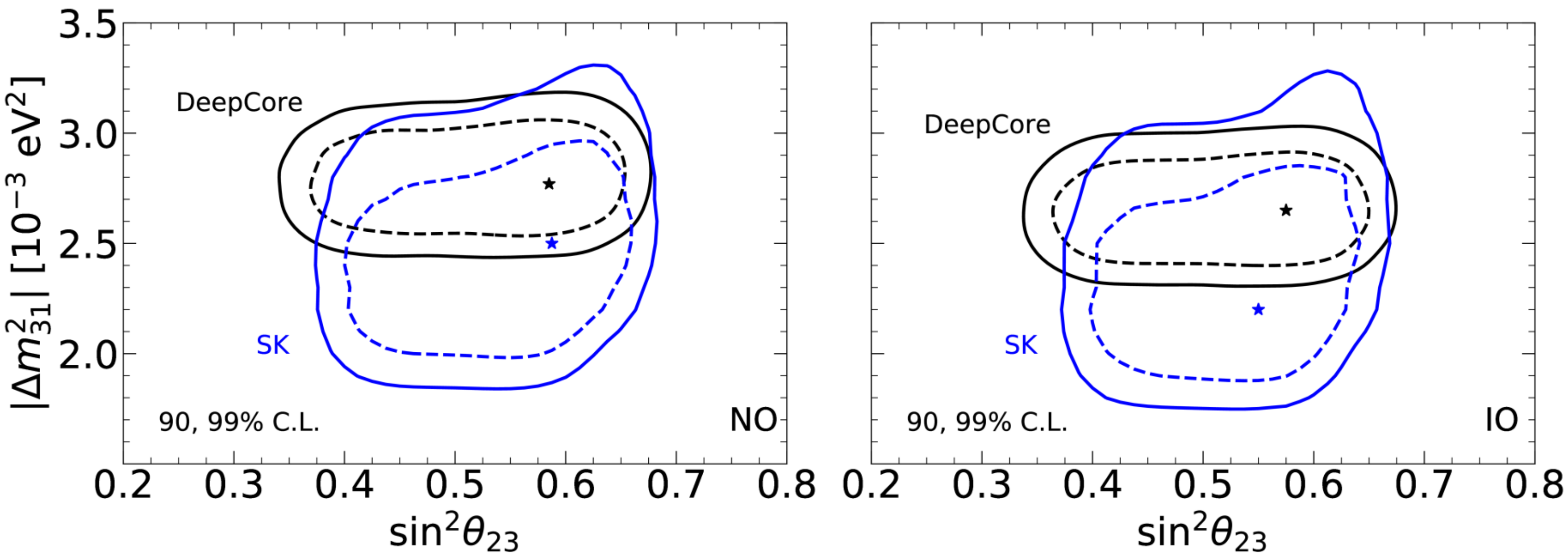


- <u>Directional information</u>
  - crucial to solve the **Atm. Neutrino Problem**



- **Neutrino-matter interactions** at the interior of the Sun (**MSW**)
- <u>NC measurements at SNO</u>, crucial to solve the **Solar Neutrino Problem**

Partial Fit results, LBL Experiments

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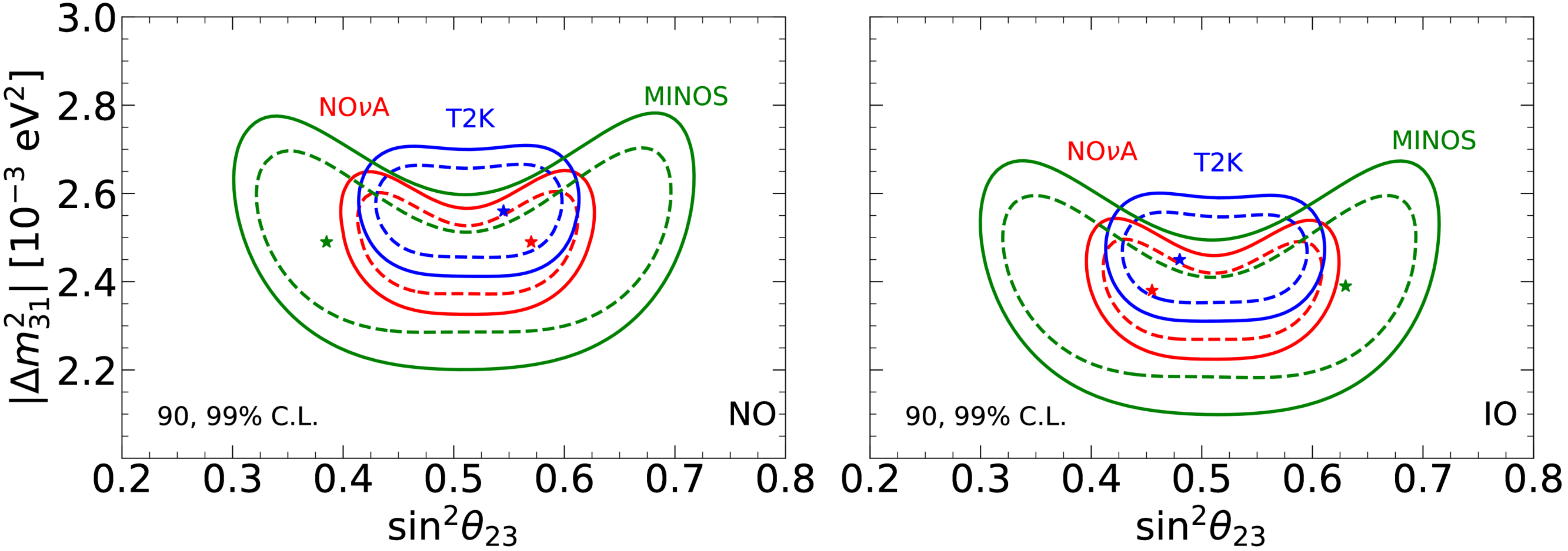
Octant degeneracy



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Partial Fit results, LBL Experiments

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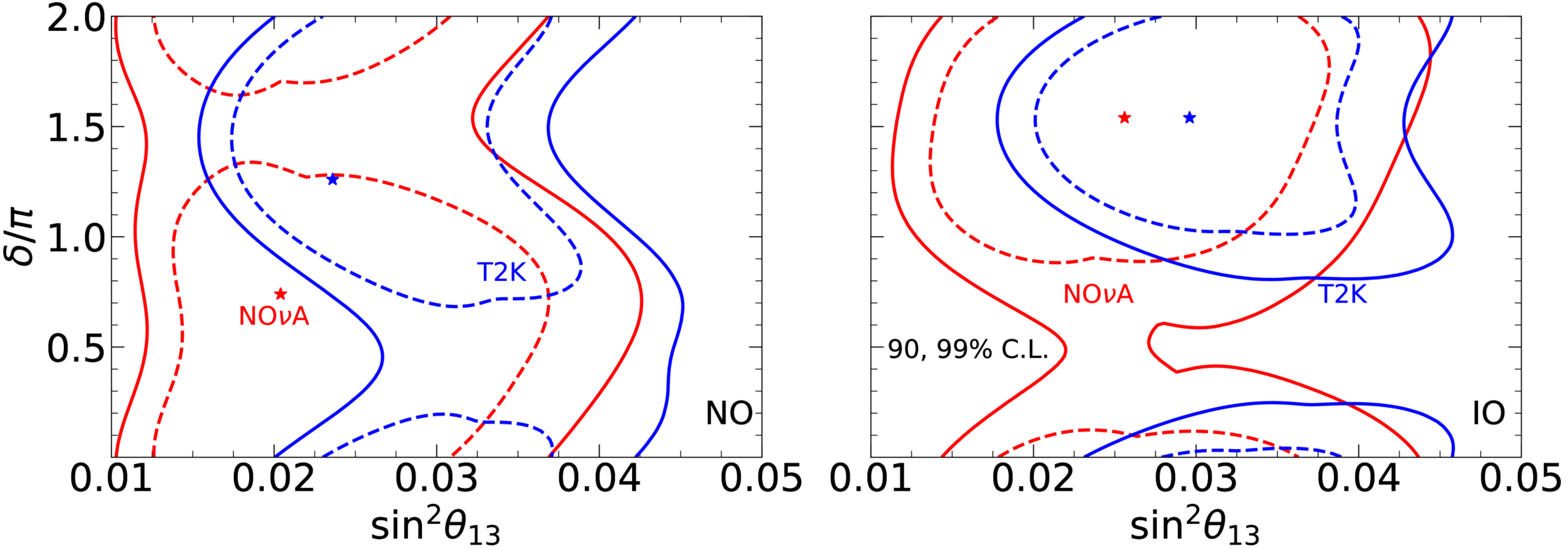

- T2K & NOvA Tension (NO)
- Notice LBL exps. allow large θ_{13} compared to Reactor Exps.

Global-fit results, Correlations I

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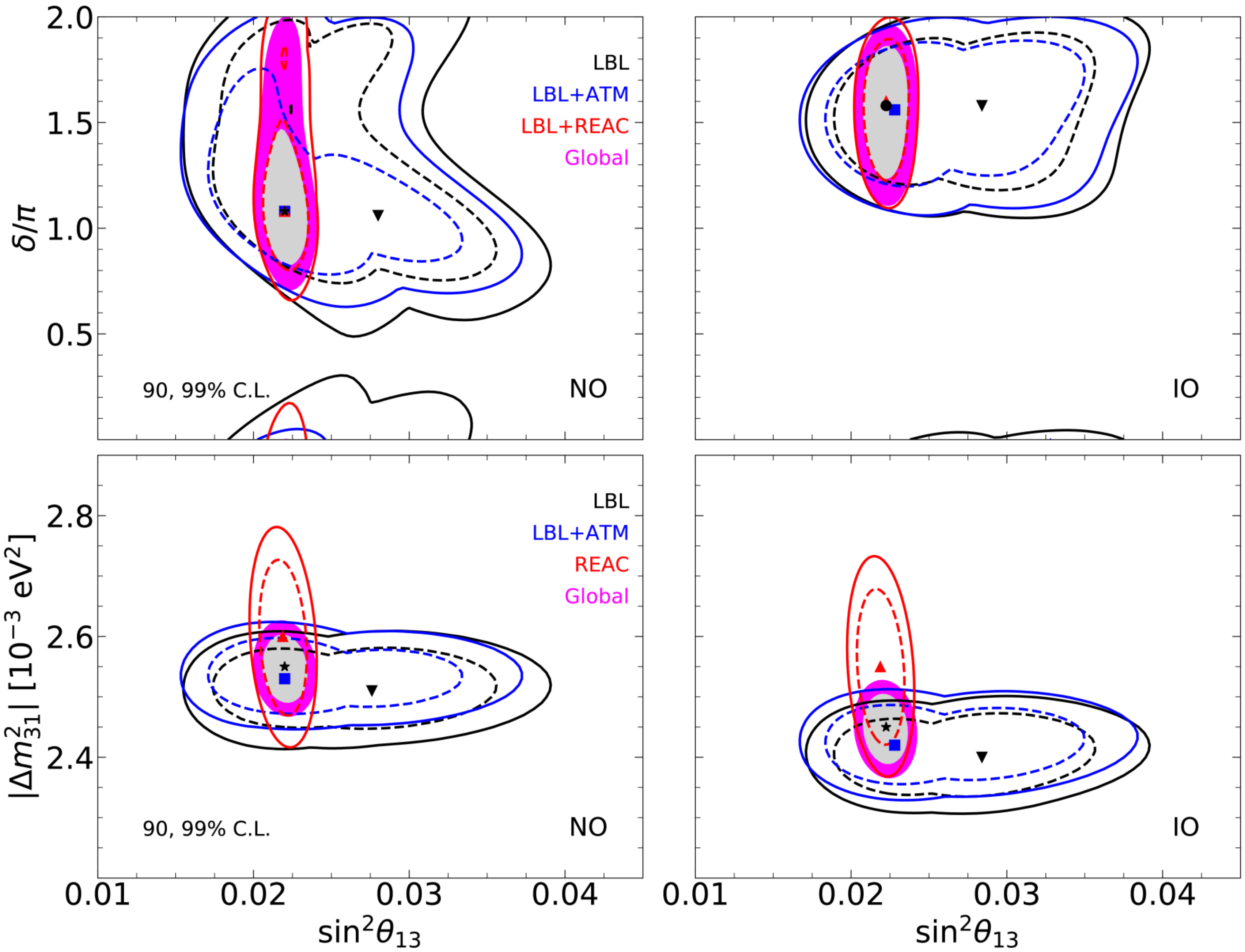

Global bfp (*)

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Global-fit results, Correlations II

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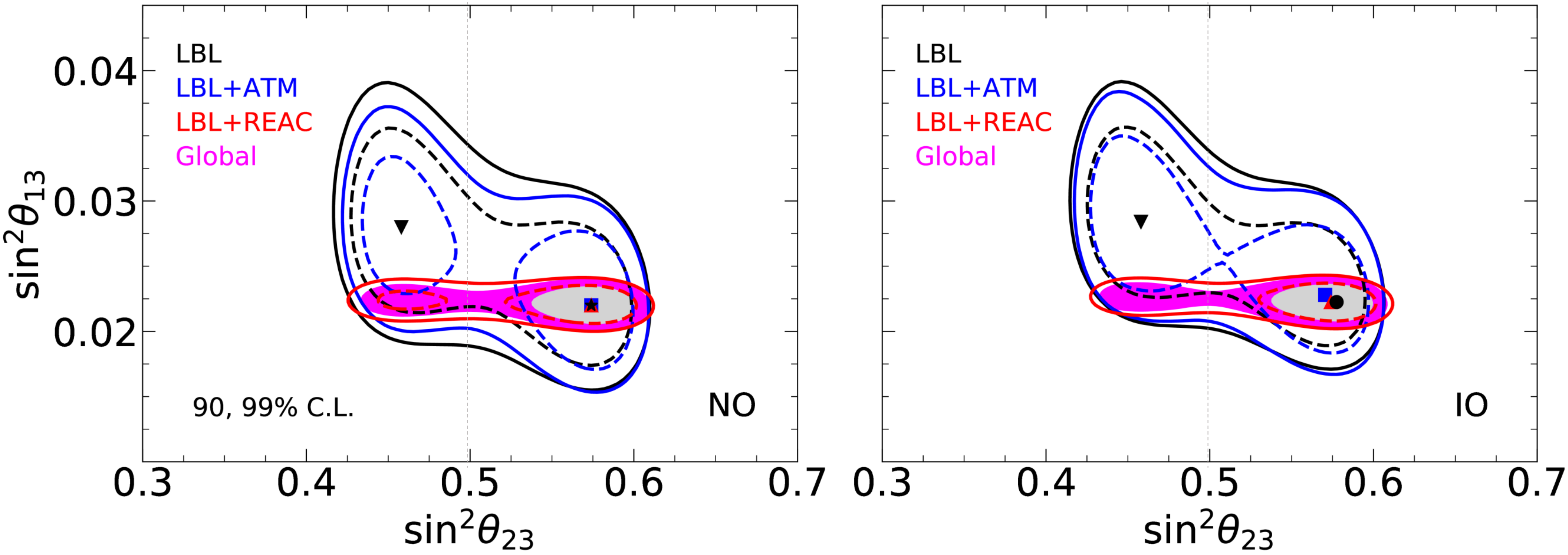
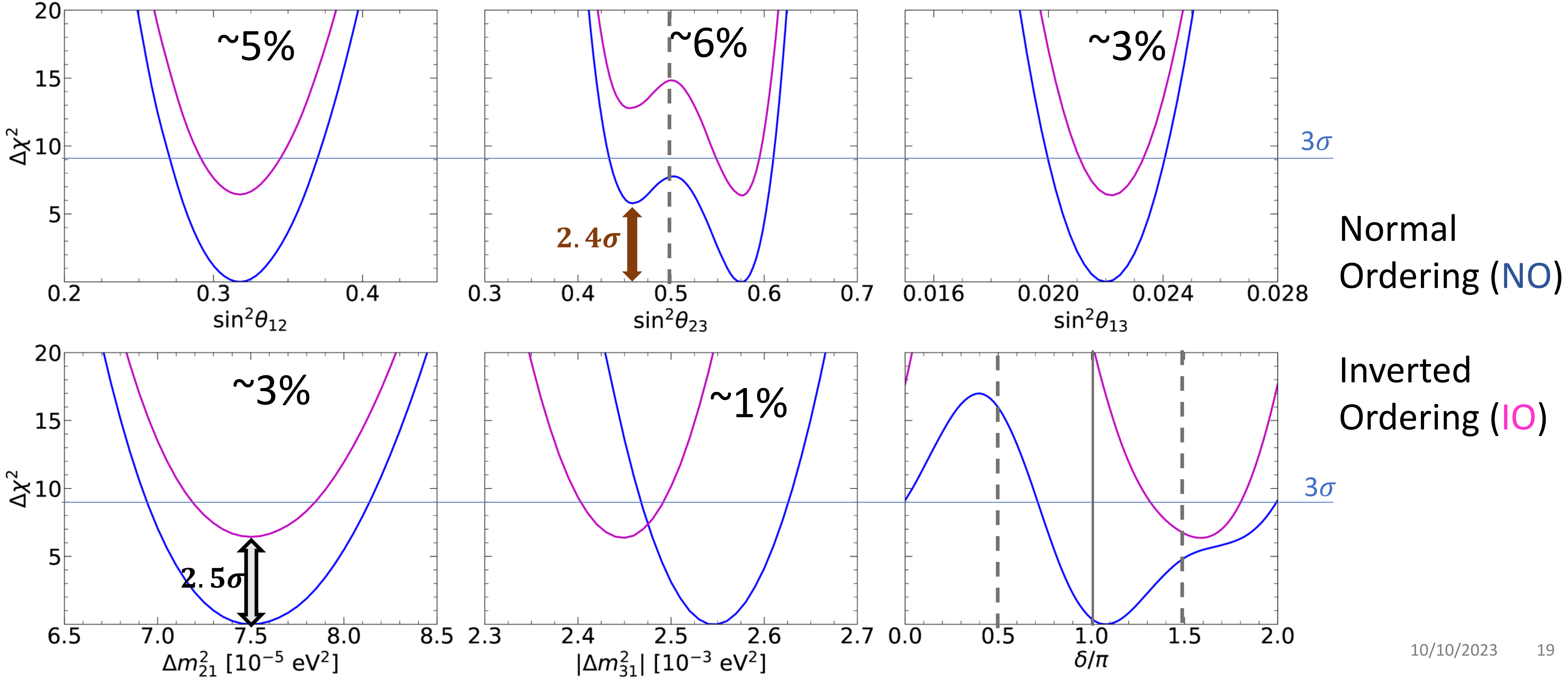


- Reactor data help to break, partially, the $\theta_{23} - \theta_{13}$ degeneracy

Global-fit results, $\Delta\chi^2$-profiles

https://globalfit.astroparticles.es/



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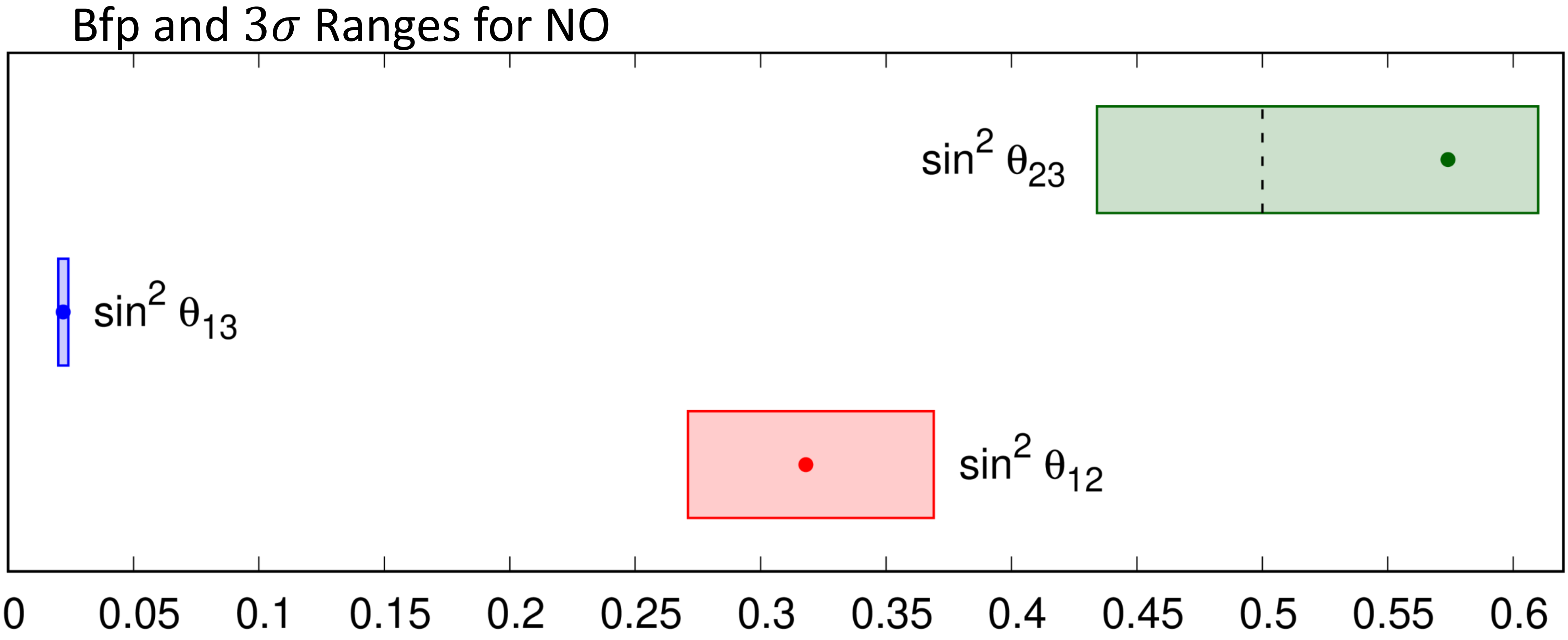
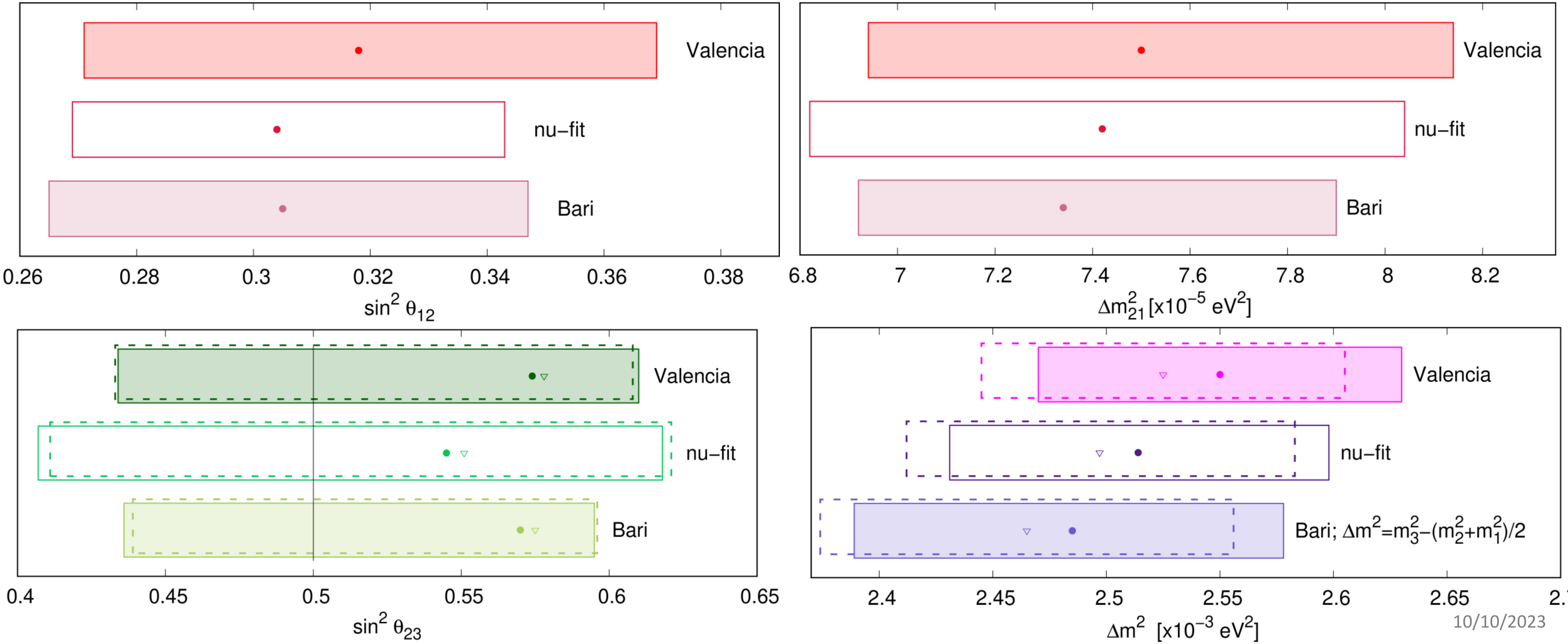
Global-fit results, lepton mixing



Could this **mixing pattern** be a result of some **underlying symmetry**?

Comparing Global-fit results: BFPs and 3σ ranges

De Salas et. al arXiv:2006.11237 (VLC) Esteban et. al arXiv: 2007.14792 (nu-fit) Capozzi et. al arXiv: 2003.08511 (Bari)



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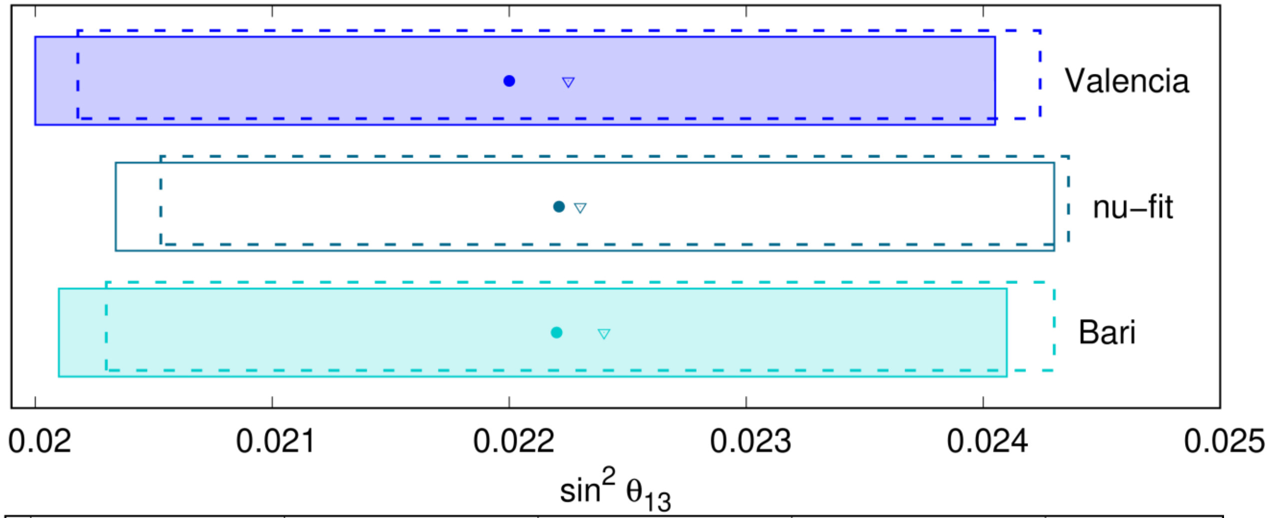

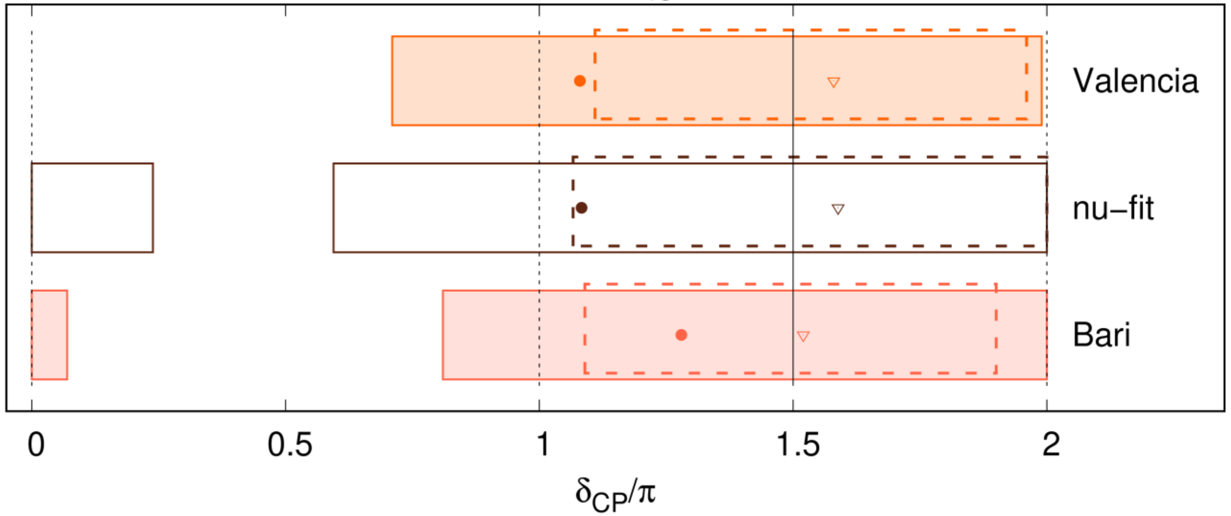

SUMMARY

- CP symmetry (δ): T2K & NOvA Tension for NO, impacted also MO significance
- MO: NO is preferred over IO with 2.5σ significance.
- Atmospheric mixing (θ_{23}): In the 2nd octant for both MO, LO disfavored $\Delta\chi^2 \geq 5.8(6.4)$ for NO (IO)
- Parameter precision: Ranges from ~1% to ~6%

After latest global-fit results, same questions remains

- Is there a violation of the CP-Symmetry in the lepton sector: $J_{CP} \propto \sin\delta \neq 0$?
- What is the correct neutrino mass ordering: NO or IO?
- Is the atm. mix. angle maximal, if not, what is its octant? $sin^2\theta_{23}(<,=,>)0.5$?

Precise measurements are needed -> FUTURE NEUTRINO EXPS.

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FINAL REMARKS

ALL 3-neutrino osc. parameters (& ordering) are aimed to be measured at **future neutrino experiments** (given the important improvement in precision):

- DUNE/T2HK (LBL): Definitive measurement of δ
- JUNO (reactor): Precise measurement of Solar parameters
- DUNE/JUNO: Different strategies to establish the correct MO
- DUNE: Precise determination of the atm. mix. angle, θ_{23}

This is not the full story: Massive neutrinos imply **BSM physics**

- BSM physics searches already been performed at Osc. Exps.
  - NSI, Sterile, LED, non-unitarity, DM scenarios
- With significant improvement in precision, *subleading effects* could be found for at neutrino oscillation Exps.

¡Thank you!


Double-Chooz
Sin²(2θ13) = 0.085
± 0.029 (sta
± 0.042 (sys
Δm²DC = 2.35 x 10⁻³ e
Sin² θ13
CBS

Back up

Neutrinos from Accelerators: LBNF/DUNE

Oscillation Probability (2-neutrino, vacuum)

Appearance: $P_{\nu_\mu \to \nu_e} = sin^2(\mathbf{2\theta}) sin^2(\frac{\Delta m^2}{4E} L)$

Disappearance: $P_{\nu_\mu \to \nu_\mu} = 1 - P_{\nu_\mu \to \nu_e}$

- **Osc. Amplitude -->** $sin^2(\mathbf{2\theta})$
- **Osc. Phase-->** $\frac{\Delta m^2}{2} (\frac{Baseline}{Energy})$