Global analysis of neutrino oscillation experiments

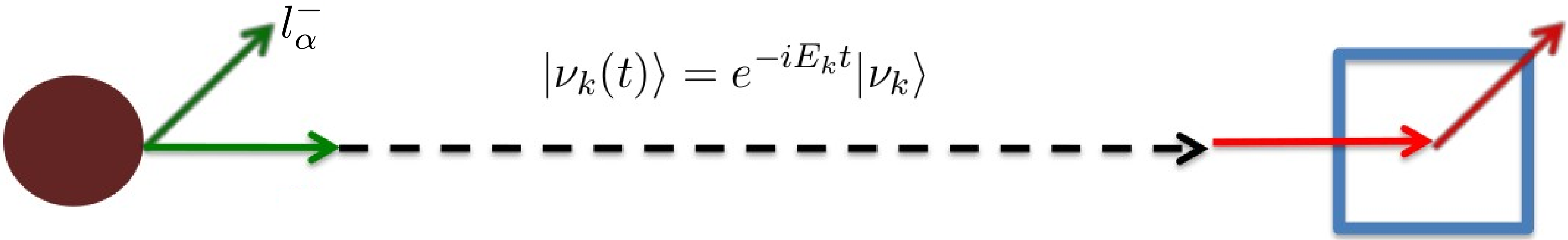
Christoph Andreas Ternes

September 7th 2022

UNIVERSITÀ DI TORINO

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Neutrino oscillations



$$|\nu_k(t)\rangle = e^{-iE_k t}|\nu_k\rangle$$

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k}^* |\nu_k\rangle$$

$$A_{\nu_\alpha \to \nu_\beta}(t) \equiv \langle \nu_\beta | \nu_\alpha(t) \rangle = \sum_k U_{\alpha k}^* \, U_{\beta k} \, e^{-iE_k t}$$

$$P_{\nu_\alpha \to \nu_\beta}(t) = \left| A_{\nu_\alpha \to \nu_\beta}(t) \right|^2 = \sum_{k,j} U_{\alpha k}^* \, U_{\beta k} \, U_{\alpha j} \, U_{\beta j}^* \, e^{-i(E_k - E_j)t}$$

Three-neutrino oscillations

Neutrino mixing matrix

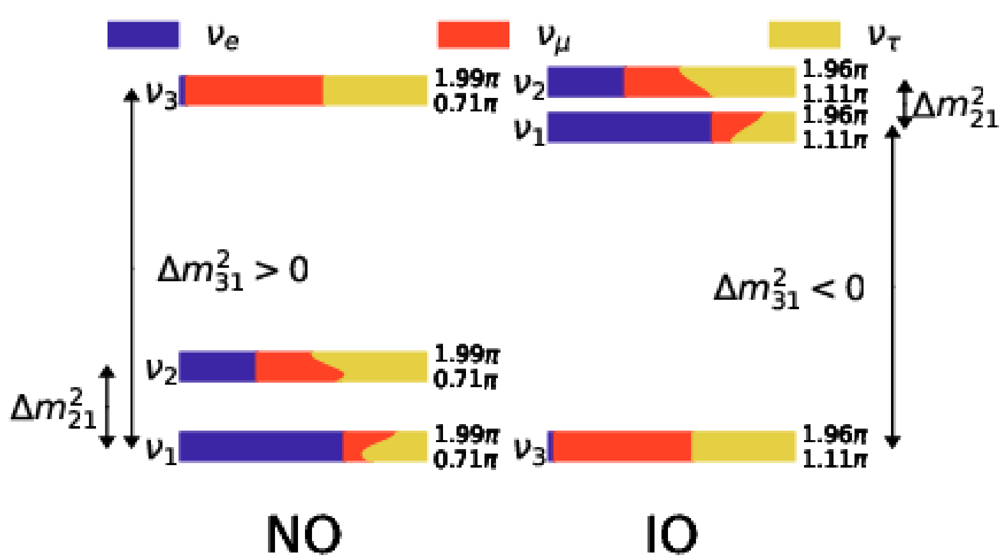
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$

1 Dirac + 2 Majorana CP-phases

Three masses m_1, m_2, m_3 for which two orderings are possible

Oscillations are only sensitive to mass splittings



Three-neutrino oscillations

Neutrino oscillation probability in vacuum is given by

$$P_{\alpha\beta}(E,L) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{i \frac{\Delta m^2_{kj}}{2E} L}$$

From the interplay of the mass splittings with energy and distance we see that different types of experiments are sensitive to different parameters

Parameter	Main contribution from	Other contributions from
Δm^2_{21}	KamLAND	SOL
$\lvert\Delta m^2_{31}\rvert$	LBL+ATM+REAC	-
θ_{12}	SOL	KamLAND
θ_{23}	LBL+ATM	-
θ_{13}	REAC	(LBL+ATM) and (SOL+KamLAND)
δ	LBL	ATM
MO	(LBL+REAC) and ATM	COSMO and $0\nu\beta\beta$

Three-neutrino oscillations

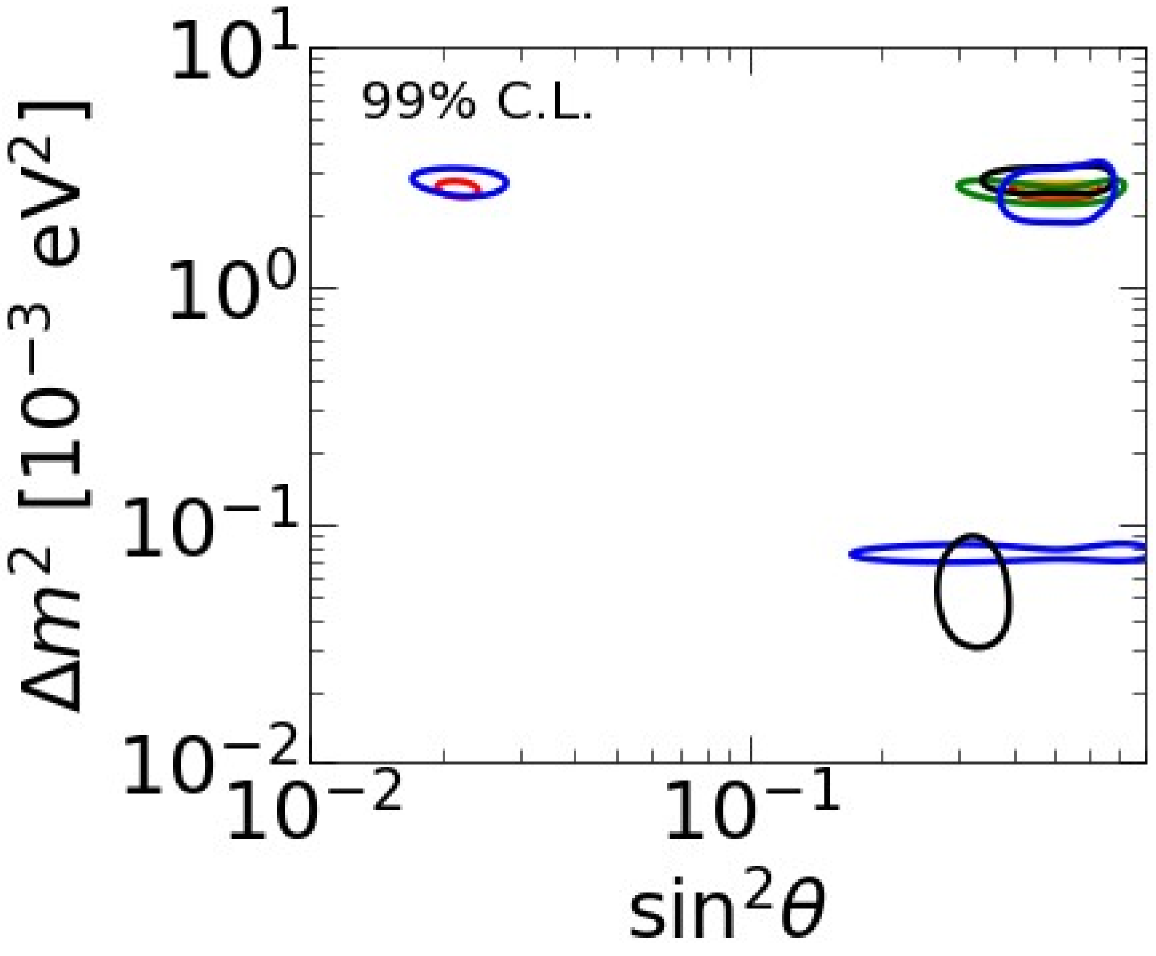
Parameter	Main contribution from	Other contributions from
Δm^2_{21}	KamLAND	SOL
$\lvert\Delta m^2_{31}\rvert$	LBL+ATM+REAC	-
θ_{12}	SOL	KamLAND
θ_{23}	LBL+ATM	-
θ_{13}	REAC	(LBL+ATM) and (SOL+KamLAND)
δ	LBL	ATM
MO	(LBL+REAC) and ATM	COSMO and $0\nu\beta\beta$

Common sensitivities from different types of experiments

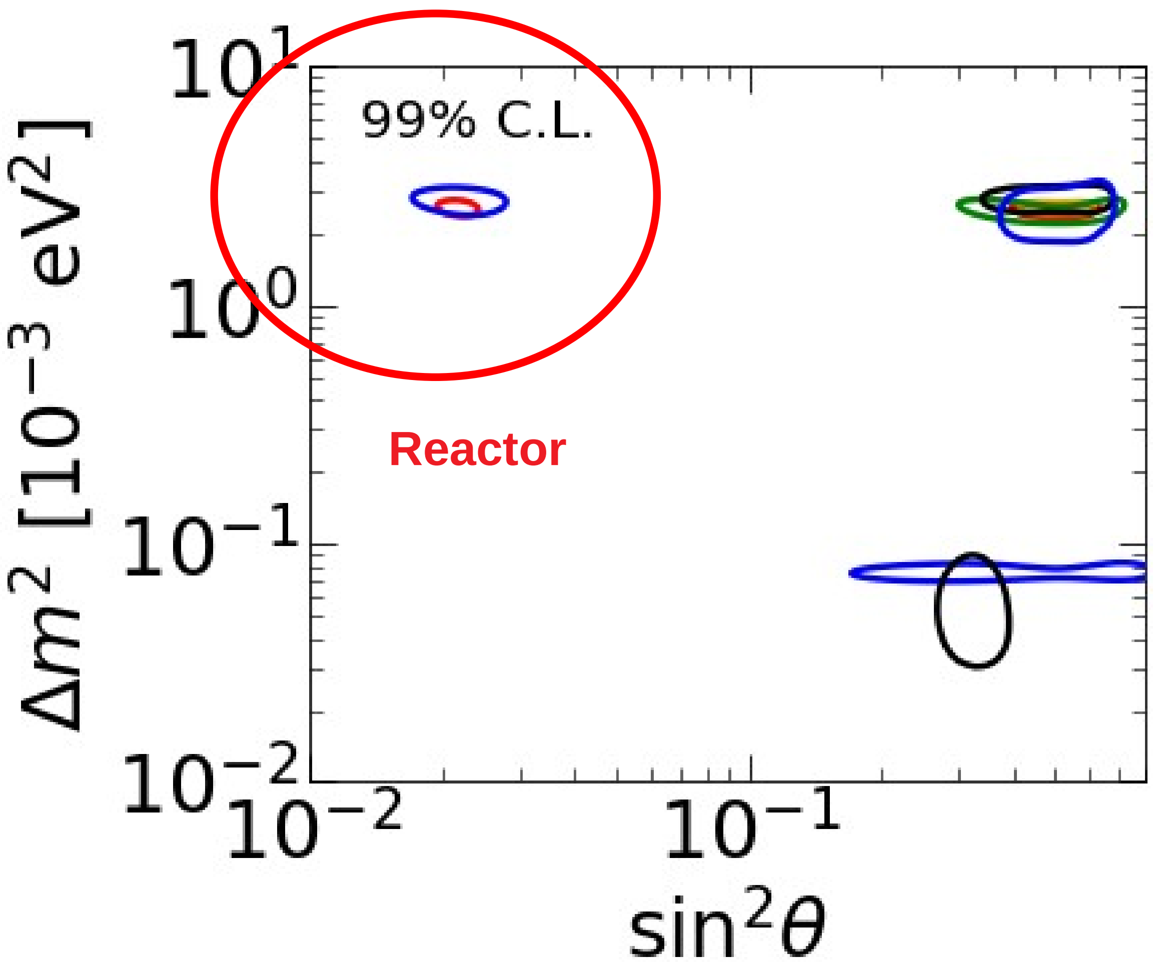
Combination of data sets can enhance sensitivities to oscillation parameters

=> Perform a global fit to neutrino oscillation data!

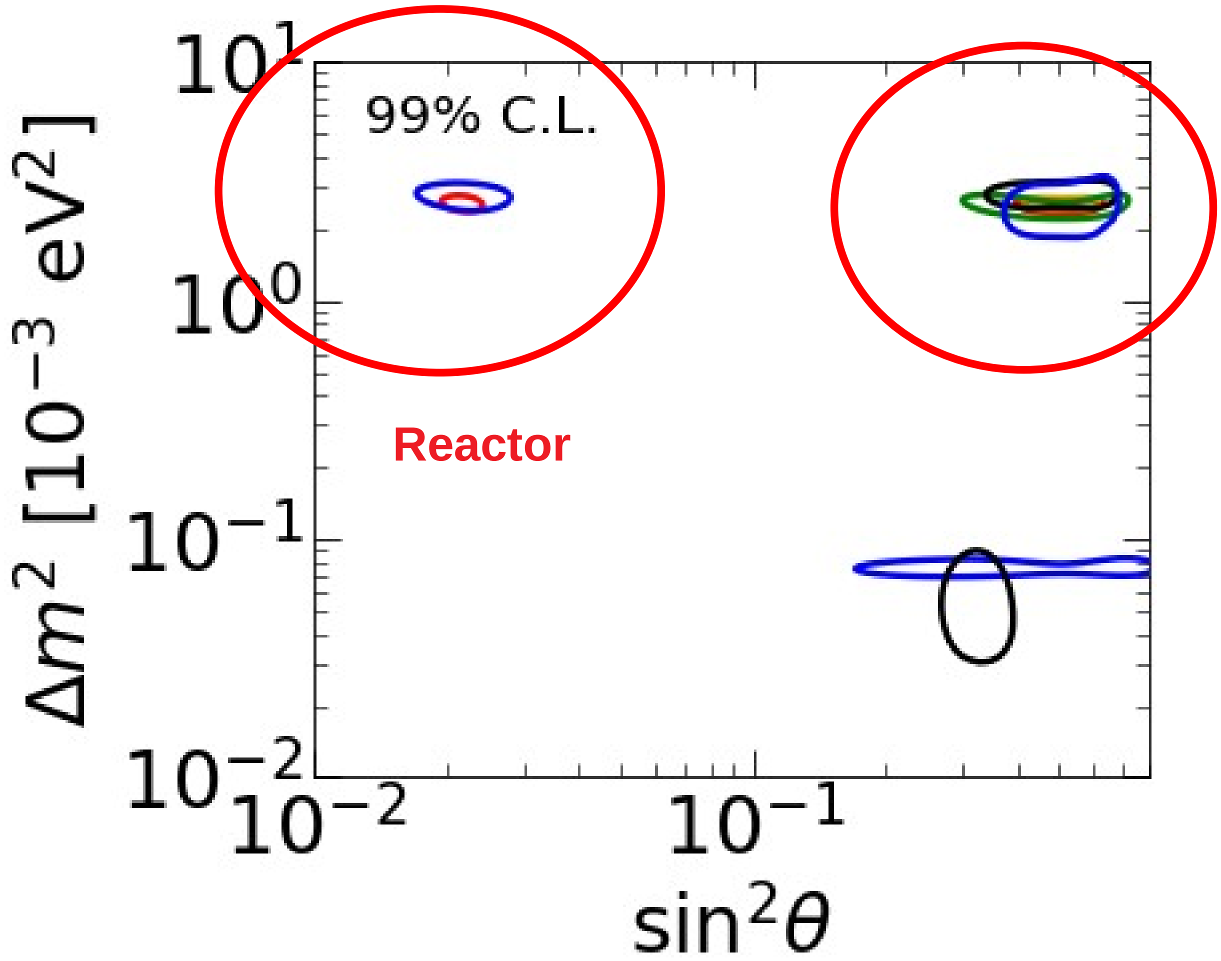
Three-neutrino oscillations



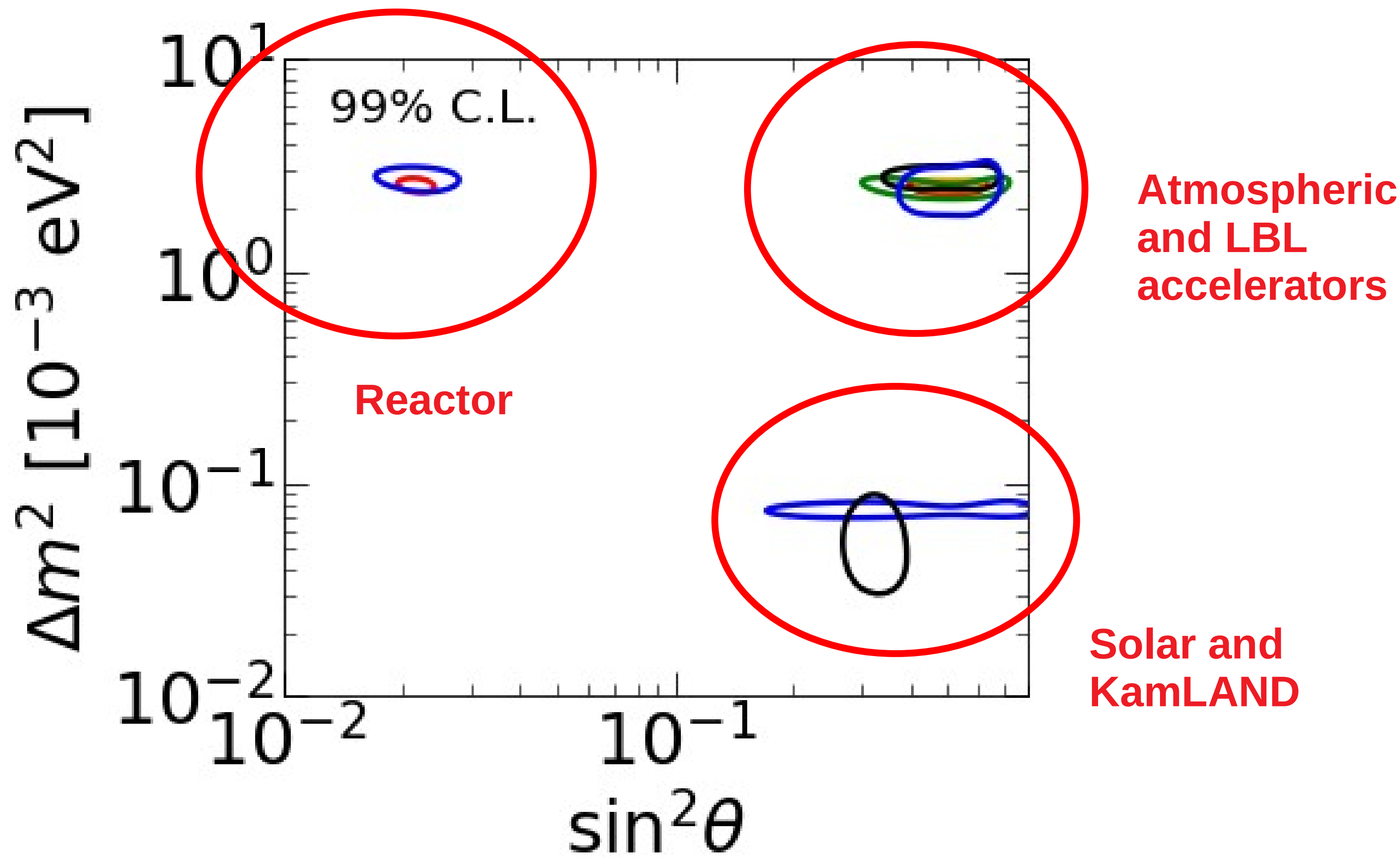
Three-neutrino oscillations



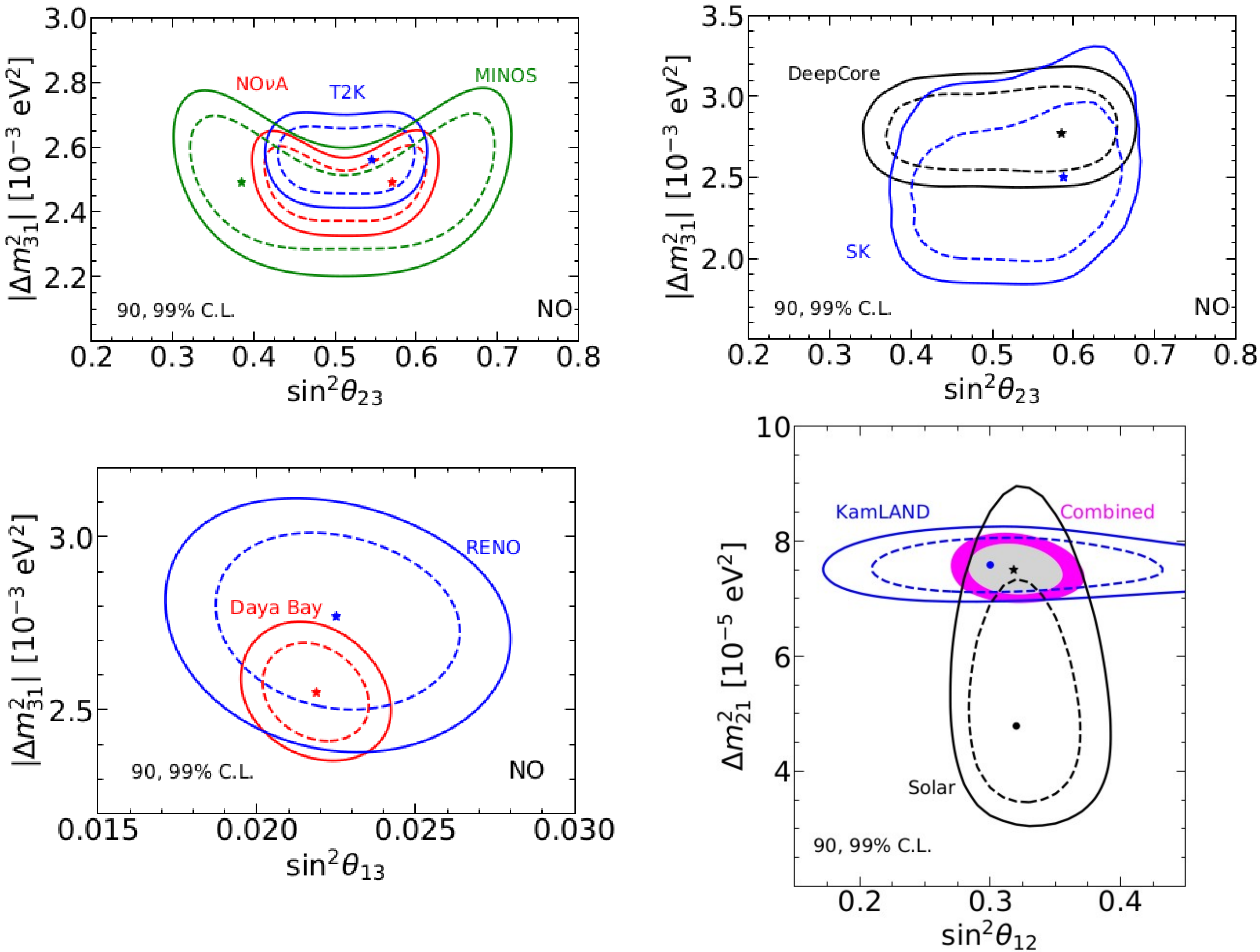
Three-neutrino oscillations



Three-neutrino oscillations

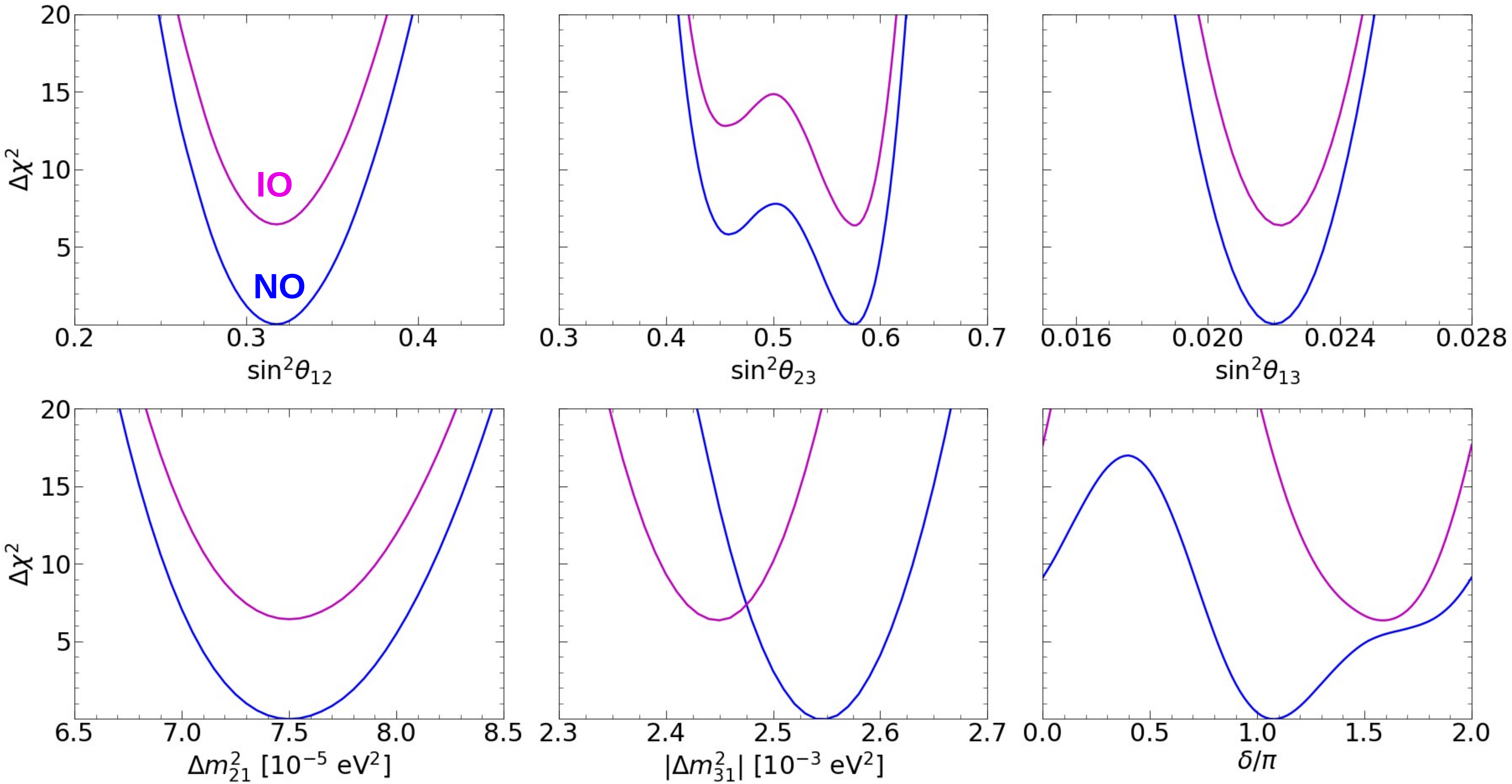


Valencia - Global Fit, 2006.11237, JHEP 2021



Global fit

Valencia - Global Fit, 2006.11237, JHEP 2021



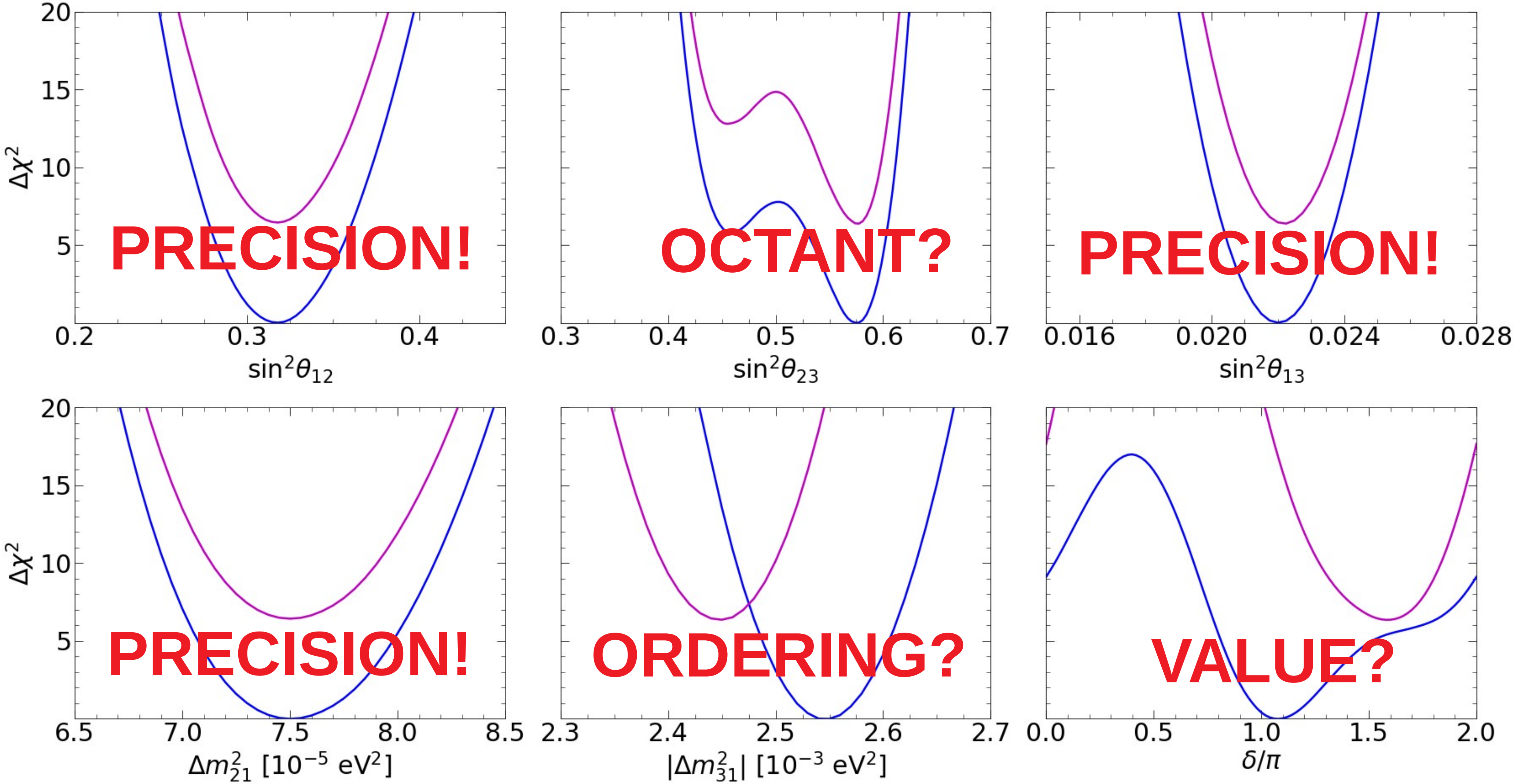
Data as of summer 2020

See also:
Bari – 2107.00532, PRD 2021

See also:
NuFit - 2111.03086 , Universe 2021

Global fit

Valencia - Global Fit, 2006.11237, JHEP 2021



Data as of summer 2020

See also:
Bari – 2107.00532, PRD 2021

See also:
NuFit - 2111.03086 , Universe 2021

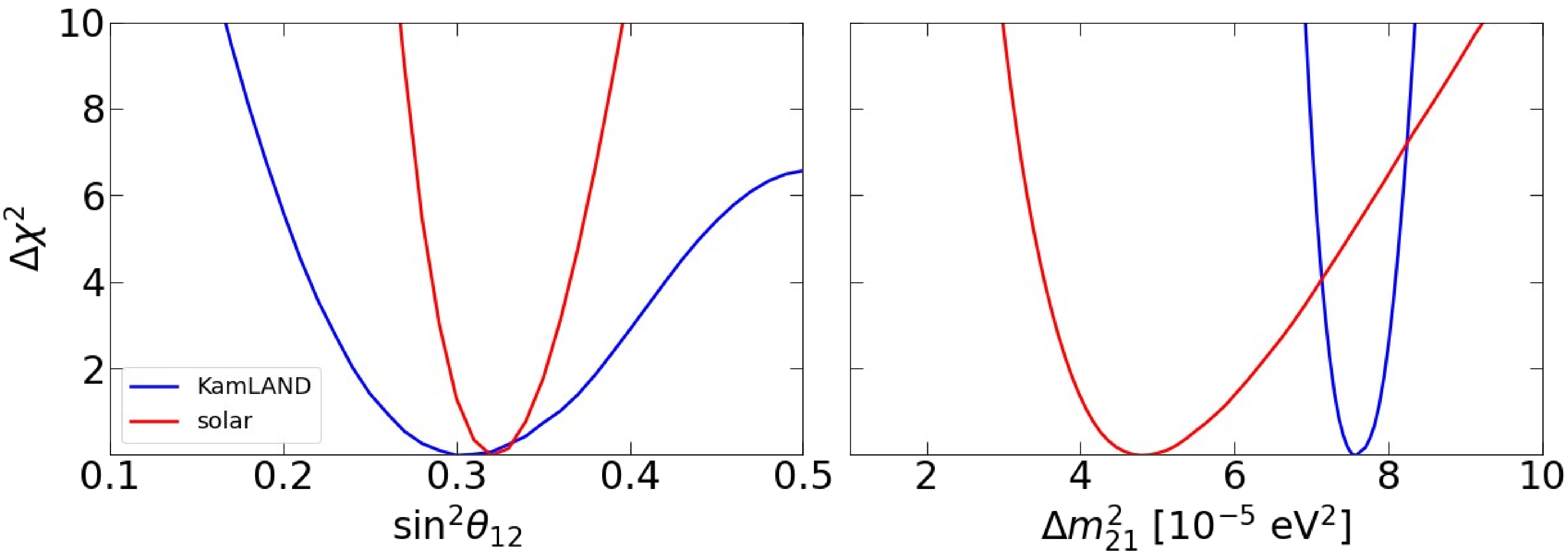
Global fit

parameter	best fit $\pm 1\sigma$		2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	**2.7%**	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	**1.2%**	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\mathrm{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$		2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	**5.0%**	2.86–3.52	2.71–3.69
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	**2.5%**	5.41–5.99	4.34–6.10
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$		5.41–5.98	4.33–6.08
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	**3.1%**	2.069–2.337	2.000–2.405
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$		2.086–2.356	2.018–2.424
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	**12%**	0.84–1.42	0.71–1.99
δ/π (IO)	$1.58^{+0.15}_{-0.16}$		1.26–1.85	1.11–1.96

Data as of summer 2020

Valencia - Global Fit, 2006.11237, JHEP 2021

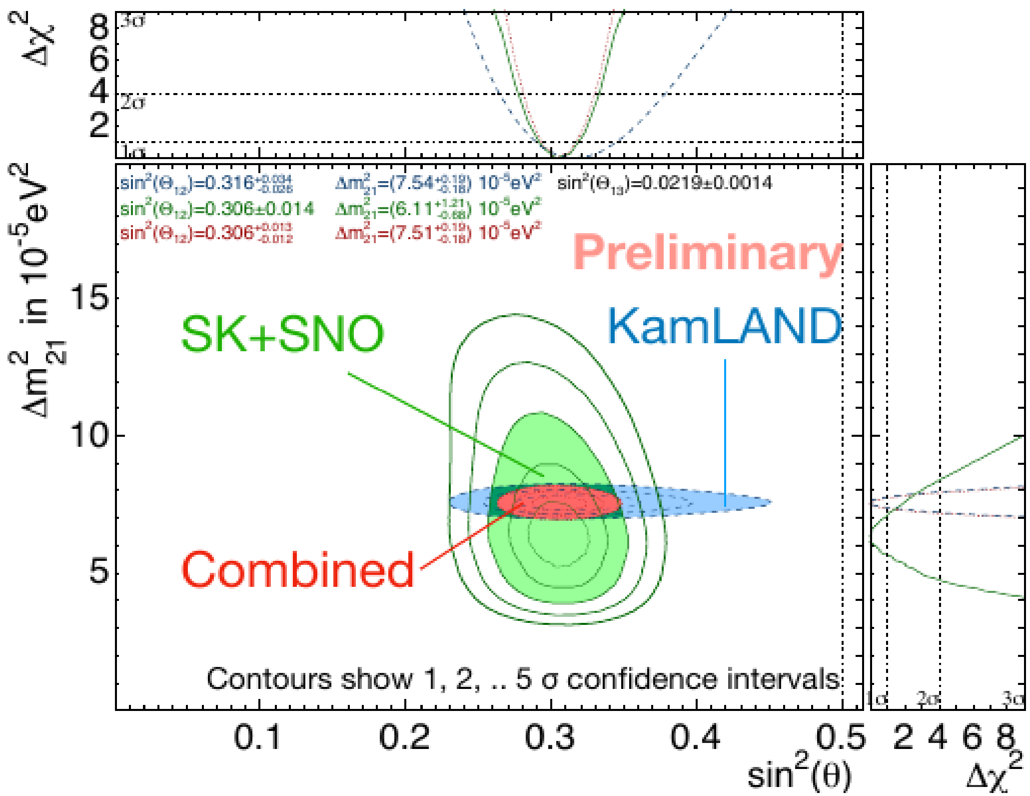
Solar sector



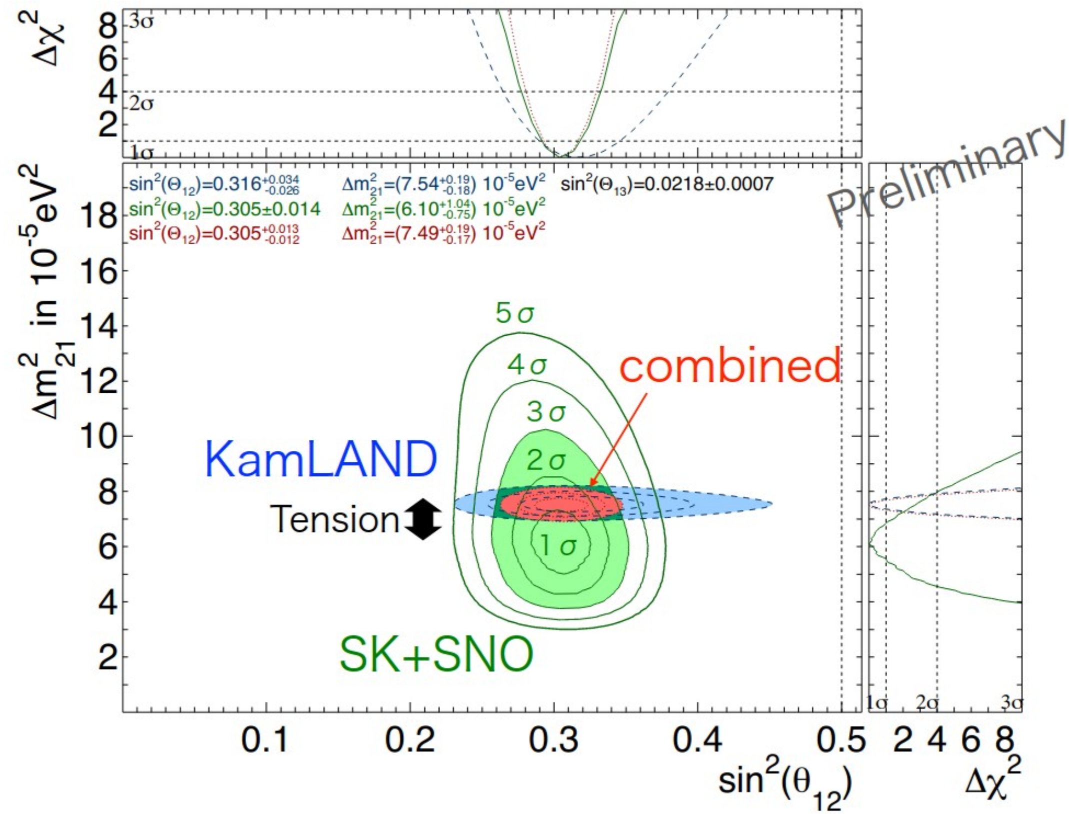
Better determination of mass splitting / mixing angle at KamLAND / solar expriments

A 2σ tension in the measurement of the mass splitting

Solar sector



Neutrino 2020



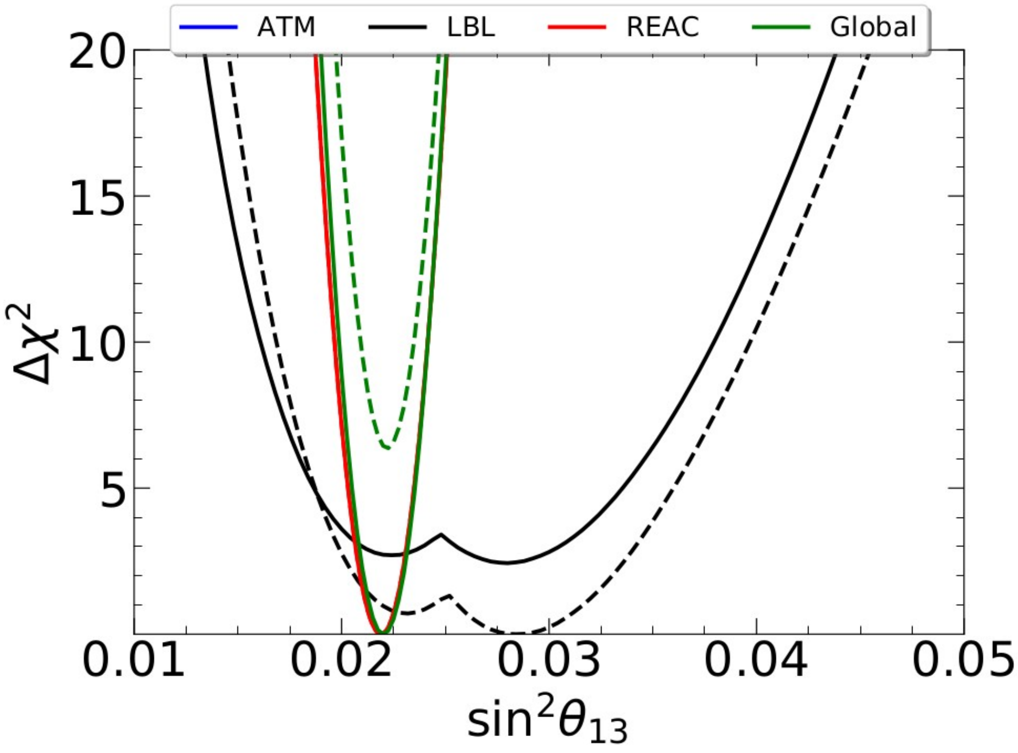
Neutrino 2022

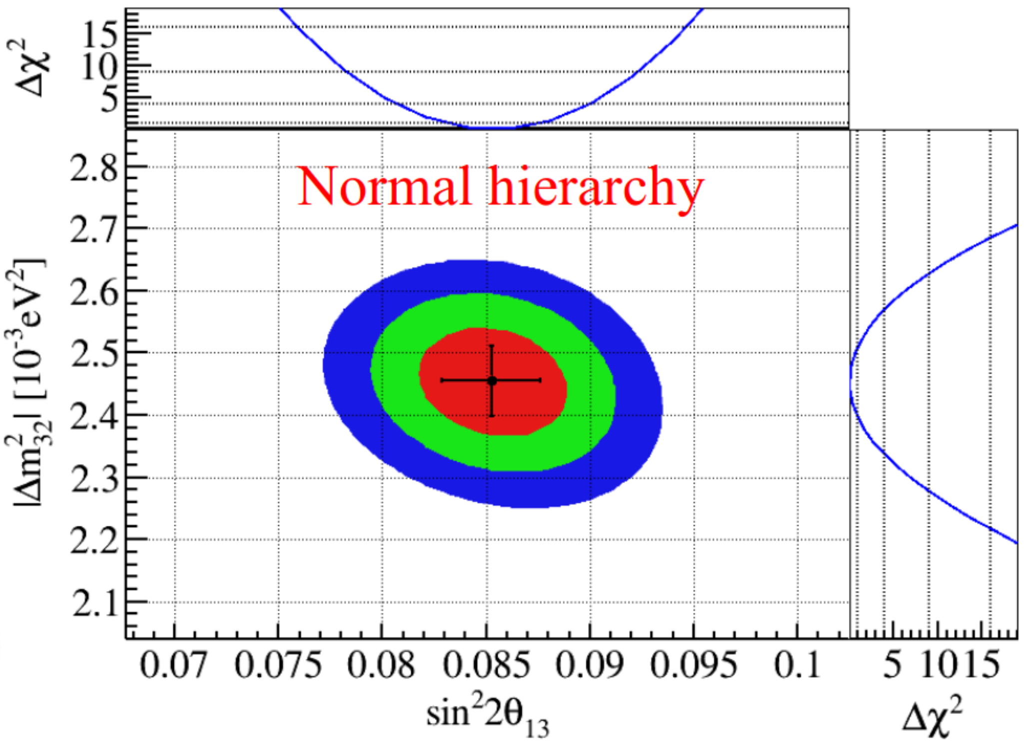
See talk by Y. Takeuchi

Discrepancy is reduced to 1.1σ due to new Super-K data in 2020

Discrepancy is raised to 1.5σ due to smaller error bars in 2022

Reactor angle





Valencia - Global Fit, 2006.11237, JHEP 2021

K. Luk, Neutrino 2022

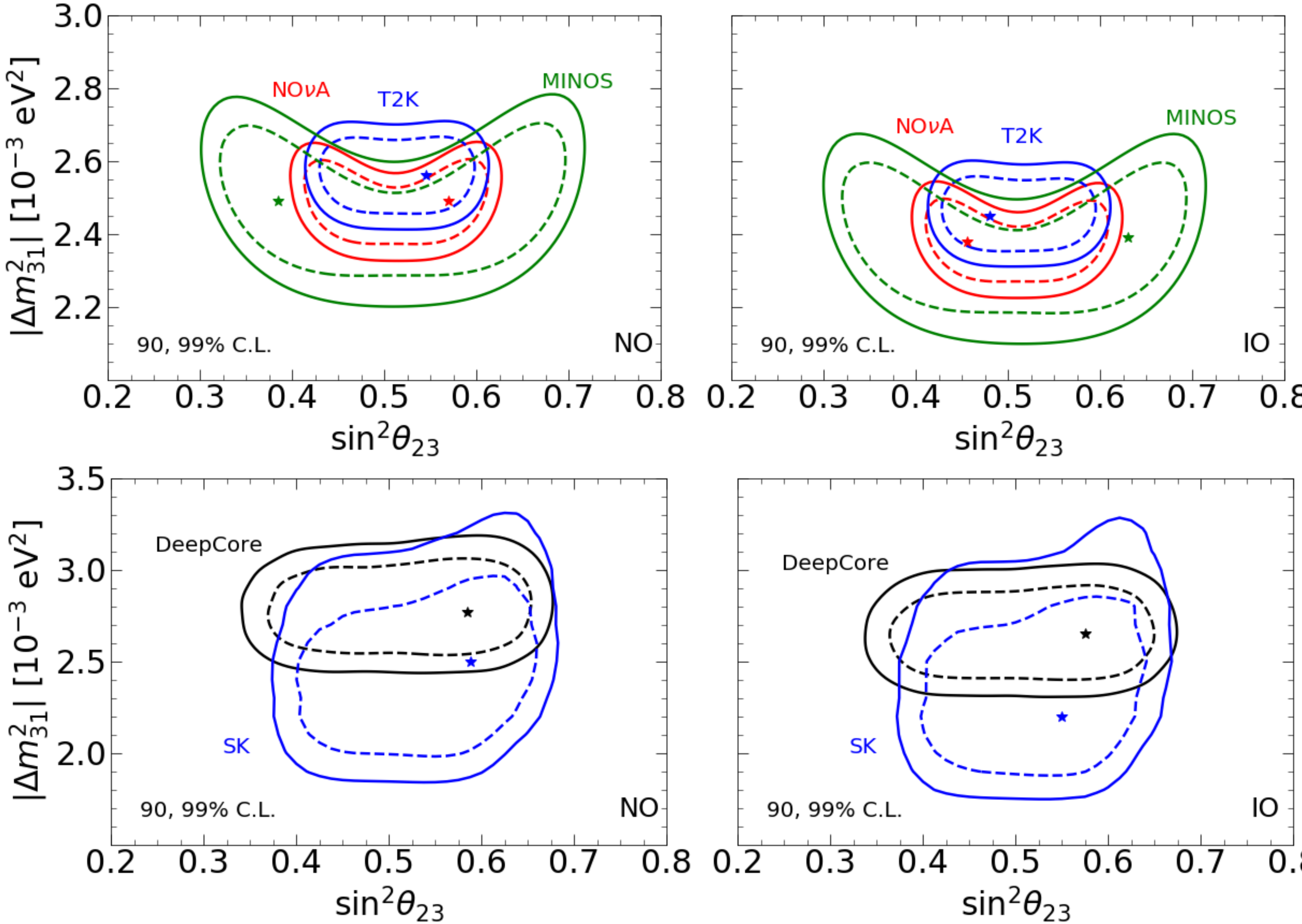
See talk by Y. Hsiung

Global fit: 3.1% precision on reactor angle

3158 days Daya Bay data: 2.8% precision!

Atmospheric sector

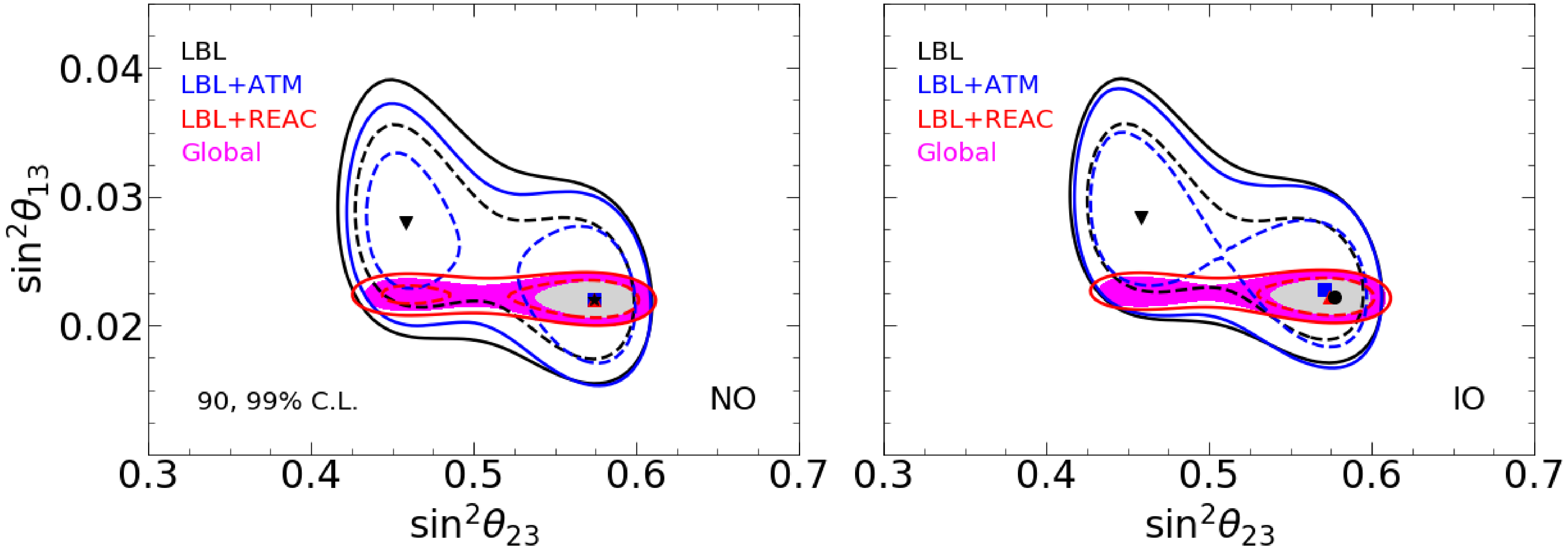
Many experiments measure the atmospheric parameters



Atmospheric octant

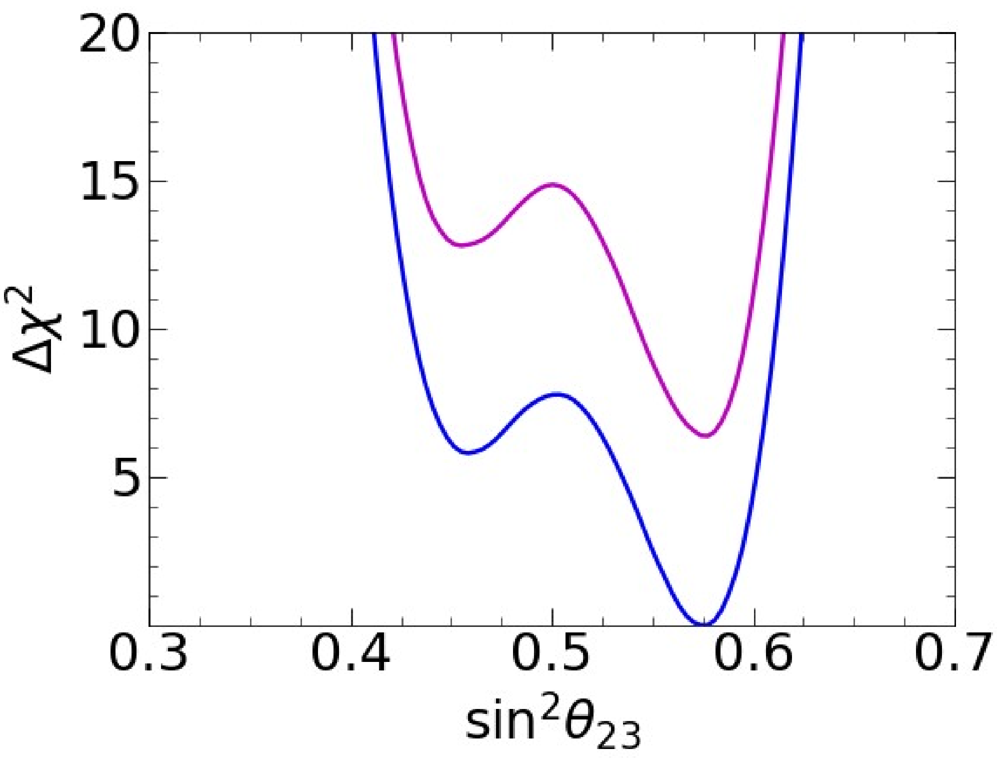
LBL data on their own do not distinguish octants

Adding ATM and REAC breaks degeneracies

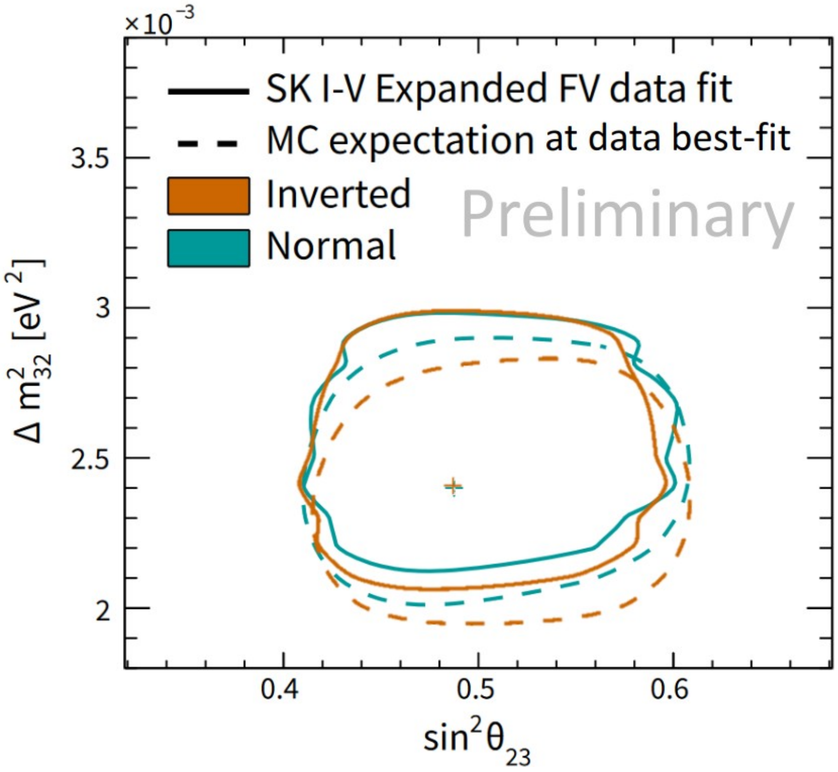


Valencia - Global Fit, 2006.11237, JHEP 2021

Atmospheric octant



Valencia - Global Fit, 2006.11237, JHEP 2021



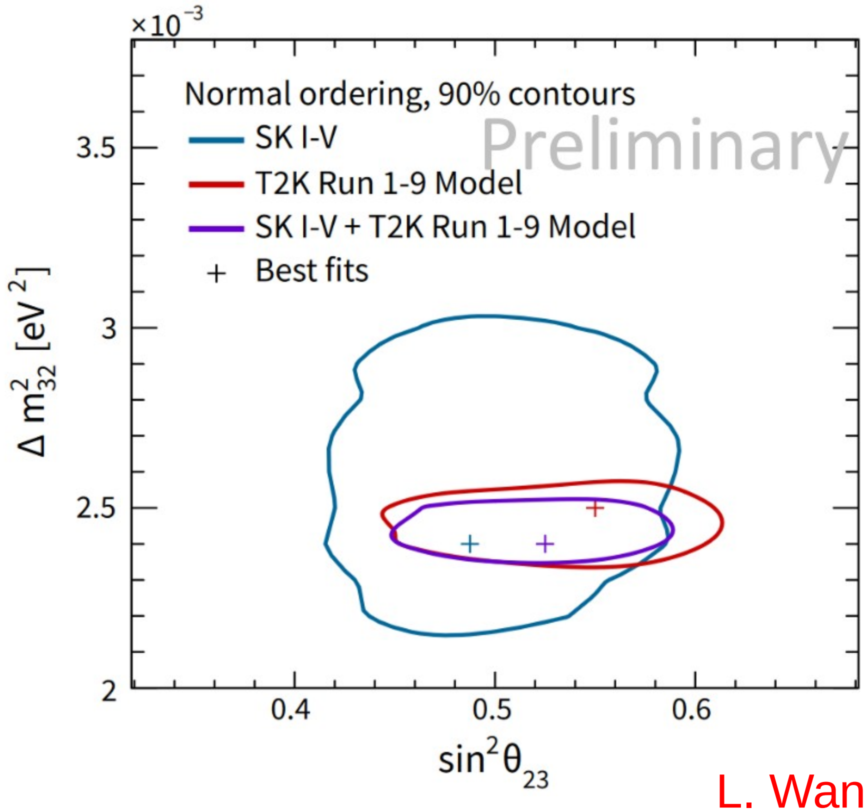
L. Wan, Neutrino 2022

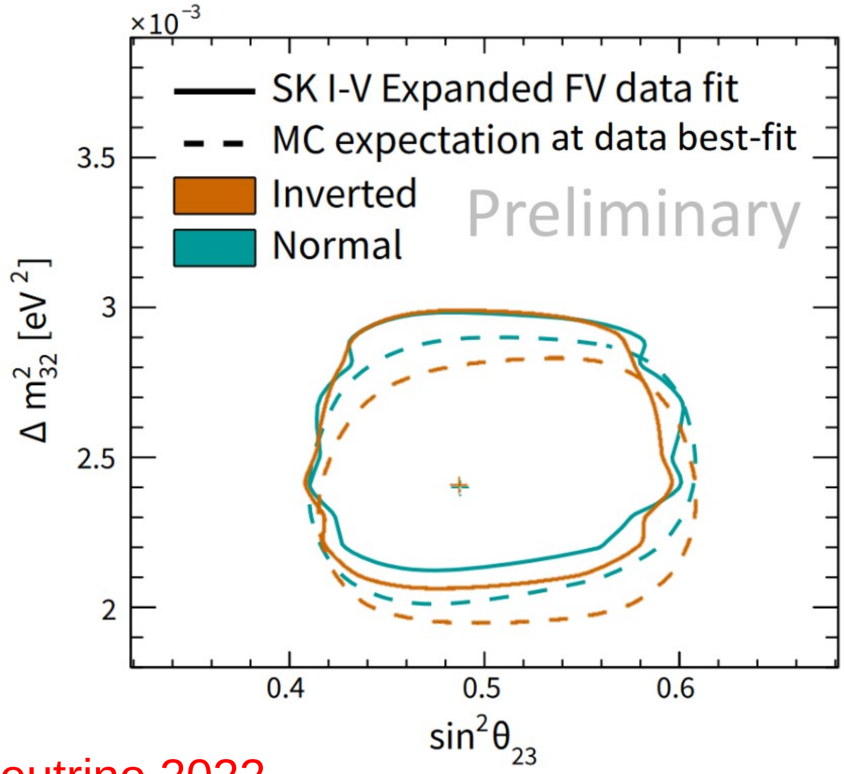
2020 global fit prefers second octant

New data from SK prefer (nearly) maximal mixing

See talk by Y. Takeuchi

Atmospheric octant





L. Wan, Neutrino 2022

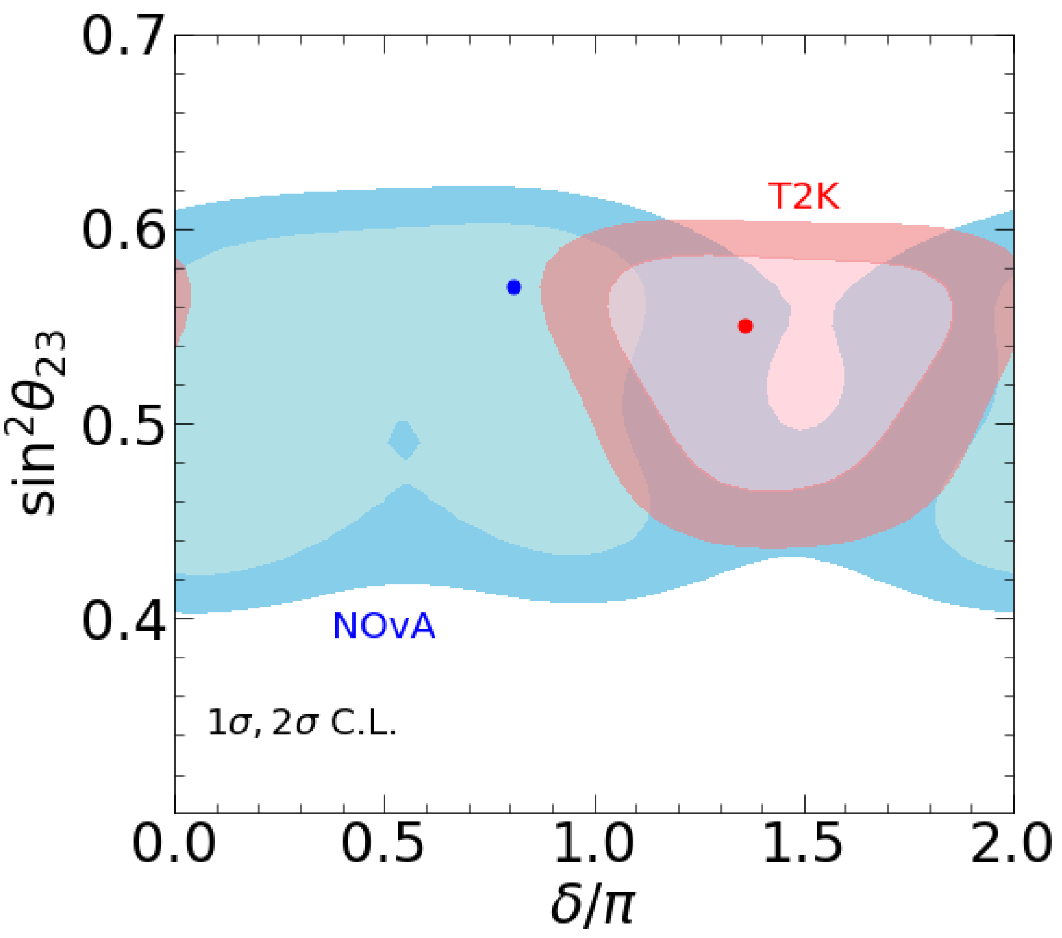
2020 global fit prefers second octant

New data from SK prefer (nearly) maximal mixing

Combined analysis of T2K+SK(+reactor angle) prefer second octant

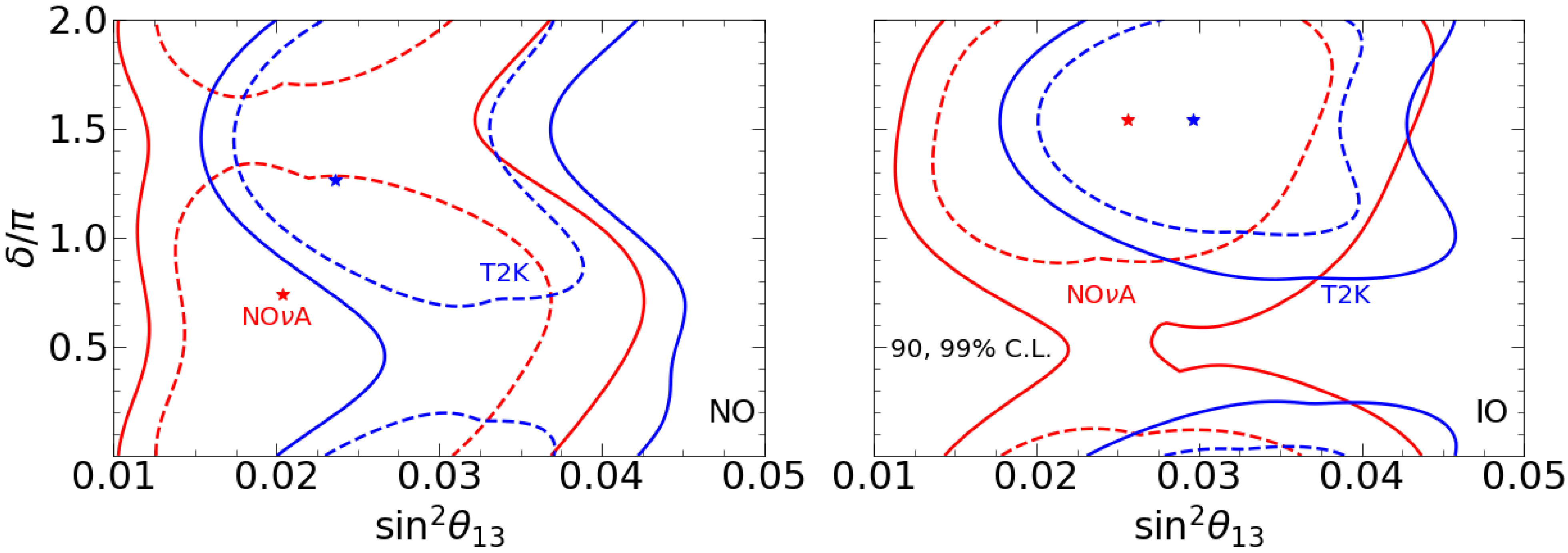
See talk by Y. Takeuchi

CP violation



“Tension” in the measurement of the CP phase in current data

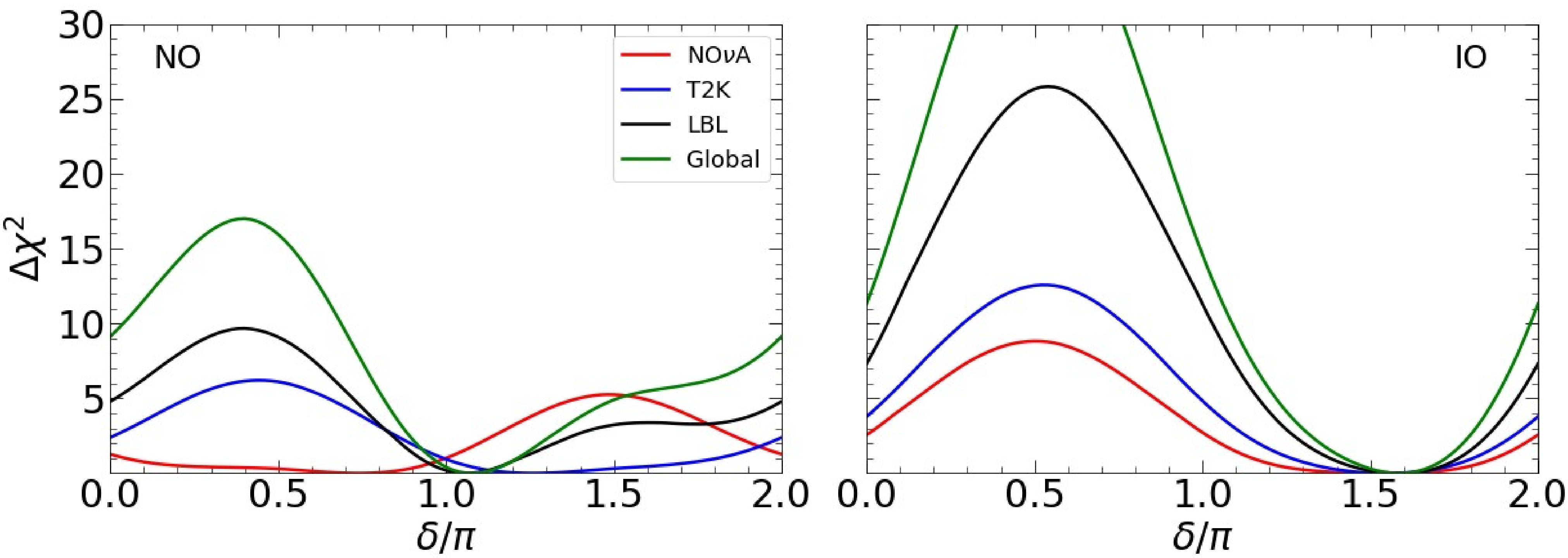
CP violation



“Tension” remains when relaxing prior from reactor neutrinos

Valencia - Global Fit, 2006.11237, JHEP 2021

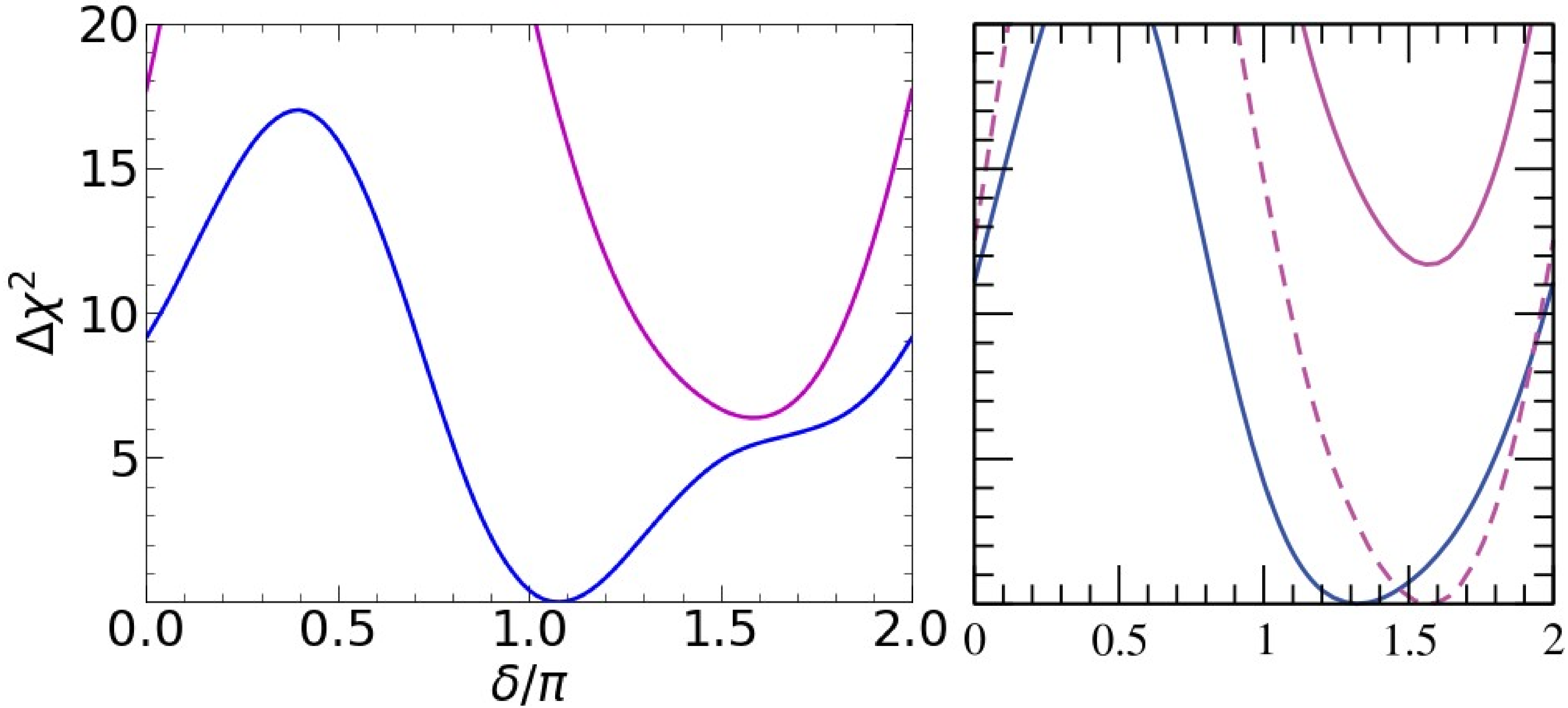
CP violation



T2K and NOνA profiles disagree for NO

Valencia - Global Fit, 2006.11237, JHEP 2021

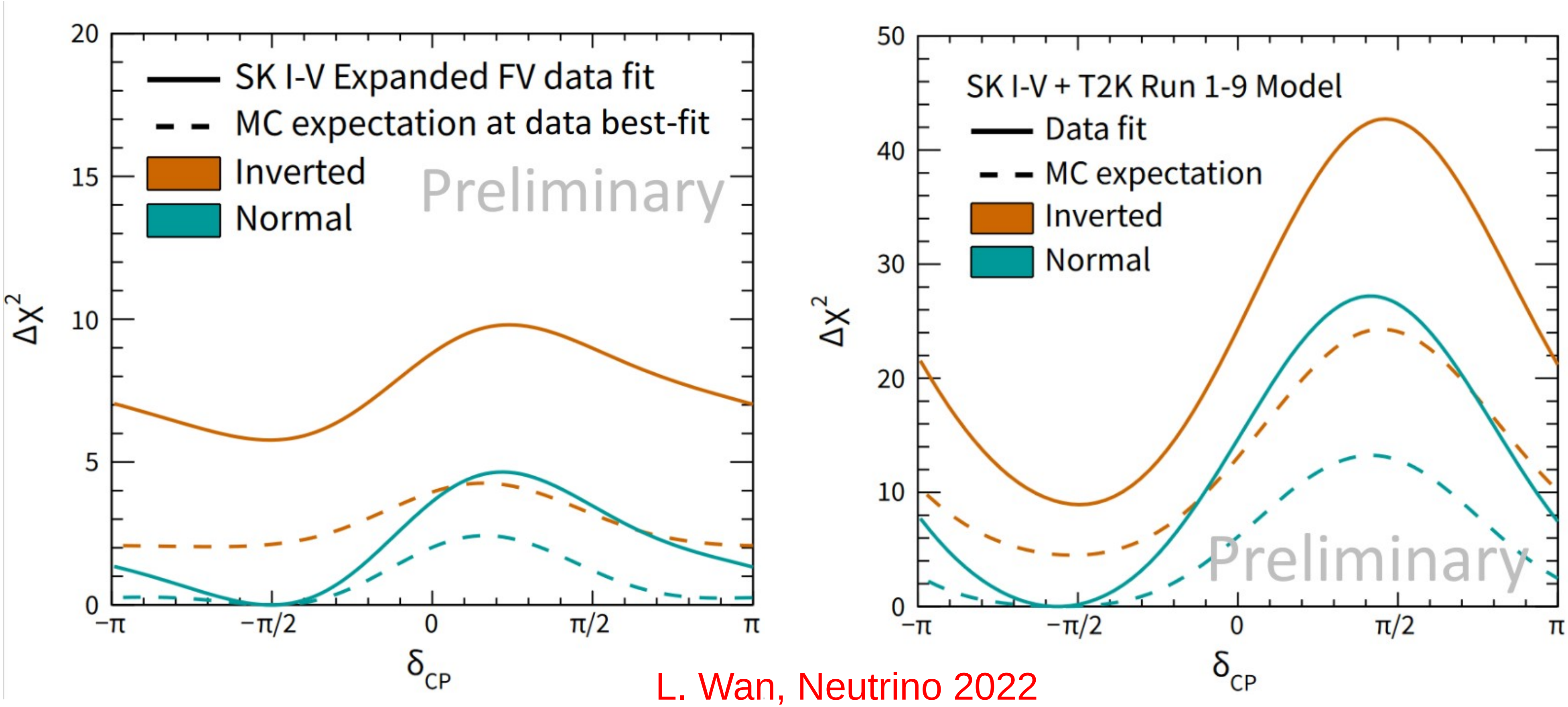
CP violation



The measurement of delta is now worse than it was before

Valencia - Global Fit 2020, 2006.11237, JHEP 2021
Valencia - Global Fit 2018, 1708.01186, PLB 2018

CP violation



L. Wan, Neutrino 2022

The measurement of delta is improved in SK data and in the SK+T2K(+reactor angle) analysis

Neutrino mass ordering

Global fit has 2.5σ preference for normal neutrino mass ordering

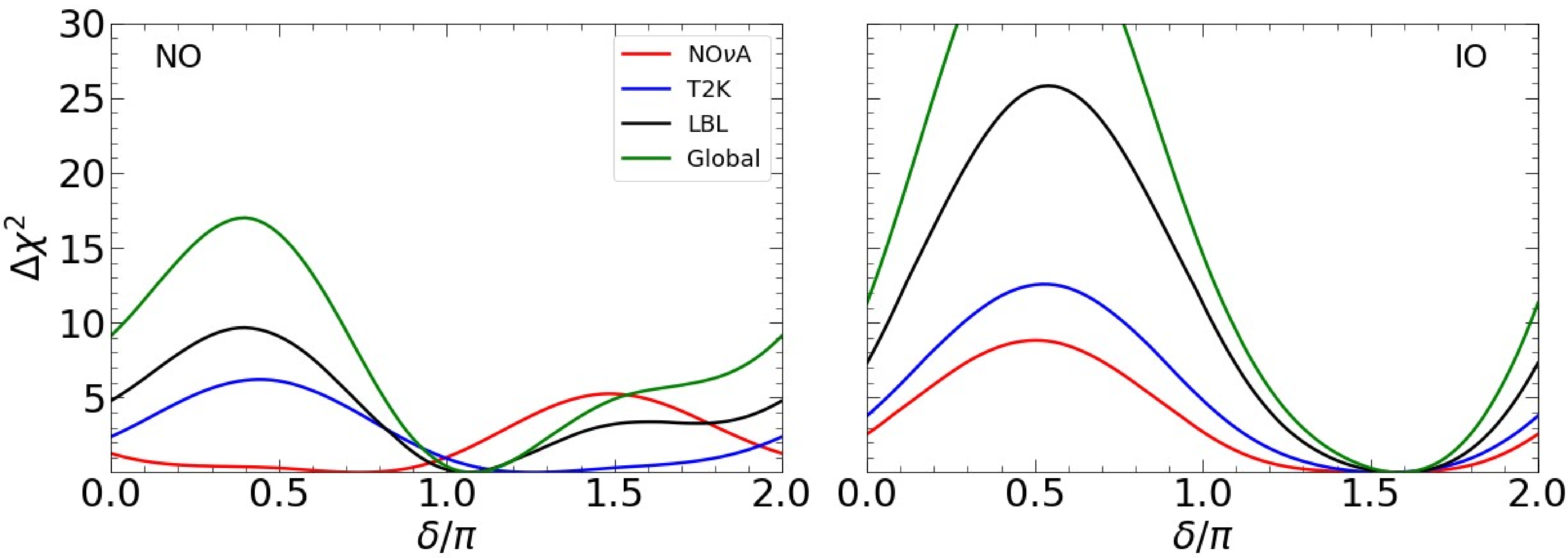
None of the experiments has a good sensitivity on its own

The 2.5σ are due to a series of small or large tensions among different data sets

The neutrino mass ordering is a sensible issue

Neutrino mass ordering

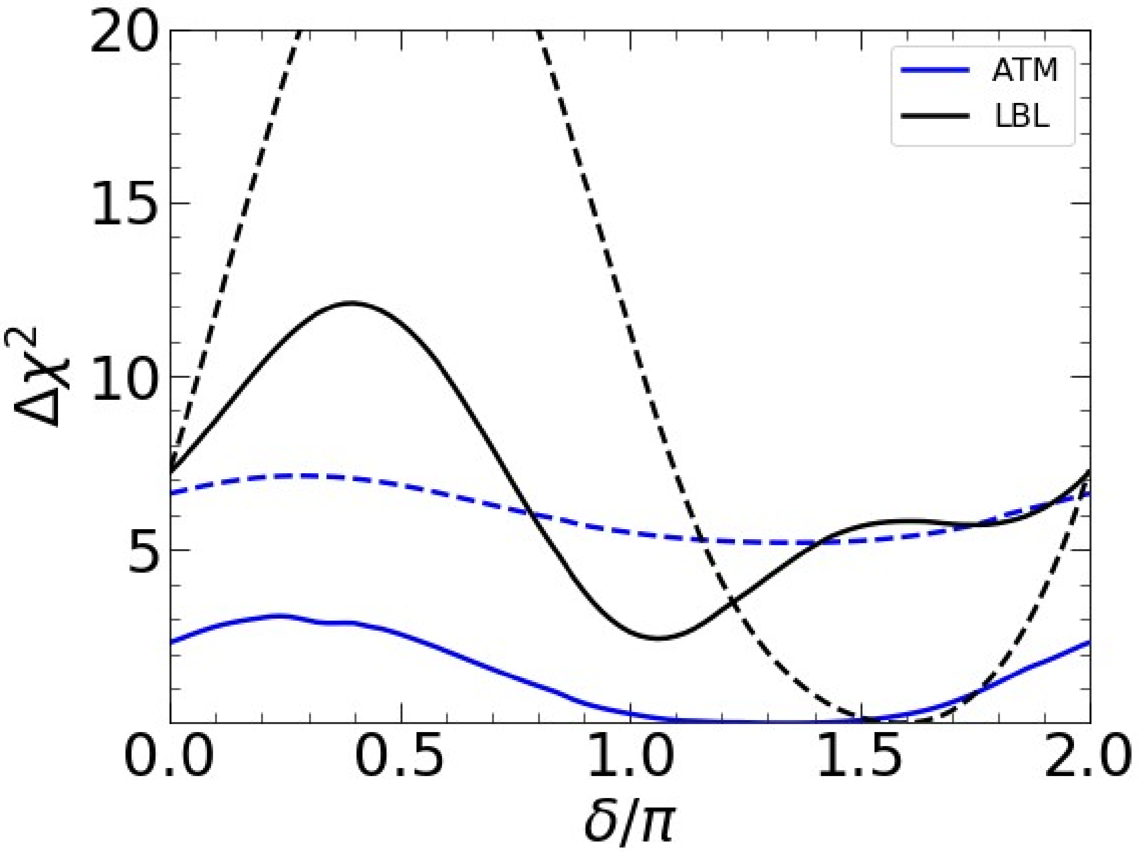
The tension between T2K and NOνA in the measurement of the CP phase appears only for normal ordering



Neutrino mass ordering

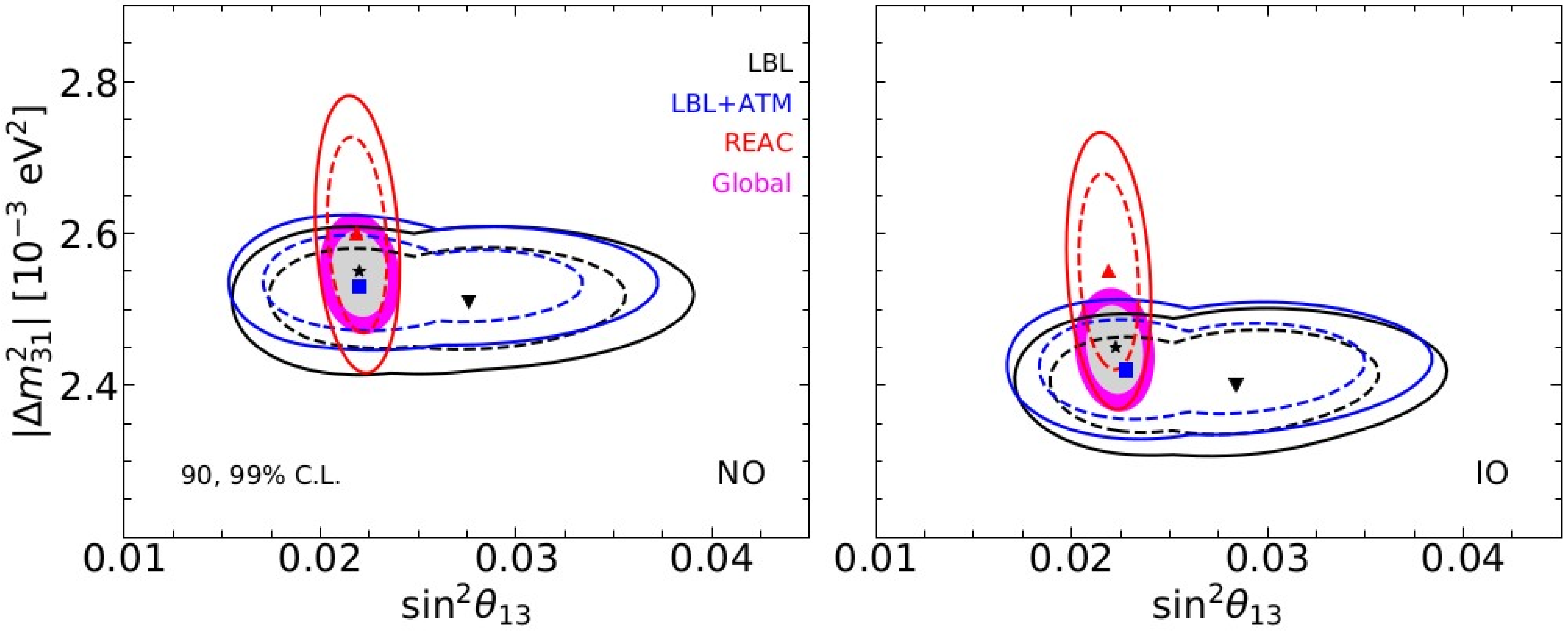
Although none of the experiments has a preference on its own, the combined analysis of all LBL data prefers IO!

At the same time there is slight preference for NO from atmospheric experiments



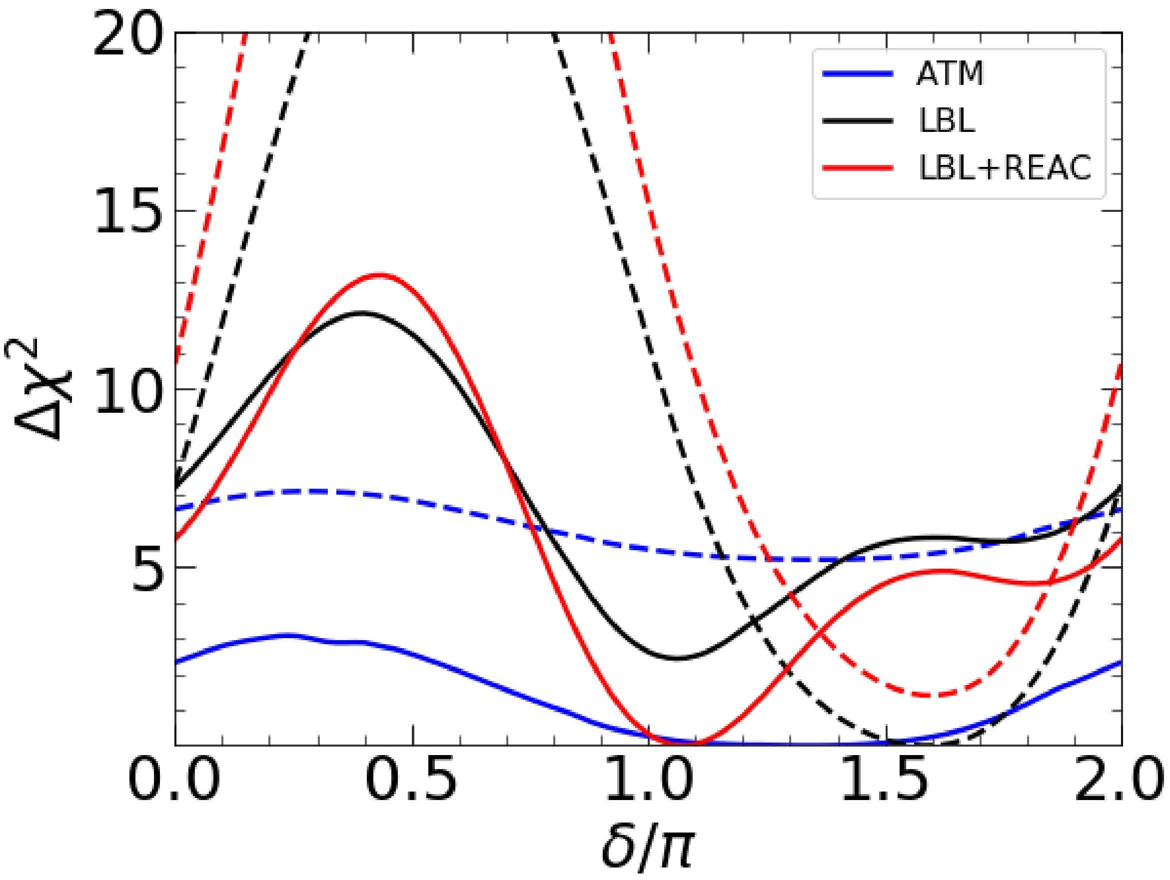
Neutrino mass ordering

When combining LBL with REAC, NO is again preferred at 1σ level, due to a better agreement in the measurement of the mass splitting among accelerators and reactor for normal ordering



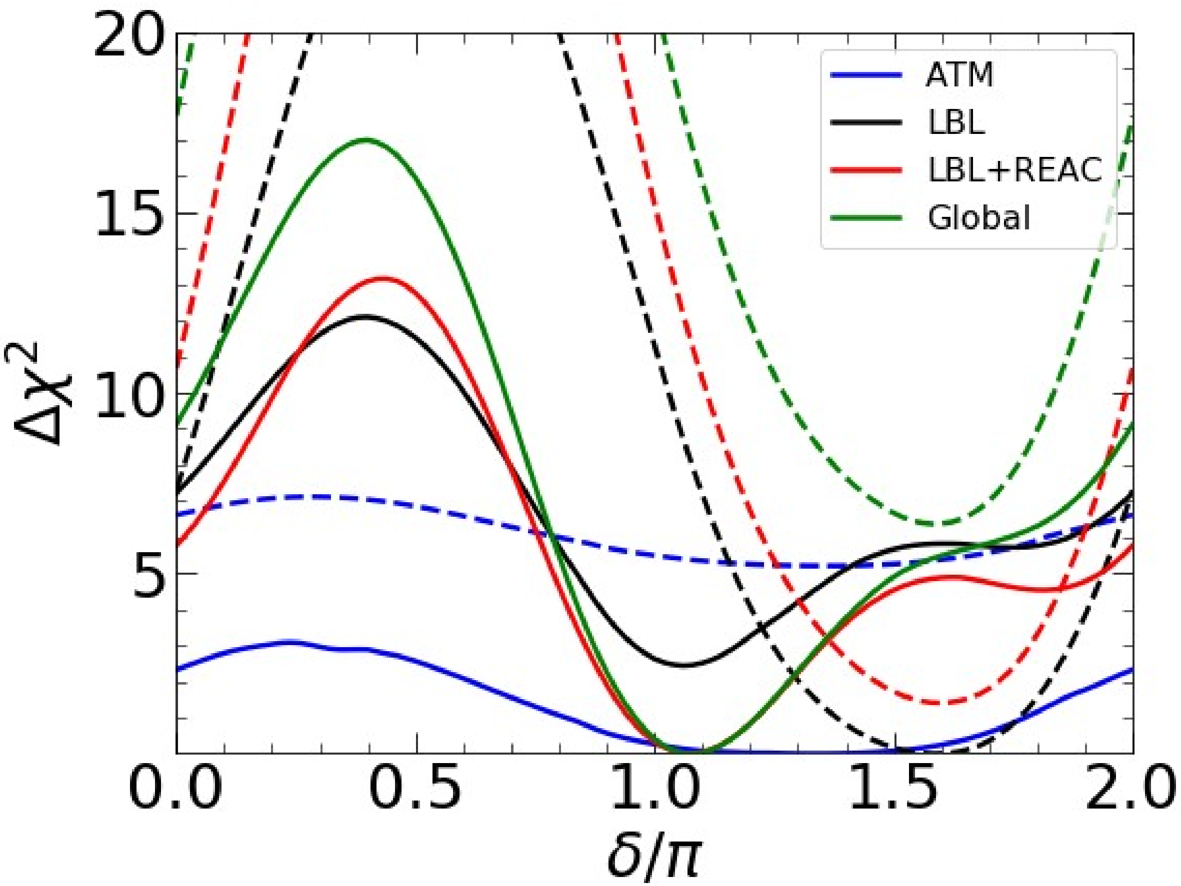
Neutrino mass ordering

When combining LBL with REAC, NO is again preferred at 1σ level, due to a better agreement in the measurement of the mass splitting among accelerators and reactor for normal ordering

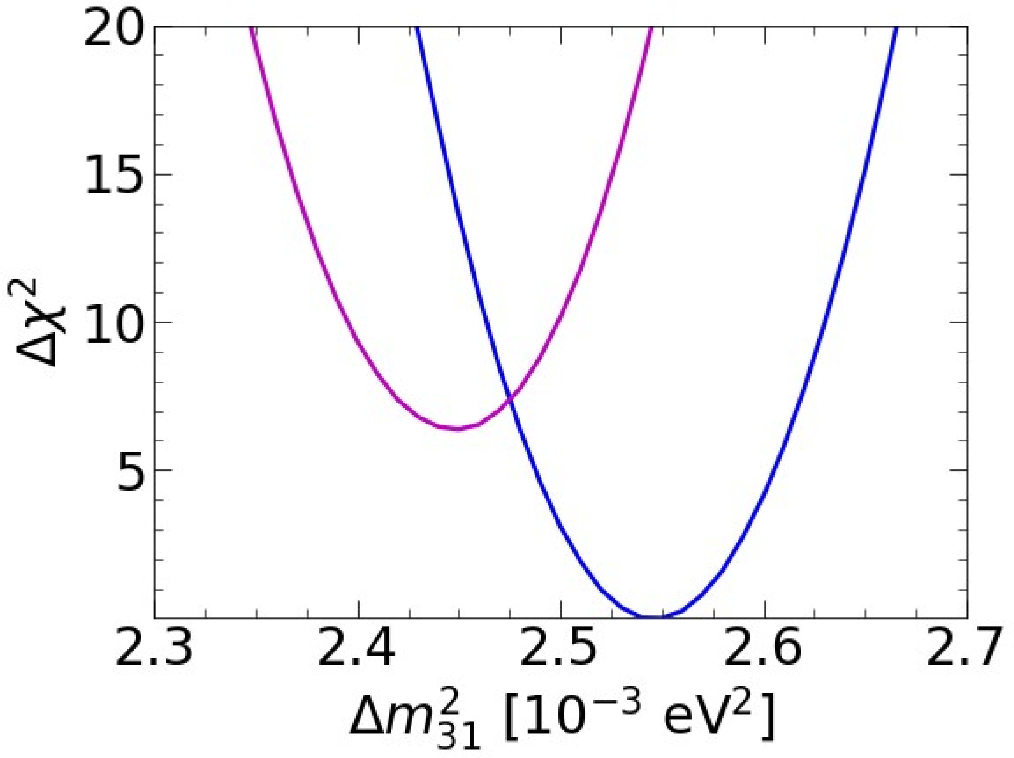


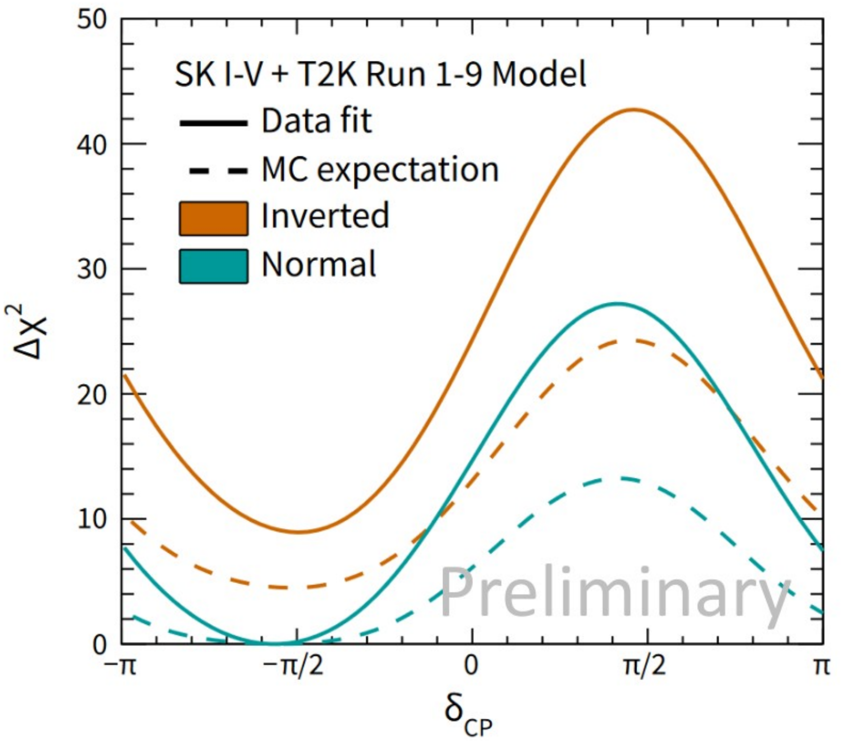
Neutrino mass ordering

After combing everything we get 2.5σ



Neutrino mass ordering





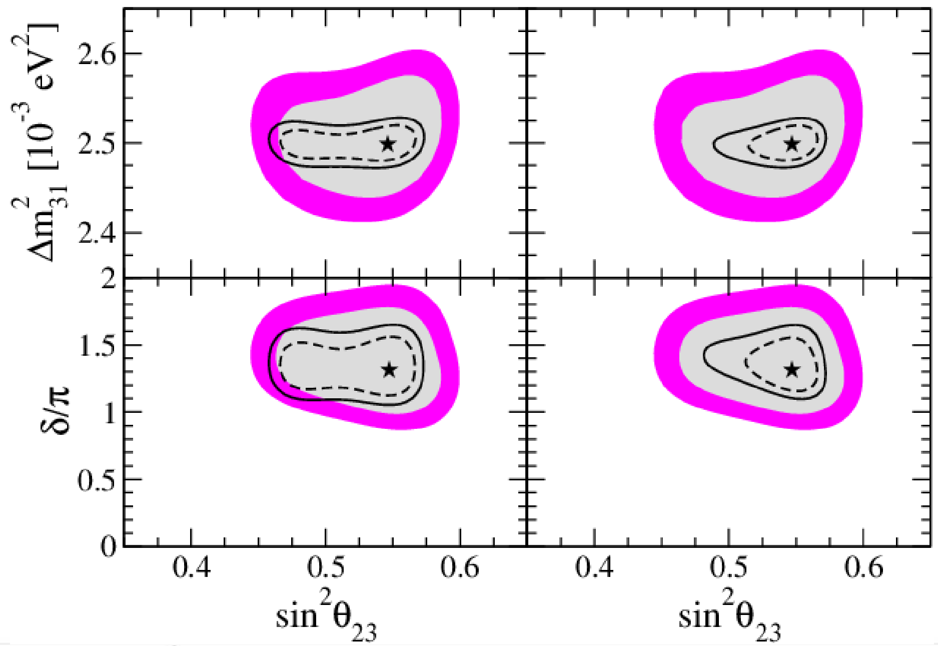
Valencia - Global Fit, 2006.11237, JHEP 2021

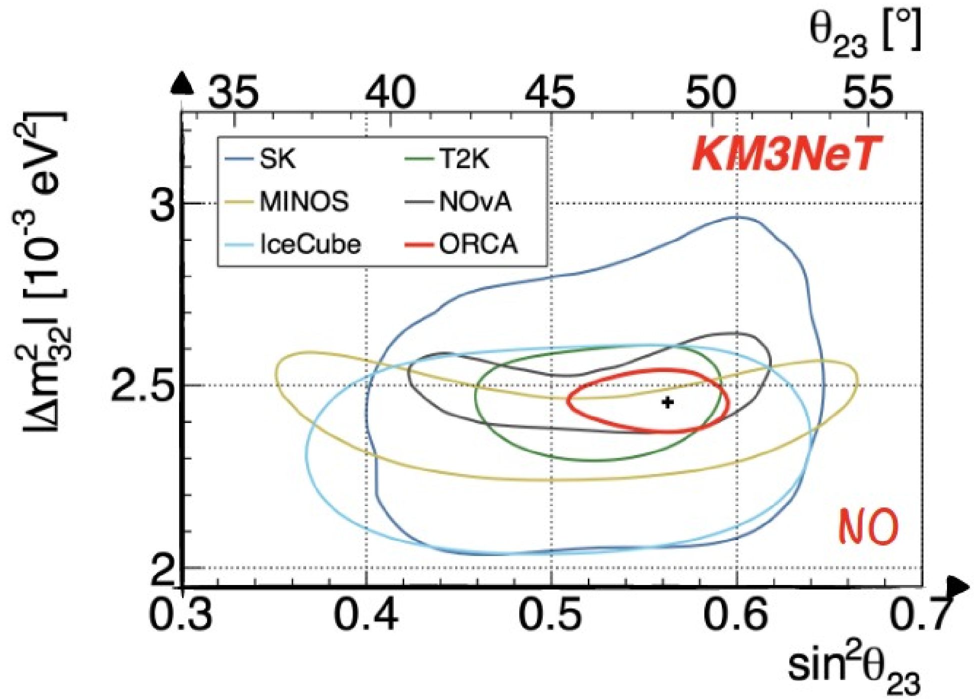
L. Wan, Neutrino 2022

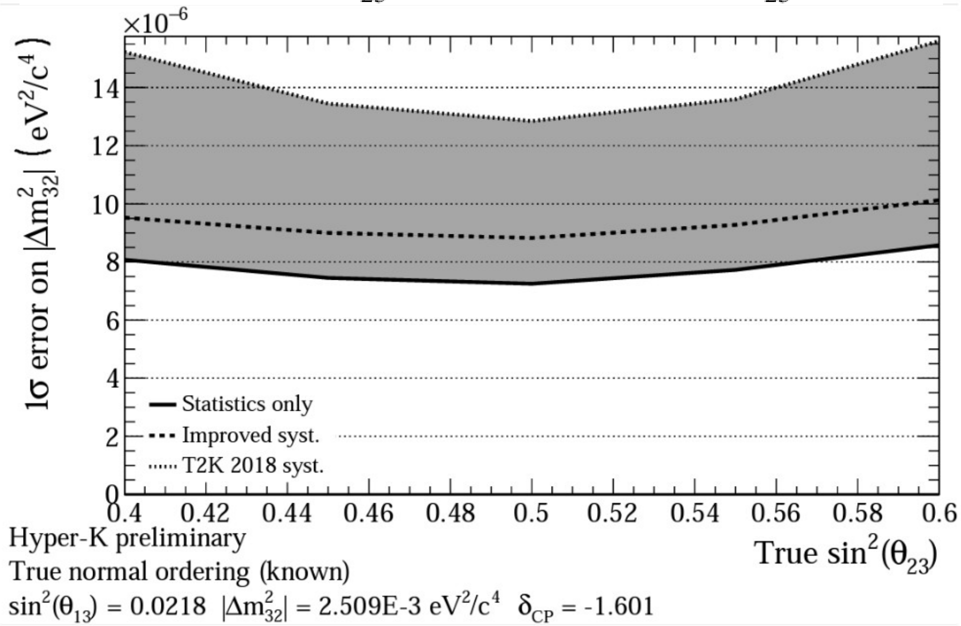
2.5σ preference, coming from different tensions

New analysis from T2K+SK preferences NO at 3σ; difficult to estimate the impact of NOνA

Far future (DUNE, ORCA and Hyper-Kamiokande)





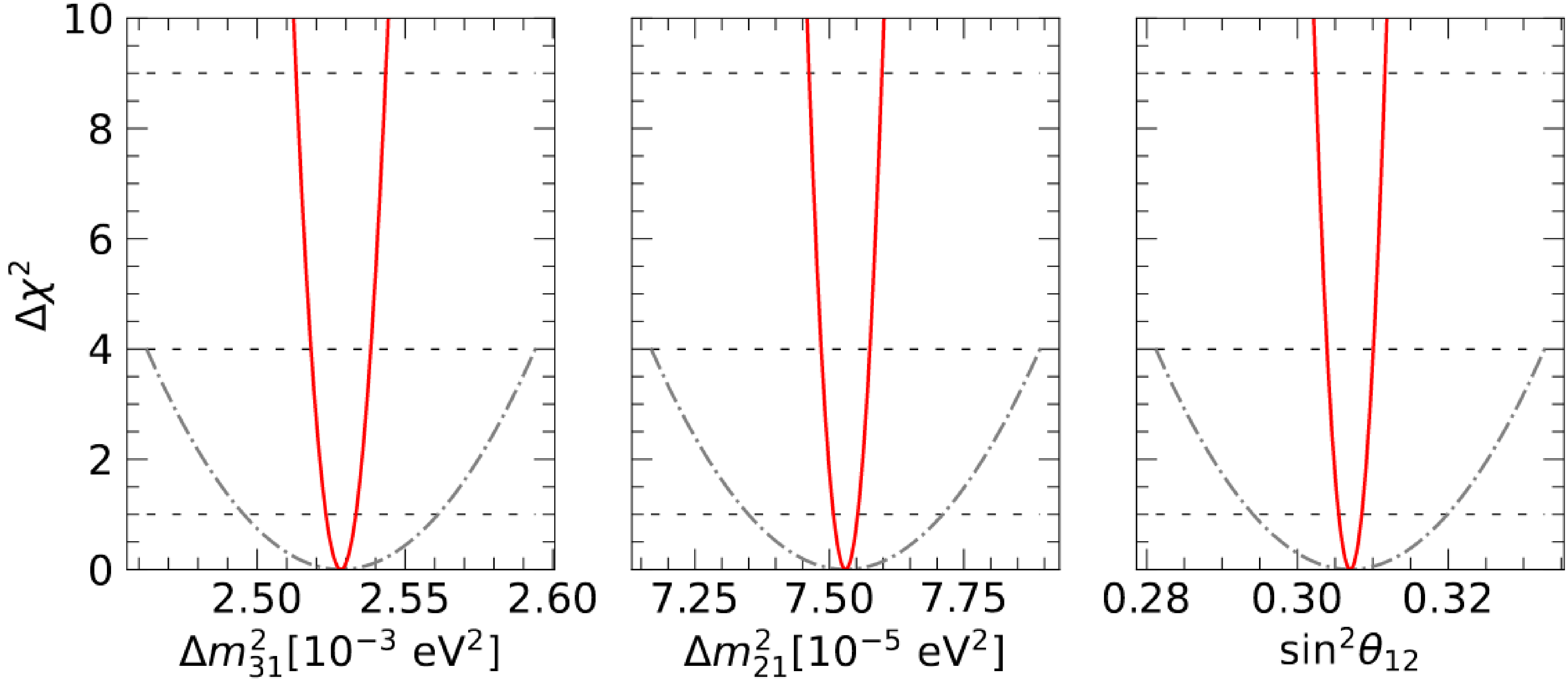


DUNE, ORCA and Hyper-K (and T2HK) will improve several measurements considerably

See talks by L. Stanco, C. Lastoria, Z. Xie

Far future (JUNO)

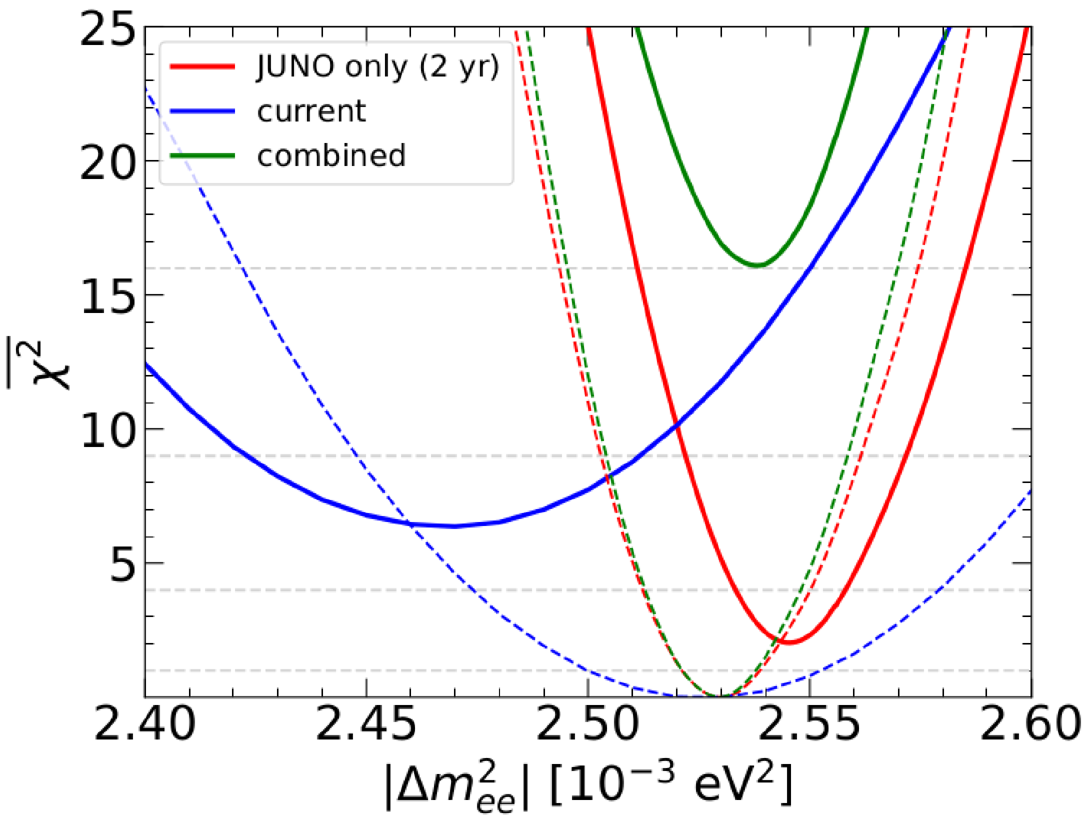
JUNO collaboration, 2204.13249



JUNO will measure solar parameters with extremely good precision

See talk by M. Sisti

(Not so) Far future (JUNO)



Forero, Parke, Ternes, Zukanovich Funchal, 2107.12410, PRD 2021

See also the combined sensitivity analyses in:

-1911.06745 (JUNO + PINGU)

-2008.11280 (JUNO + T2K-II)

-2108.06293 (JUNO + ORCA)

The addition of JUNO will boost the mass ordering sensitivity of the global neutrino oscillation fit to the 4σ-5σ level

Conclusions

Some of the neutrino oscillation parameters are well measured

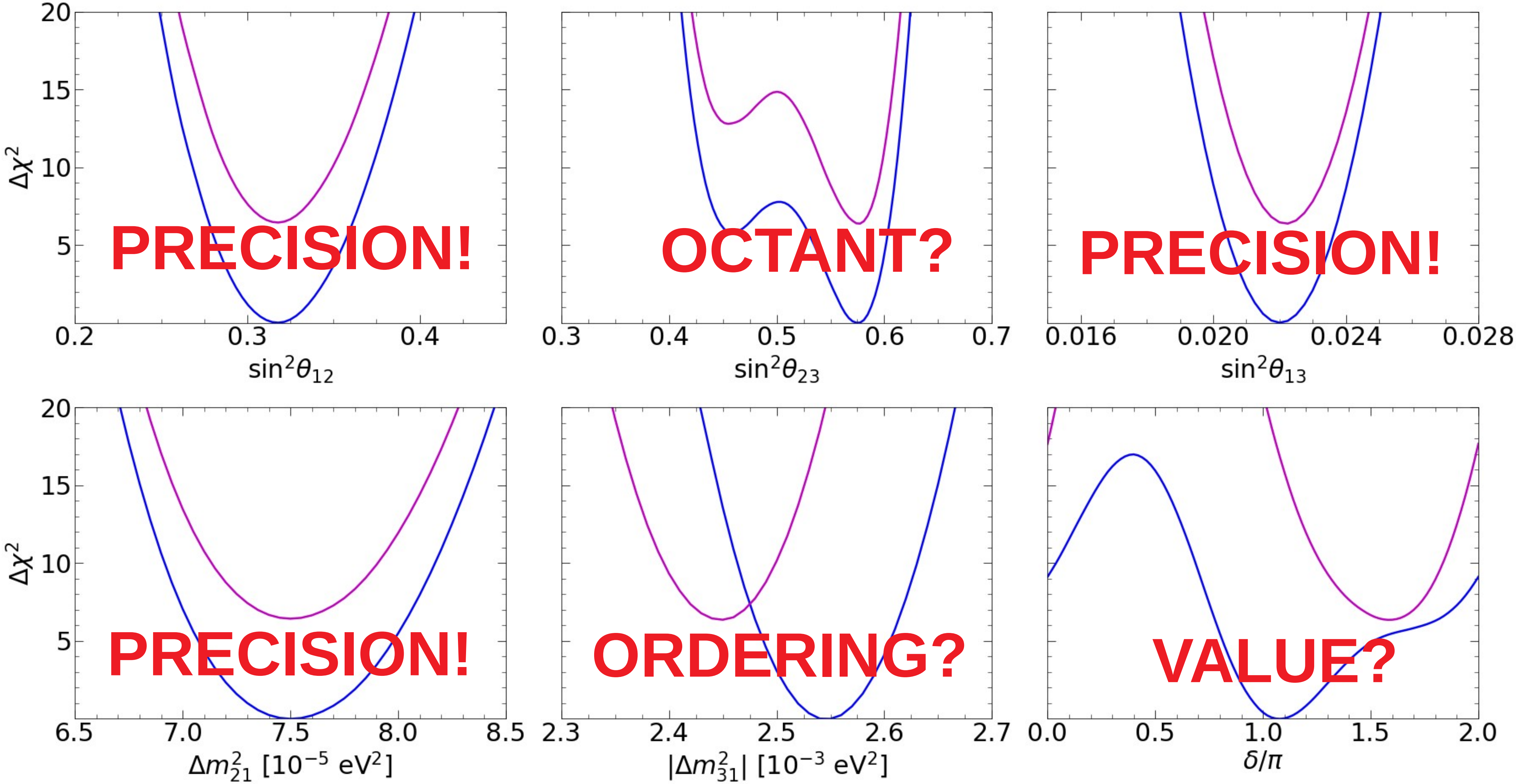
T2K/NOνA disagreement not resolved after Neutrino 2022

Due to this disagreement the determination of the CP phase and the neutrino mass ordering are worse than in 2018

Open issues in the current picture are CP violation, atmospheric octant and neutrino mass ordering (apart from some anomalies)

Next generation of experiments will address these issues

Conclusions

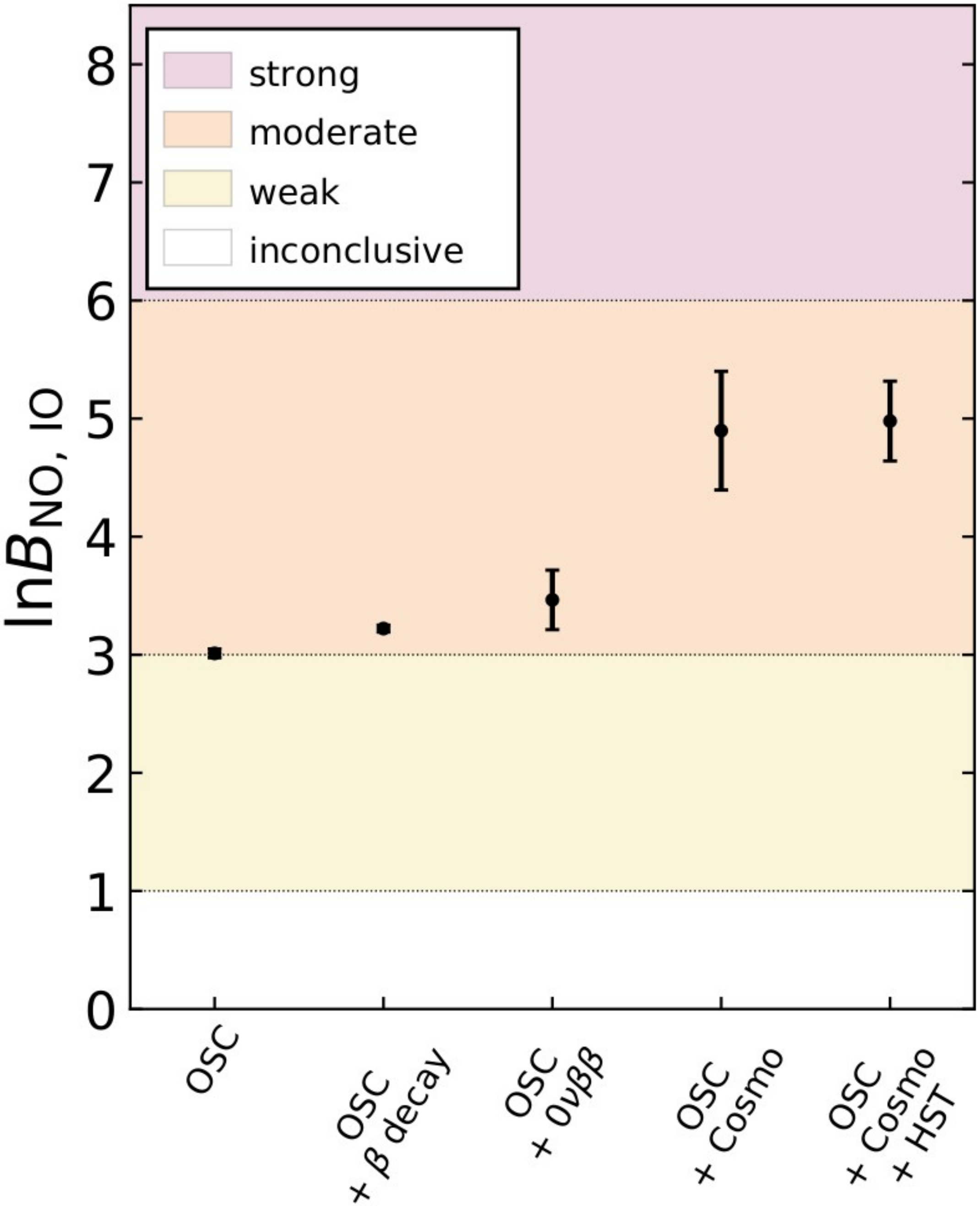


Valencia - Global Fit, 2006.11237, JHEP 2021

Data as of summer 2020


Grazie!
electron-neutrino
muon neutrino
tau-neutrino

Oscillation + Cosmology



Oscillation + Cosmology