Current status of neutrino oscillations

Christoph Andreas Ternes

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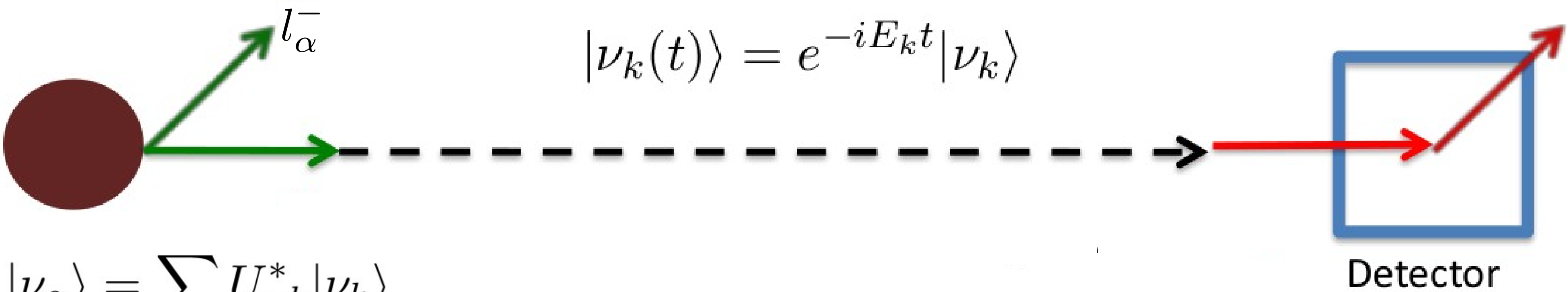
Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

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

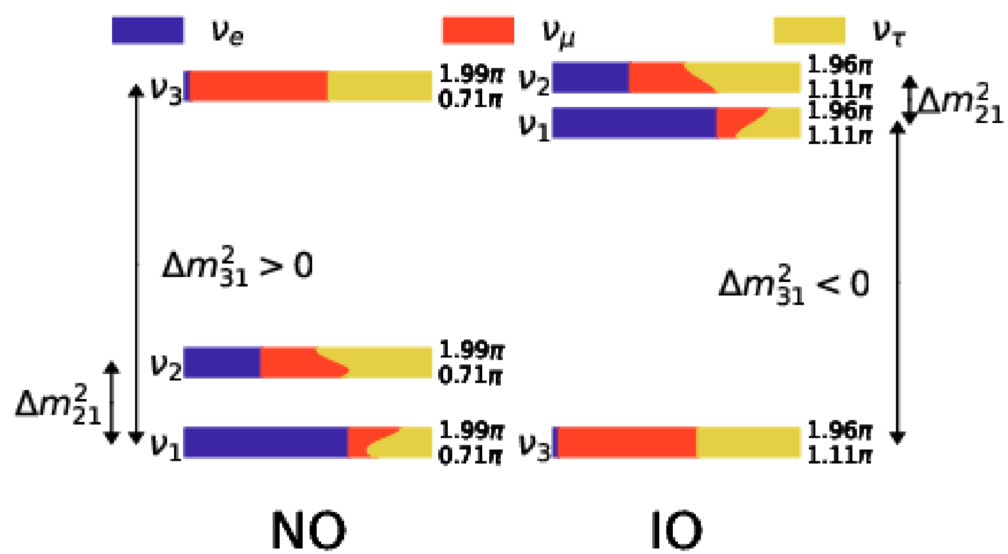
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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
$\|\Delta m^2_{31}\|$	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 $0\nu\beta\beta$

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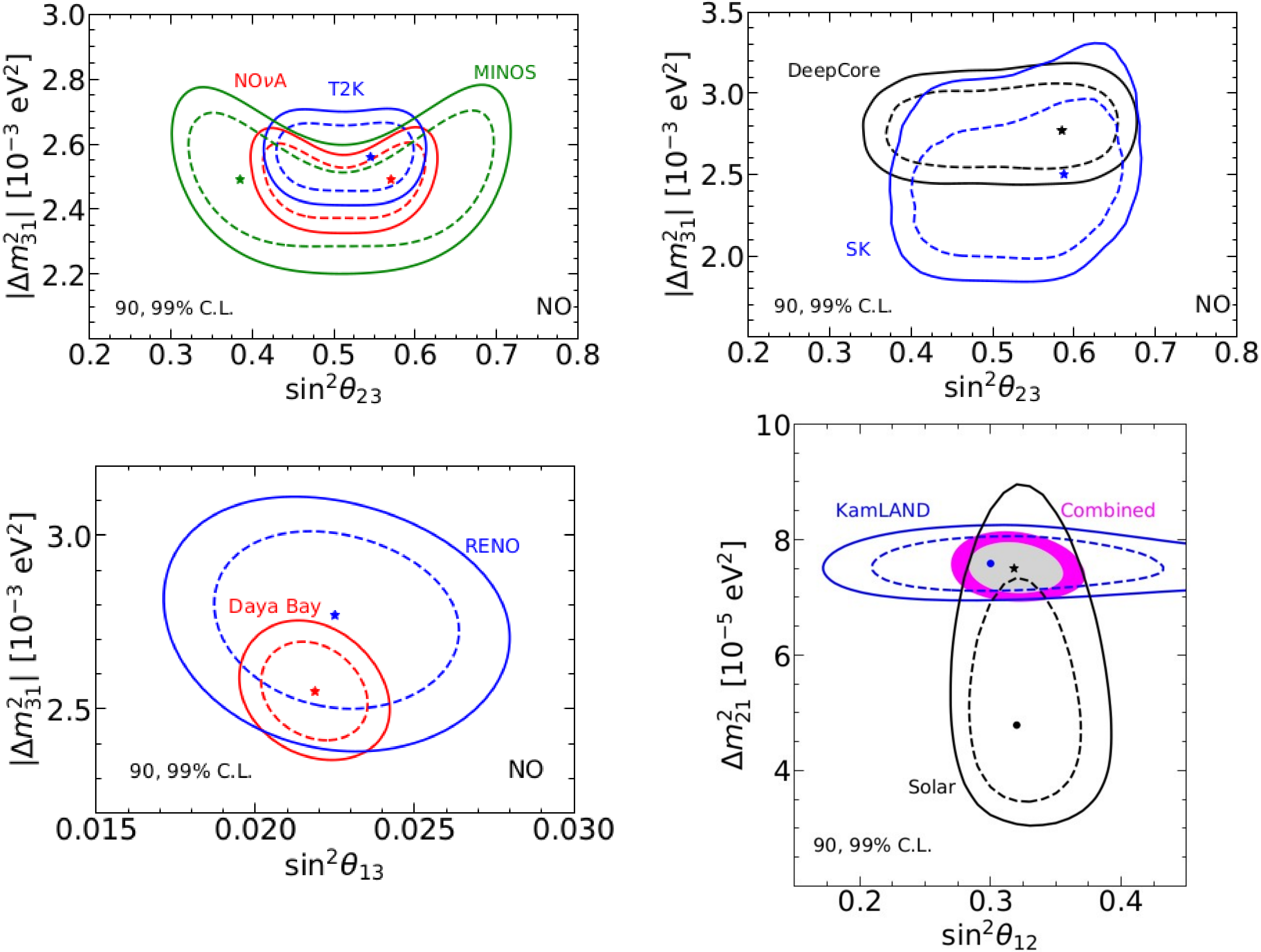
Common sensitivities from different types of experiments

Combination of data sets can enhance sensitivities to oscillation parameters

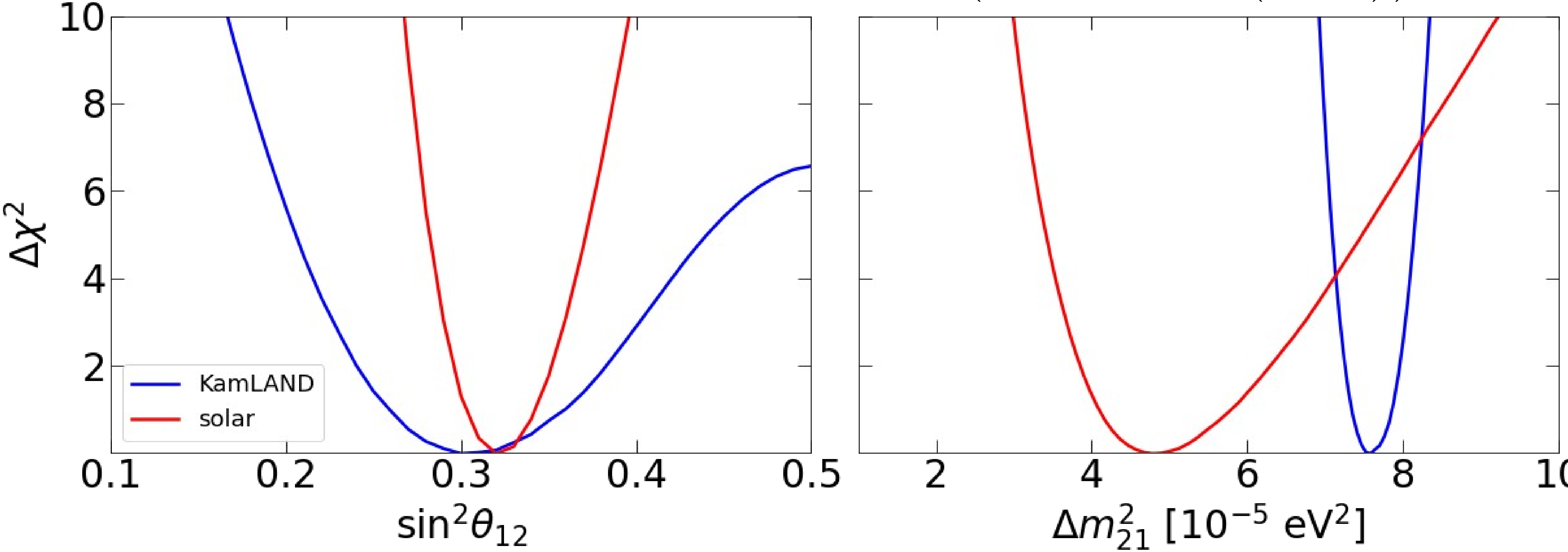
=> Perform a global fit to neutrino oscillation data!

Valencia – 2020 Global Fit, 2006.11237, JHEP 2021



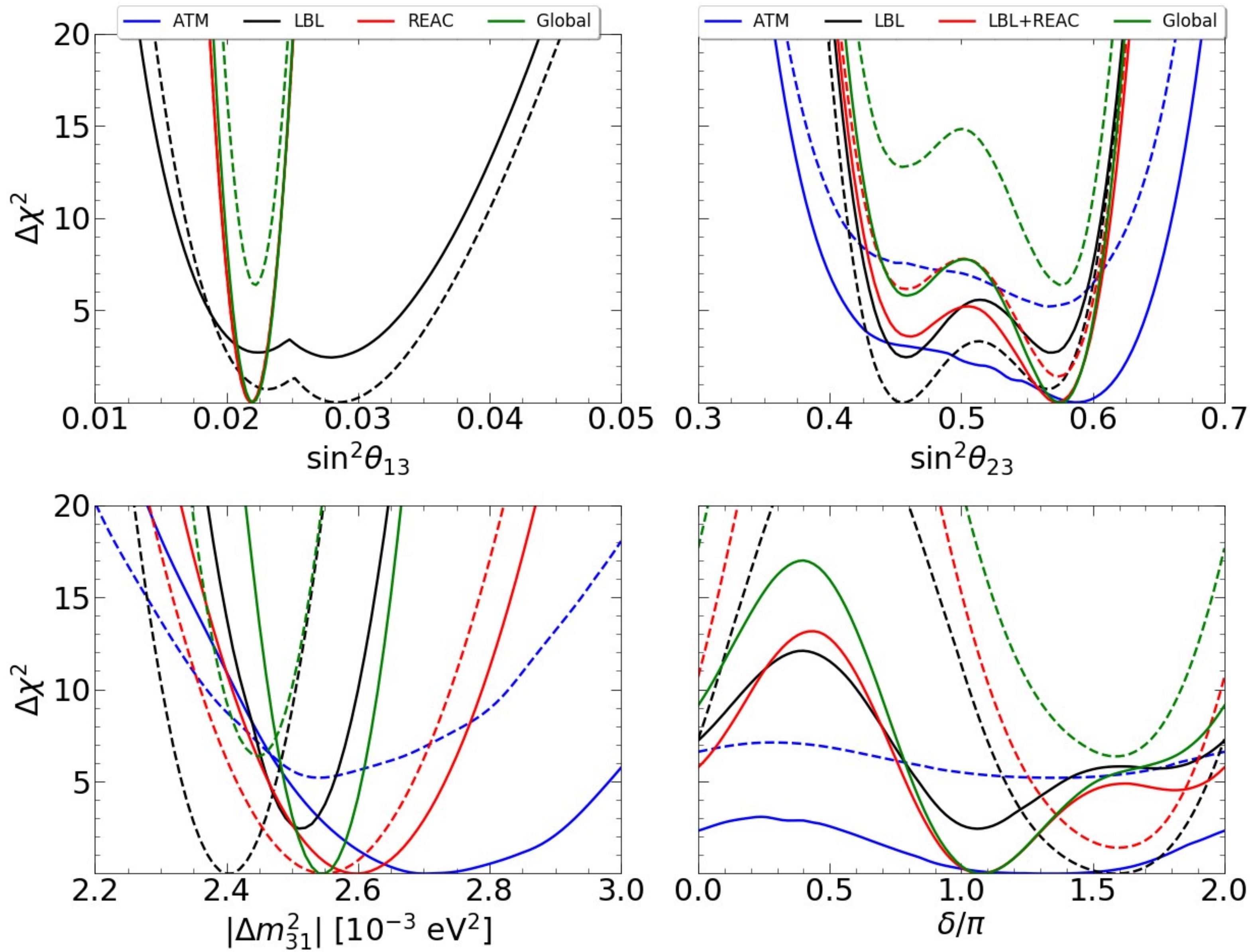
Solar sector

$$P_{ee}^{\mathrm{SOL}} = \frac{1}{2} c_{13}^2 (c_{13}^m)^2 (1 + c_{12} c_{12}^m) + s_{13}^2 (s_{13}^m)^2 \qquad P_{ee}^{\mathrm{KL}} = c_{13}^4 \left(1 - \frac{1}{2} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E}\right)\right) + s_{13}^4$$

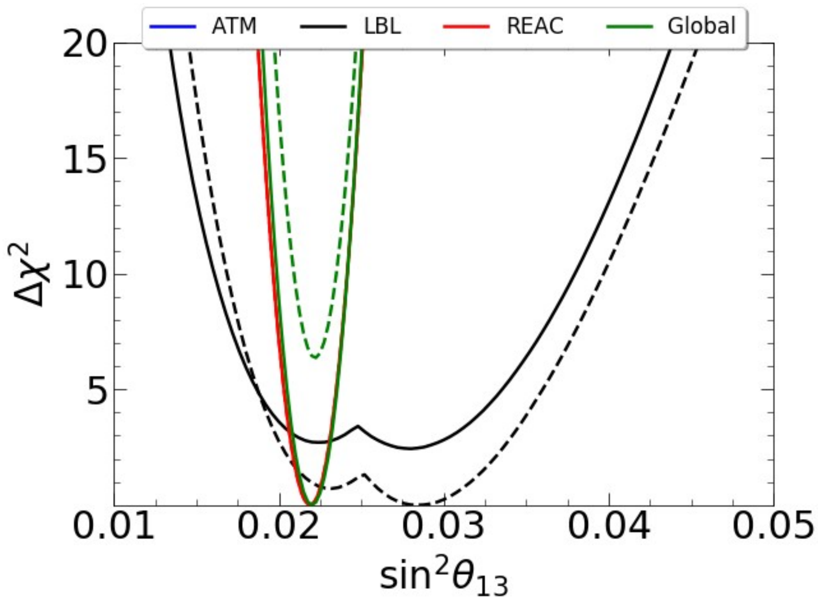


Better determination of mass splitting / mixing angle at KamLAND / solar expriments

Remaining parameters



Remaining parameters



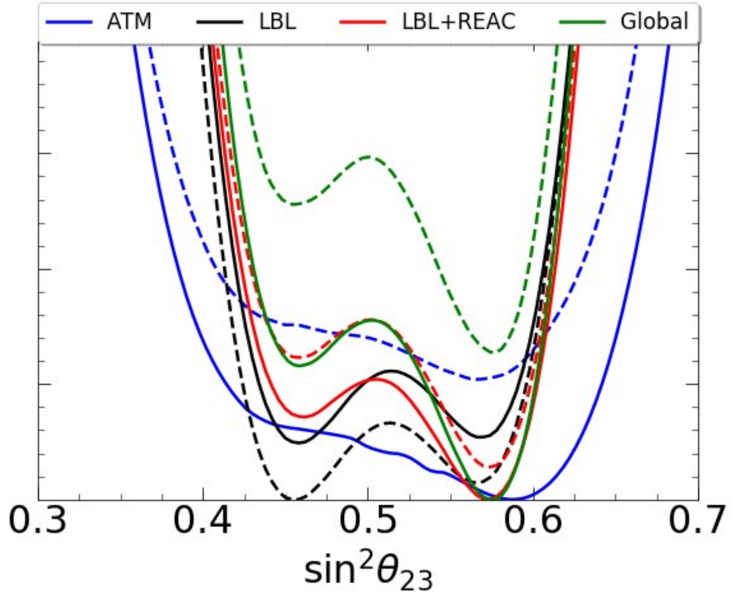
$$P_{ee}^{\mathrm{REAC}} = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{ee}^2 L}{4E}\right)$$

Nunokawa, Parke, Zukanovich Funchal, hep-ph/0503283 , PRD 2005

Atmospheric octant

LBL data on their own do not distinguish octants

Adding ATM and REAC breaks degeneracies



$$P_{\mu\mu}^{\mathrm{LBL}} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2\left(\frac{\Delta m^2_{\mu\mu} L}{4E}\right)$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) \;\; \simeq \;\; & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2 \\ & + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31} + \delta_{\mathrm{CP}}) \\ & + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2, \end{aligned}$$

Atmospheric octant

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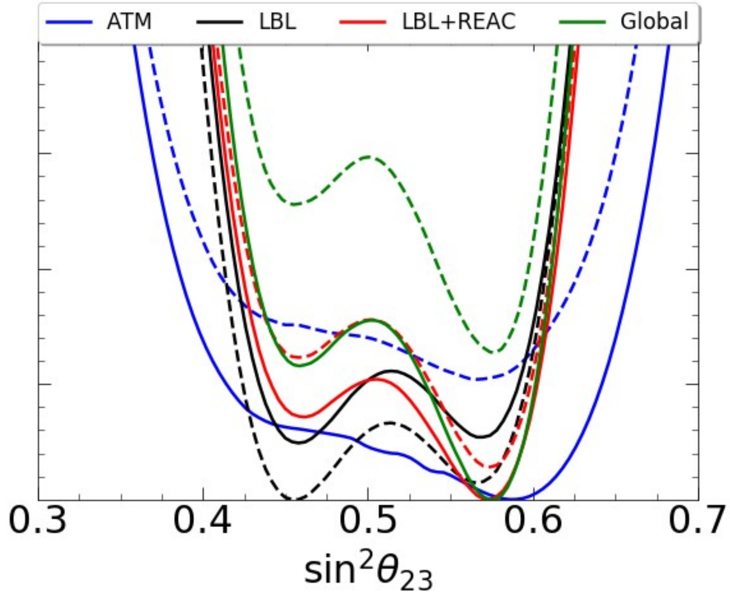
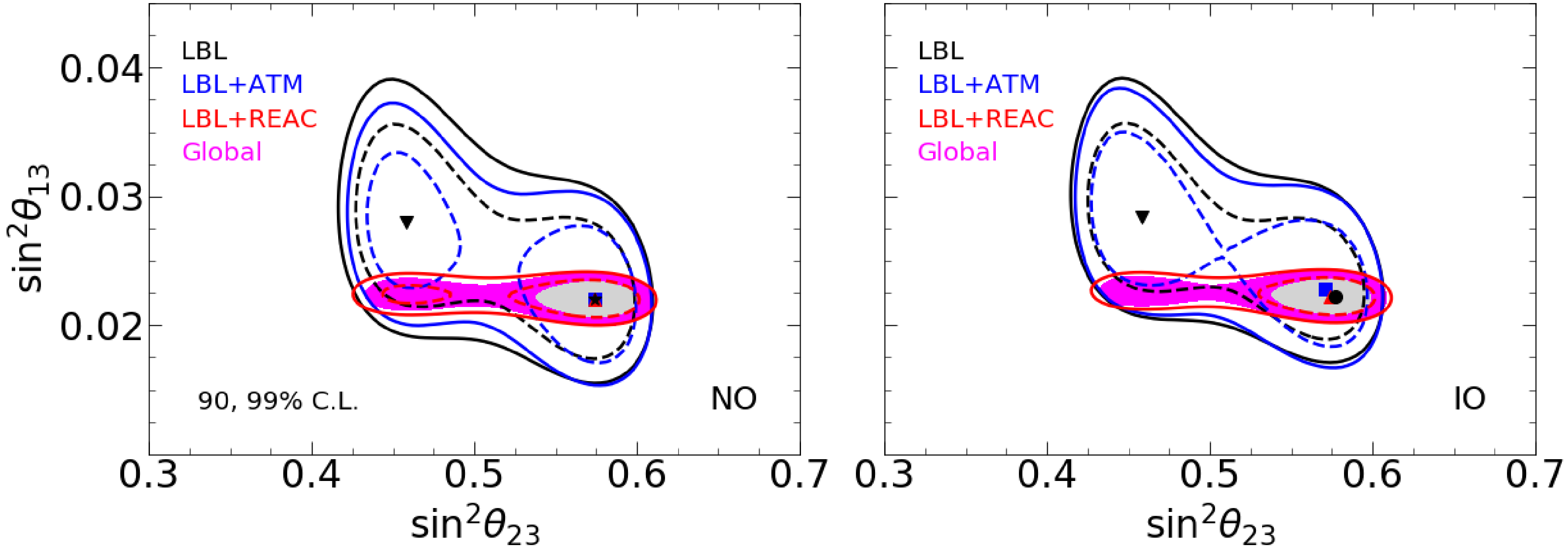
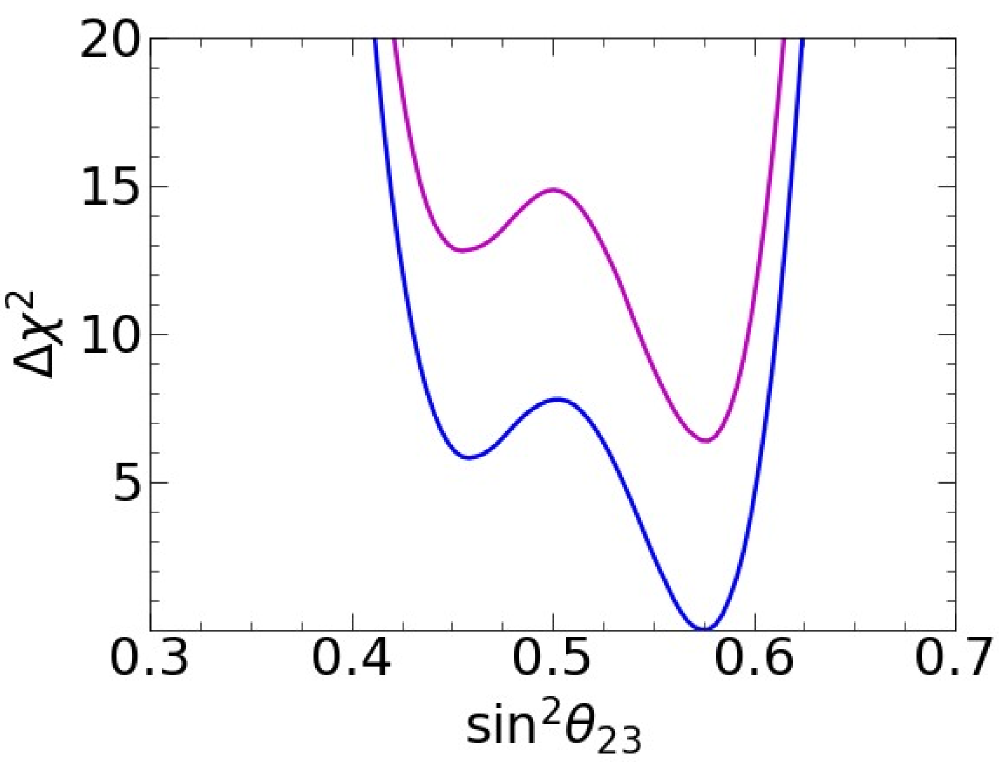




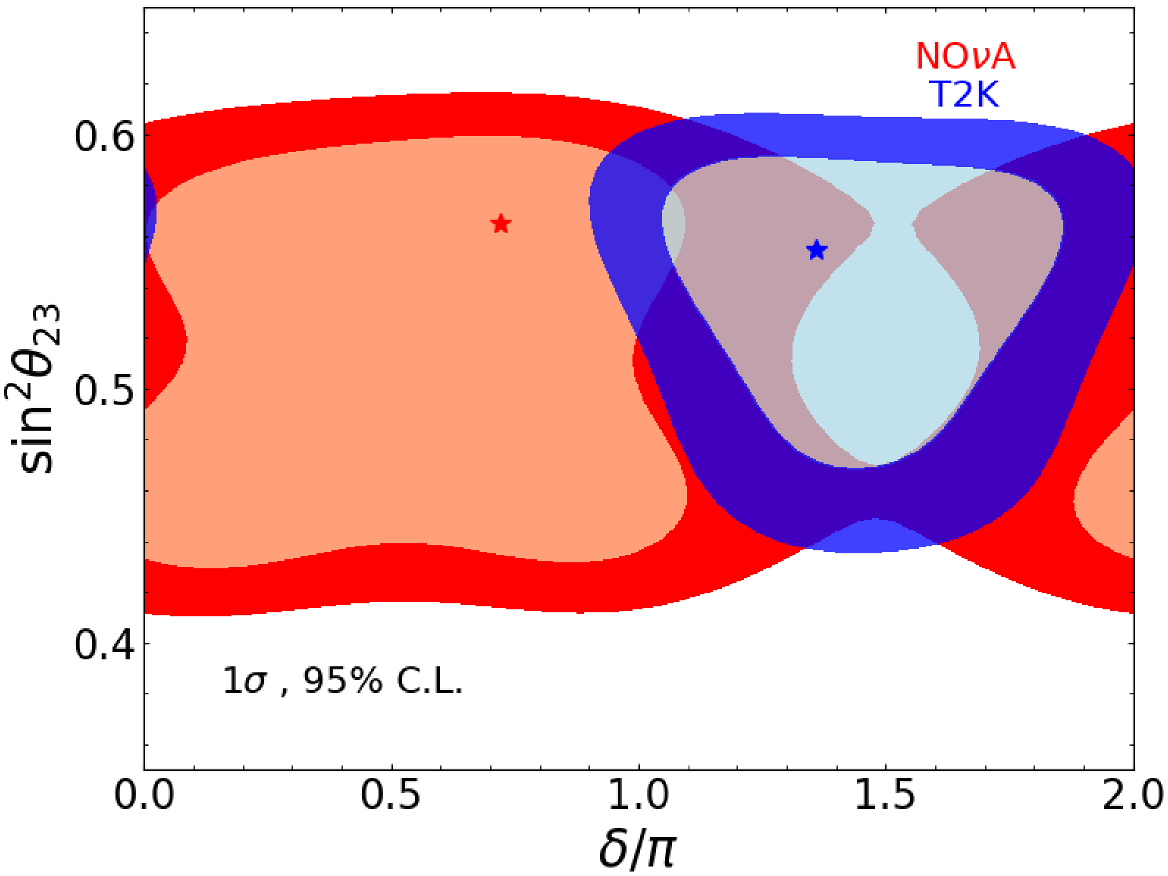
Atmospheric octant



Current global fit prefers second octant

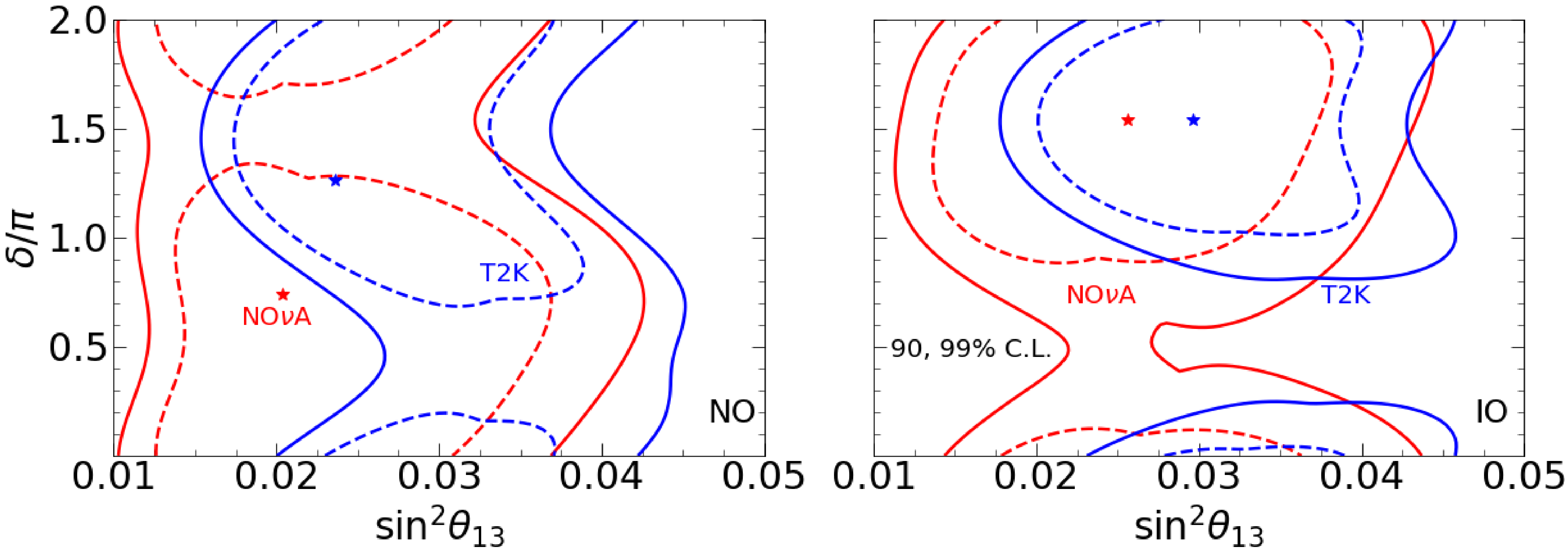
Valencia - Global Fit, 2006.11237, JHEP 2021

CP violation



Tension in the measurement of the CP phase in current data

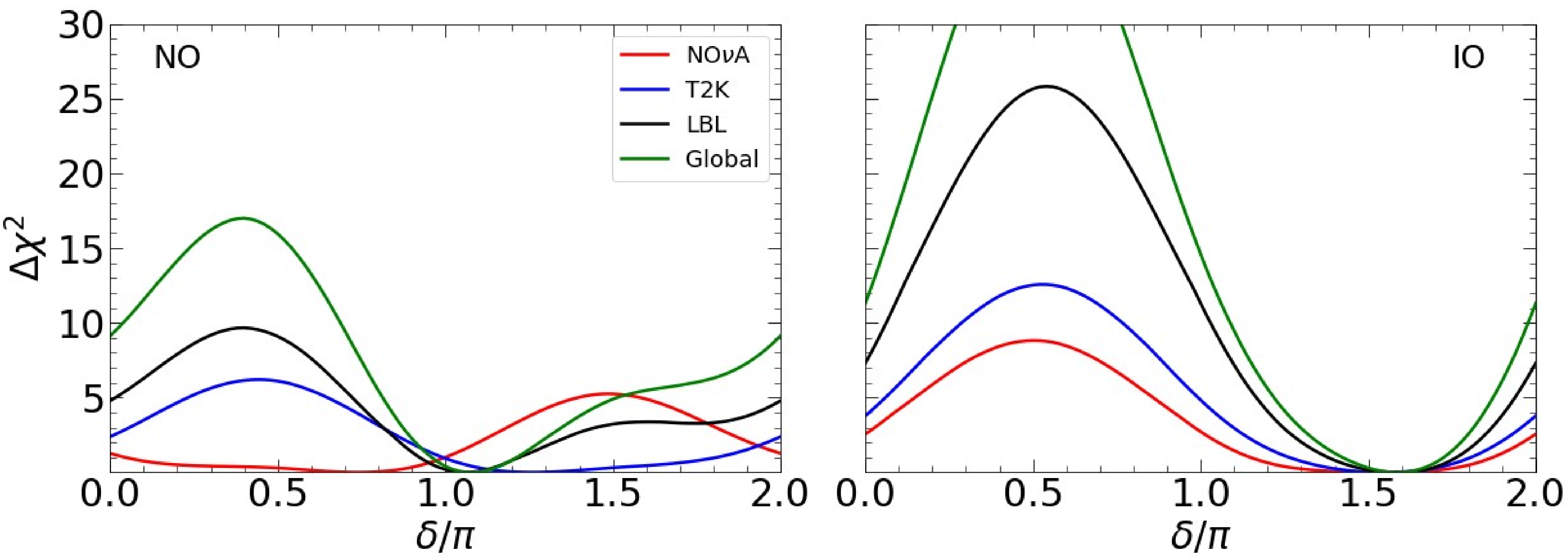
CP violation



Tension remains when relaxing prior from reactor neutrinos

Valencia - Global Fit, 2006.11237, JHEP 2021

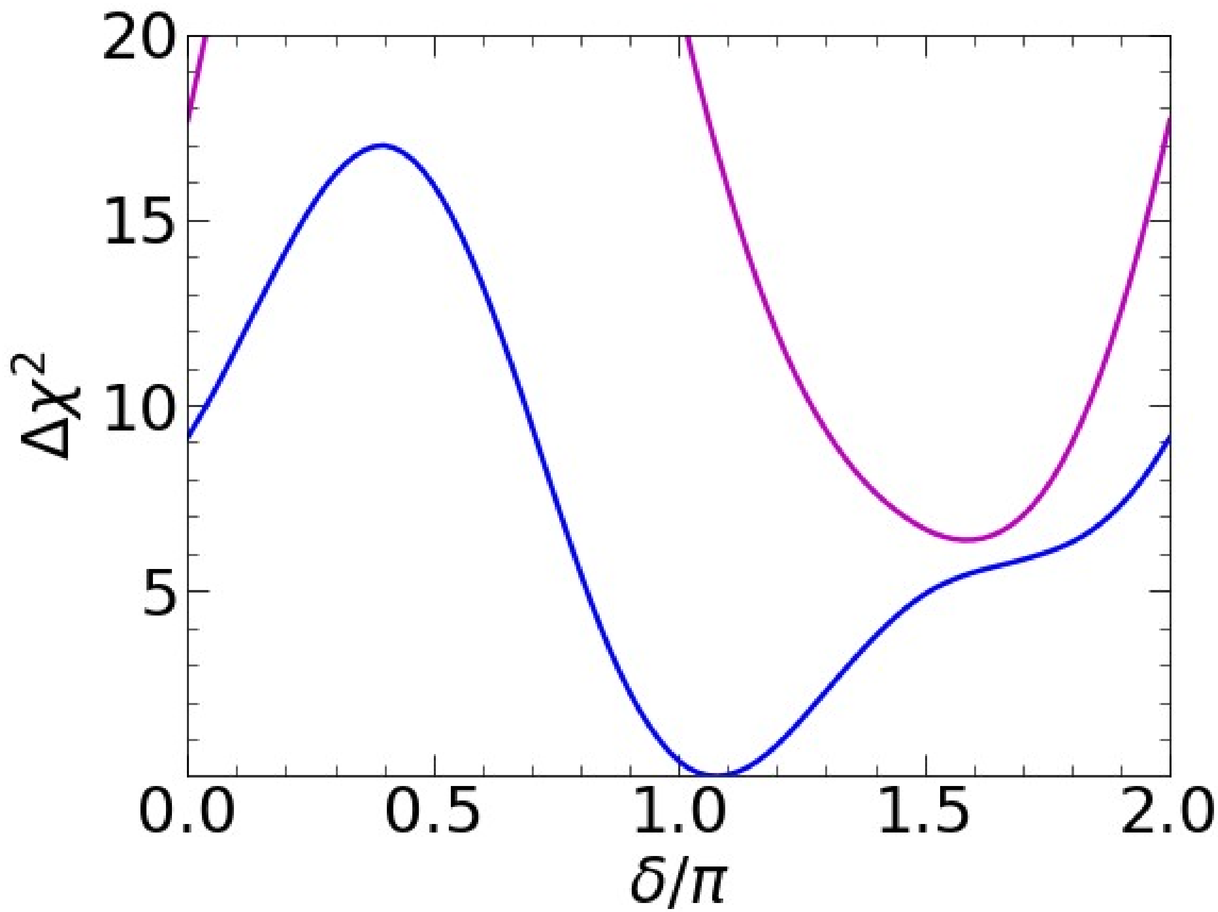
CP violation

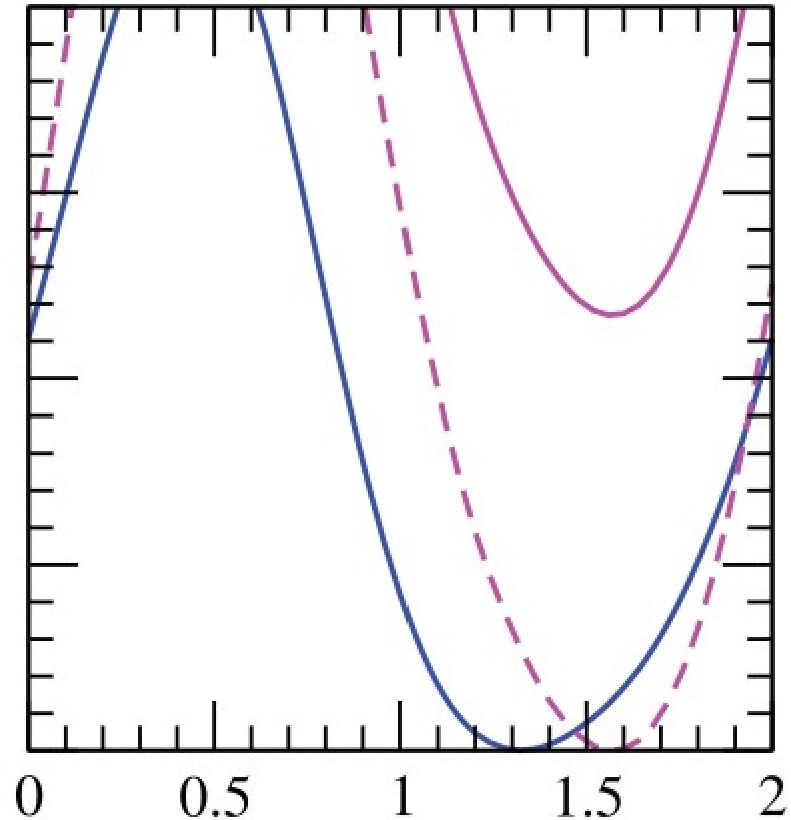


T2K and NOνA profiles disagree for NO

Valencia - Global Fit, 2006.11237, JHEP 2021

CP violation





The measurement of delta is now worse than it was before

Valencia - Global Fit (current), 2006.11237, JHEP 2021
Valencia - Global Fit 2018, 1708.01186, PLB 2018

Neutrino mass ordering

Global fit has 2.5σ preference for normal neutrino mass ordering

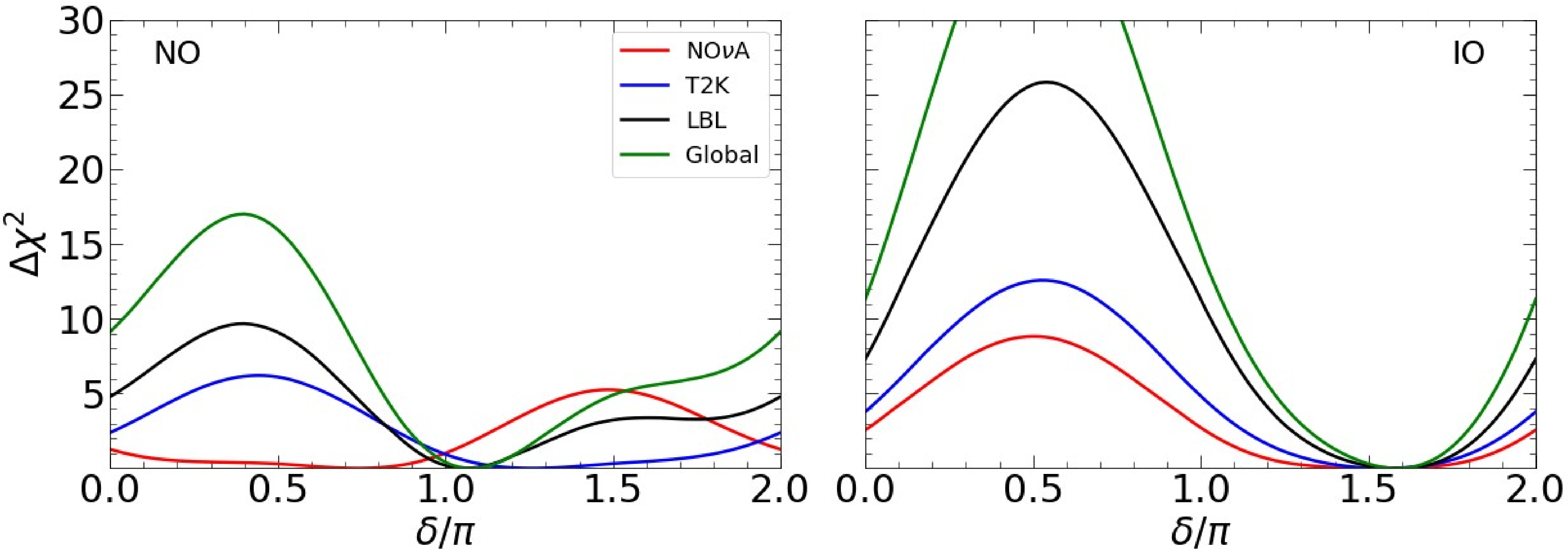
None of the experiments has a good sensitivity on its own

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

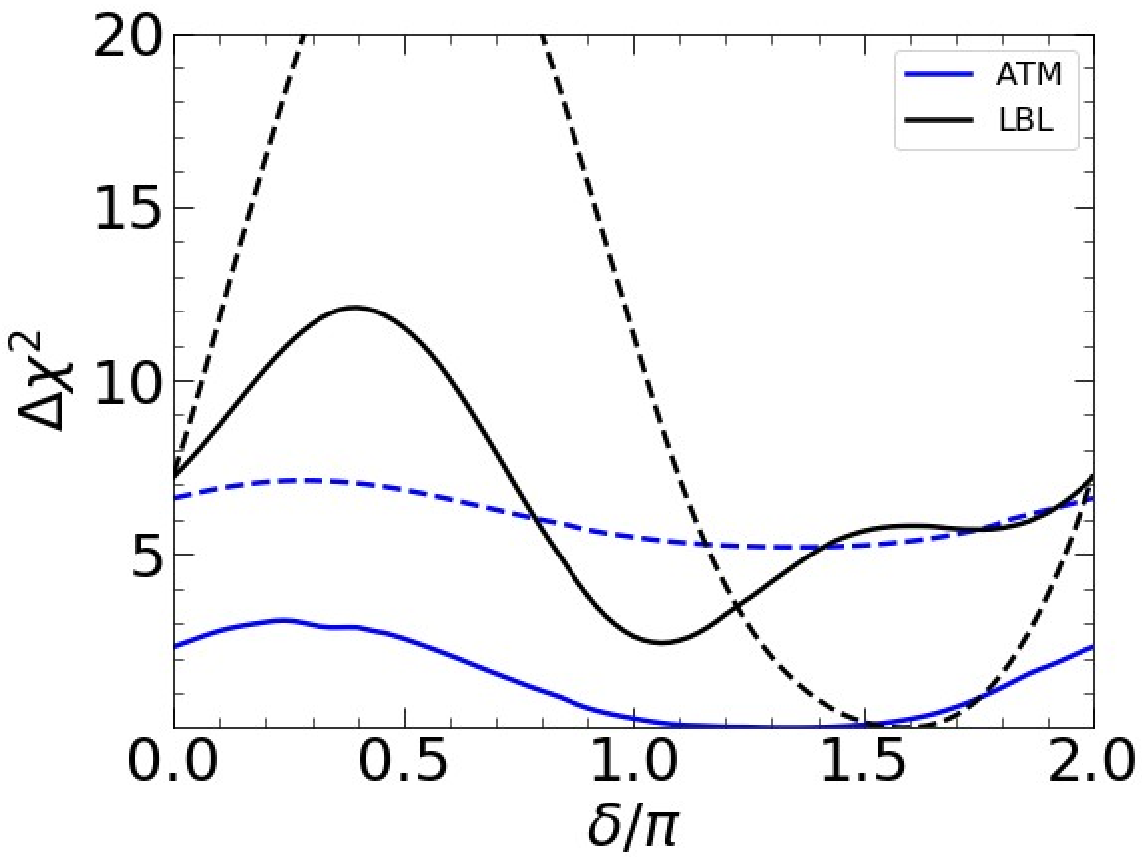
The tension between T2K and NOνA in the measurement of the CP phase appears only for normal ordering



Neutrino mass ordering

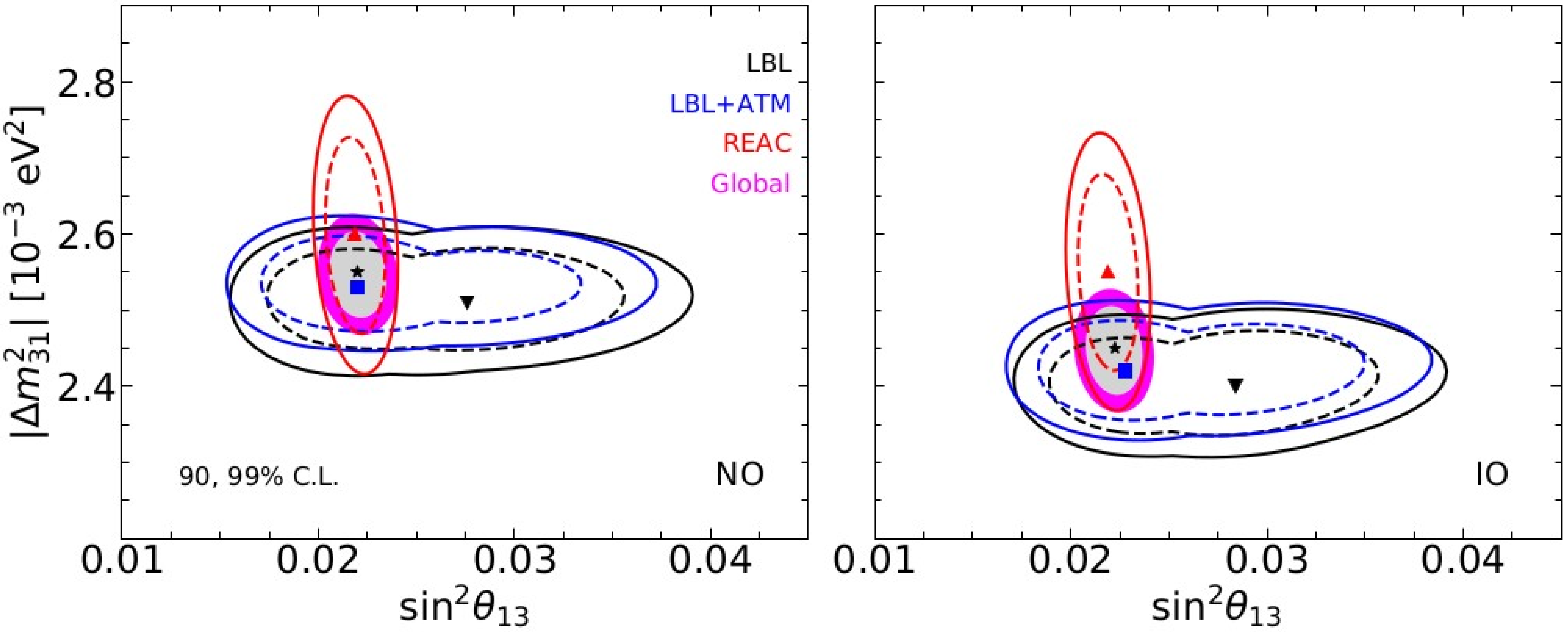
Although none of the experiments has a preference on its own, the combined analysis of all LBL data prefers IO!

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



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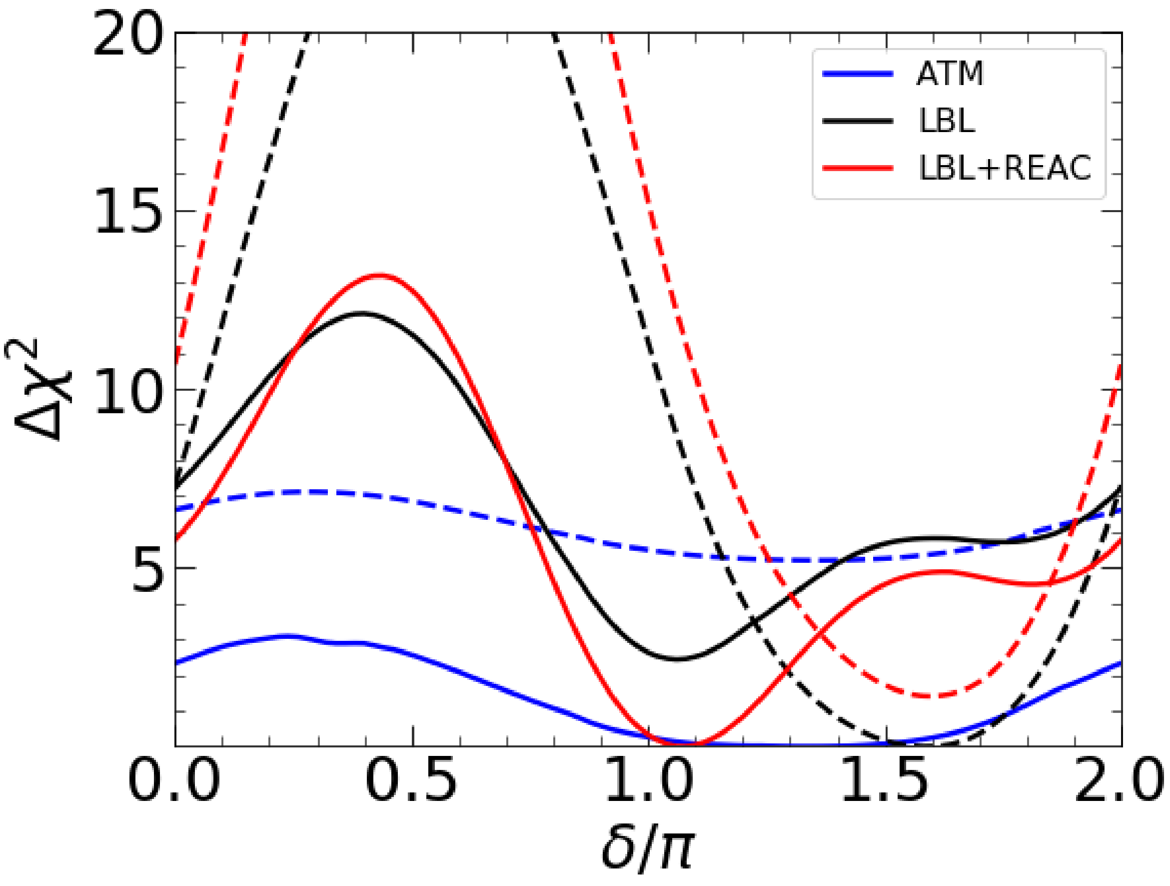
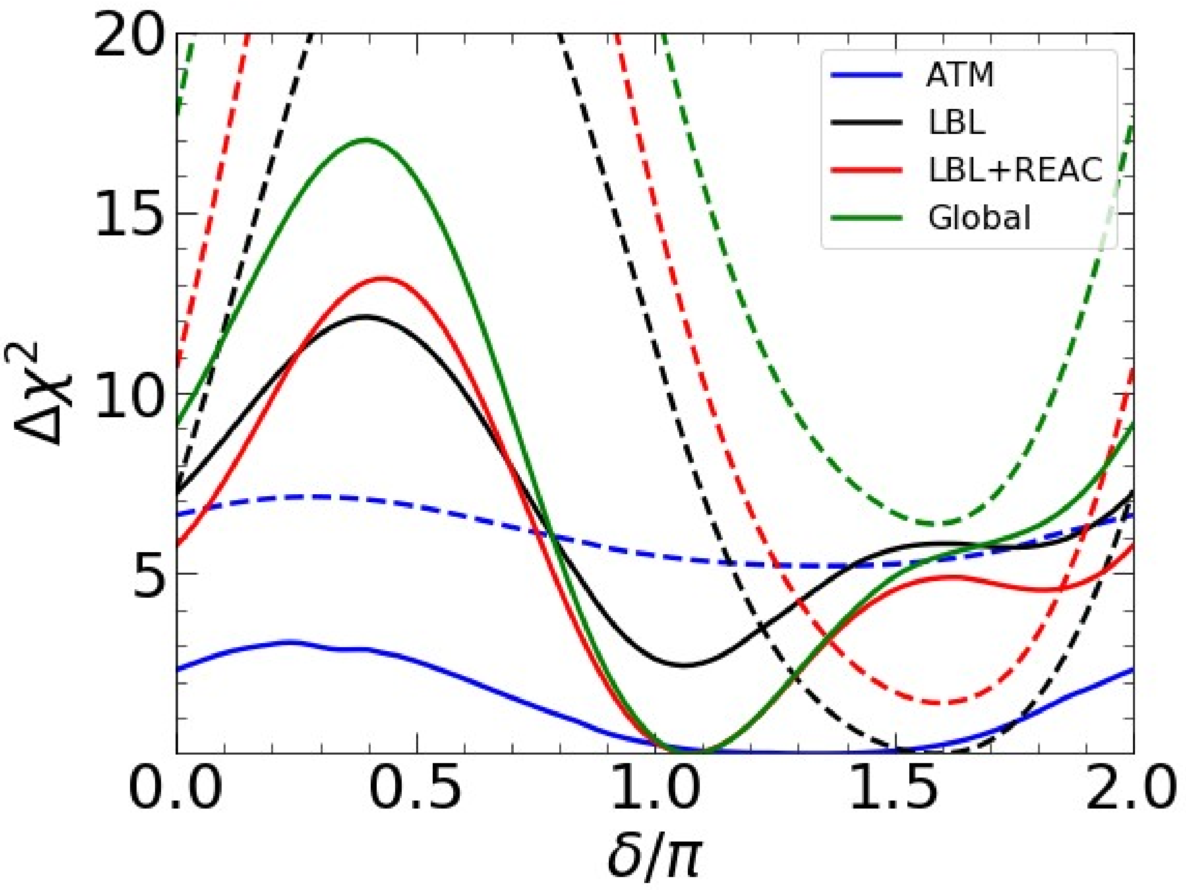


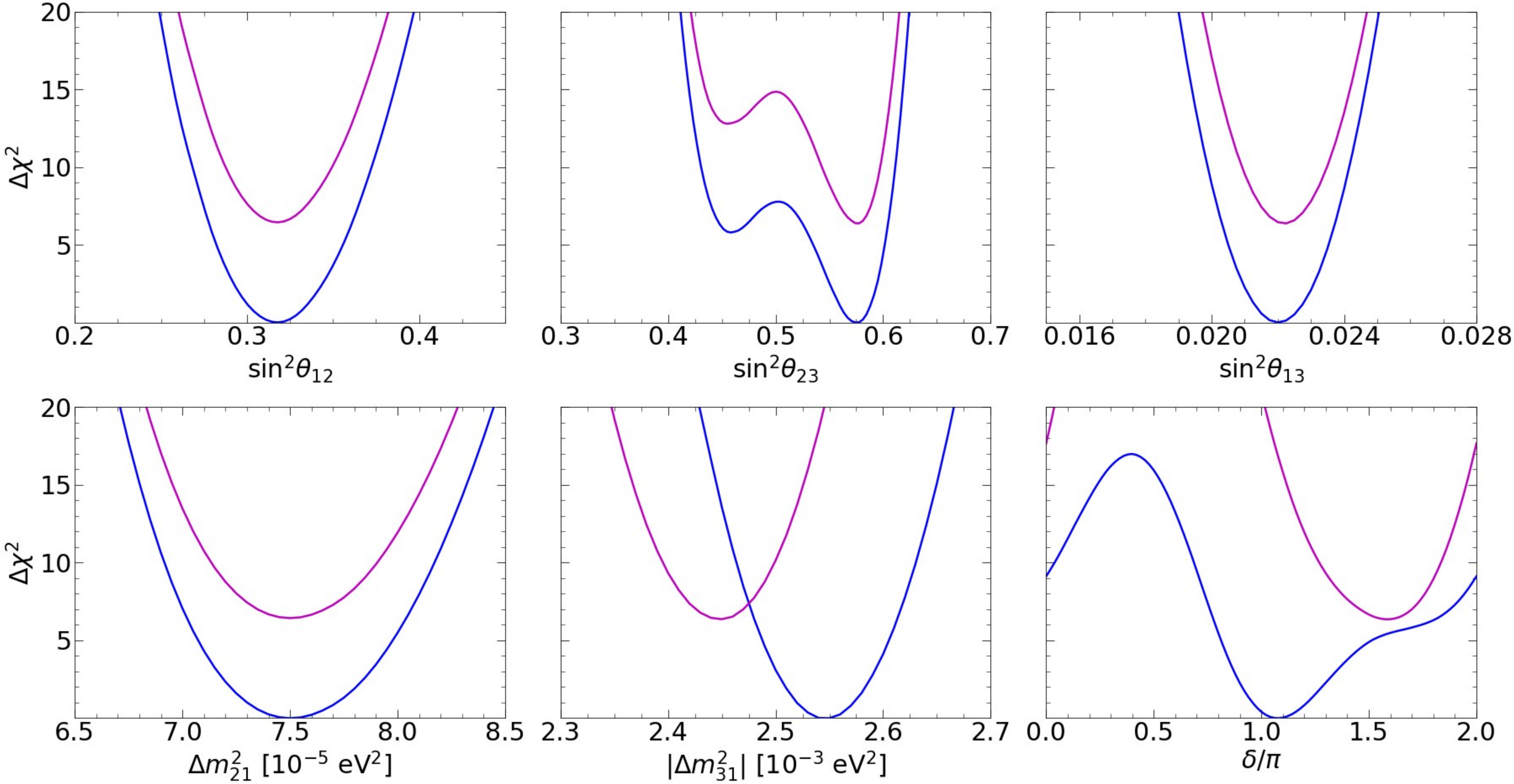
Neutrino mass ordering

After combing everything we get 2.5σ



Global fit

Valencia – 2020 Global Fit, 2006.11237, JHEP 2021



See also:
Bari – 2107.00532

See also:
NuFit - 2007.14792, JHEP 2020

Global fit

parameter	best fit ± 1σ		2σ range	3σ range
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	**2.7%**	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	**1.2%**	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}\text{eV}^2]$ (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

Valencia - Global Fit, 2006.11237, JHEP 2021

Conclusions

Some of the neutrino oscillation parameters are well measured

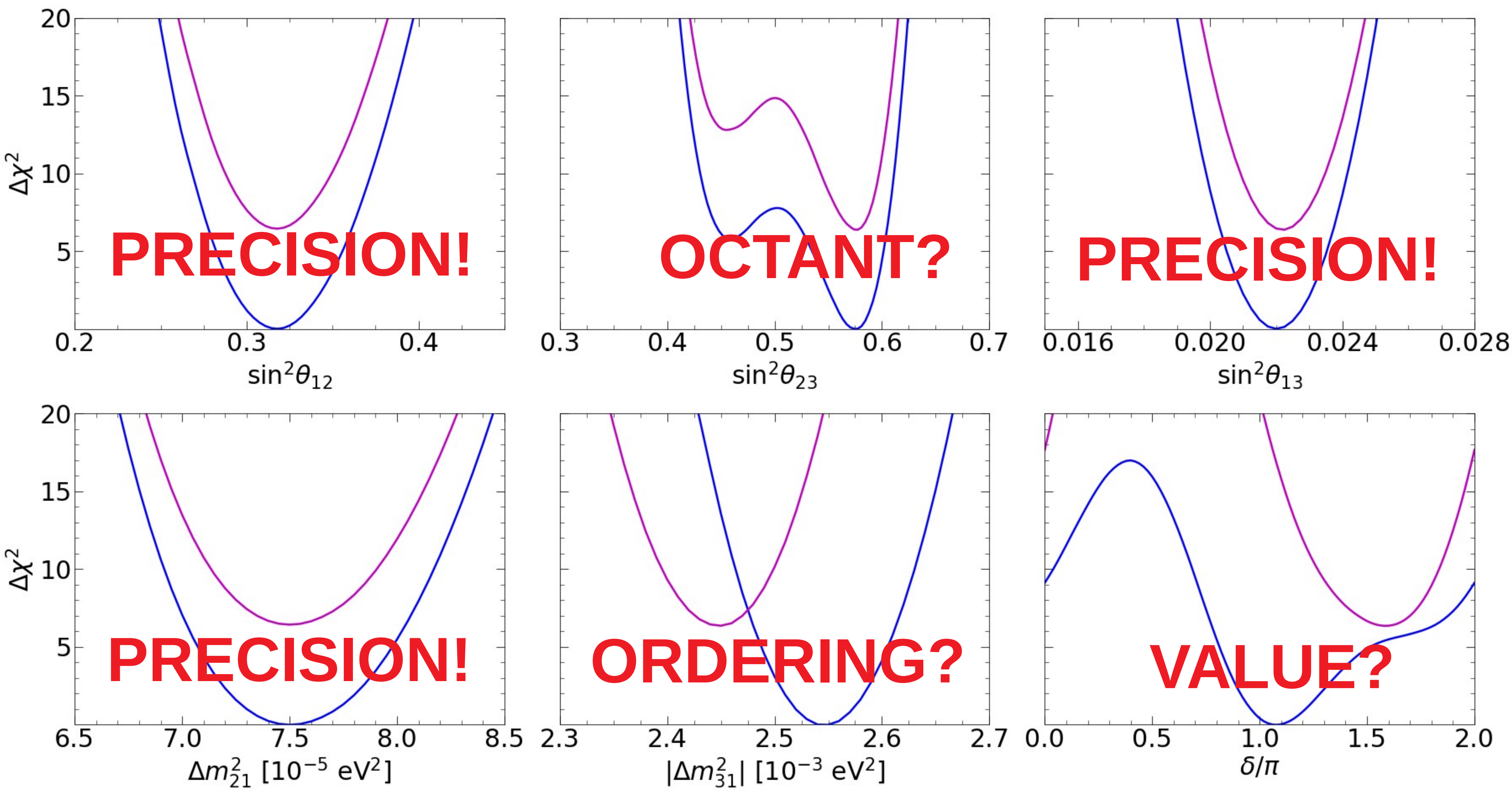
Open issues are CP violation, atmospheric octant and neutrino mass ordering

In the updated data there is an overall lower sensitivity to the to CP phase due to the T2K/NOνA tension

The same tension worsens the determination of the neutrino mass ordering

We have to wait for more data (or even for the next generation of neutrino experiments) to clarify these issues

Conclusions

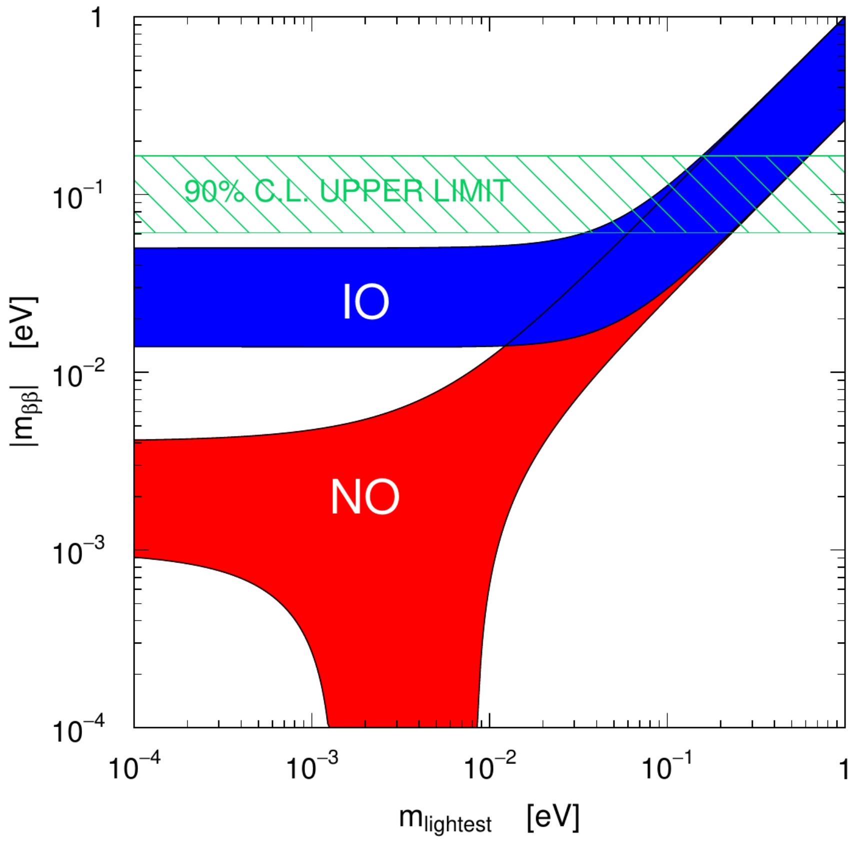


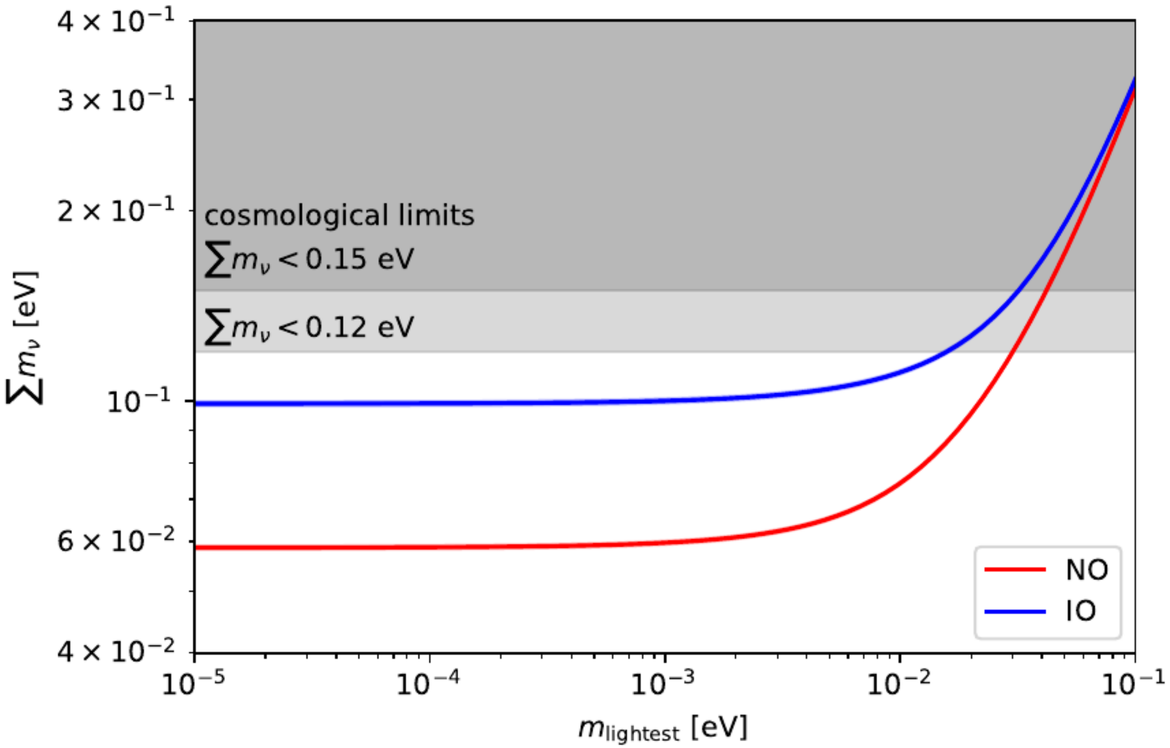
Valencia - Global Fit, 2006.11237, JHEP 2021


Grazie!
electron-
neutrino
muon
neutrino
tau-
neutrino

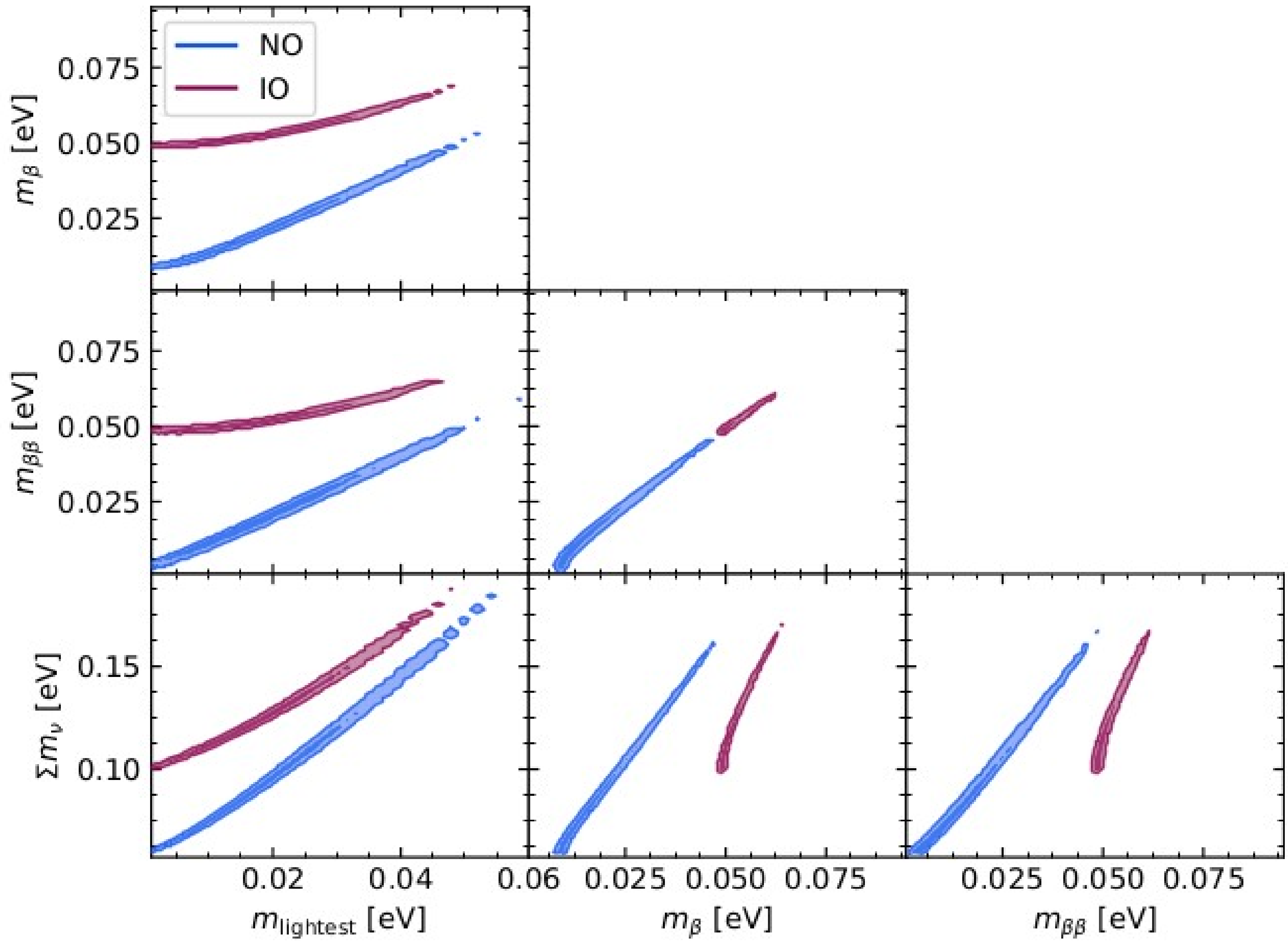
More on mass ordering

We can get additional information from neutrinoless double beta decay experiments and cosmological observations

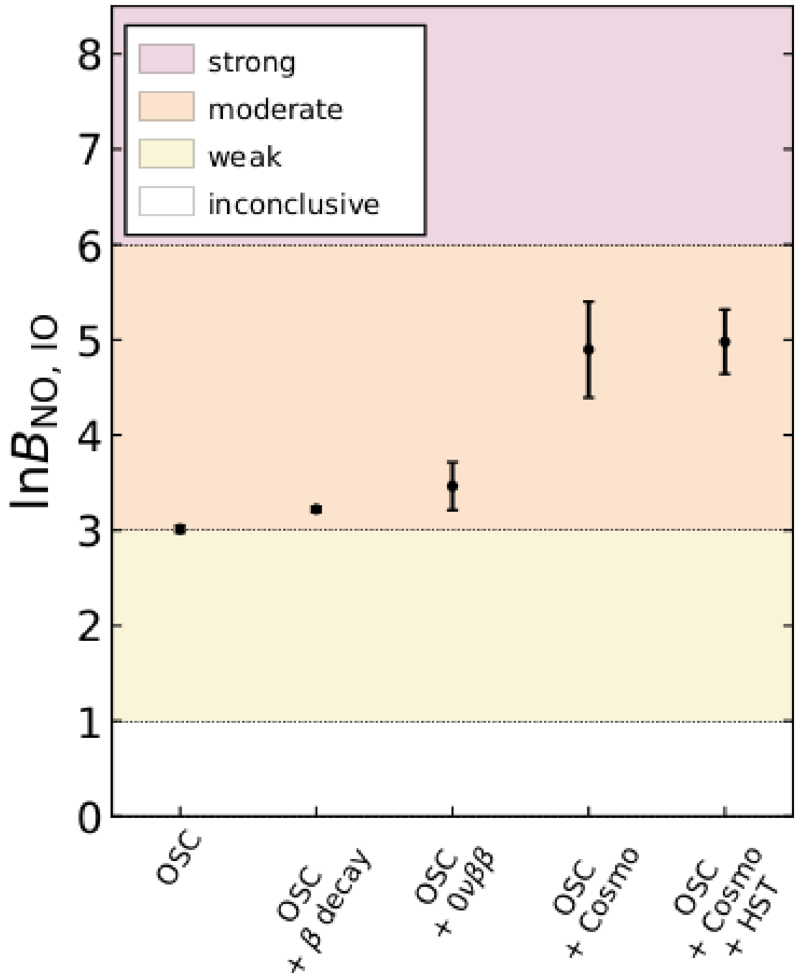




More on mass ordering



More on mass ordering



data set	$\ln B_{\rm NO,IO}$	$N\sigma$
OSC	3.01 ± 0.04	2.00
OSC + β decay	3.22 ± 0.03	2.07
OSC + $0\nu\beta\beta$	3.46 ± 0.25	2.17
OSC + Cosmo	4.90 ± 0.50	2.68
OSC + Cosmo + H_0	4.98 ± 0.34	2.70