Neutrinos and CPT violation

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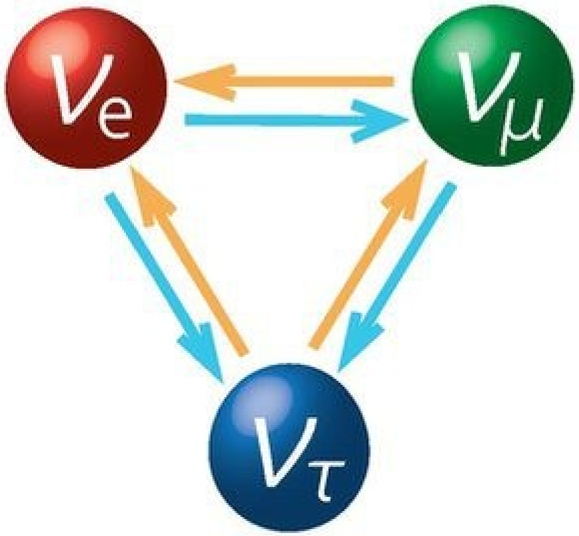
SEZIONE DI TORINO

Current status of neutrino oscillations



Three-neutrino oscillations

Neutrino mixing matrix

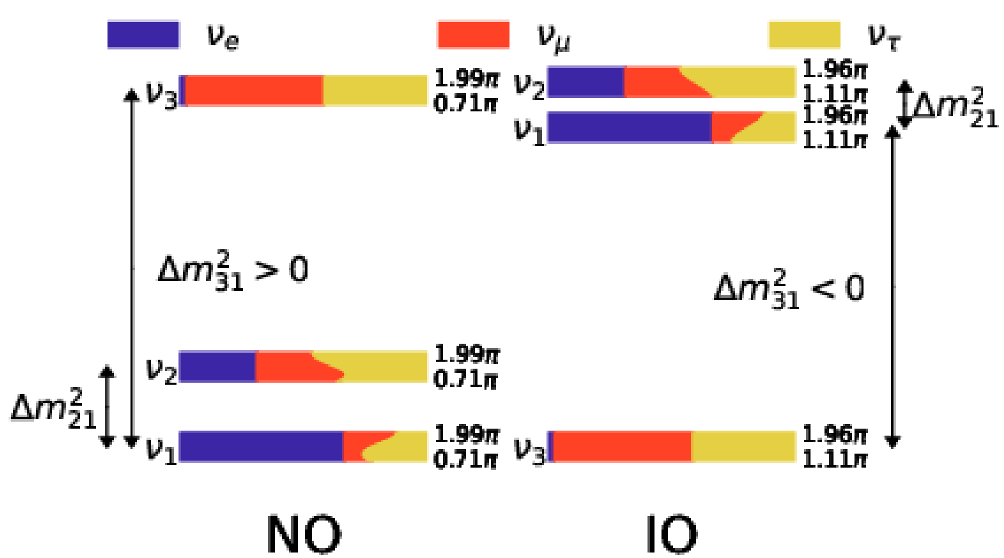
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

A neutrino flavor state is a superposition of mass eigenstates

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}|\nu_k\rangle, \quad \text{with} \qquad \langle\nu_\alpha|\nu_\beta\rangle = \delta_{\alpha\beta}, \langle\nu_k|\nu_j\rangle = \delta_{kj}$$

The massive neutrino states are eigenstates of the Hamiltonian

$$\mathcal{H}|\nu_k\rangle = E_k|\nu_k\rangle, \quad E_k = \sqrt{\vec{p}^2 + m_k^2}$$

The Schrödinger equation is then solved

$$i\partial_t|\nu_k(t)\rangle = \mathcal{H}|\nu_k(t)\rangle \quad \Rightarrow \quad |\nu_k(t)\rangle = e^{-iE_k t}|\nu_k\rangle$$

Three-neutrino oscillations

Therefore the flavor state evolves as

$$|\nu_\alpha(t)\rangle = \sum_k U^*_{\alpha k} |\nu_k(t)\rangle = \sum_k U^*_{\alpha k} e^{-iE_k t} |\nu_k\rangle$$

Re-substituting we obtain

$$|\nu_\alpha(t)\rangle = \sum_{k,\beta} U^*_{\alpha k} U_{\beta k} e^{-iE_k t} |\nu_\beta\rangle$$

The transition amplitude is then

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

Three-neutrino oscillations

The transition probability is then

$$P(\alpha \to \beta, t) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i(E_k - E_j)t}$$

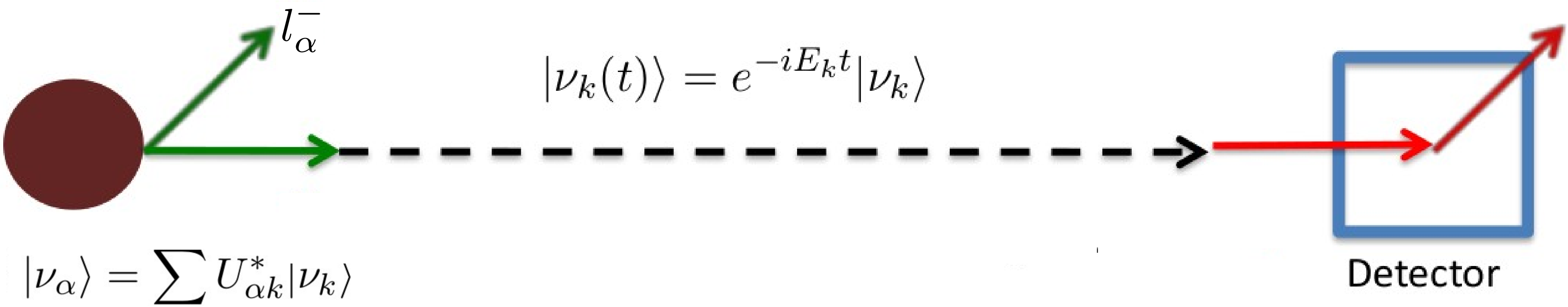
We use the approximations

$$E_k = E + \frac{m_k^2}{2E}, \quad t = L$$

The final result is

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

Pictorial description



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

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

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

Three-neutrino oscillations

Neutrino 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

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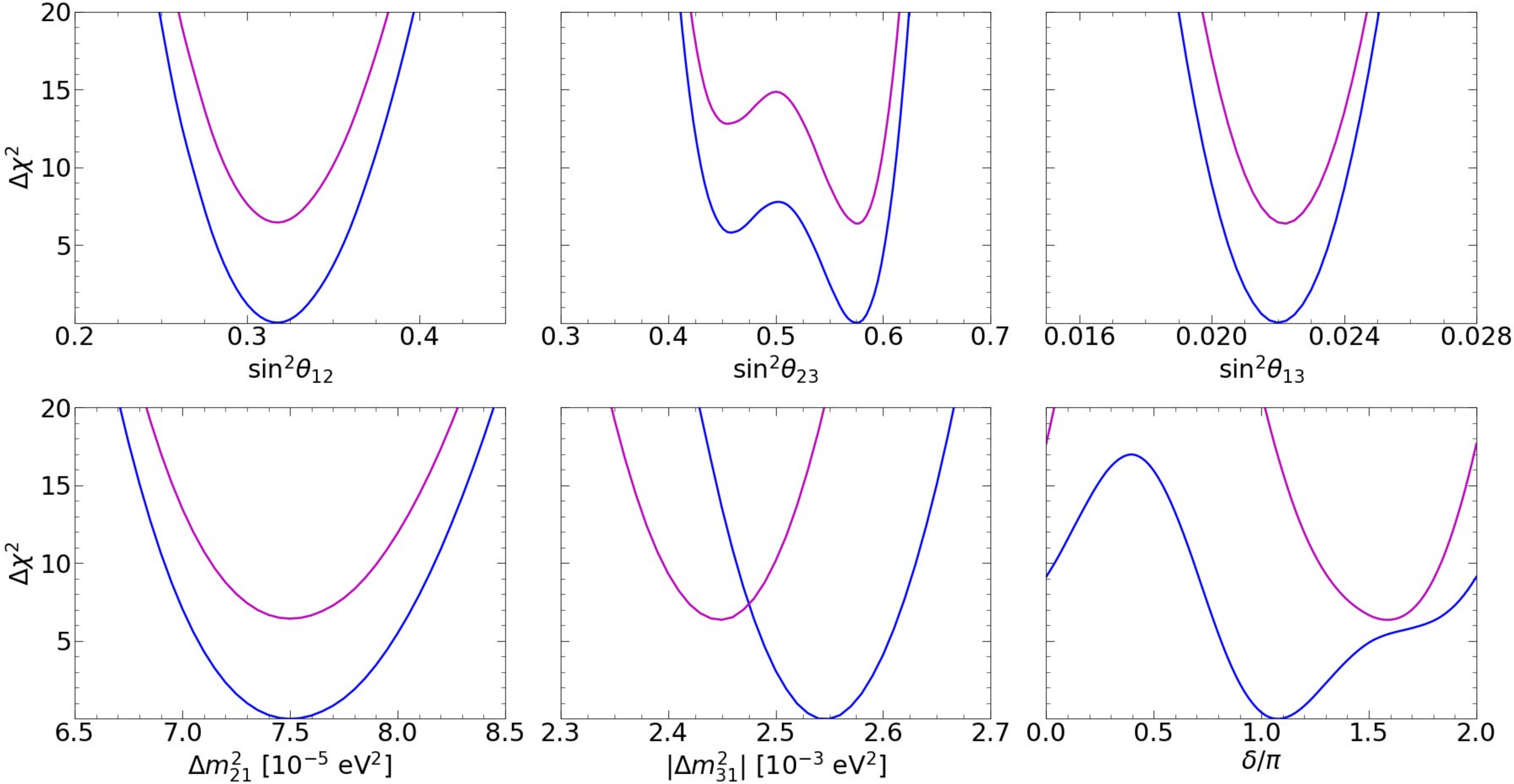
Common sensitivities from different types of experiments

Combination of data sets can enhance sensitivities to oscillation parameters

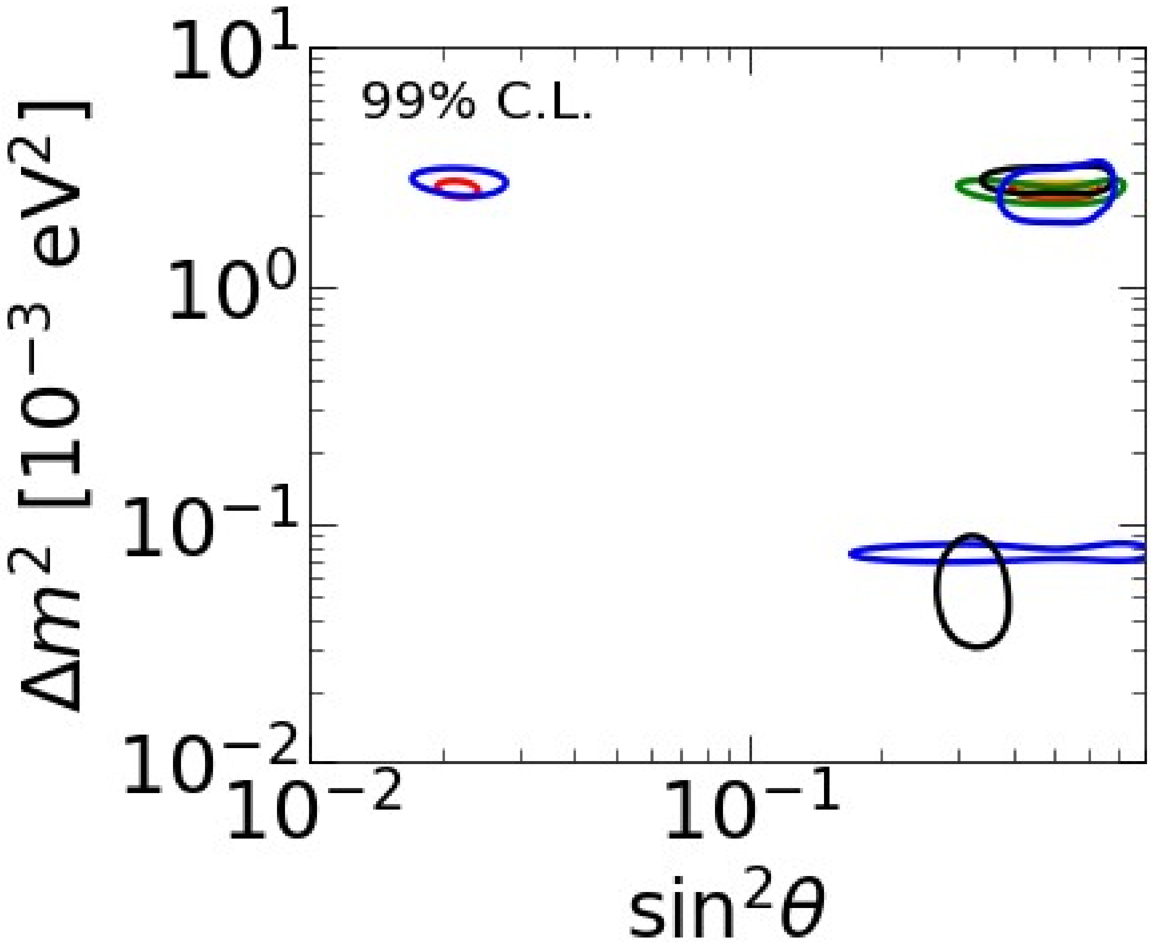
=> Perform a global fit to neutrino oscillation data!

Three-neutrino oscillations

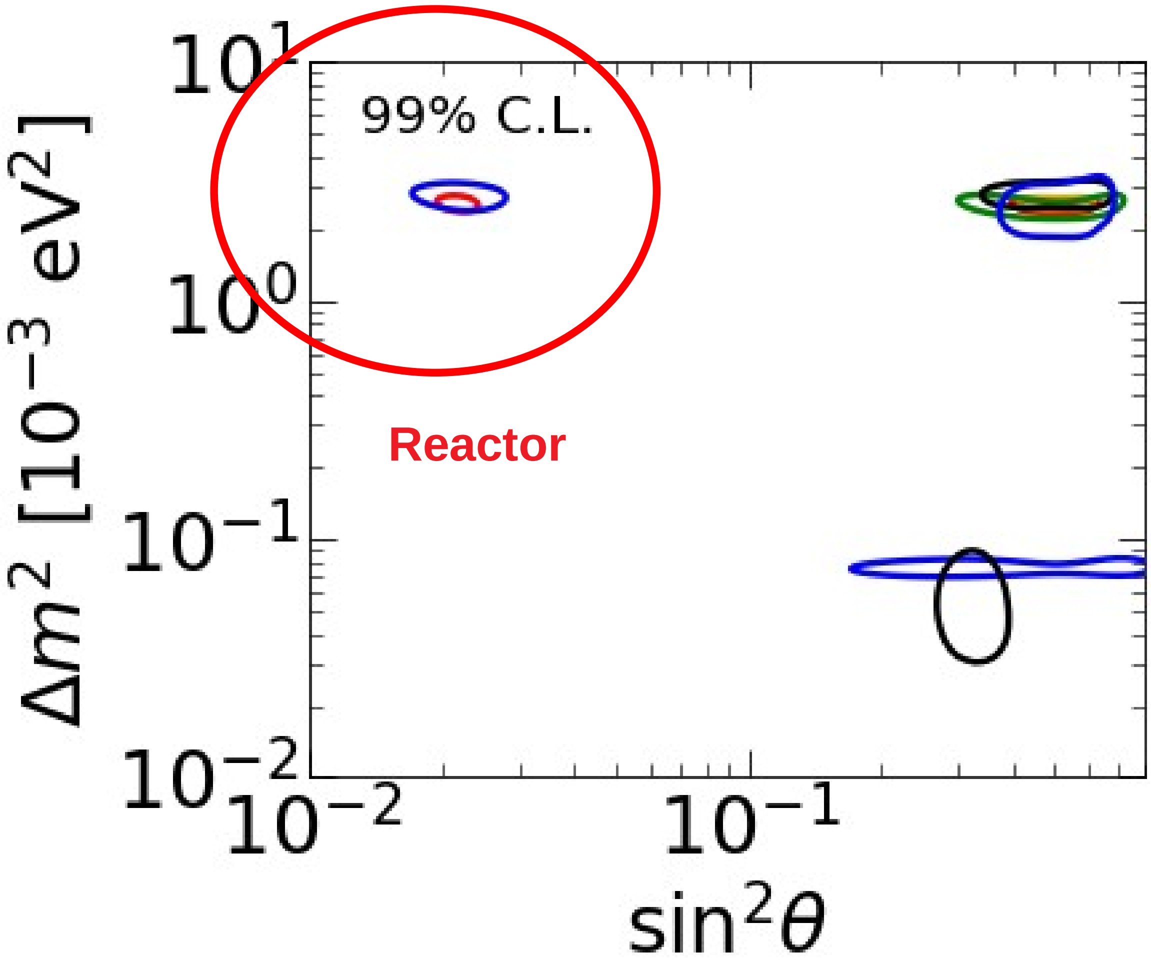


Valencia - Global Fit, 2006.11237, JHEP 2021

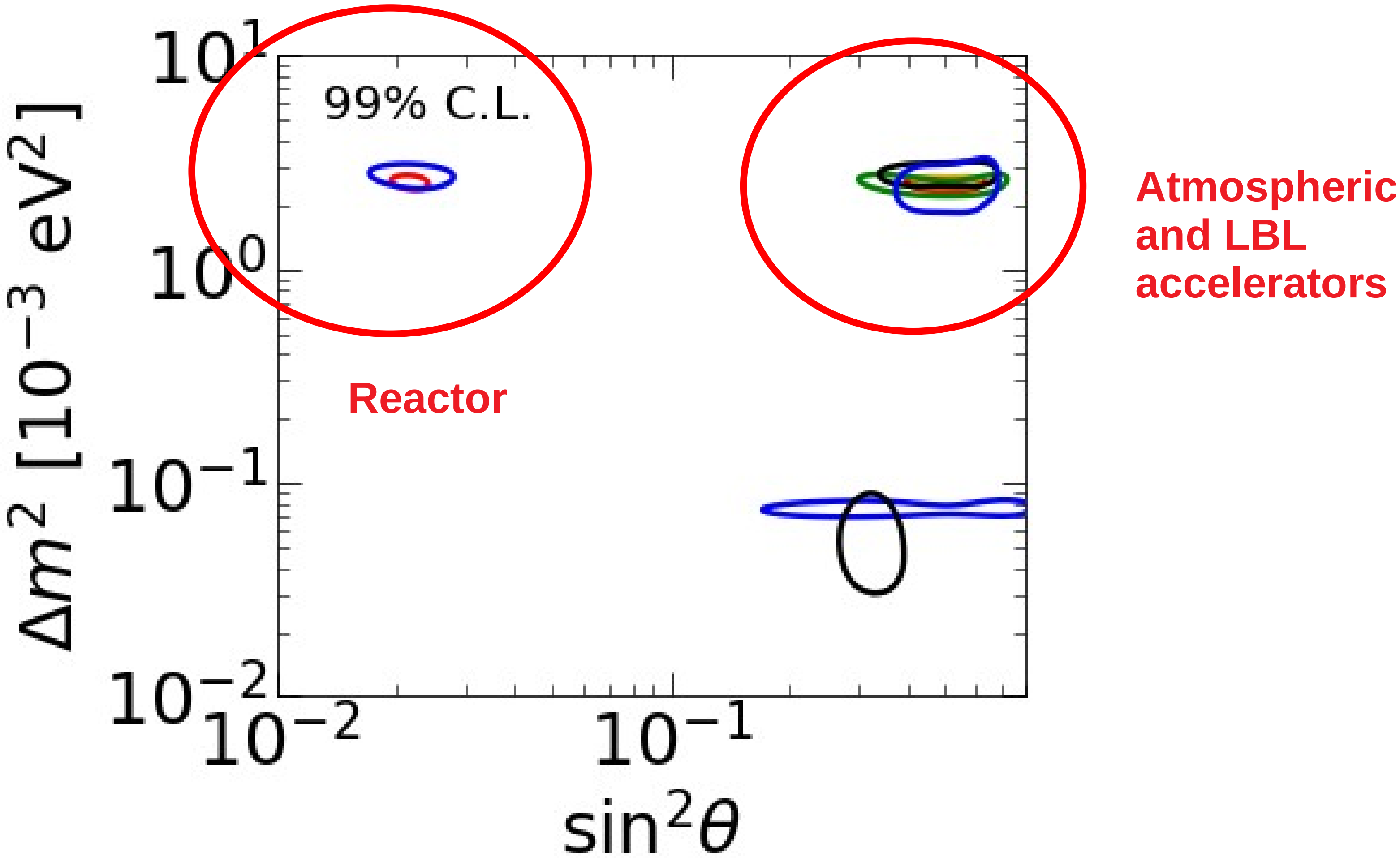
Three-neutrino oscillations



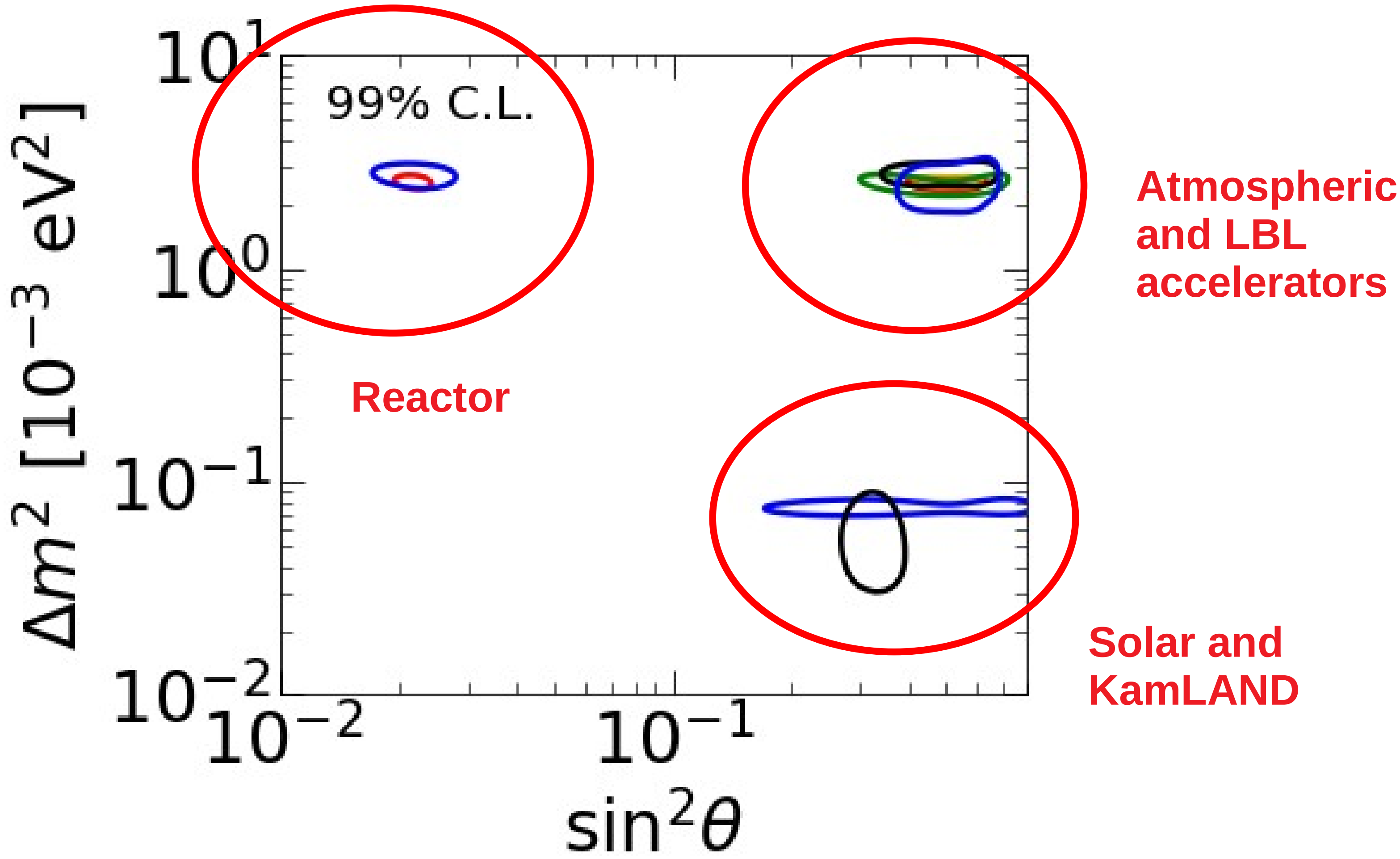
Three-neutrino oscillations



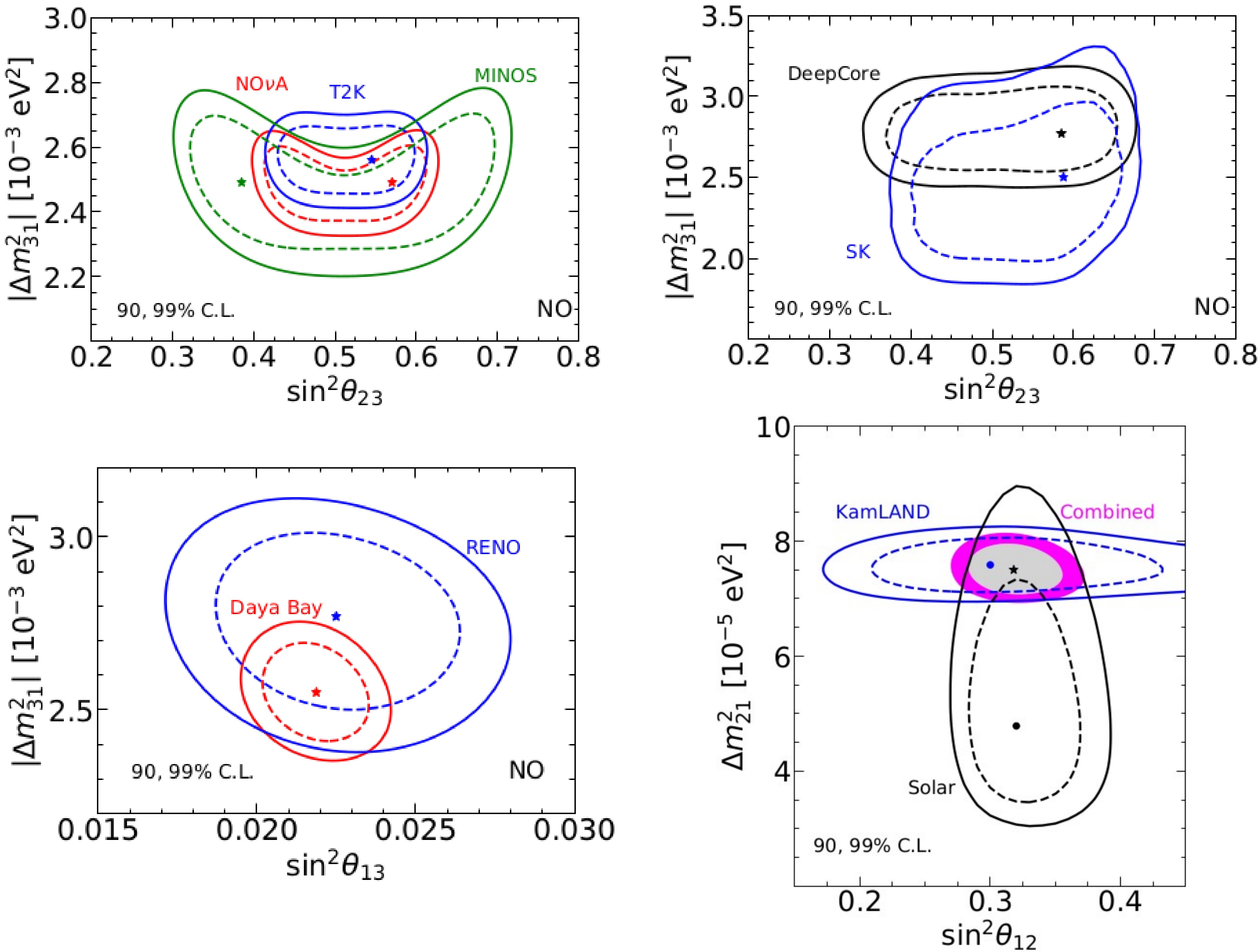
Three-neutrino oscillations



Three-neutrino oscillations



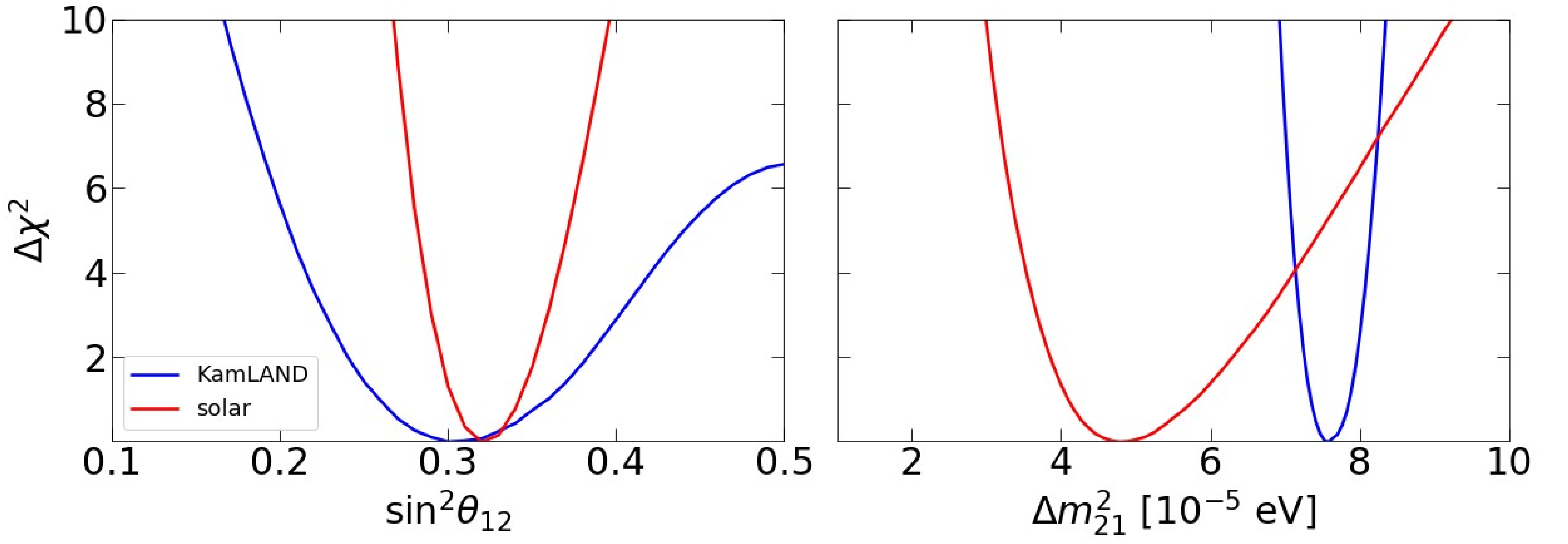
Valencia - Global Fit, 2006.11237, JHEP 2021



Solar sector

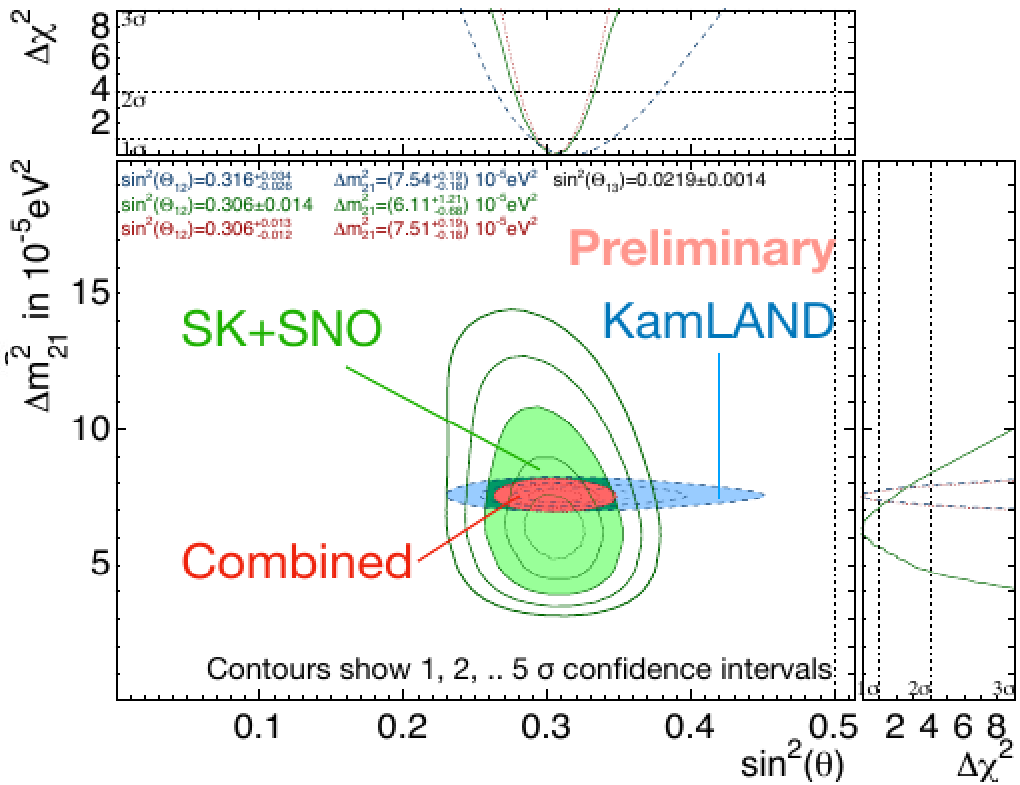
$$P_{ee}^{\mathrm{SOL}} = \frac{1}{2} c_{13}^2 (c_{13}^m)^2 (1 + c_{12} c_{12}^m) + s_{13}^2 (s_{13}^m)^2$$

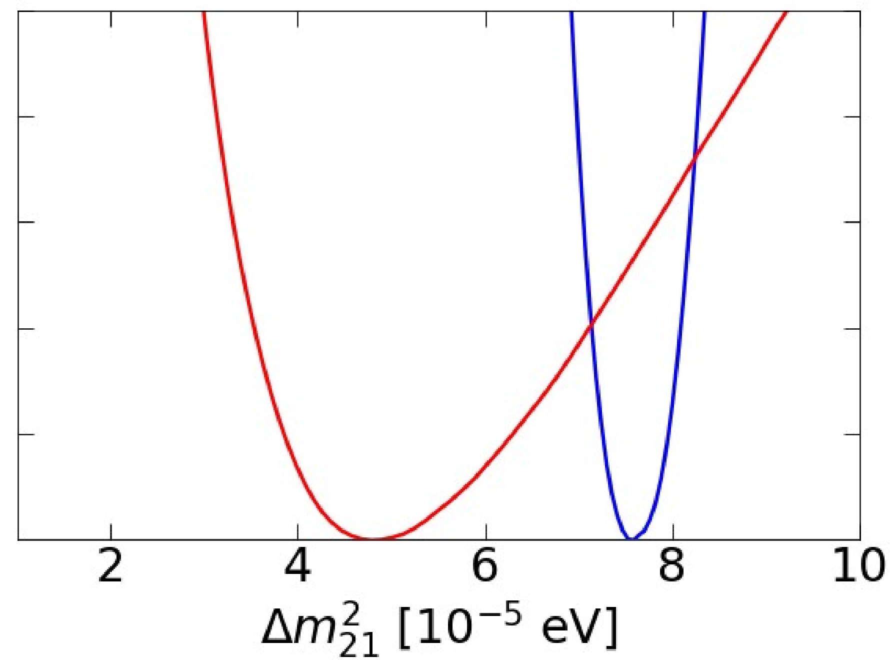
$$P_{ee}^{\mathrm{KL}} = c_{13}^4 \left(1 - \frac{1}{2} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)\right) + s_{13}^4$$



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

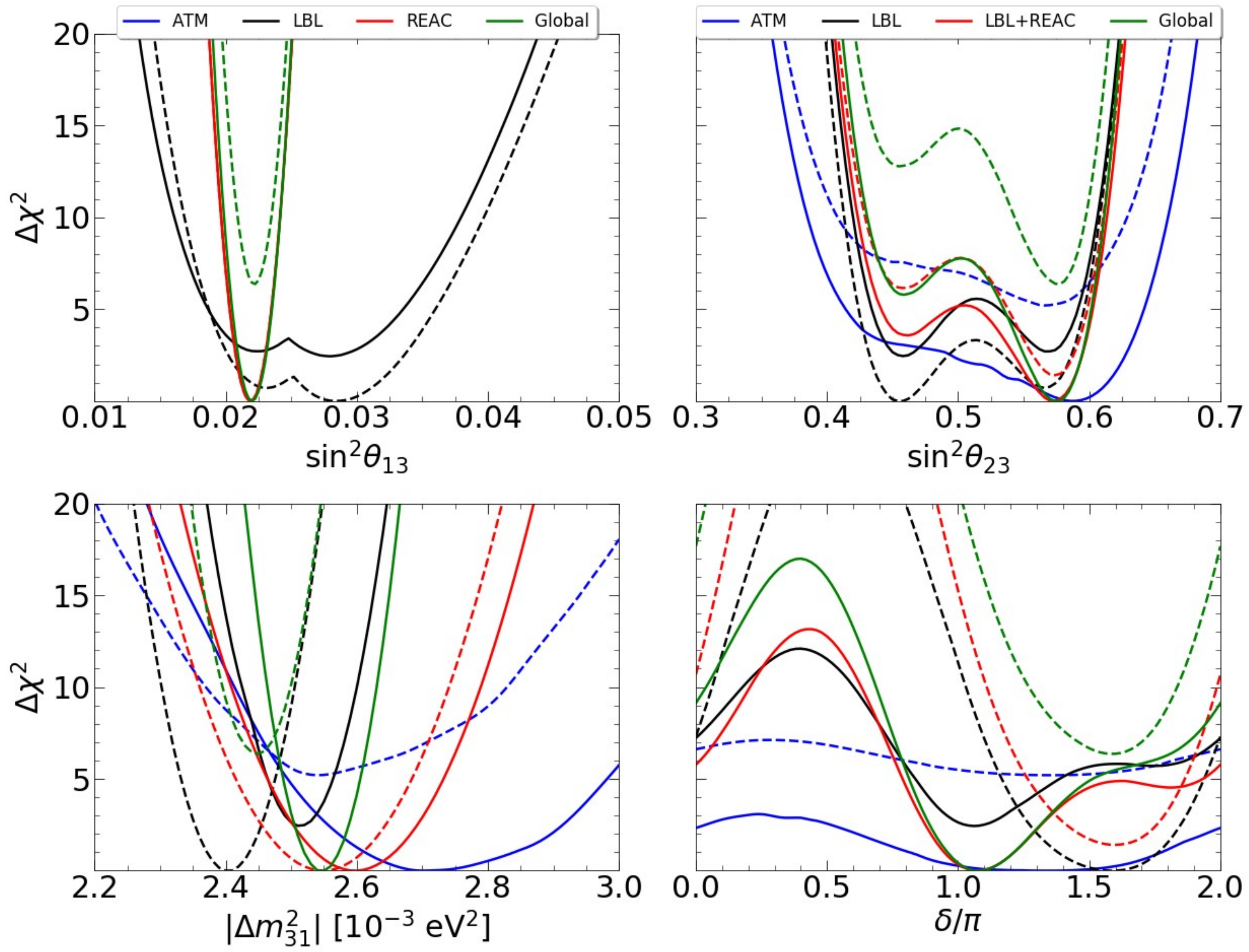
Solar sector



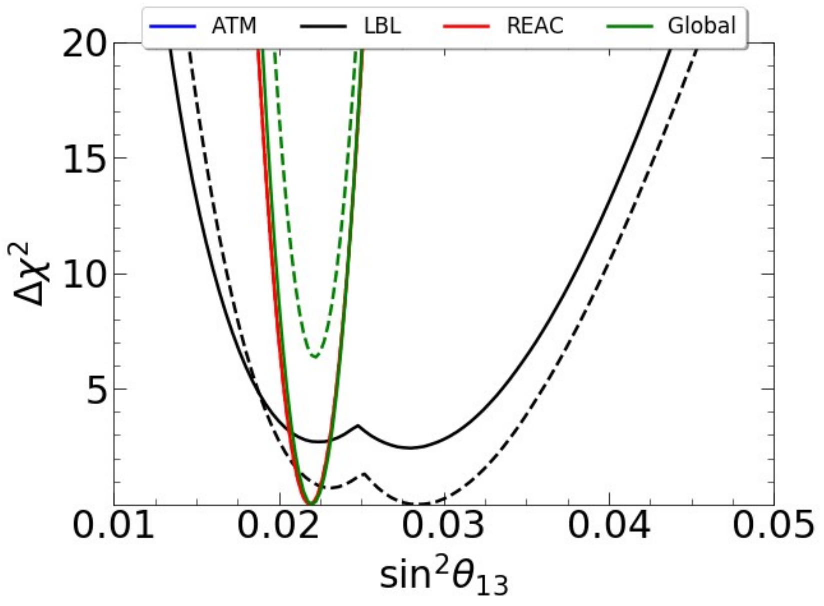


Discrepancy is reduced in new solar data from Super-K

Remaining parameters



Remaining parameters



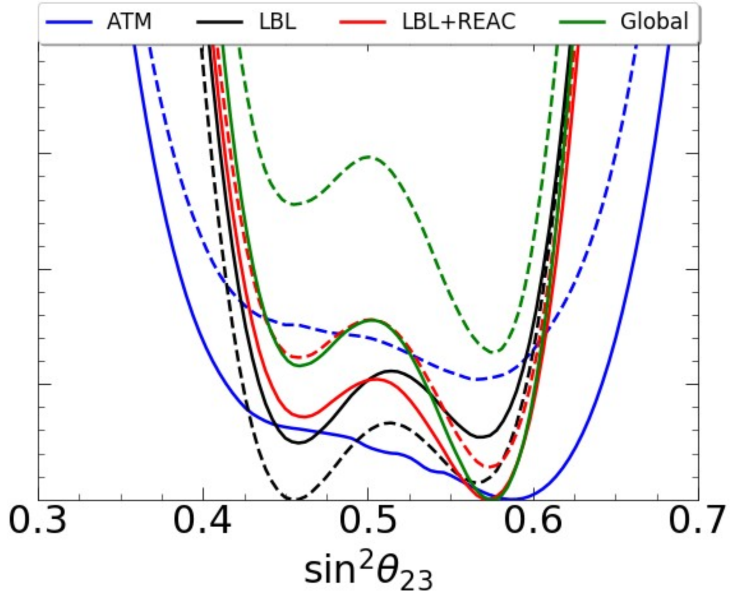
$$P_{ee}^{\mathrm{REAC}} = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$$

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



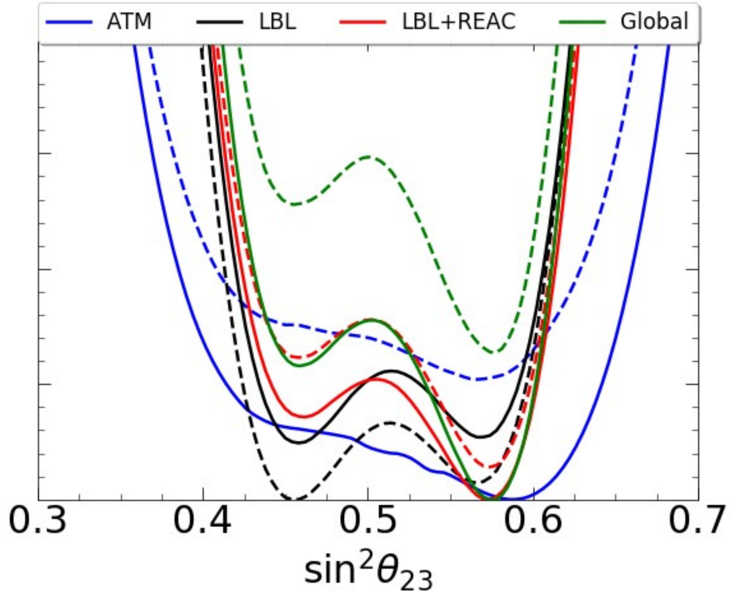
$$P_{\mu\mu}^{\rm LBL} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2\left(\frac{\Delta m^2_{\mu\mu} L}{4E}\right)$$

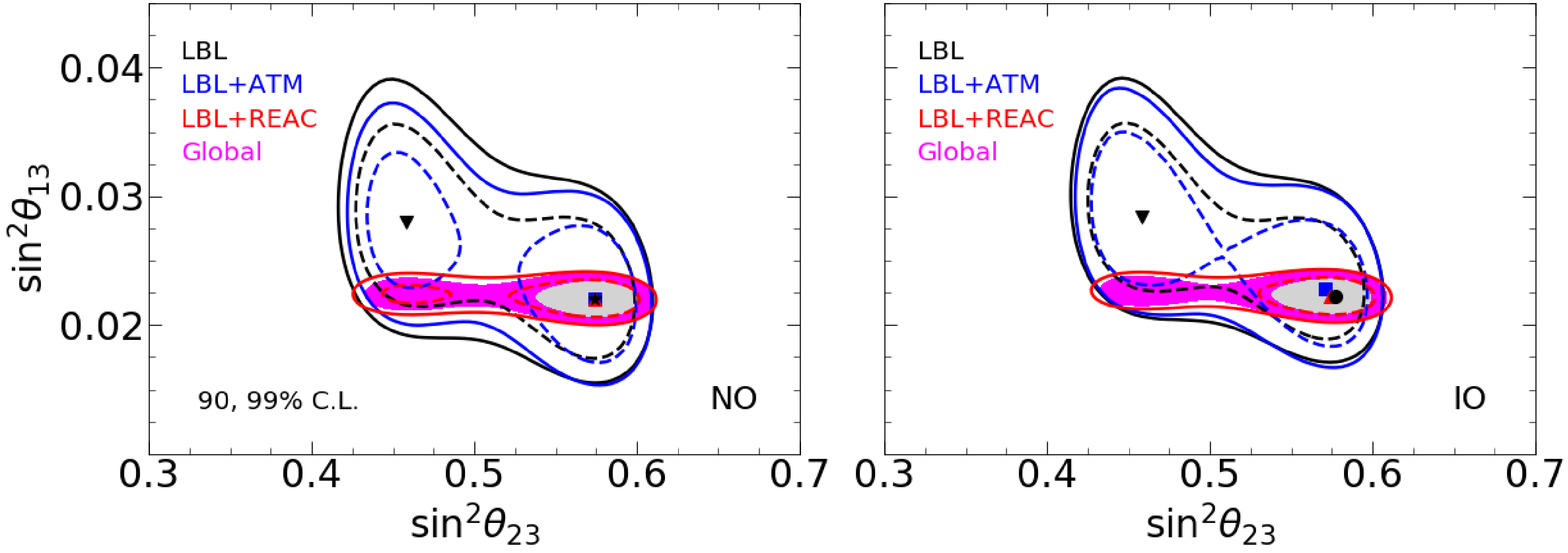
$$\begin{aligned} P(\nu_\mu \to \nu_e) \ \simeq \ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\ & + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{\rm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

Atmospheric octant

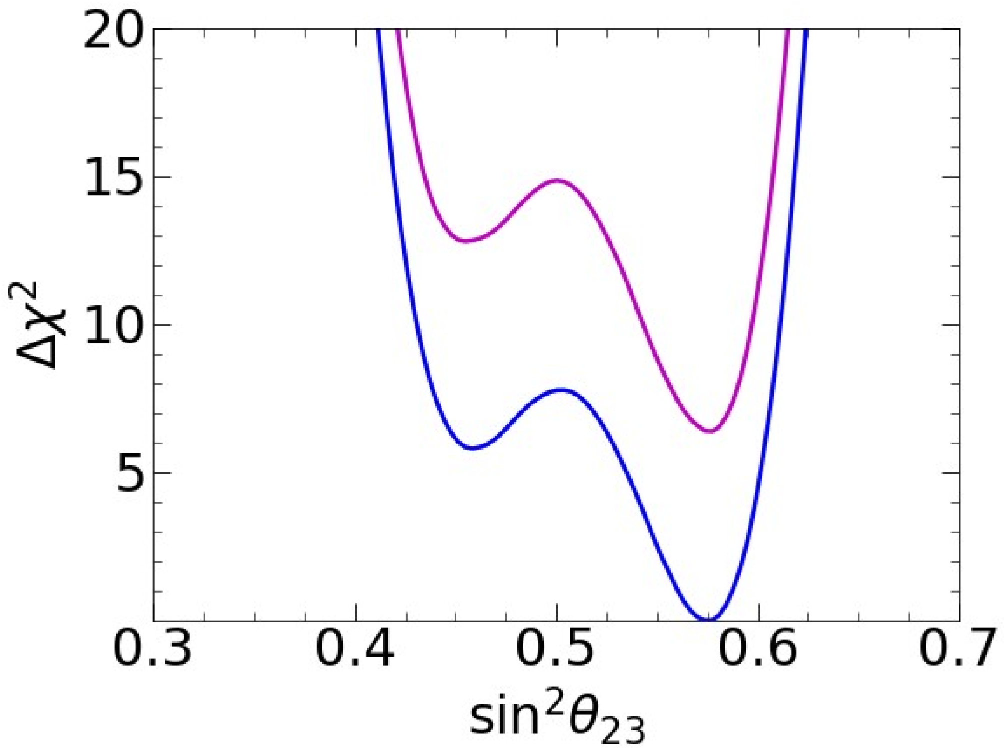
LBL data on their own do not distinguish octants

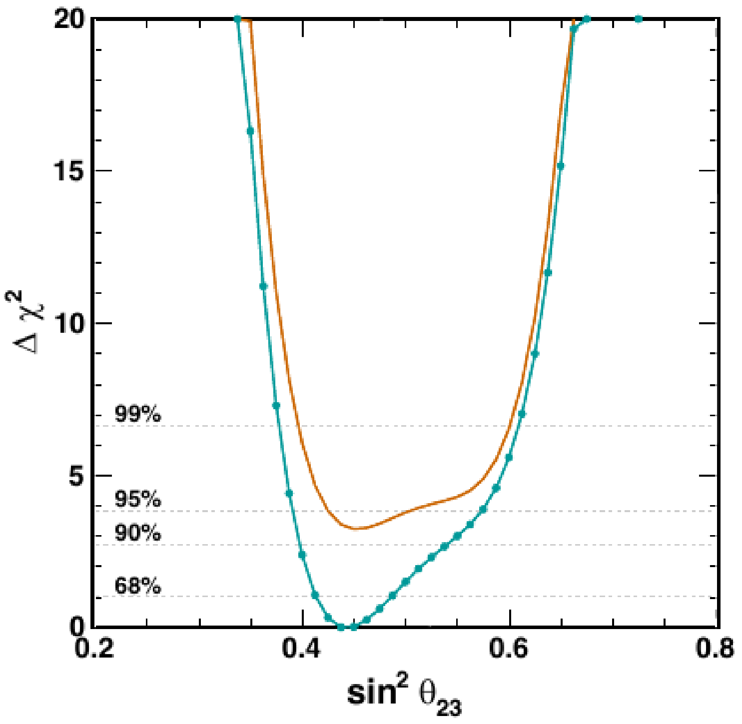
Adding ATM and REAC breaks degeneracies





Atmospheric octant



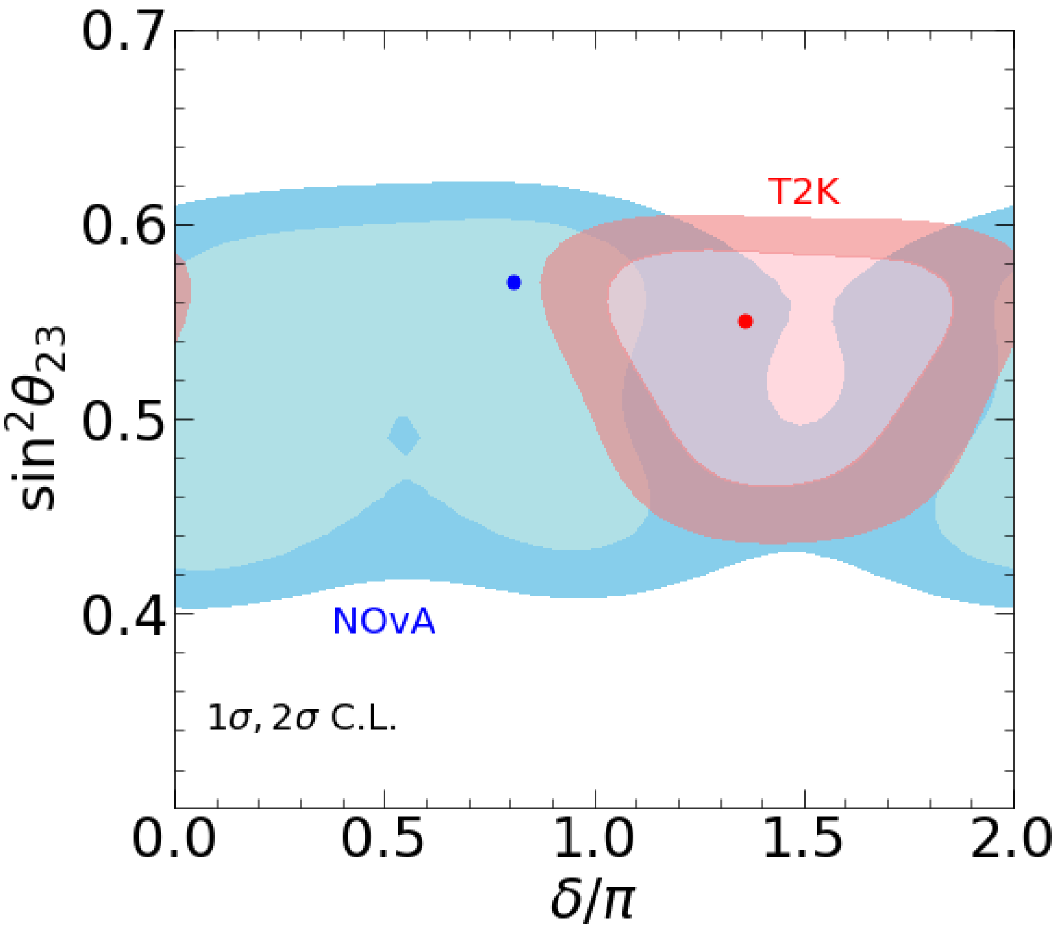


Current global fit prefers second octant

New data from Super-K prefer first octant

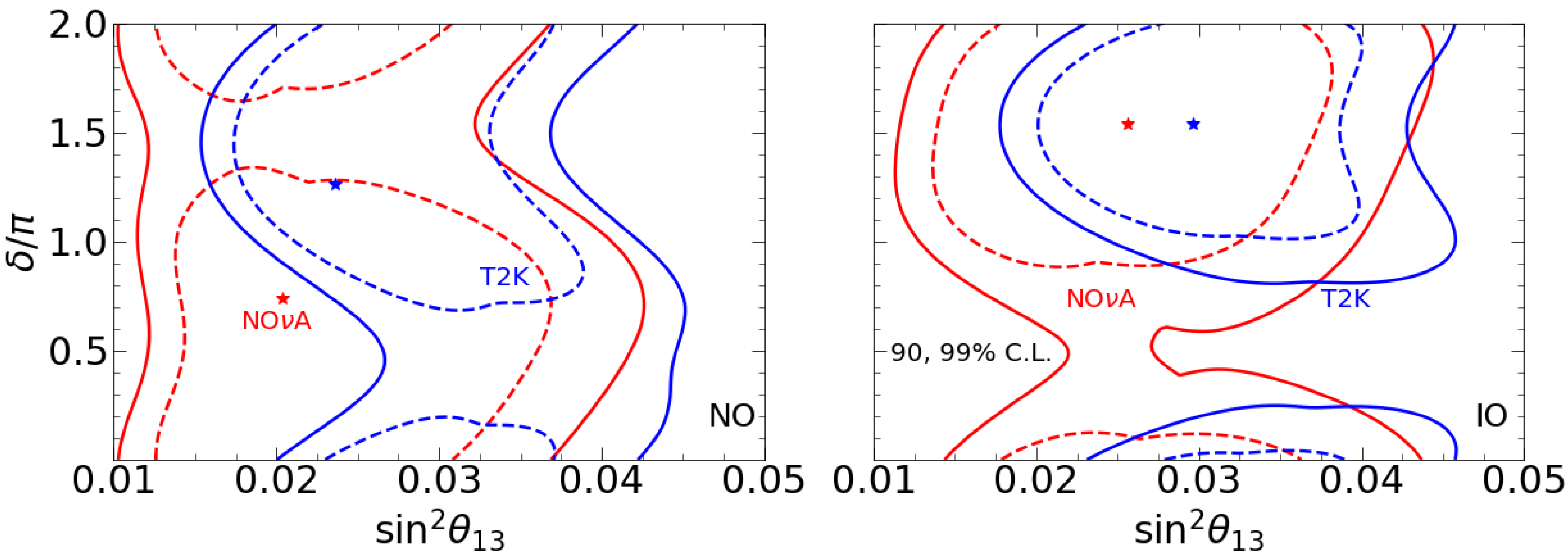
Valencia - Global Fit, 2006.11237, JHEP 2021

CP violation



Tension in the measurement of the CP phase in current data

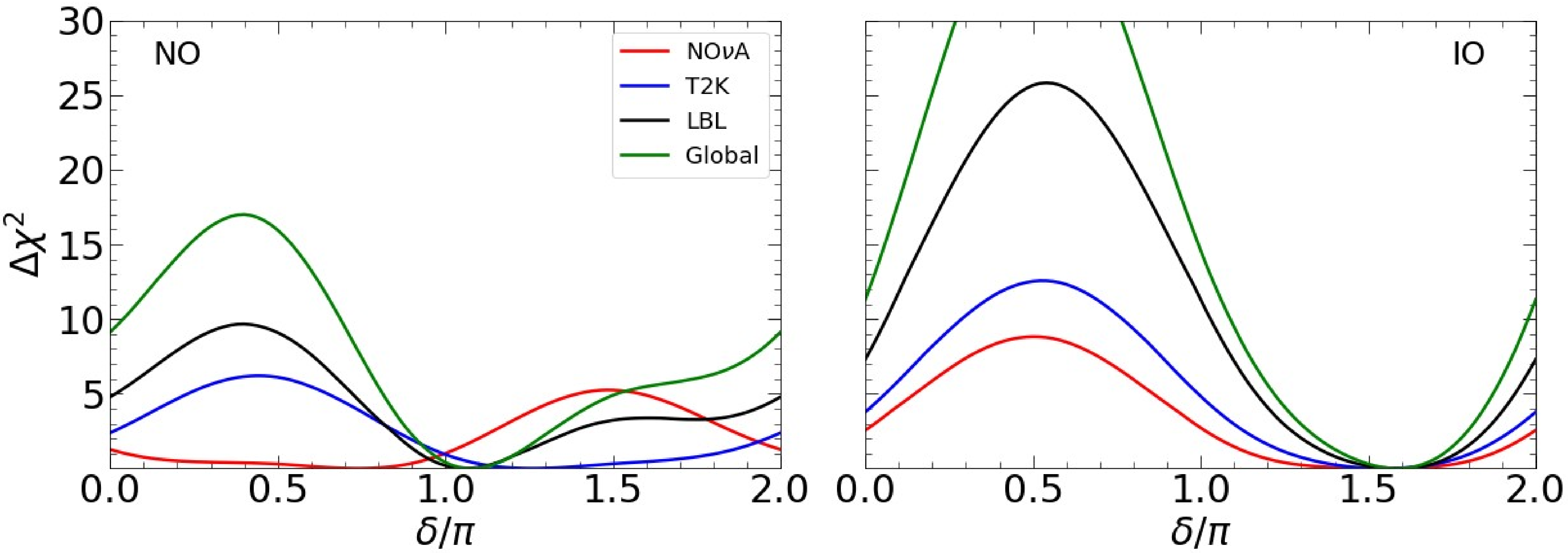
CP violation



Tension remains when relaxing prior from reactor neutrinos

Valencia - Global Fit, 2006.11237, JHEP 2021

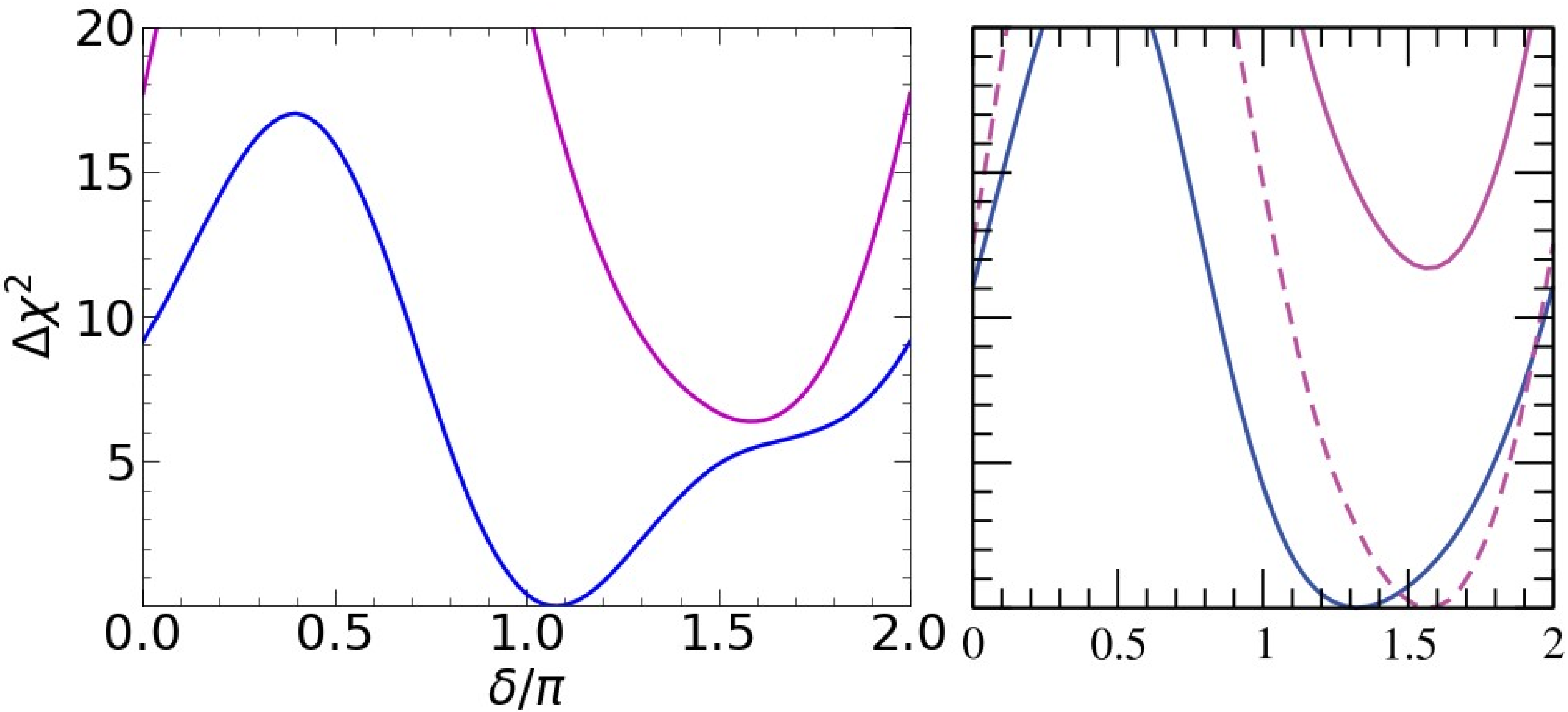
CP violation



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

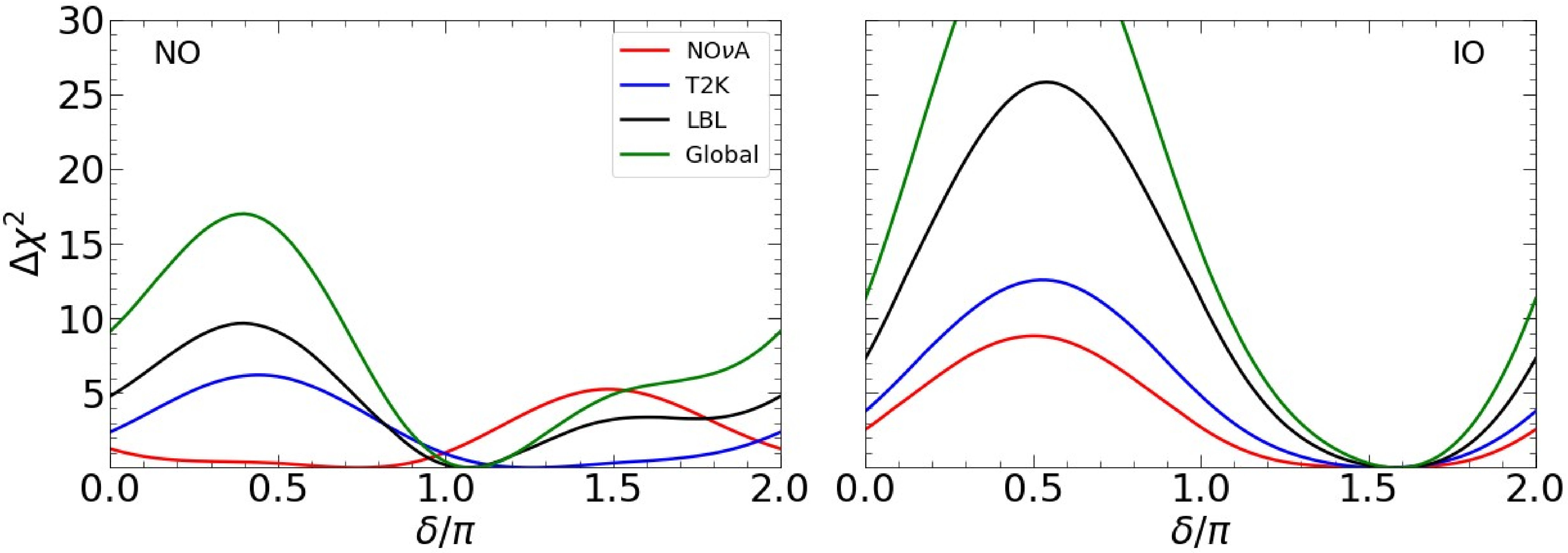
None of the experiments has a good sensitivity on its own

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

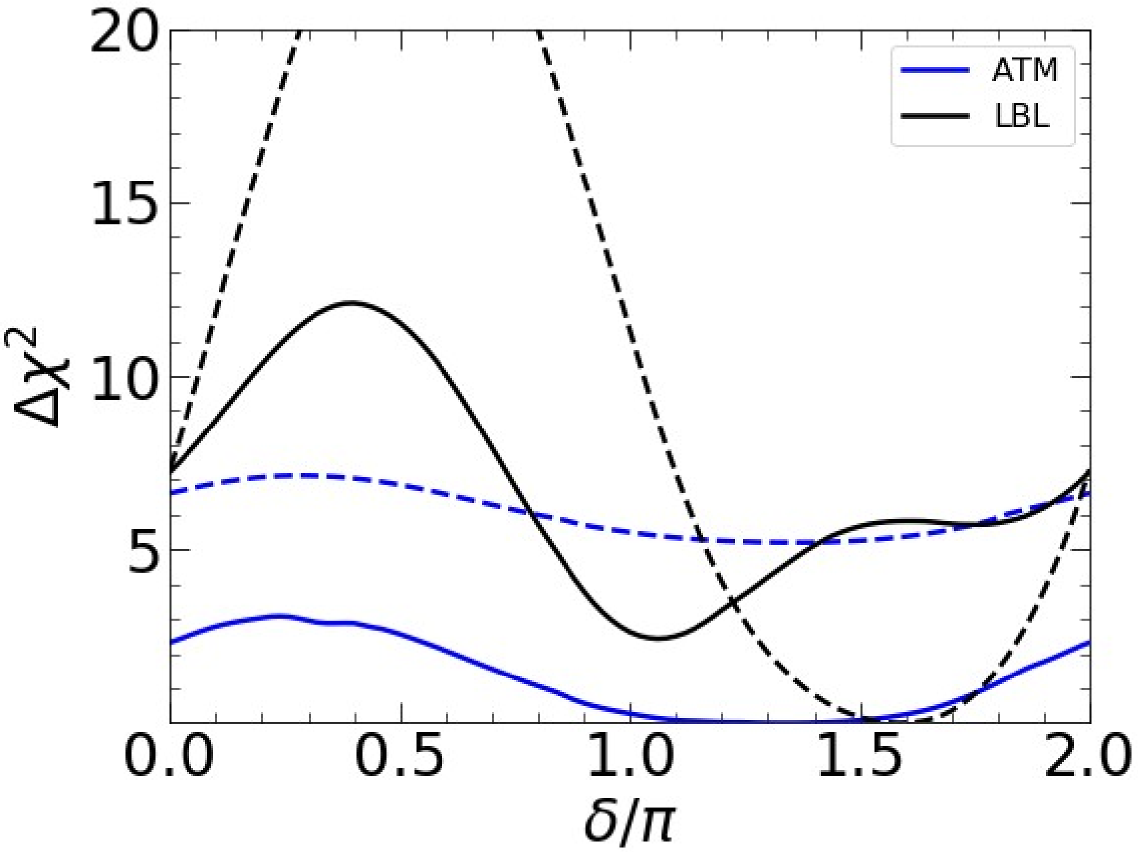
The tension between T2K and NOνA in the measurement of the CP phase appears only for normal ordering



Neutrino mass ordering

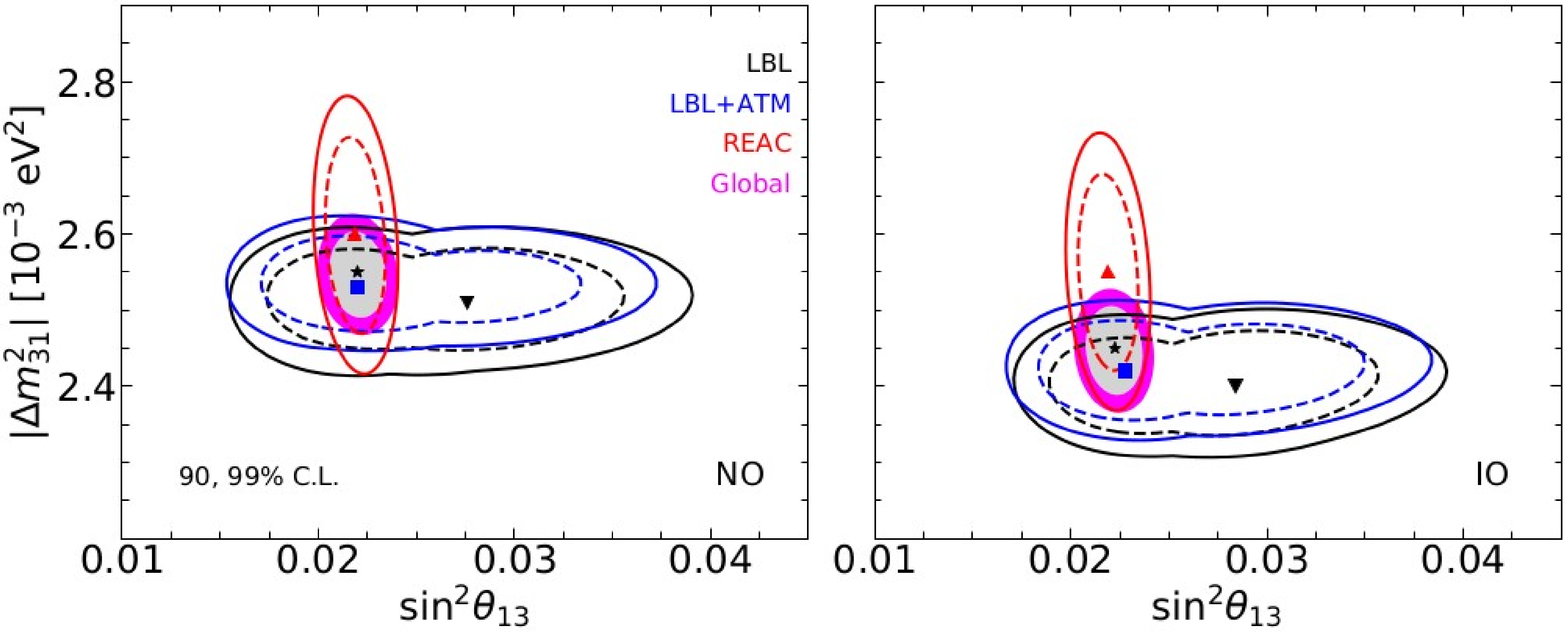
Although none of the experiments has a preference on its own, the combined analysis of all LBL data prefers IO!

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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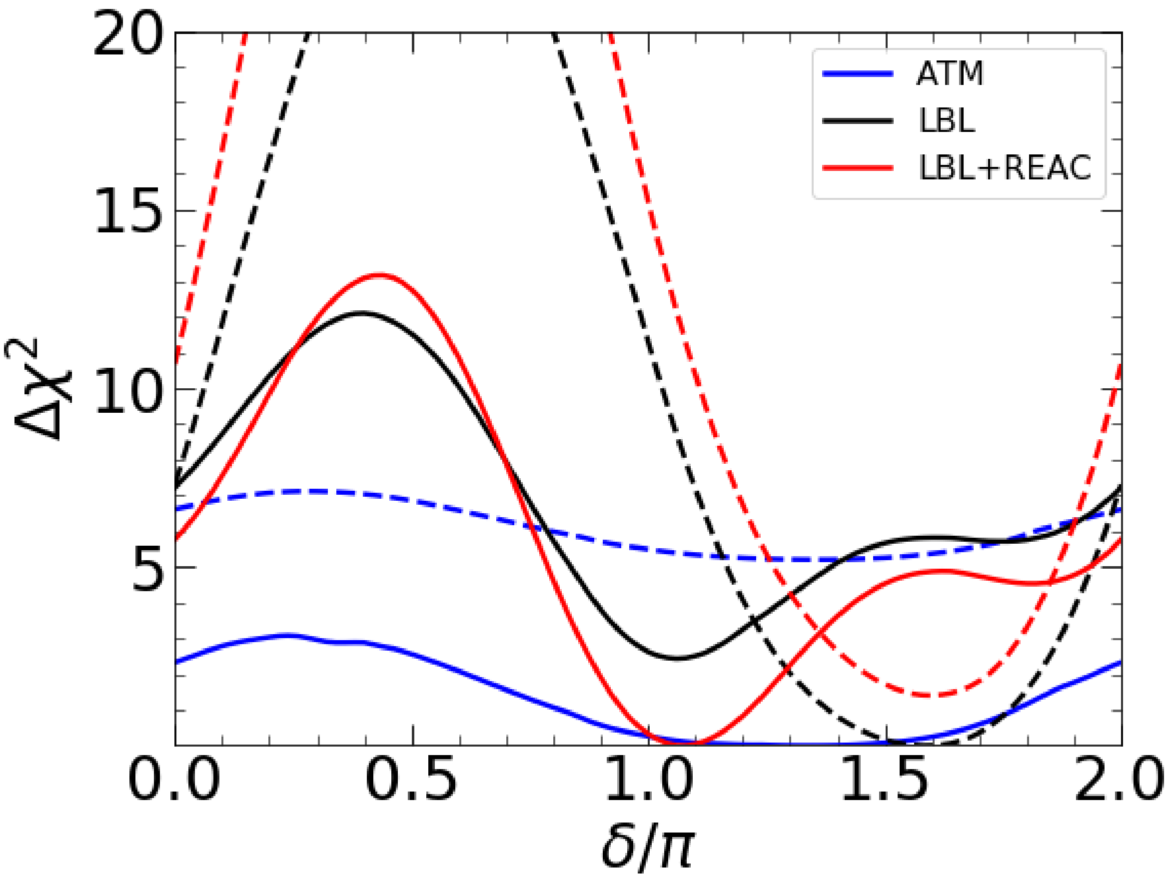
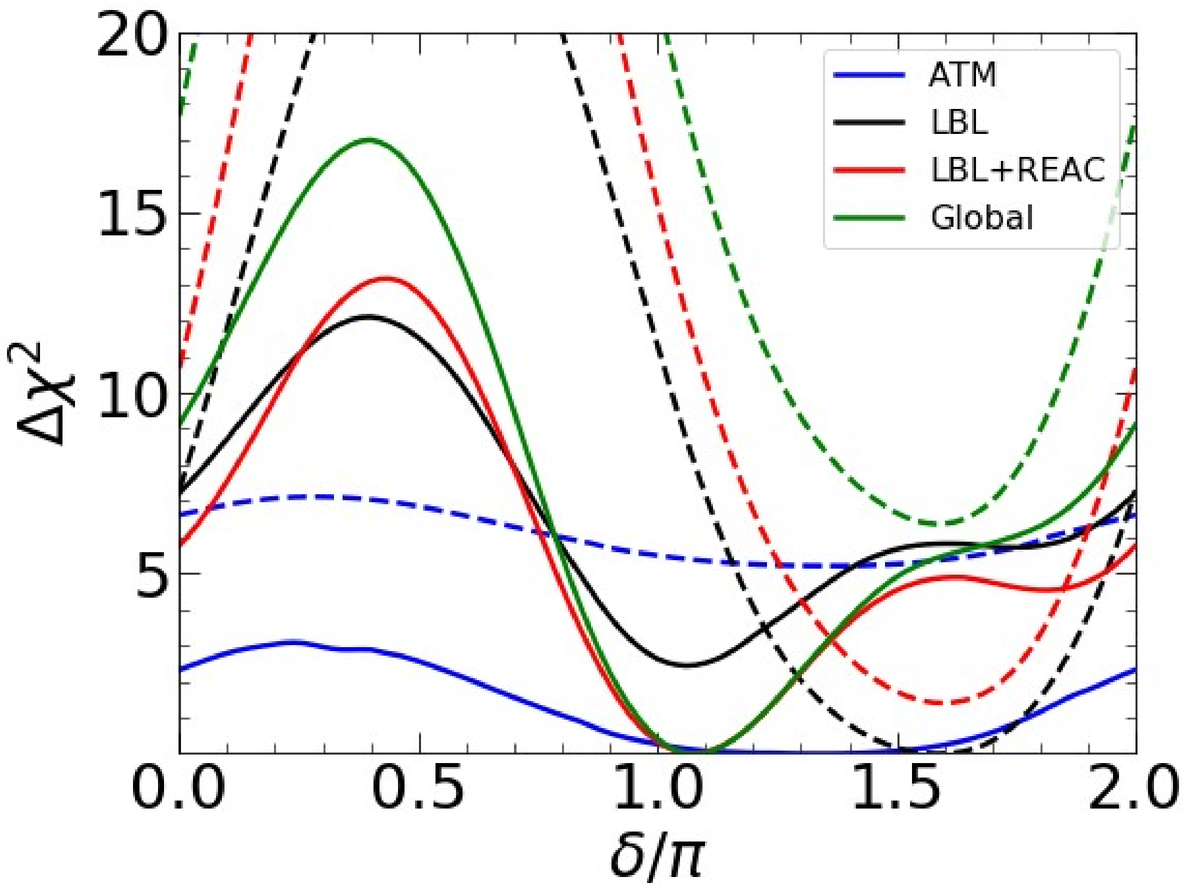
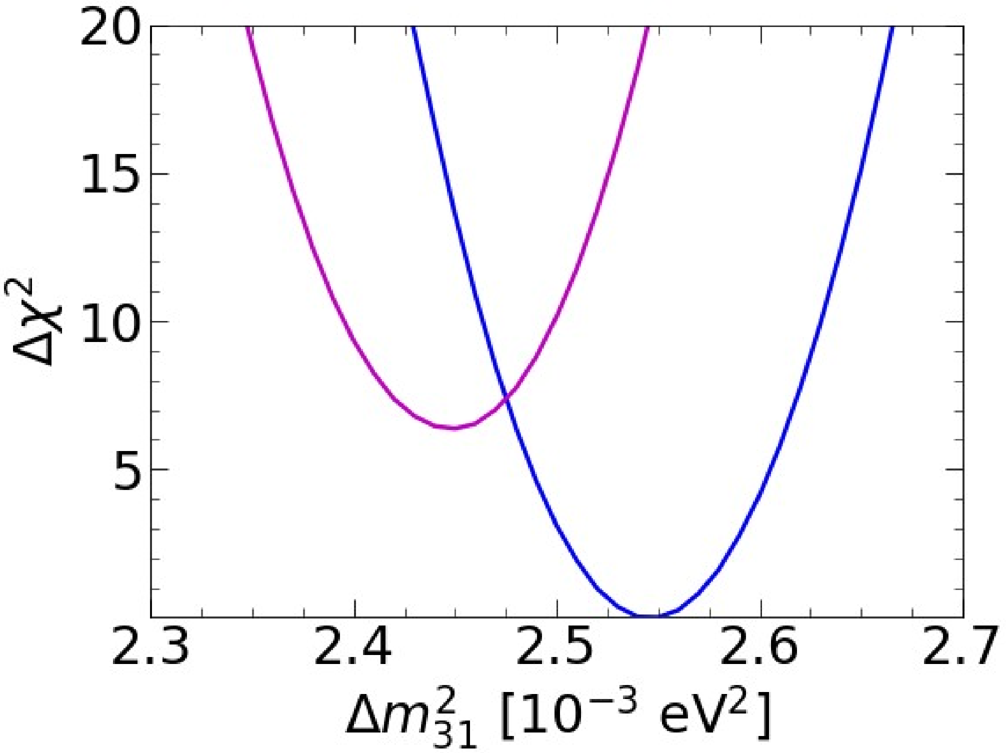


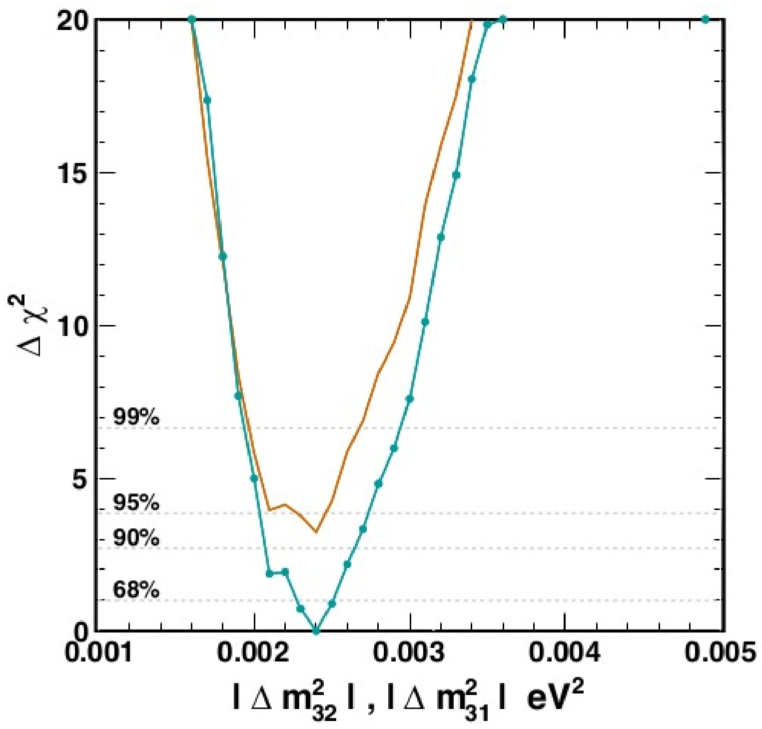
Neutrino mass ordering

After combing everything we get 2.5σ



Neutrino mass ordering



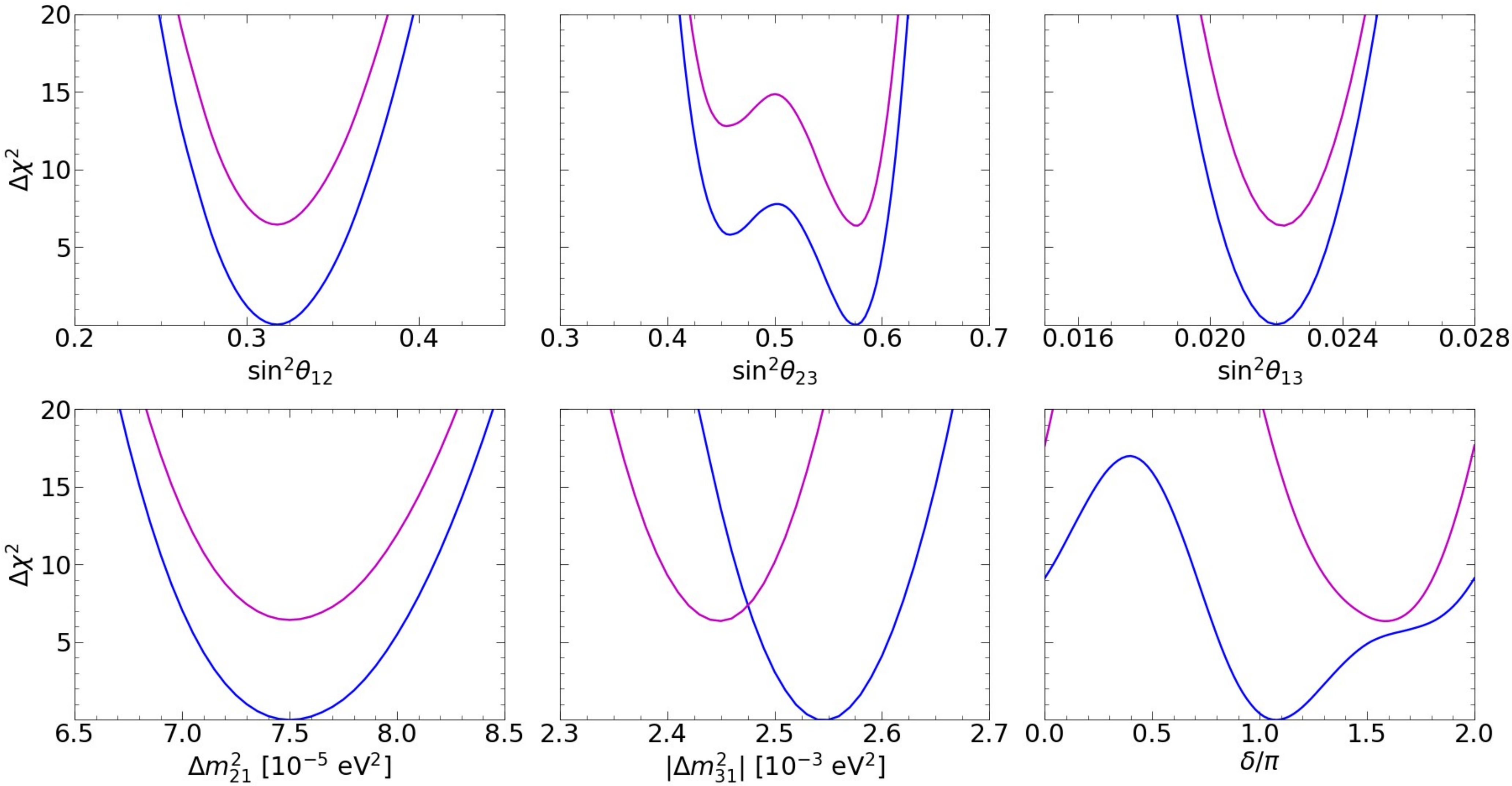


2.5σ preference, coming from different tensions

New data from Super-K has weaker preference

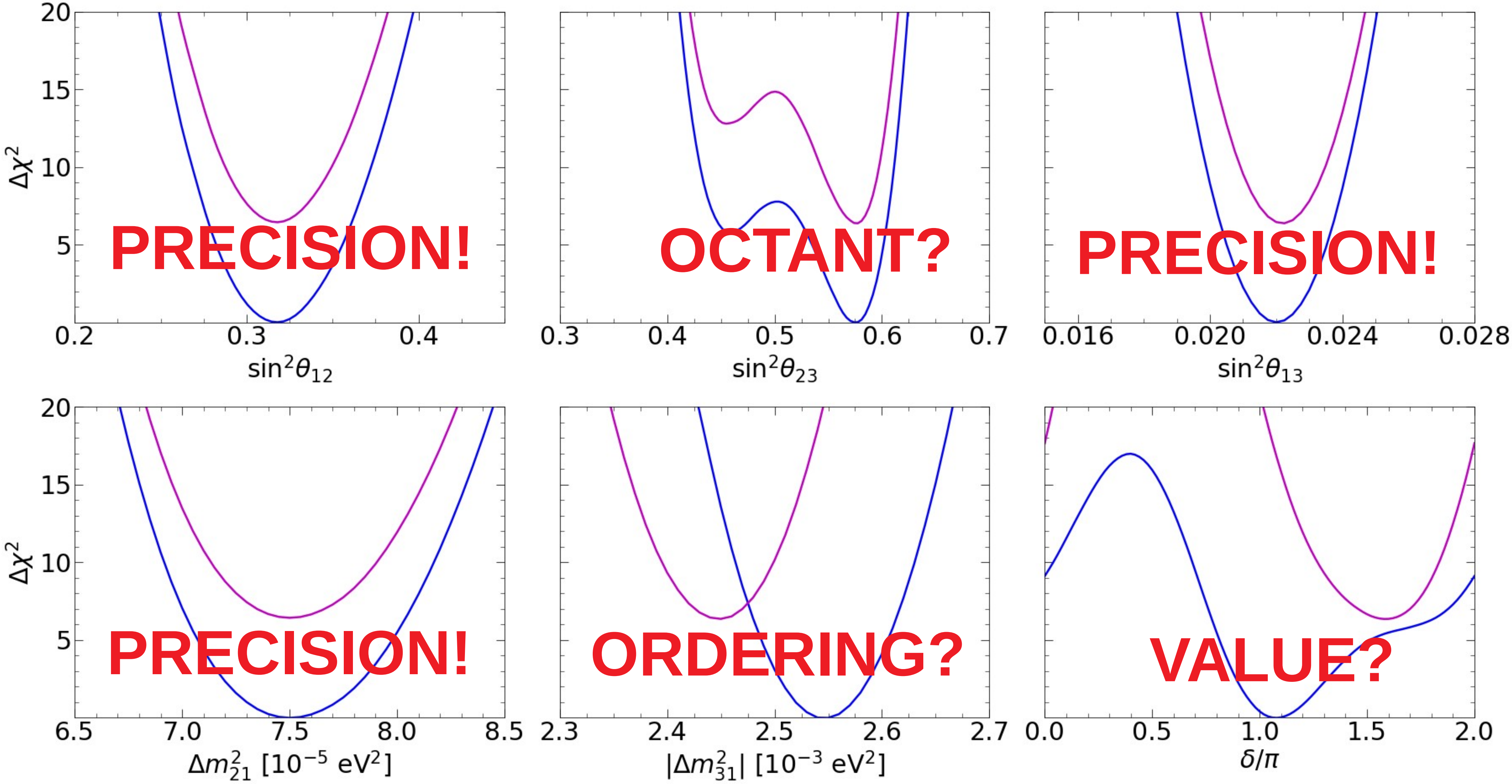
Valencia - Global Fit, 2006.11237, JHEP 2021

Global fit



Valencia - Global Fit, 2006.11237, JHEP 2021

Global fit



Valencia - Global Fit, 2006.11237, JHEP 2021

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, part 1

Some of the neutrino oscillation parameters are well measured

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

Due to the updated data there is an overall lower sensitivity to the mass ordering, further worsened by the T2K/NOνA tension

The same tension worsens the determination of the CP phase with respect to 2018

However, these parameters will be measured very well at future facilities (the only problematic one might be the octant)

BUT….

All results so far have been derived under the assumption of standard neutrino oscillations

If new physics is present in the neutrino sector, the oscillation picture might be altered

New degeneracies might spoil several of the measurements

- More than three neutrinos: light or heavy steriles, large extra dimensions
- New interactions: new interactions in production/detection, new matter effects (NSI)
- Decoherence effects due to different things
- etc, etc, etc

CPT violation

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

Discovery of P violation in weak interactions

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§

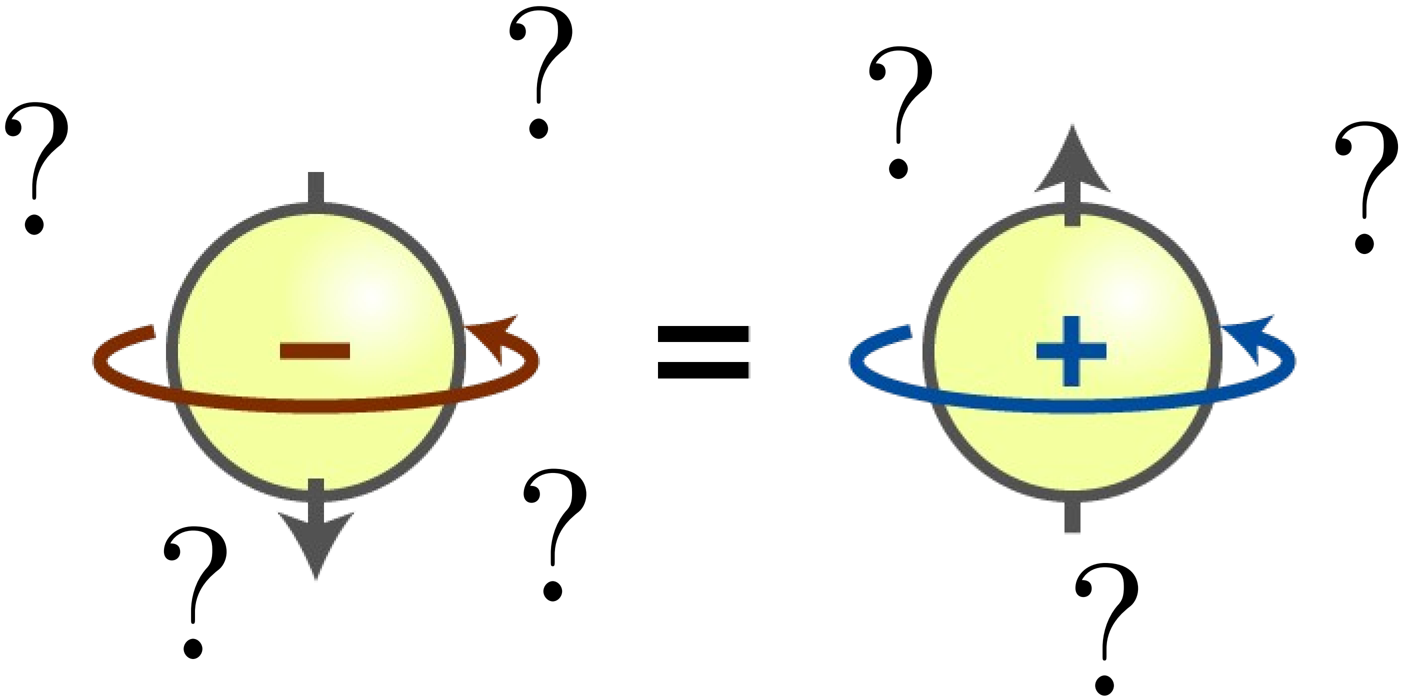
Princeton University, Princeton, New Jersey

(Received 10 July 1964)

Discovery for CP volation in kaon decays

Is CPT violated as well?

CPT violation



CPT violation

CPT from EFT:

Kostelecky and collaborators, many papers, in particular:
Kostelecky, Mewes, PRD 2004, hep-ph/0309025

CPT from non-locality:

Barenboim, Lykken, PLB 2002, hep-ph/0201080

CPT from decoherence

Papers by Mavromatos et al, Gago et al, Capolupo et al

CPT violation

If CPT is not conserved: $P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu}_\beta \to \overline{\nu}_\alpha)$

We reanalyze the data from the global fit without the assumption of CPT conservation

- neutrinos oscillate with $\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta$
- and antineutrinos with $\Delta \overline{m}^2_{21}, \Delta \overline{m}^2_{31}, \overline{\theta}_{12}, \overline{\theta}_{13}, \overline{\theta}_{23}, \overline{\delta}$

Most important data sets are T2K, NOνA, reactors and solar experiments

To prove the CPT-theorem of QFT one needs:

- Hermiticity of the Hamiltonian
- Locality
- Lorentz invariance

If CPT is violated, one of the three ingredients above must be violated, resulting in a gigantic impact on fundamental physics

CPT violation

Assume that neutrinos oscillate with parameters

$$\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta$$

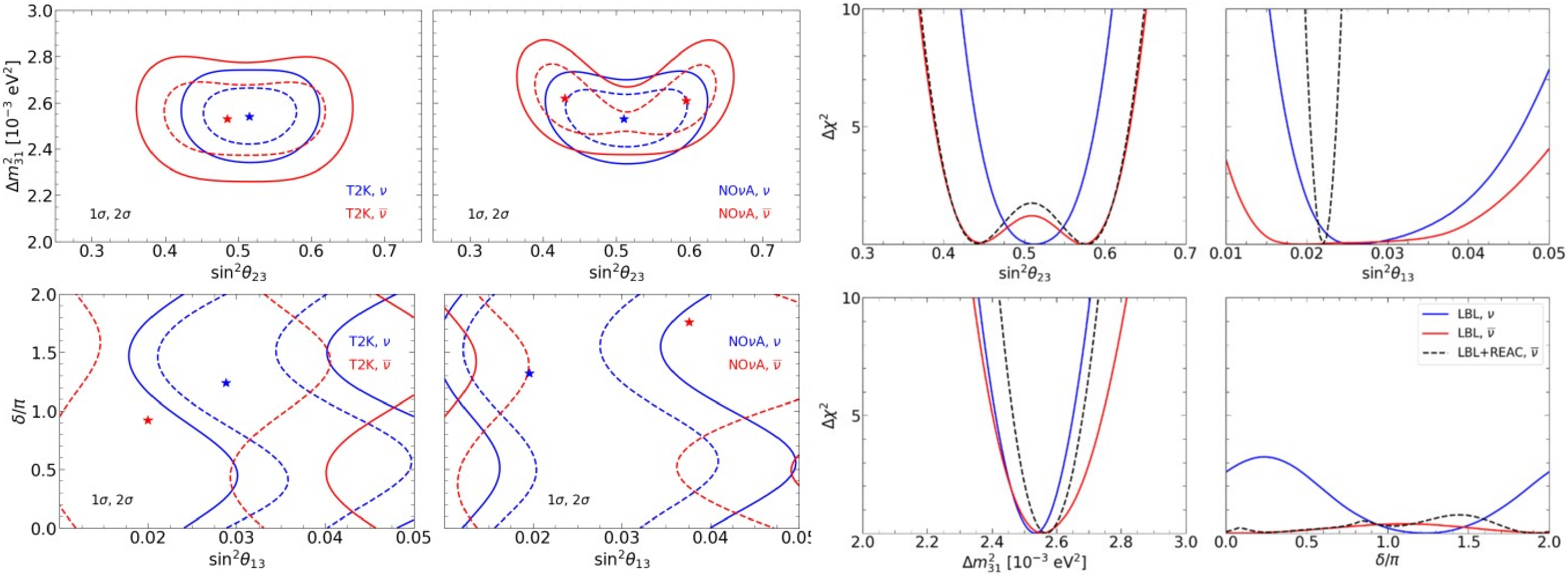
while the antineutrinos oscillate with a new set of parameters

$$\Delta \overline{m}^2_{21}, \Delta \overline{m}^2_{31}, \overline{\theta}_{12}, \overline{\theta}_{13}, \overline{\theta}_{23}, \overline{\delta}$$

Different parameters for neutrinos and antineutrino would indicate a violation of CPT symmetry

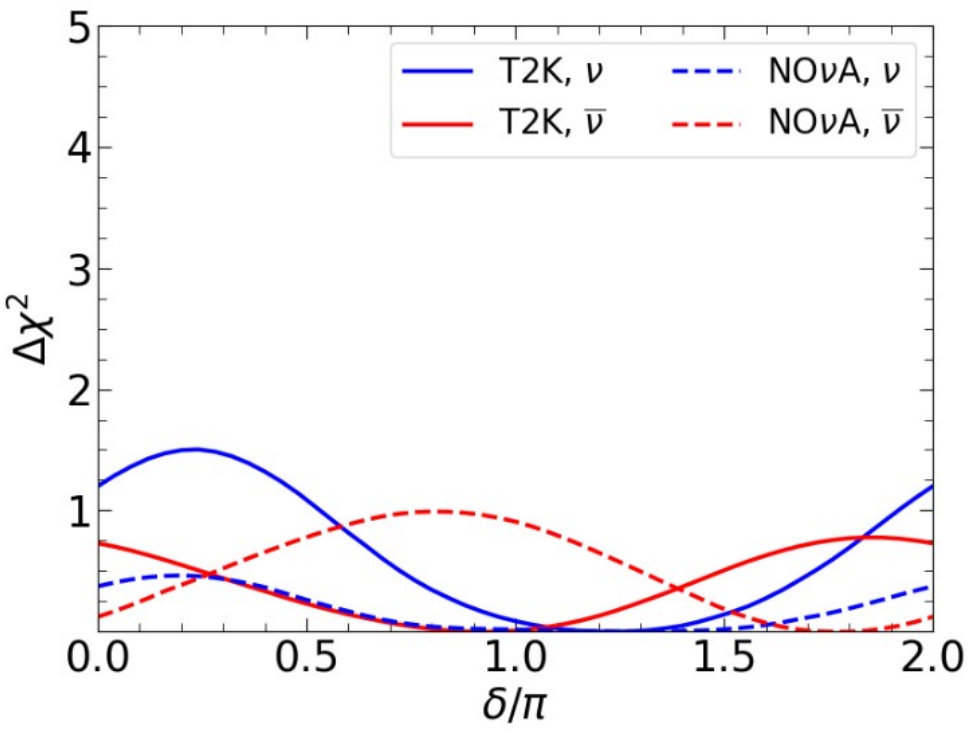
Current experiments

Current experiments



Barenboim, Ternes, Tórtola, 2005.05975, JHEP 2020

Current experiments

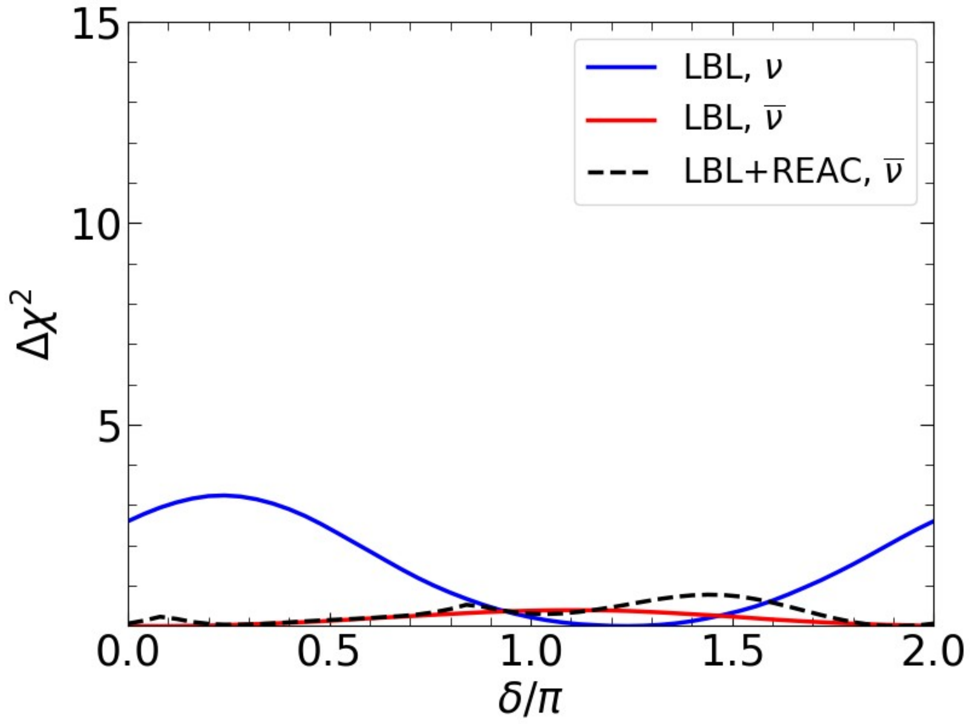


If CPT is not conserved a measurement of CP violation is currently not possible

The different event spectra could be explained with different reactor mixing angles

Barenboim, Ternes, Tórtola, 2005.05975, JHEP 2020

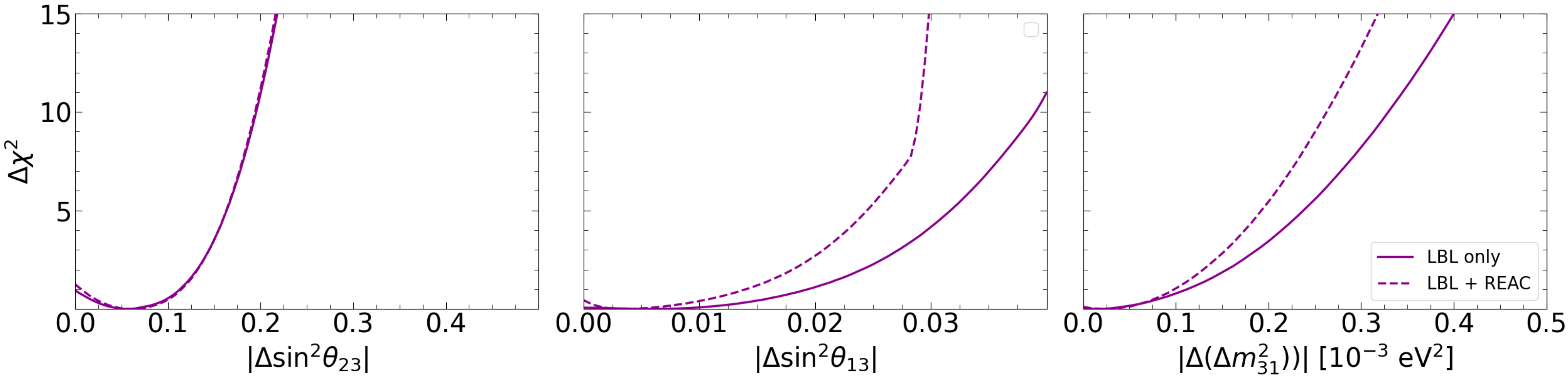
Current experiments



Combining accelerator and reactor data does not improve the situation

Barenboim, Ternes, Tórtola, 2005.05975, JHEP 2020

Current experiments

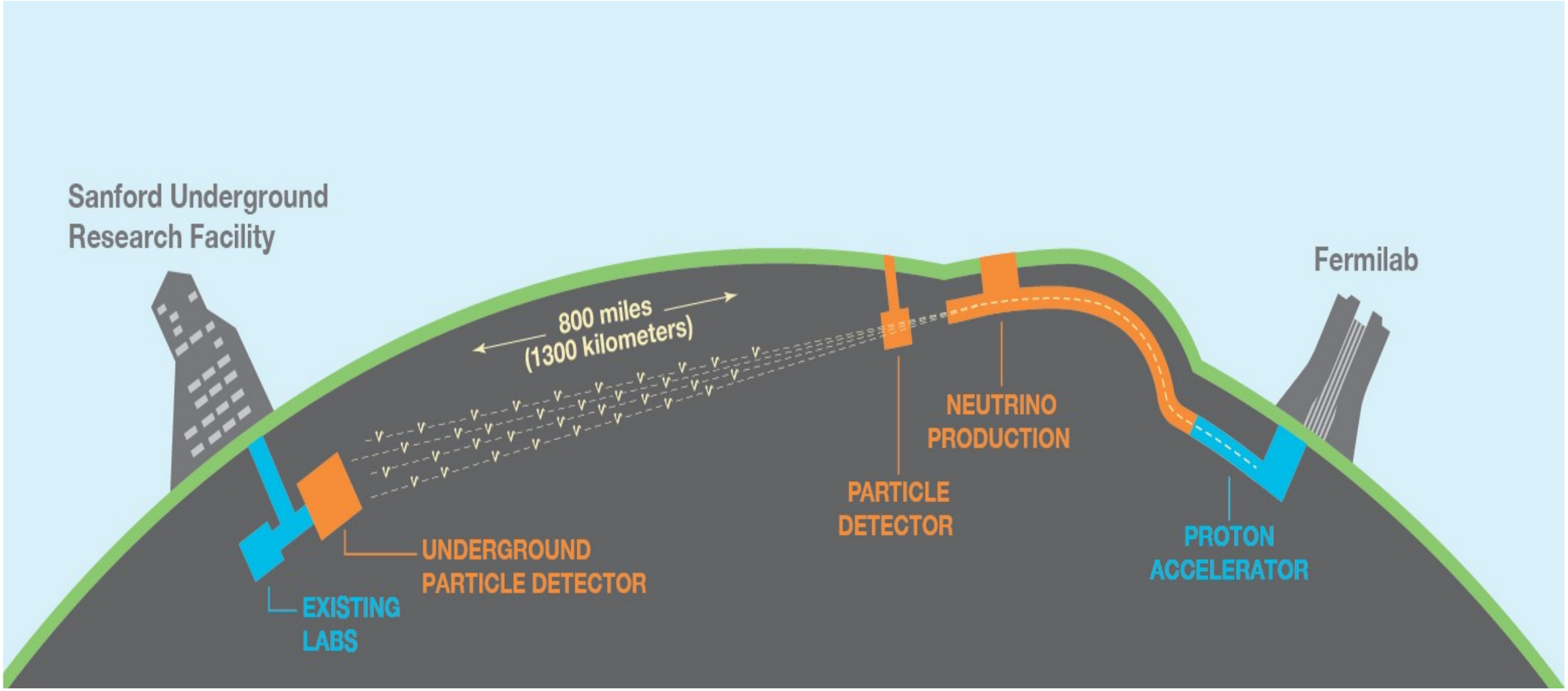


The same data allows us to bound CPT-violating neutrino oscillation parameters

$$
\begin{aligned}
|\Delta m^2_{21} - \Delta\overline{m}^2_{21}| &< 4.7\times10^{-5}\ \text{eV}^2,\\
|\Delta m^2_{31} - \Delta\overline{m}^2_{31}| &< 2.5\times10^{-4}\ \text{eV}^2,\\
|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| &< 0.14,\\
|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| &< 0.029,\\
|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| &< 0.19.
\end{aligned}
$$

Barenboim, Ternes, Tórtola, 2005.05975, JHEP 2020

Future perspectives at DUNE

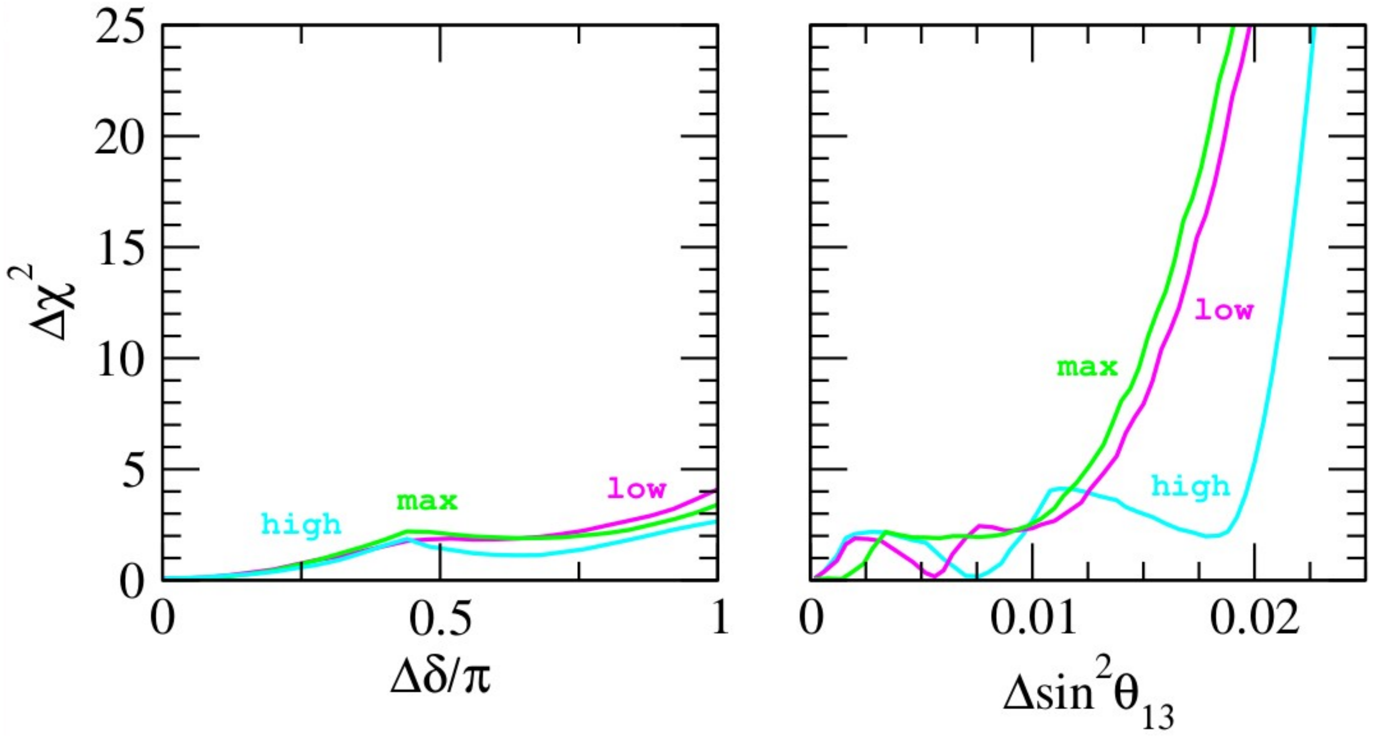


Future perspectives at DUNE

How will this improve with DUNE?

Poor sensitivity to CP phases and reactor angles

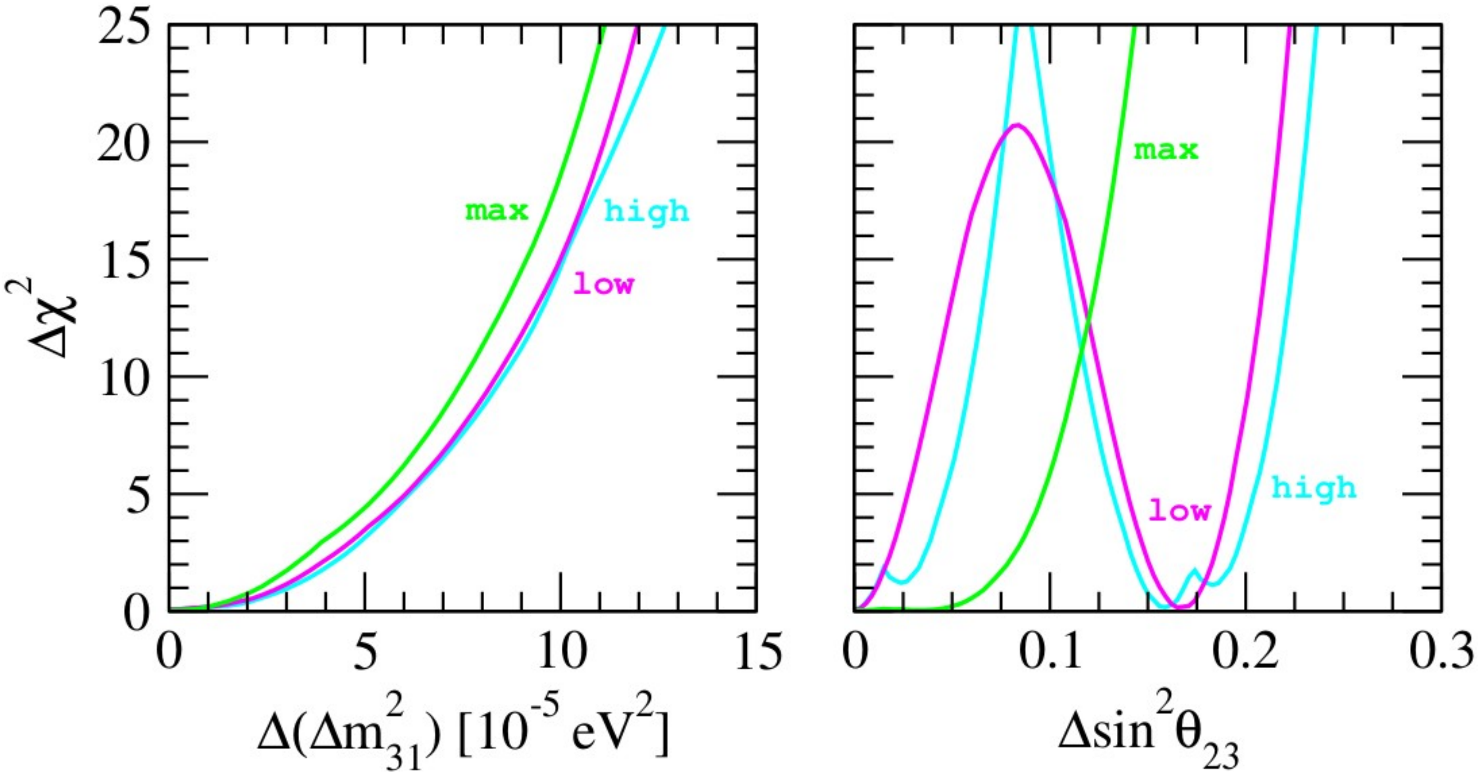
Barenboim, Ternes, Tórtola, 1712.01714, PLB 2018



Valencia - 2017 Global Fit, 1708.01186, PLB 2018

parameter	value
Δm^2_{21}	$7.56 \times 10^{-5}\text{eV}^2$
Δm^2_{31}	$2.55 \times 10^{-3}\text{eV}^2$
$\sin^2\theta_{12}$	0.321
$\sin^2\theta_{23}$	0.43, 0.50, 0.60
$\sin^2\theta_{13}$	0.02155
δ	1.50π

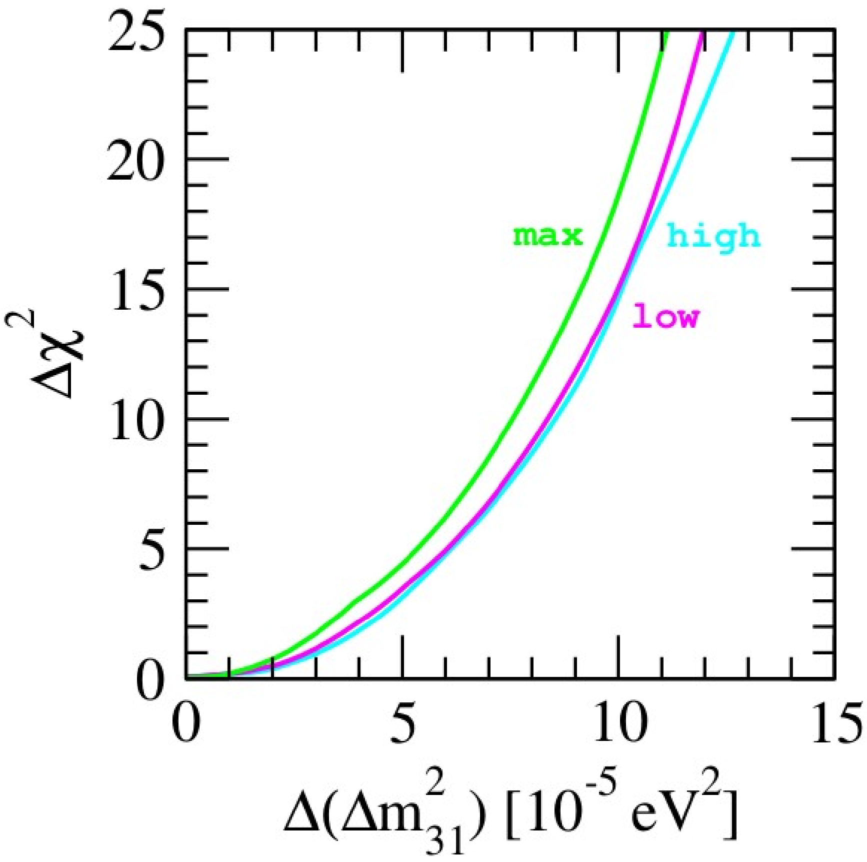
Future perspectives at DUNE



Good improvement for the atmospheric mass splitting and mixing angle

Barenboim, Ternes, Tórtola, 1712.01714, PLB 2018

Future perspectives at DUNE

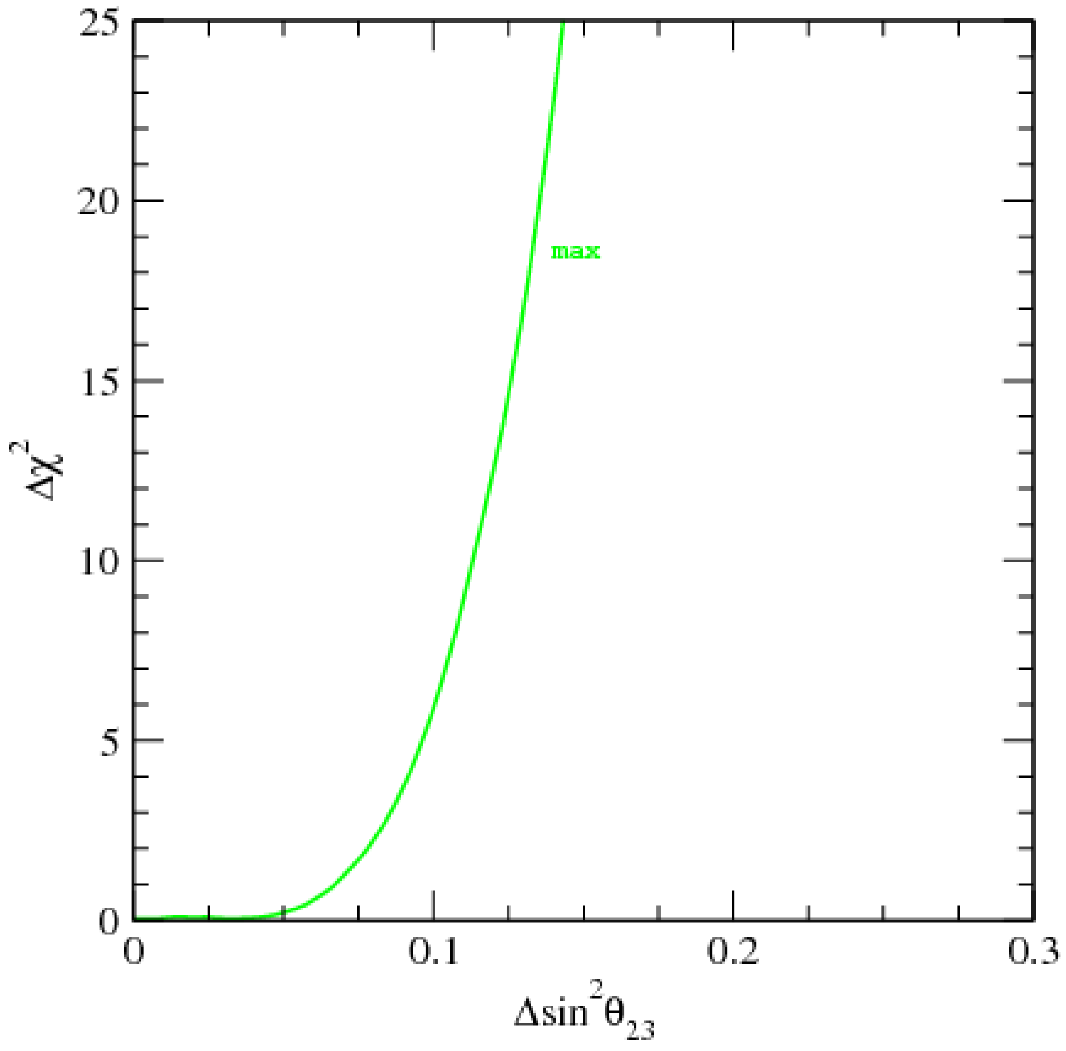


We could obtain

$$\Delta(\Delta m^2_{31}) < 8.1 \times 10^{-5} \mathrm{eV}^2$$

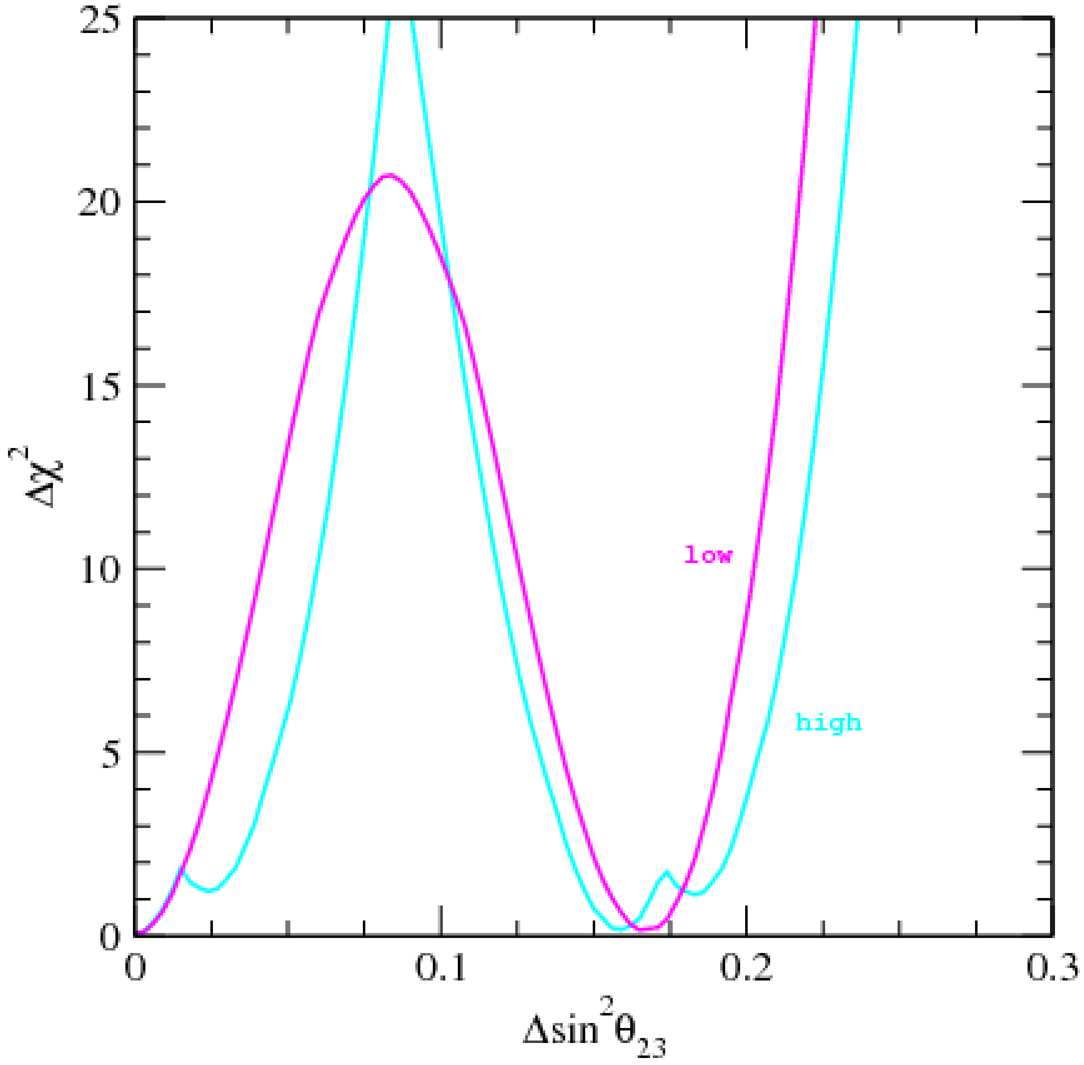
at 3σ C.L.

Future perspectives at DUNE



For the atmospheric angle we obtain increasing sensitivity for maximal mixing

Future perspectives at DUNE



For the atmospheric angle we obtain increasing sensitivity for maximal mixing

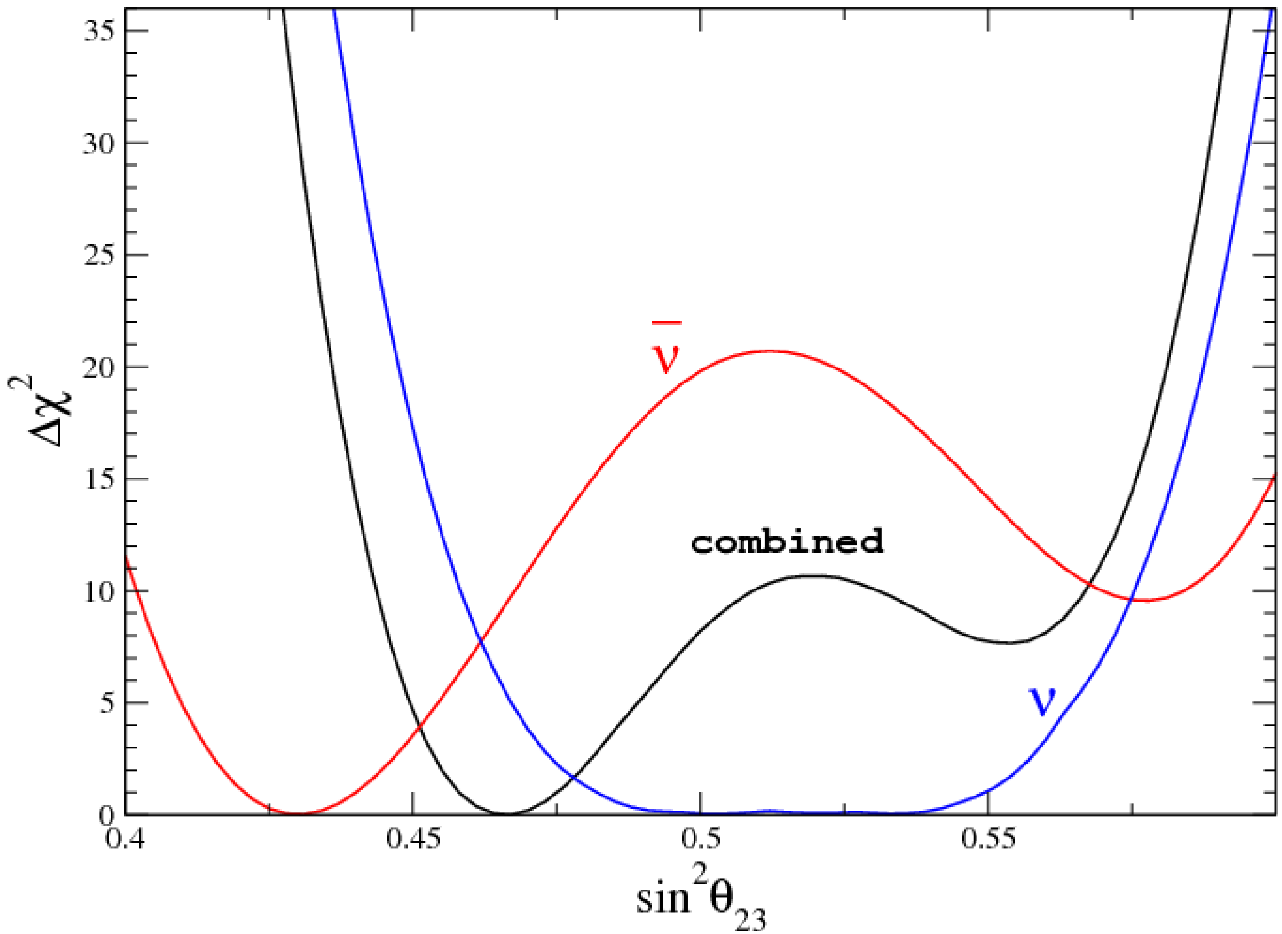
For the other values instead it increases and then decreases again

This is due to degenerate solutions

Obtaining impostor solutions

Obtaining impostor solutions

Assume $\sin^2\theta_{23} = 0.5,\ \sin^2\overline{\theta}_{23} = 0.43$



The combined best fit value is now

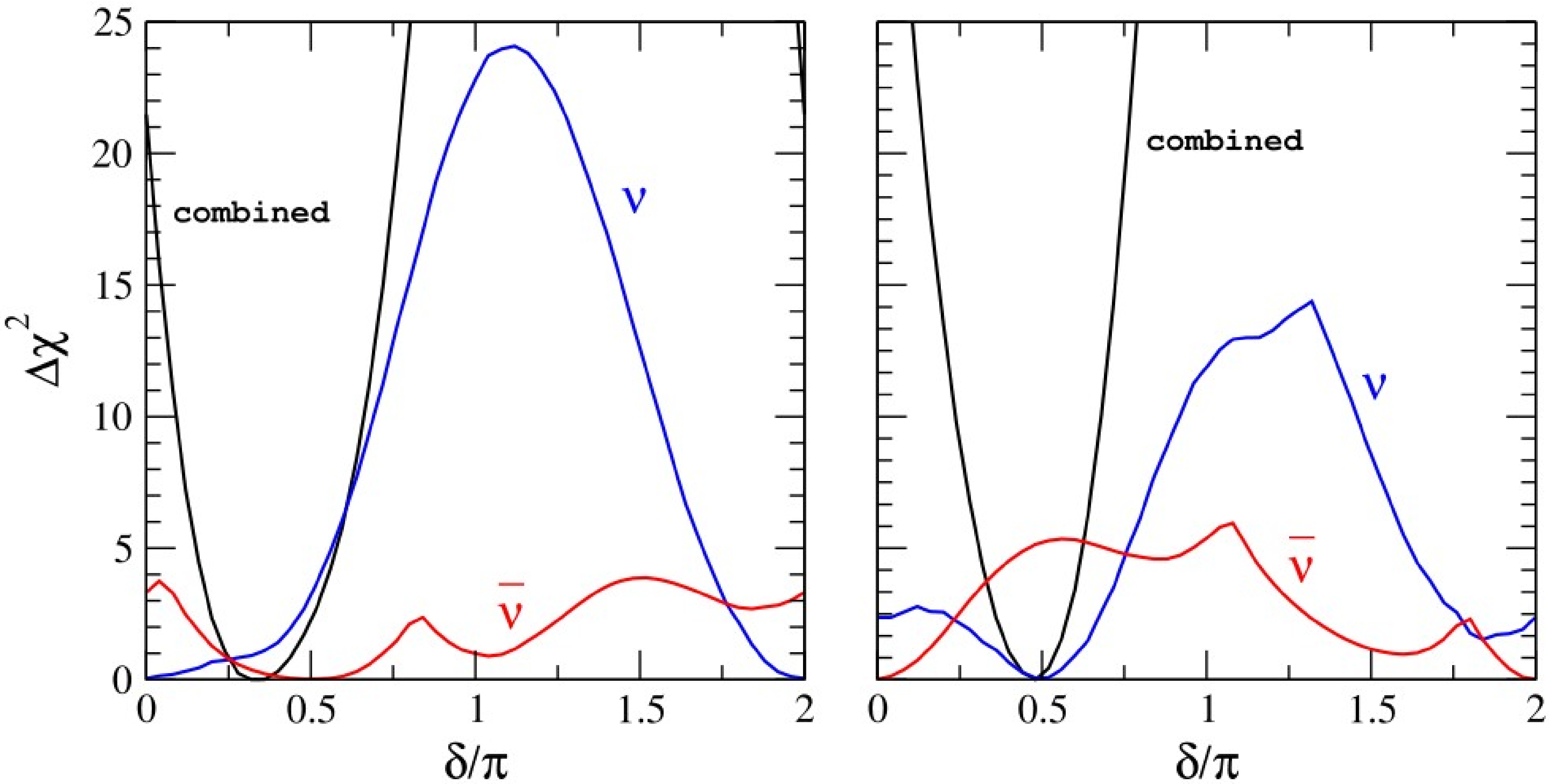
$$\sin^2\theta_{23}^{\text{comb}} = 0.467$$

The real true values are disfavored at close to 3σ and more than 5σ confidence levels

Barenboim, Ternes, Tórtola, 1712.01714, PLB 2018

Obtaining impostor solutions

This can also happen for other parameters

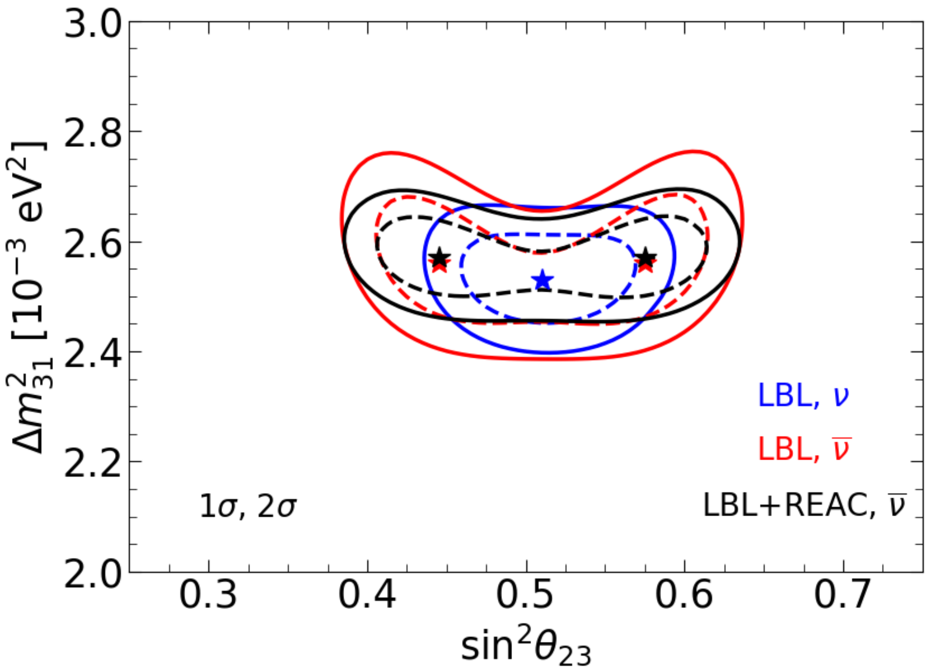


Barenboim, Ternes, Tórtola, 1712.01714, PLB 2018

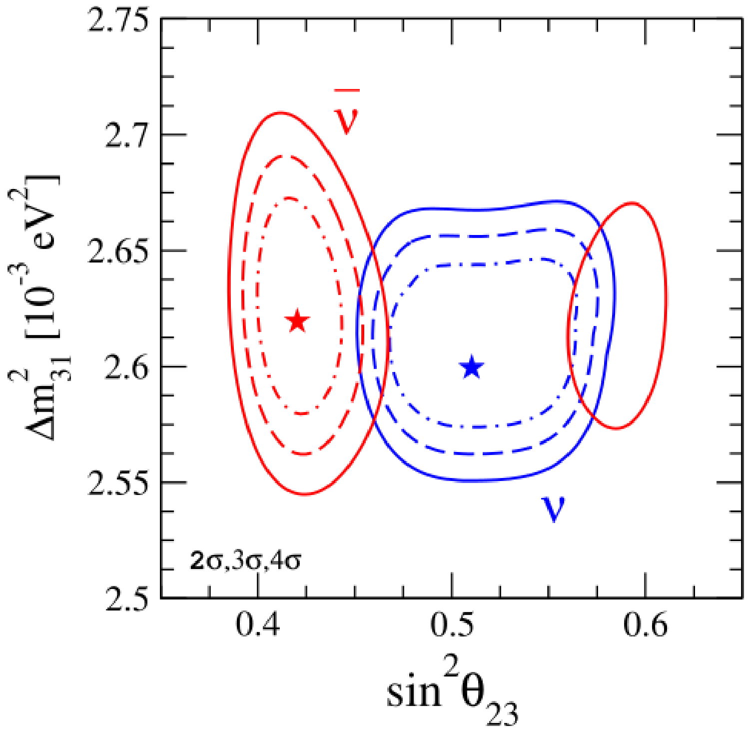
Observing CPT violation

Observing CPT violation

What if the values obtained in T2K and NOvA turn out to be true?

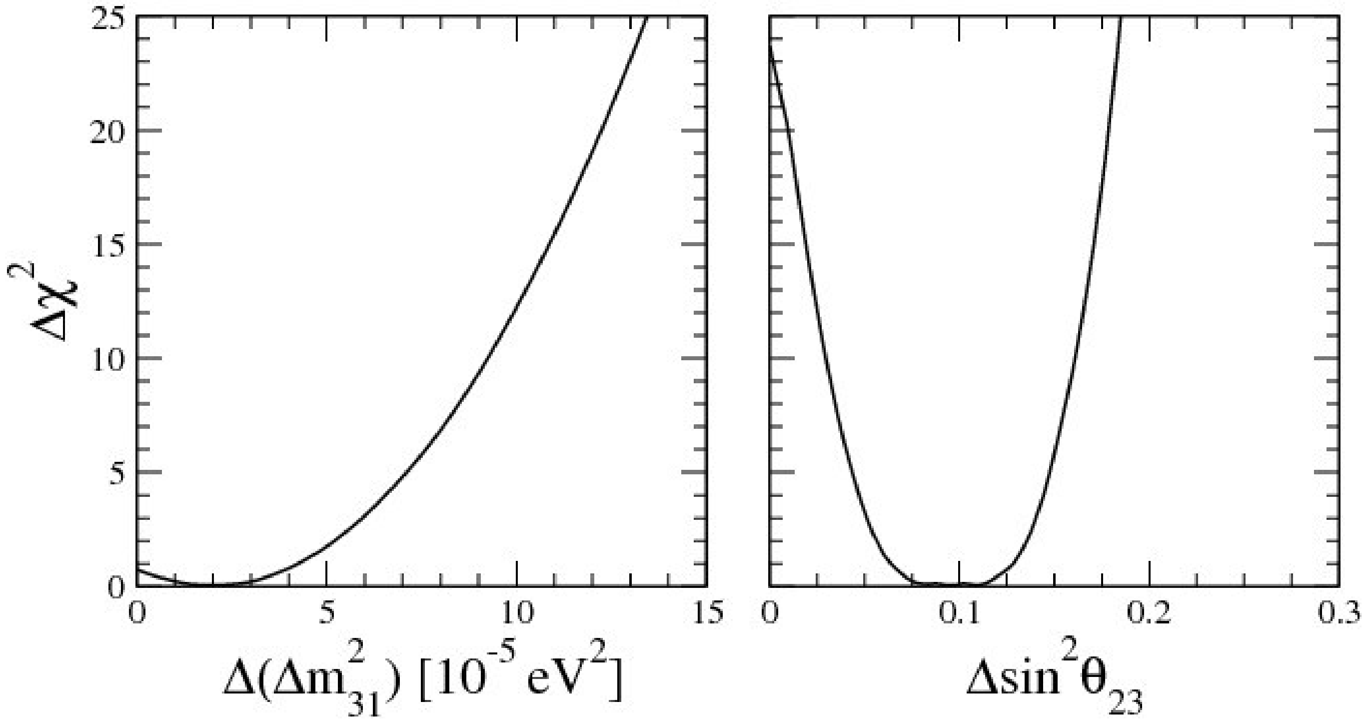


Barenboim, Ternes, Tórtola,
2005.05975, JHEP 2020



Barenboim, Ternes, Tórtola
1712.01714, PLB 2018

Observing CPT violation



If the different different best fit values obtained for neutrino and antineutrino oscillations turned out to be true, DUNE could observe CPT violation at very high significance

Barenboim, Ternes, Tórtola, 1712.01714, PLB 2018

Observing CPT violation

CPT violation effects can be mimicked by nonstandard interactions

$$\mathcal{H}_F = \frac{1}{2E}\left\{U\begin{pmatrix}0 & 0\\ 0 & \Delta m^2\end{pmatrix}U^\dagger + A_{CC}\begin{pmatrix}\epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau}\\ \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau}\end{pmatrix}\right\}$$

Oscillation probability

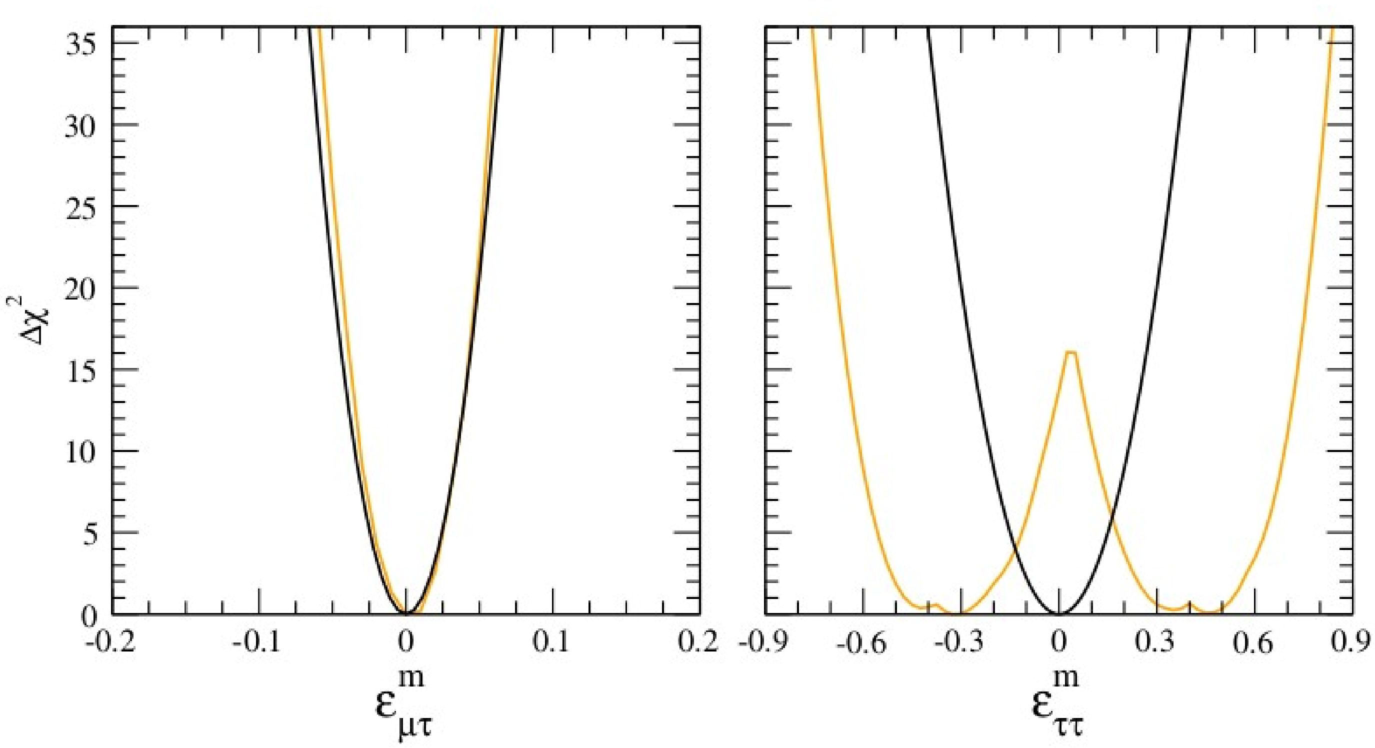
$$P_{\mu\mu} = 1 - \sin^2 2\tilde{\theta}\sin^2\left(\frac{\Delta\tilde{m}^2}{4E}\right)$$

Matter parameters given by

$$\Delta m^2_\nu \cos 2\theta_\nu = \Delta m^2 \cos 2\theta + \epsilon^m_{\tau\tau} A$$
$$\Delta m^2_\nu \sin 2\theta_\nu = \Delta m^2 \sin 2\theta + 2\epsilon^m_{\mu\tau} A$$

$$\Delta m^2_{\overline{\nu}} \cos 2\theta_{\overline{\nu}} = \Delta m^2 \cos 2\theta - \epsilon^m_{\tau\tau} A$$
$$\Delta m^2_{\overline{\nu}} \sin 2\theta_{\overline{\nu}} = \Delta m^2 \sin 2\theta - 2\epsilon^m_{\mu\tau} A$$

Observing CPT violation



Need to be careful to disentangle CPT violation and neutrino non standard interactions, since they can mimic CPT effects

Barenboim, Ternes, Tórtola, 1804.05842, EPJC 2019

Conclusions, part 2

Determination of neutrino oscillation parameters worsens when CPT is not conserved

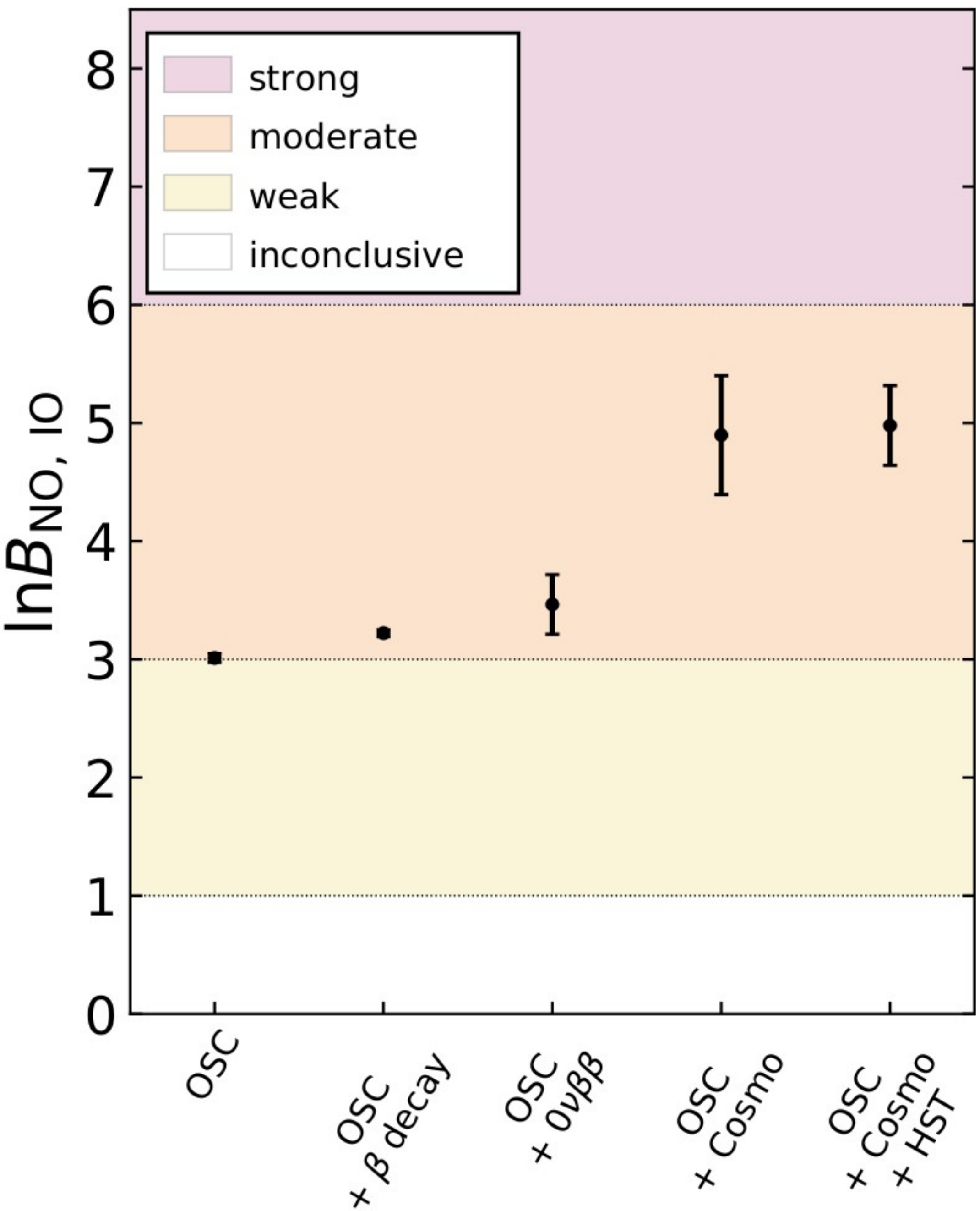
DUNE will improve the current bounds on CPT violation in the neutrino sector

Impostor solutions can arise in the determination of oscillation parameters when combining channels

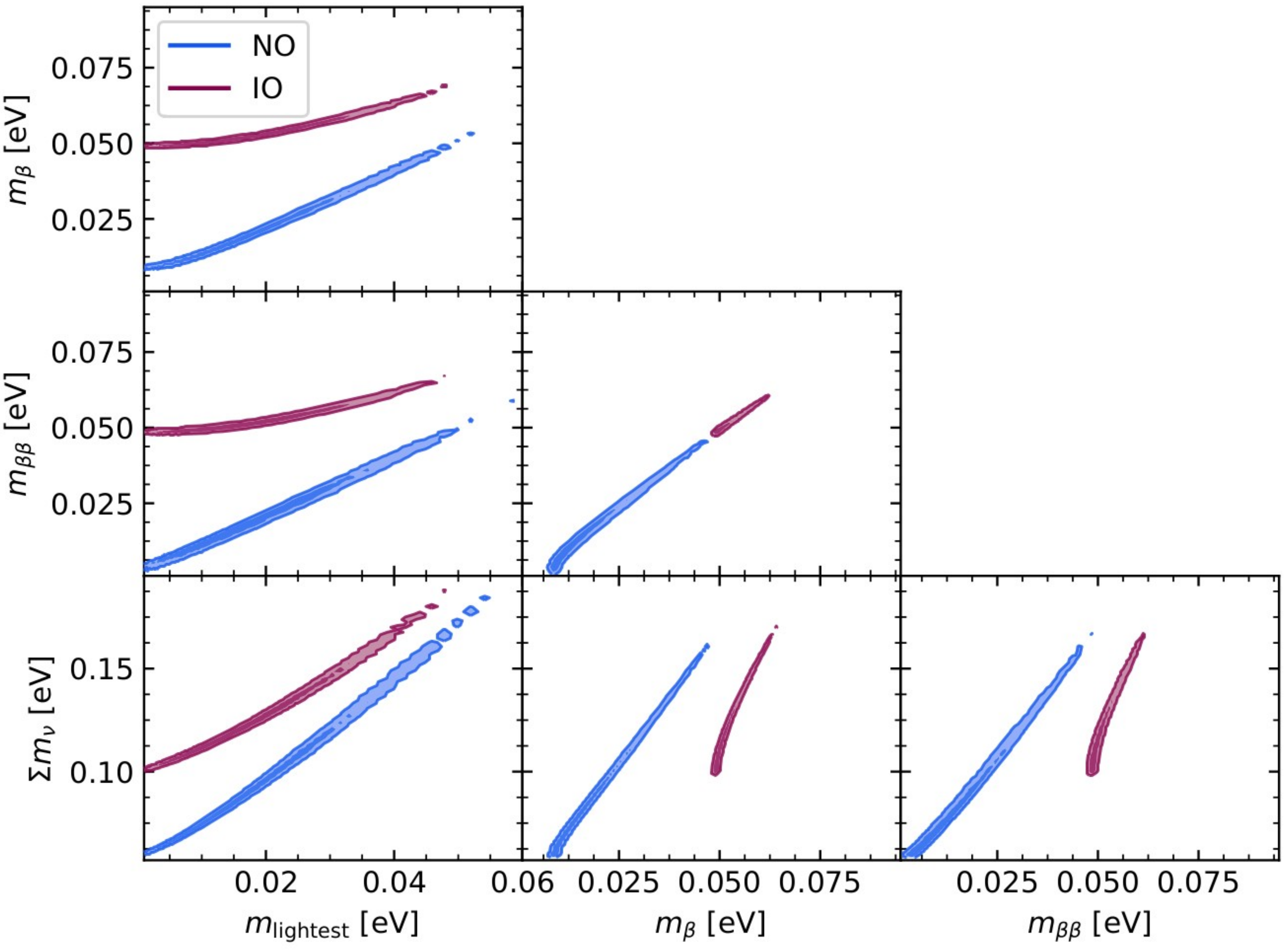
DUNE might distinguish CPT violation from NSI


Thanks!
electron-neutrino
muon neutrino
tau-neutrino

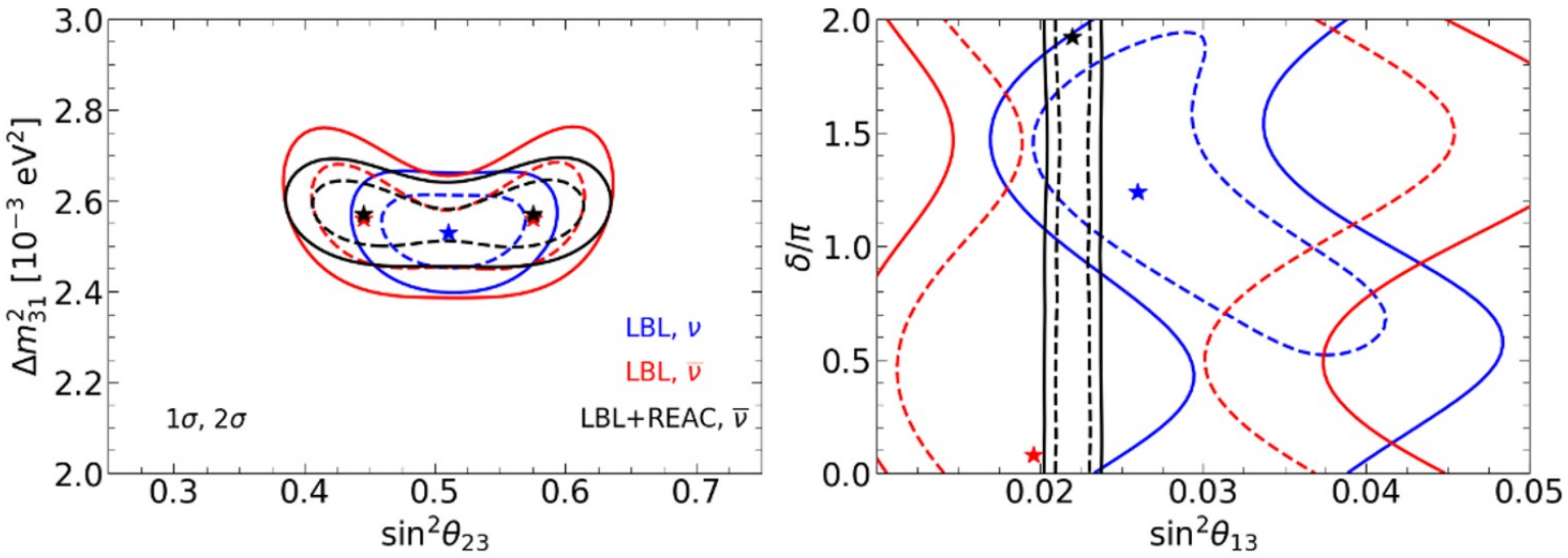
Oscillation + Cosmology



Oscillation + Cosmology

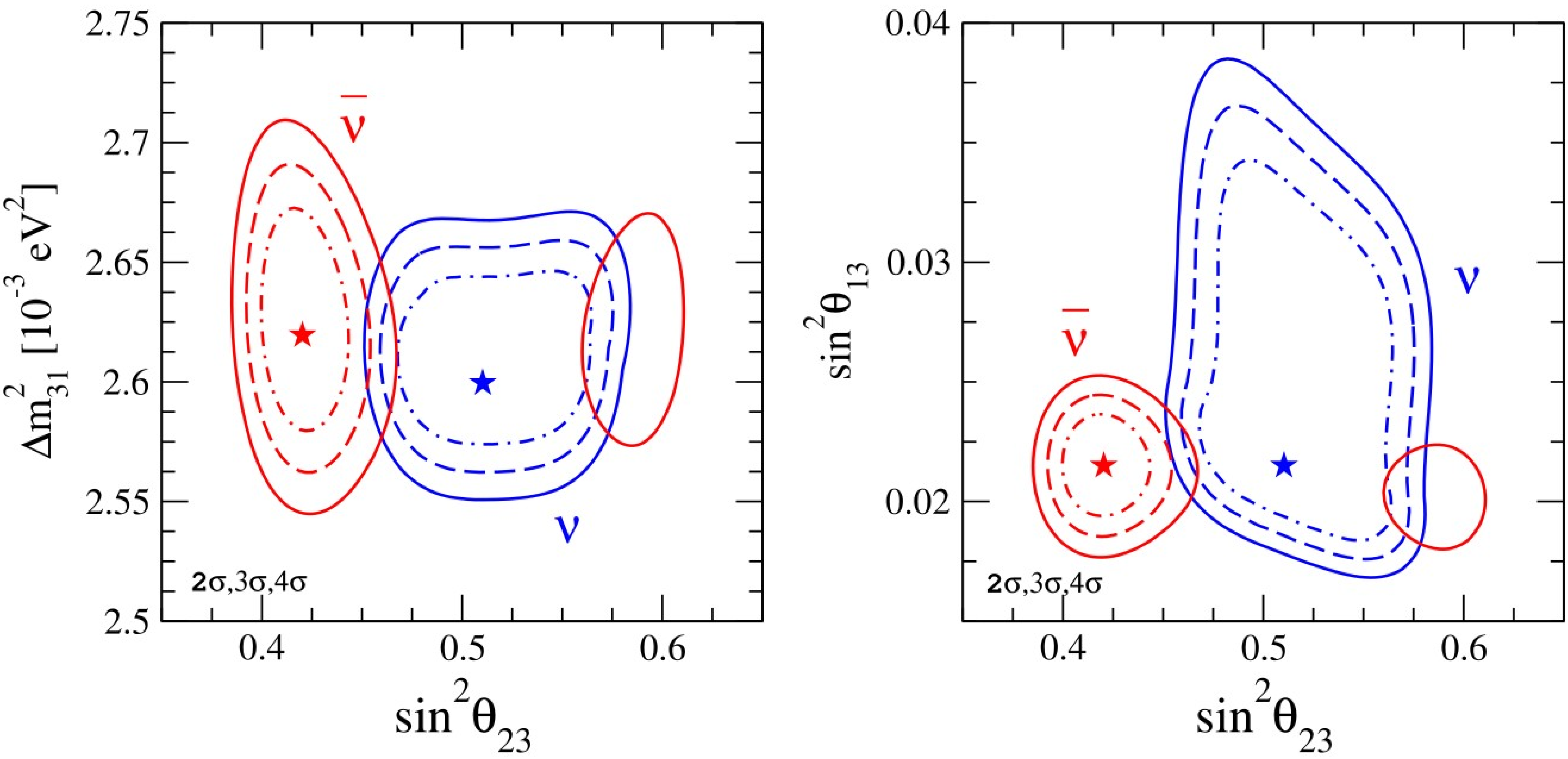


CPT current



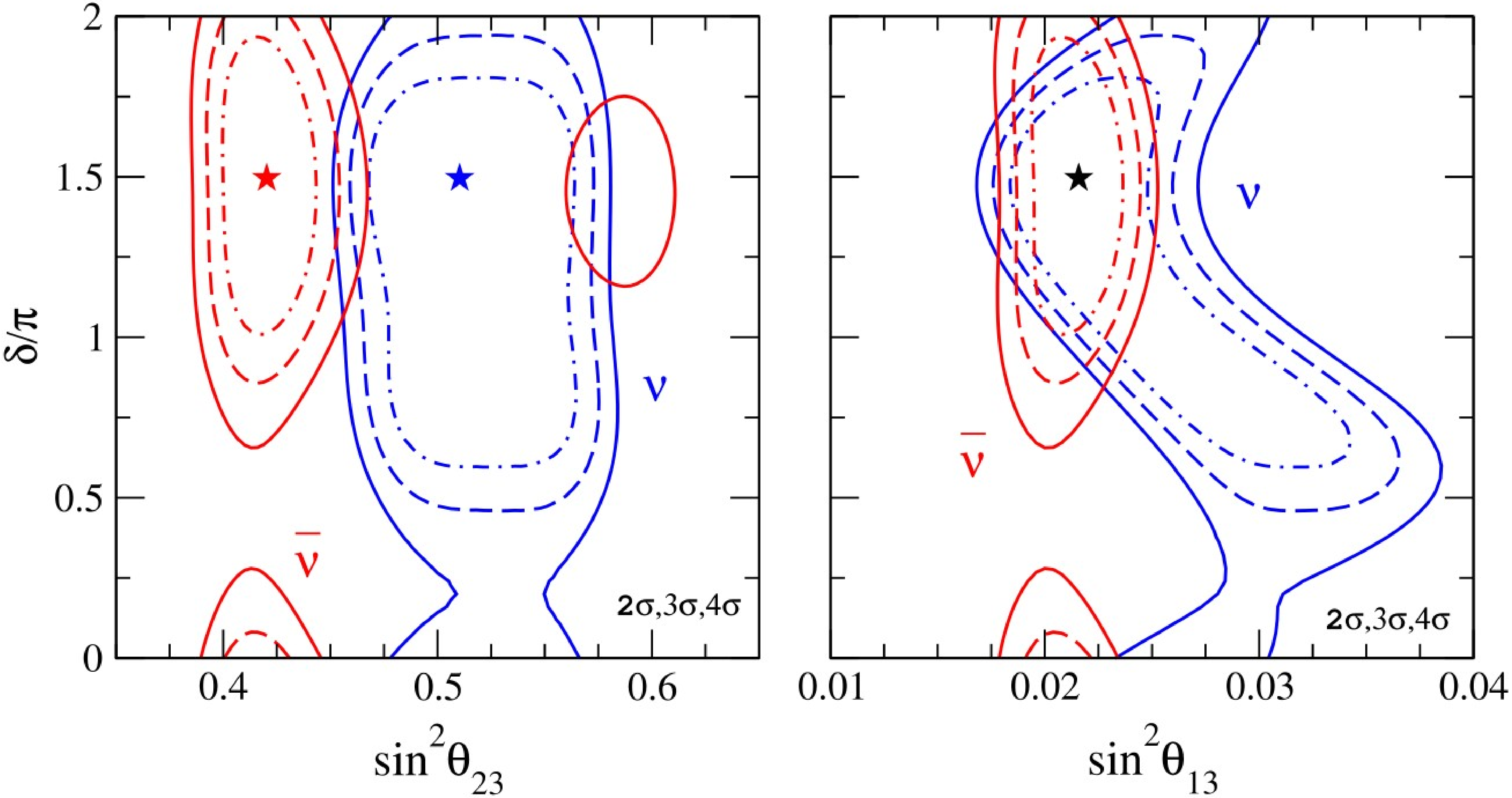
3.0
2.8
2.6
2.4
2.2
2.0
Δm^2_{31} [10^{-3} eV^2]
0.3
0.4
0.5
0.6
0.7
$\sin^2\theta_{23}$
LBL, ν
LBL, $\overline{\nu}$
1σ, 2σ
LBL+REAC, $\overline{\nu}$
2.0
1.5
1.0
0.5
0.0
δ/π
0.02
0.03
0.04
0.05
$\sin^2\theta_{13}$

CPT future



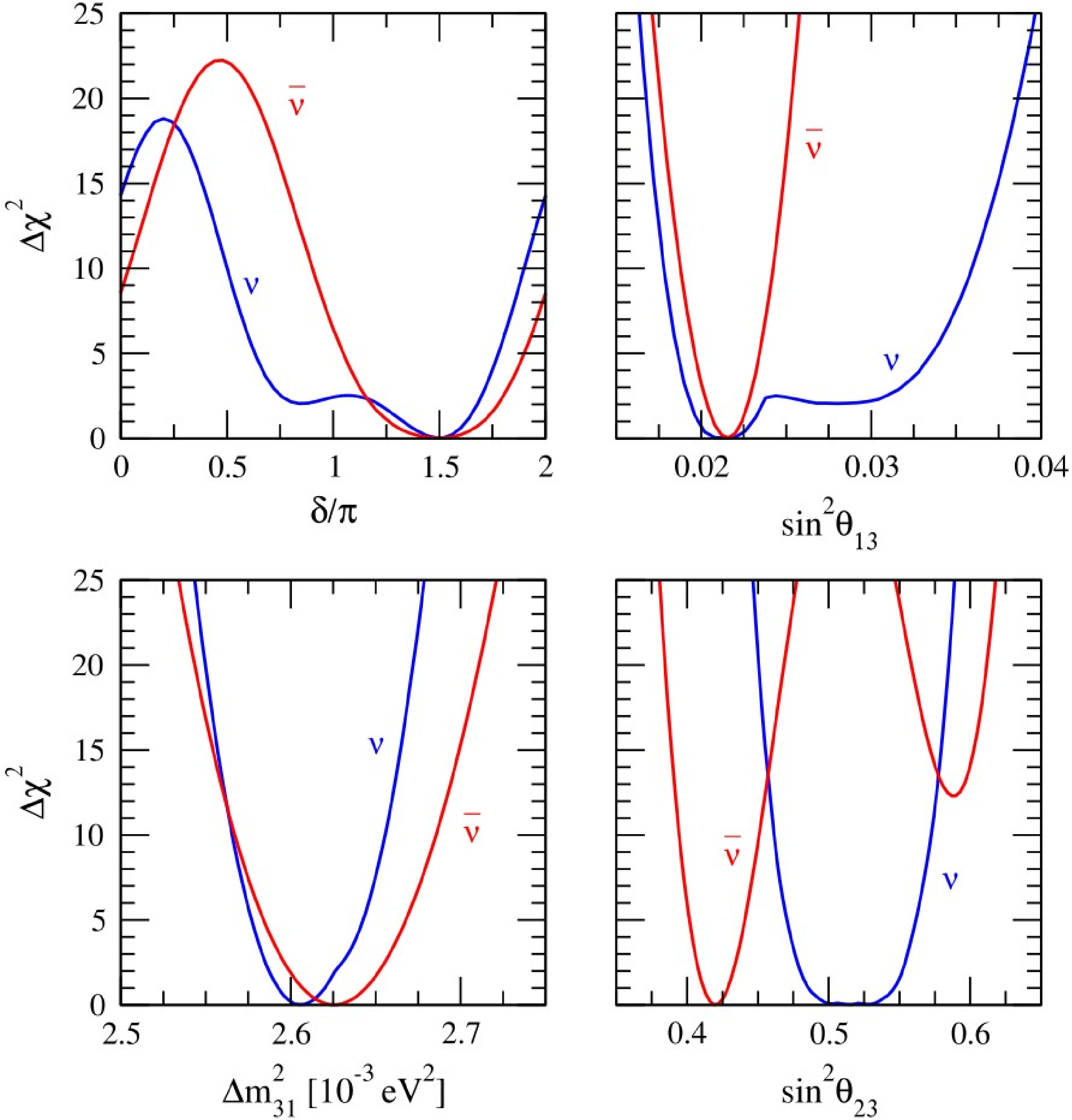
2.75
2.7
2.65
2.6
2.55
2.5
Δm^2_{31} [10^{-3} eV^2]
$\bar{\nu}$
ν
2σ,3σ,4σ
0.4
0.5
0.6
$\sin^2\theta_{23}$
0.04
0.03
0.02
$\sin^2\theta_{13}$
$\bar{\nu}$
ν
2σ,3σ,4σ
0.4
0.5
0.6
$\sin^2\theta_{23}$

CPT future



2
1.5
1
0.5
0
δ/π
0.4
0.5
0.6
$\sin^2\theta_{23}$
ν
$\bar{\nu}$
2σ,3σ,4σ
0.01
0.02
0.03
0.04
$\sin^2\theta_{13}$
ν
$\bar{\nu}$
2σ,3σ,4σ

CPT future



25
20
15
10
5
0
Δχ²
0
0.5
1
1.5
2
δ/π
ν̄
ν
0.02
0.03
0.04
sin²θ13
2.5
2.6
2.7
Δm²31 [10⁻³ eV²]
0.4
0.5
0.6
sin²θ23

CPT-NSI