CPT violation and neutrino oscillation experiments

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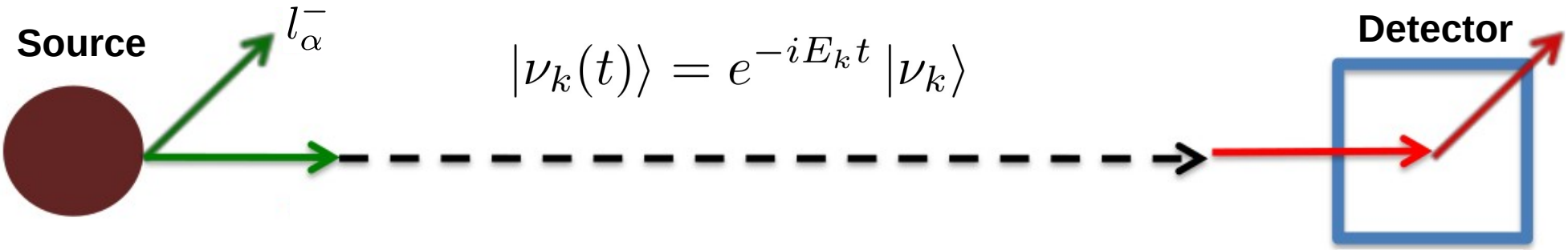
SEZIONE DI TORINO

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

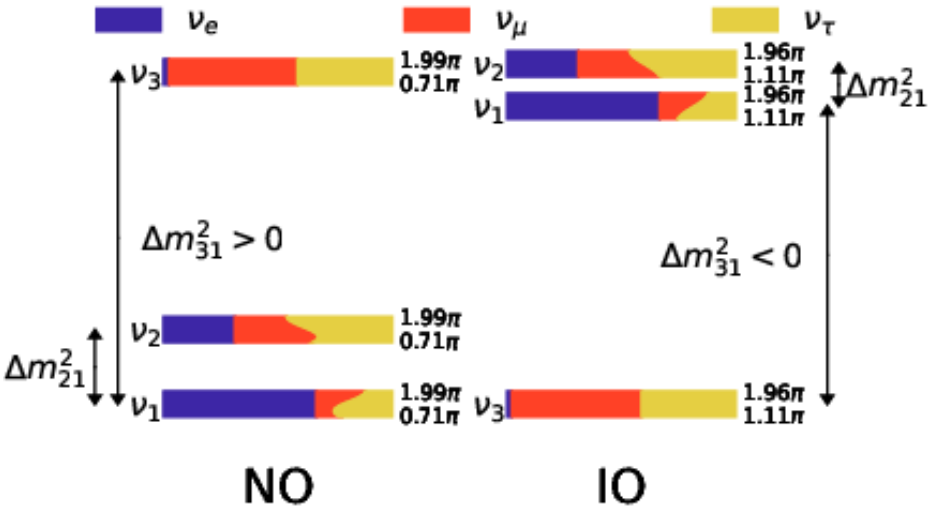
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

1 Dirac + 2 Majorana CP-phases

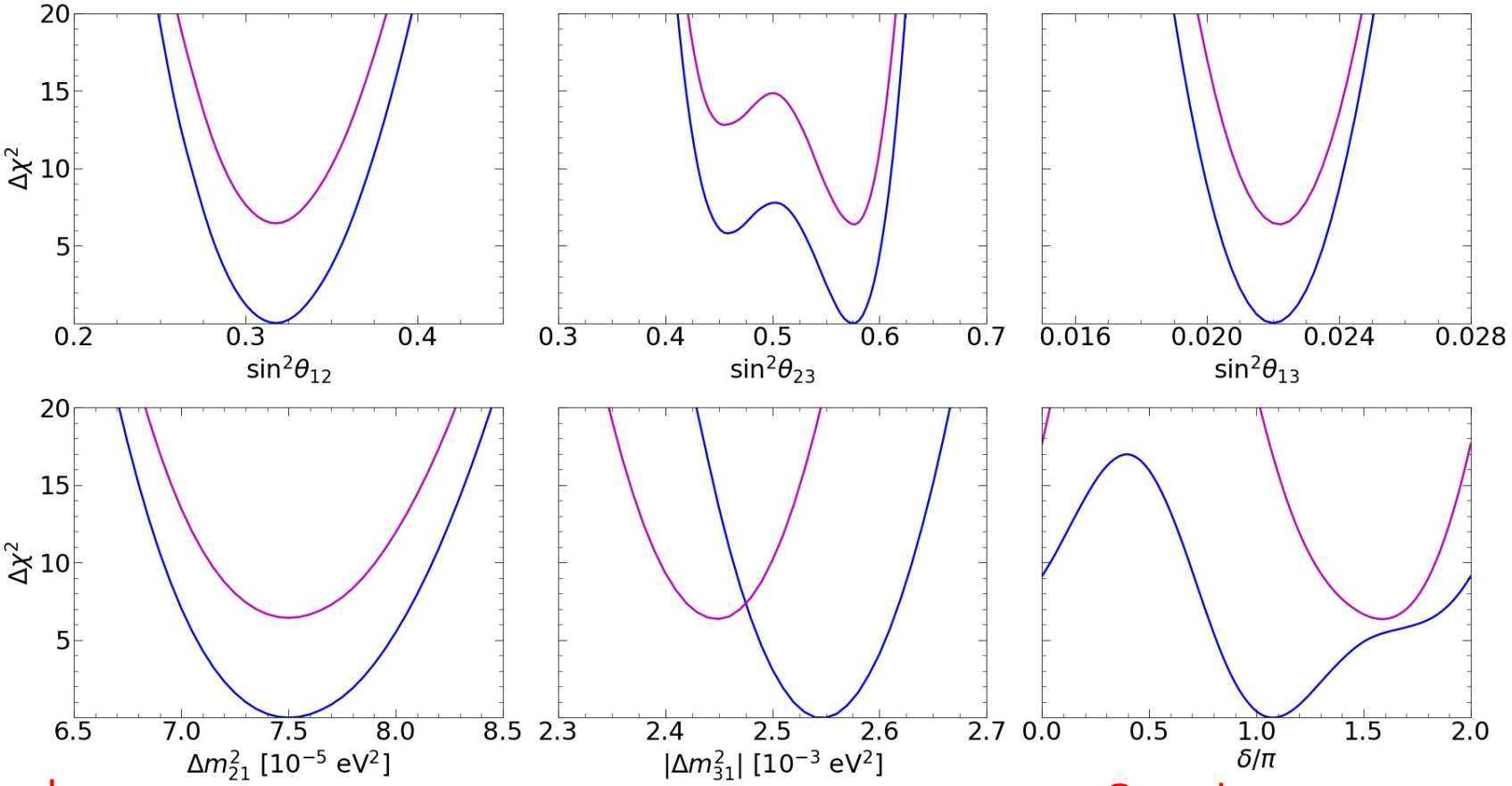
Three masses m_1, m_2, m_3 for which two orderings are possible

Oscillations are only sensitive to mass splittings



Three-neutrino oscillations

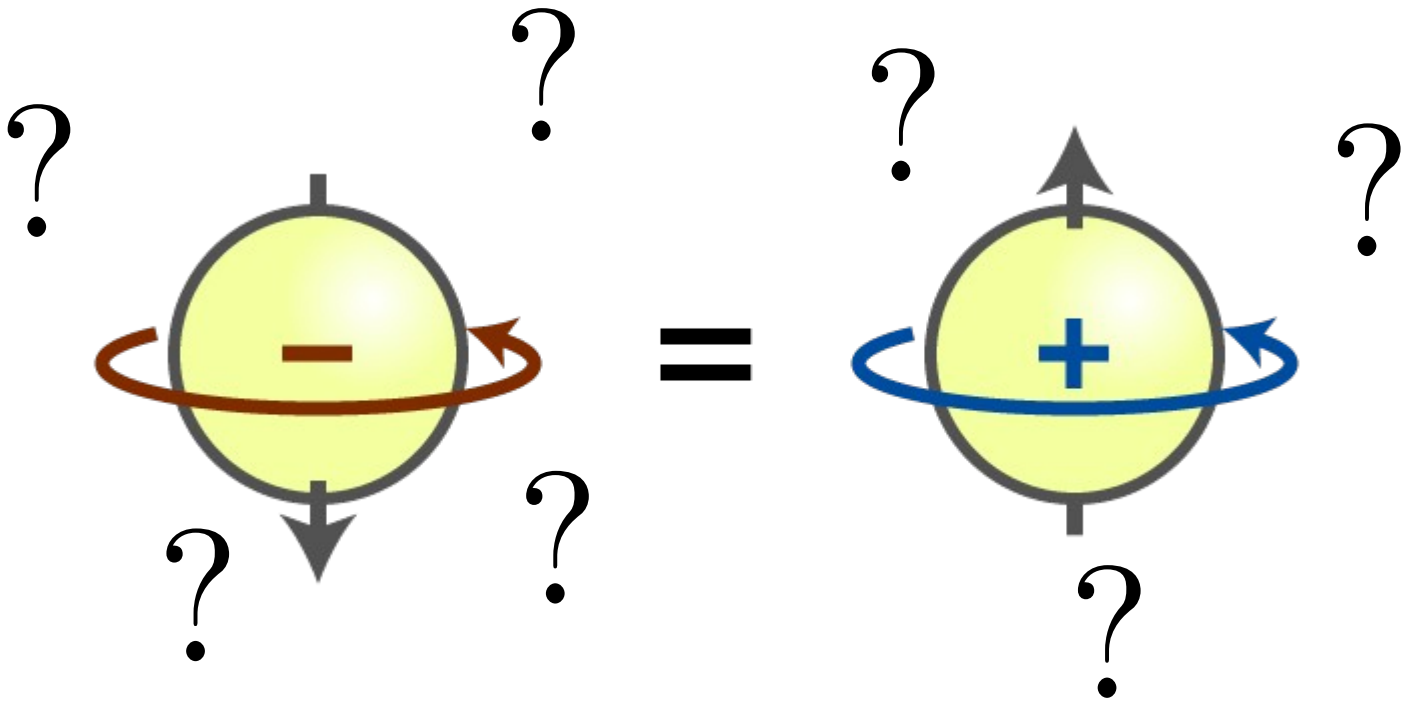
Valencia - Global Fit, 2006.11237, JHEP 2021
https://globalfit.astroparticles.es/



See also:
Bari – 2107.00532, PRD 2021

See also:
NuFit - 2111.03086

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

Assume that neutrinos oscillate with parameters

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

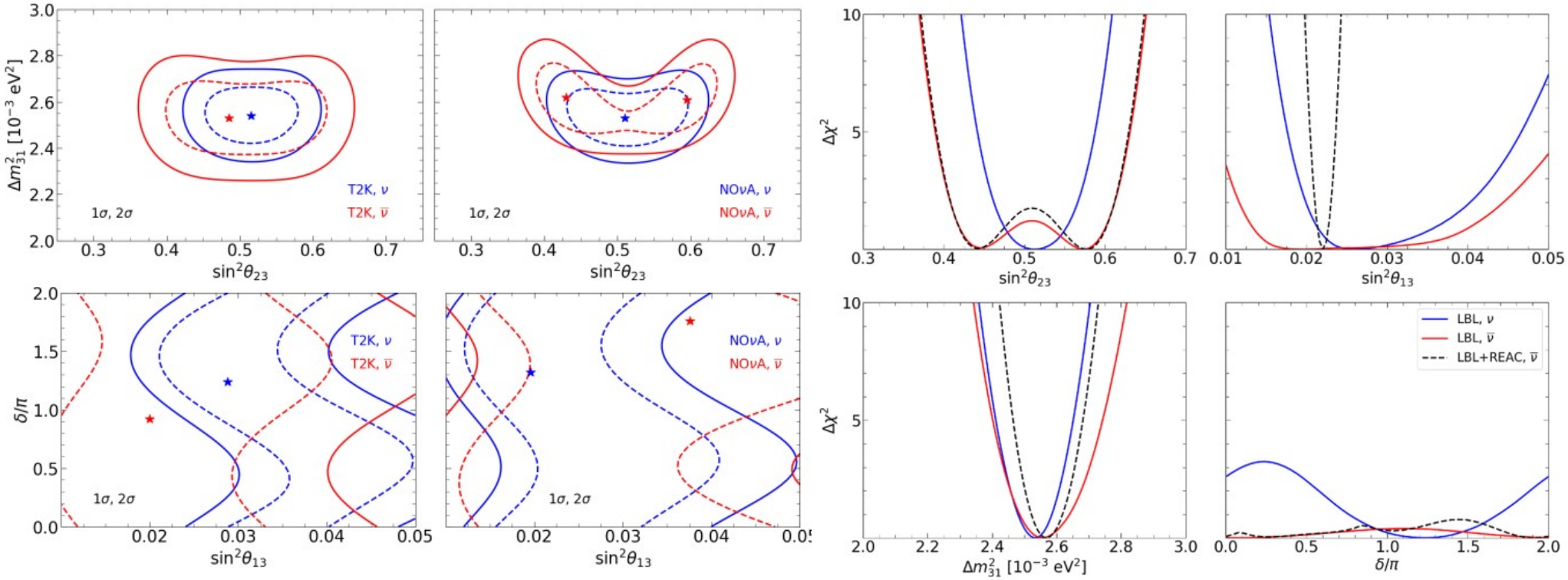
while the antineutrinos oscillate with a new set of parameters

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

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

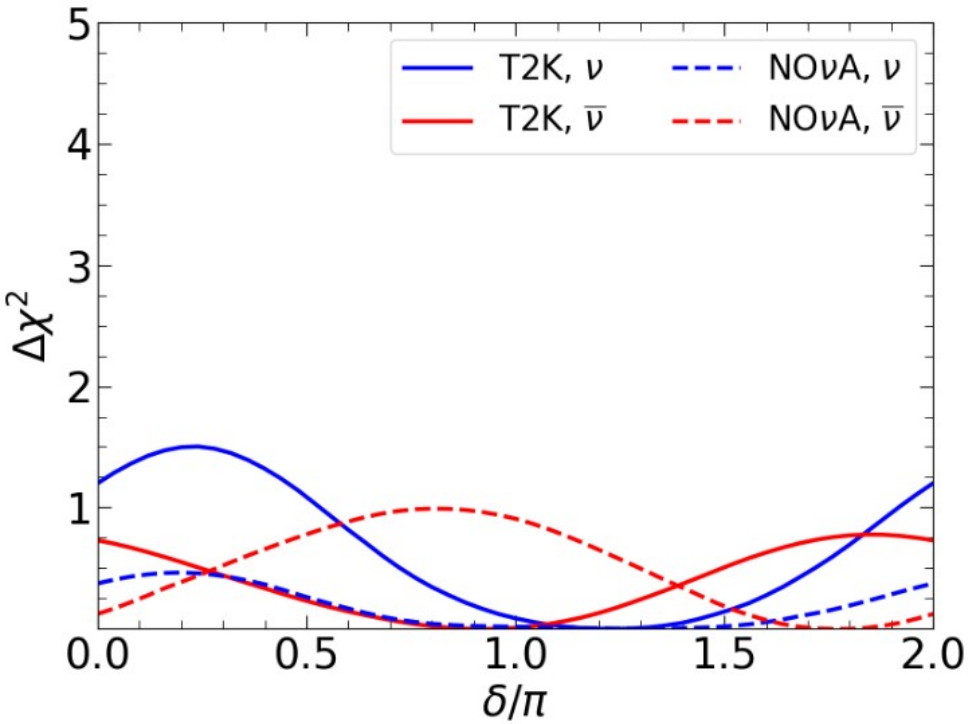
Current experiments

Current experiments



Barenboim, Ternes, Tórtola, 2005.05975, JHEP 2020

Current experiments

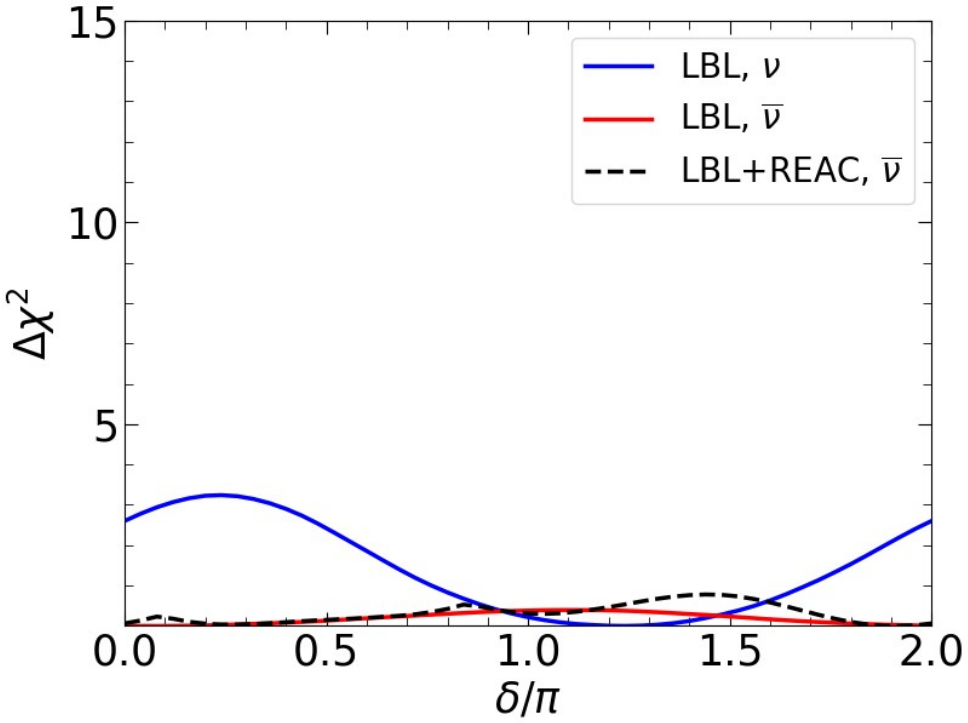


If CPT is not conserved a measurement of CP violation is currently not possible

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

Barenboim, Ternes, Tórtola, 2005.05975, JHEP 2020

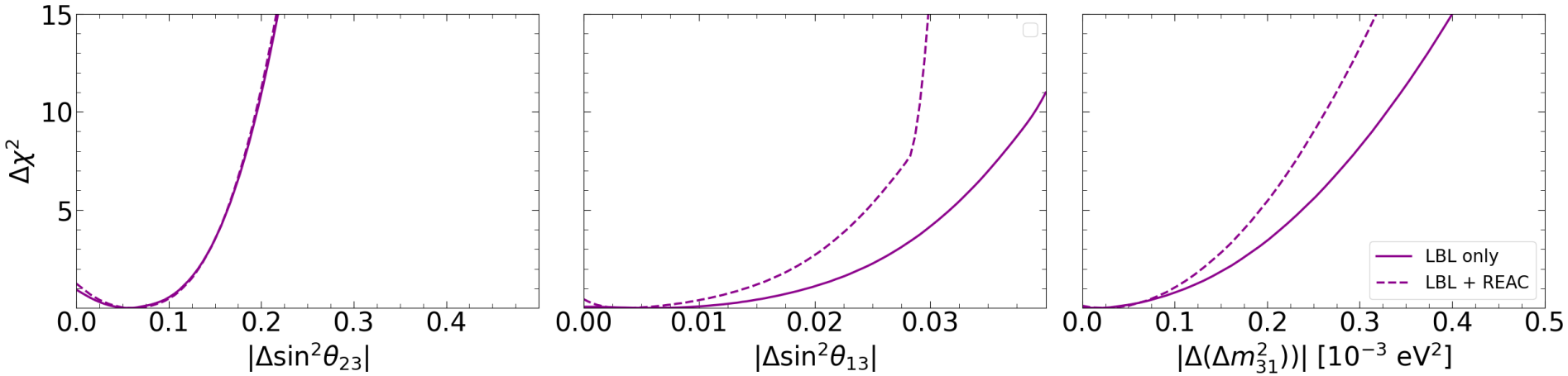
Current experiments



Combining accelerator and reactor data does not improve the situation

Barenboim, Ternes, Tórtola, 2005.05975, JHEP 2020

Current experiments

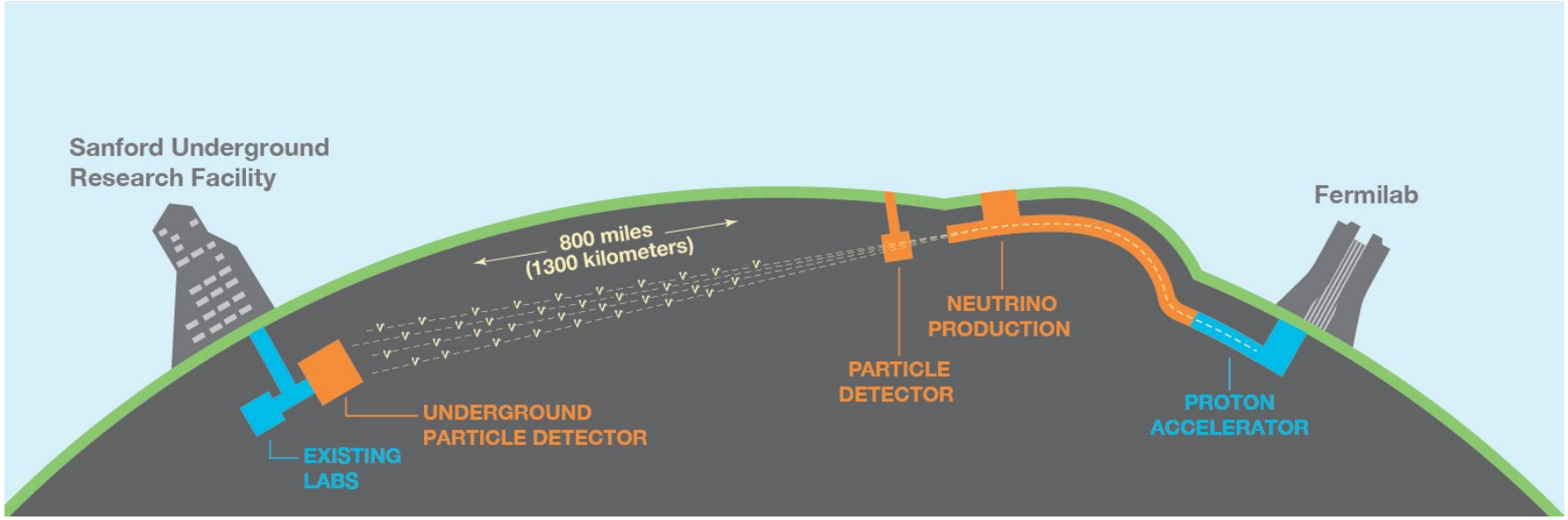


The same data allows us to bound CPT-violating neutrino oscillation parameters

$$
\begin{aligned}
|\Delta m^2_{21} - \Delta\overline{m}^2_{21}| &< 4.7 \times 10^{-5}\ \mathrm{eV}^2, \\
|\Delta m^2_{31} - \Delta\overline{m}^2_{31}| &< 2.5 \times 10^{-4}\ \mathrm{eV}^2, \\
|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| &< 0.14, \\
|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| &< 0.029, \\
|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| &< 0.19.
\end{aligned}
$$

Barenboim, Ternes, Tórtola, 2005.05975, JHEP 2020

Future perspectives at DUNE

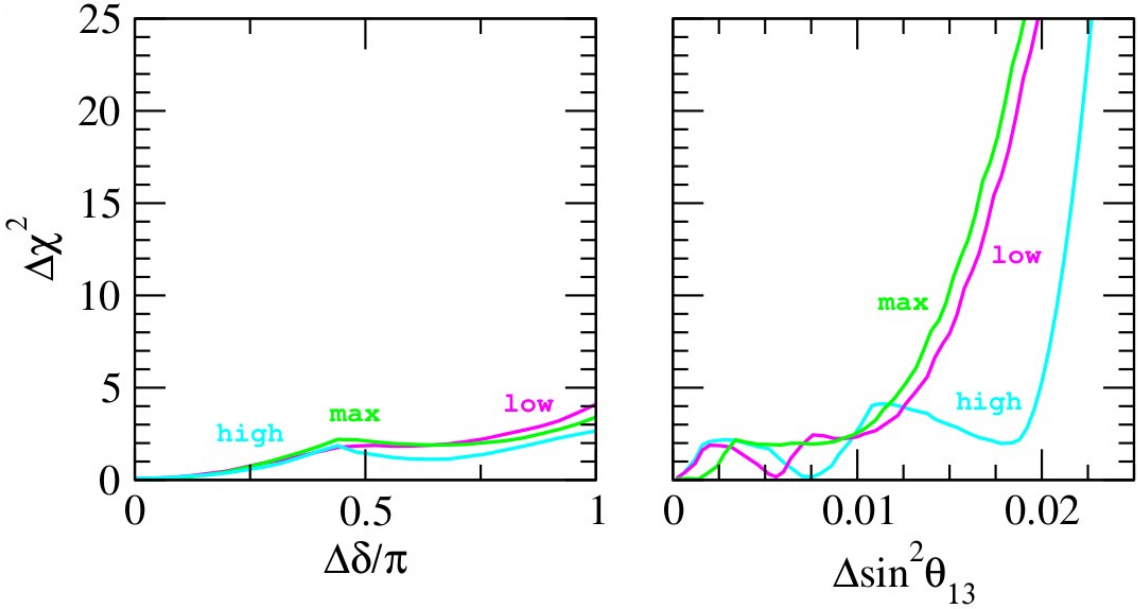


Future perspectives at DUNE

How will this improve with DUNE?

Poor sensitivity to CP phases and reactor angles

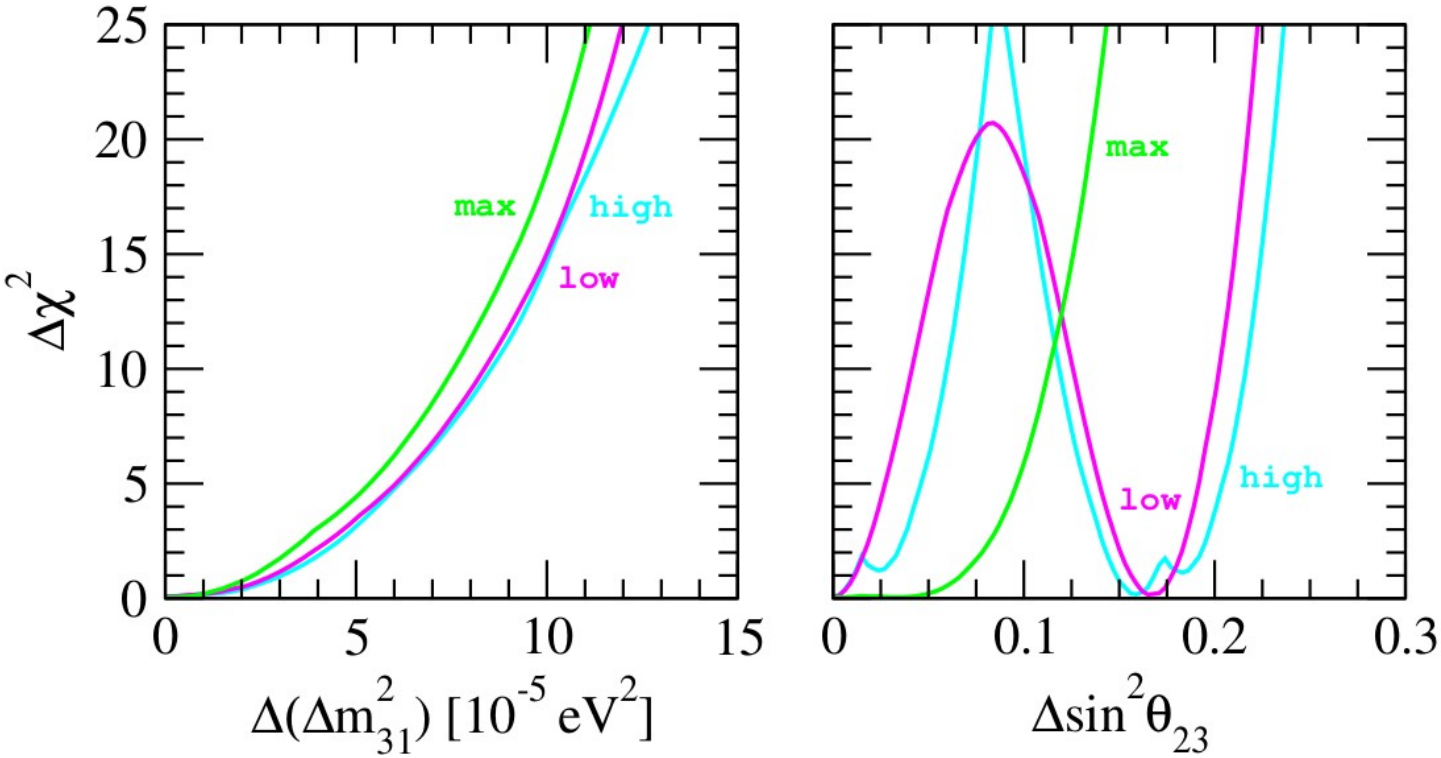
Barenboim, Ternes, Tórtola, 1712.01714, PLB 2018



Valencia - 2017 Global Fit, 1708.01186, PLB 2018

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

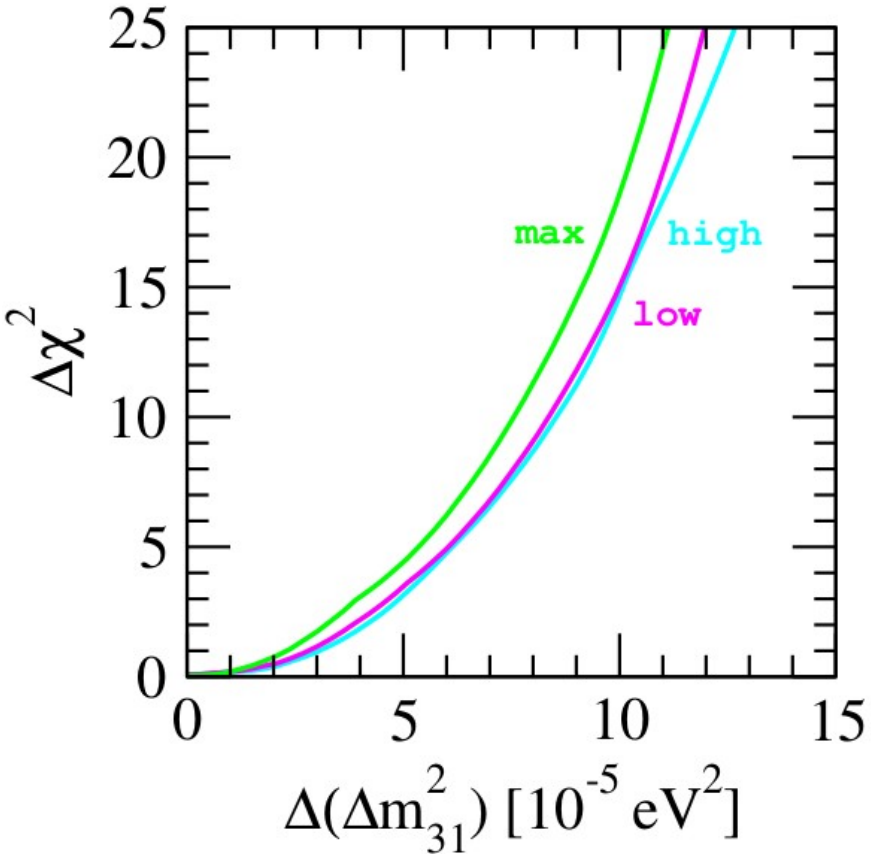
Future perspectives at DUNE



Good improvement for the atmospheric mass splitting and mixing angle

Barenboim, Ternes, Tórtola, 1712.01714, PLB 2018

Future perspectives at DUNE

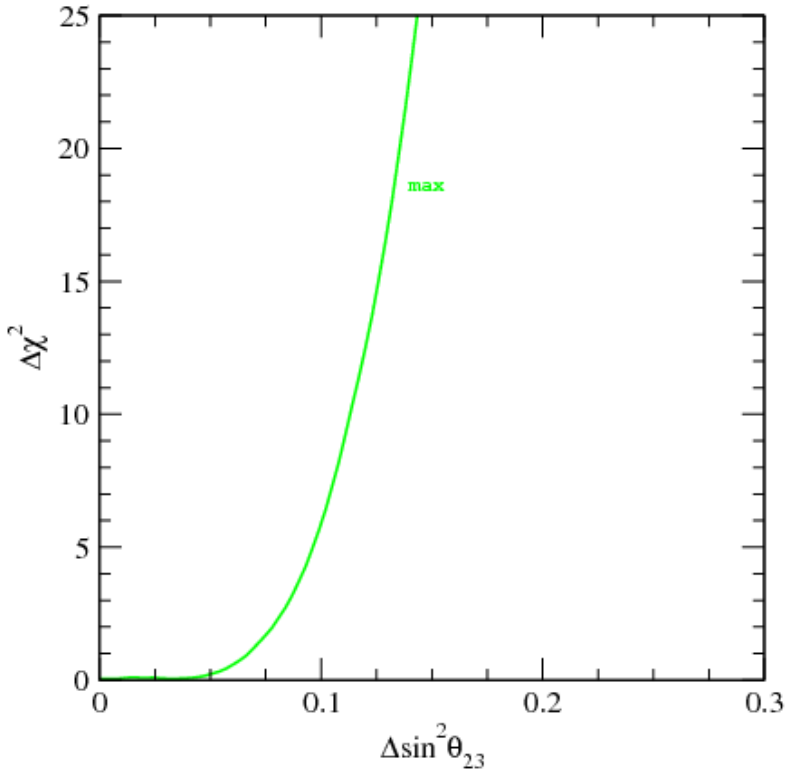


We could obtain

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

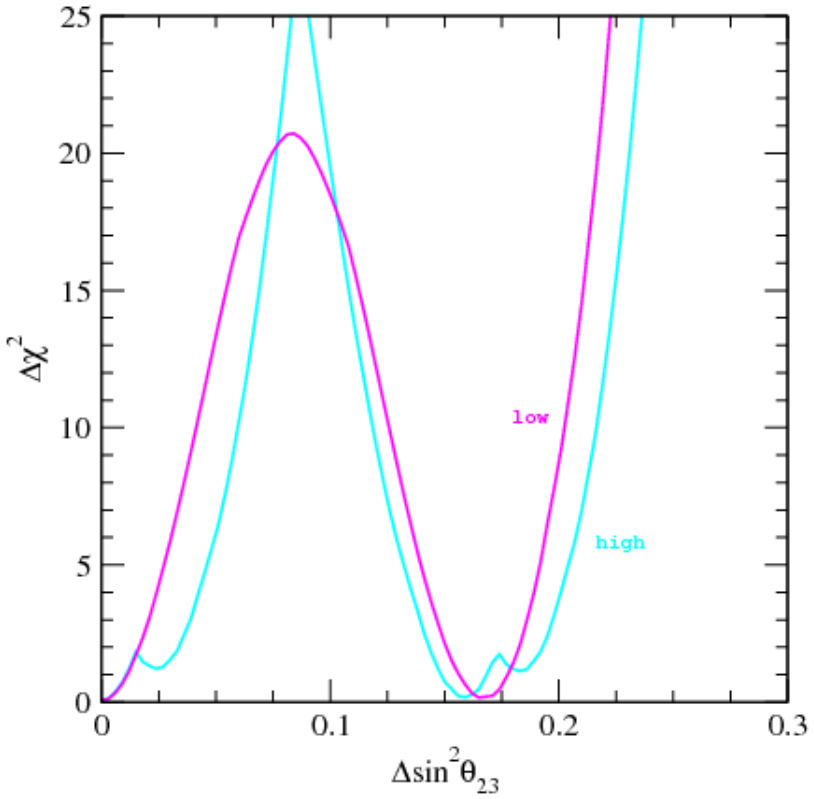
at 3σ C.L.

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

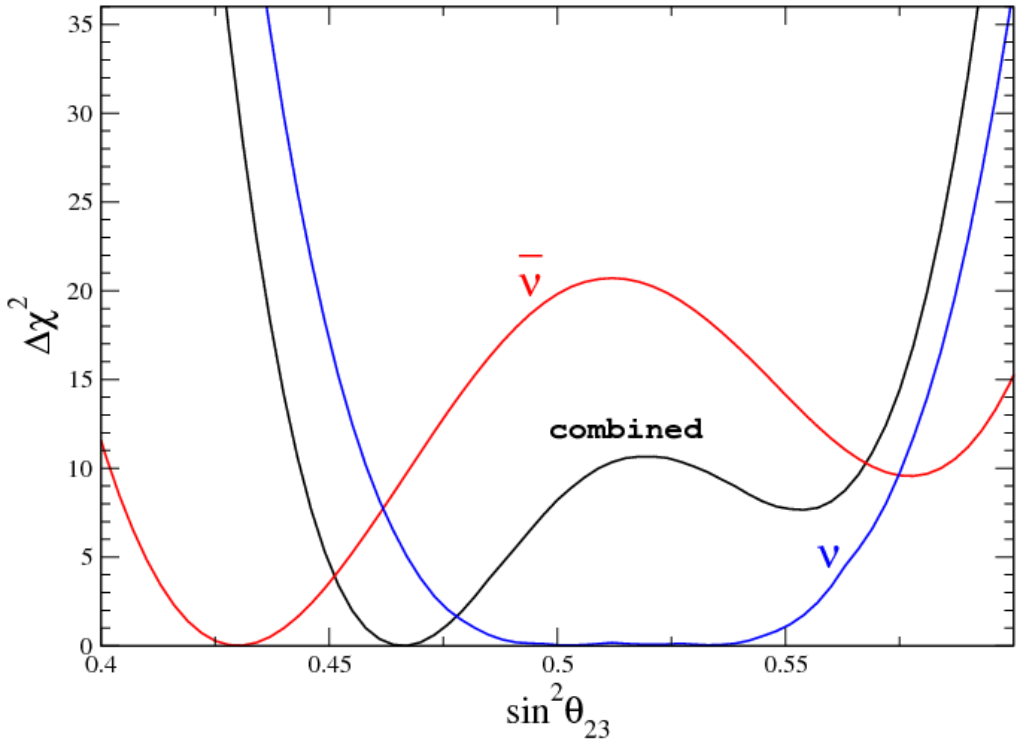
For the other values instead it increases and then decreases again

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

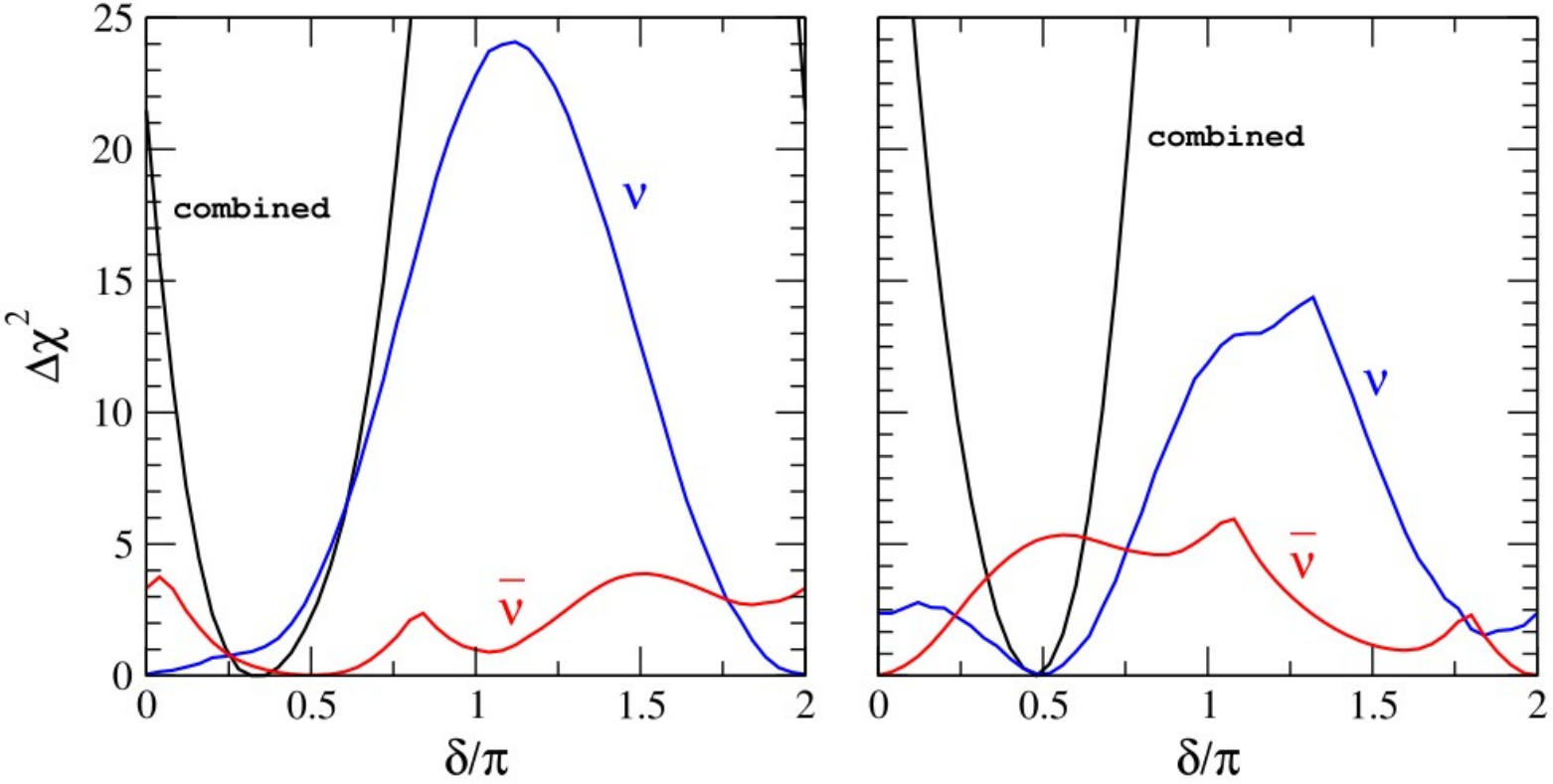
$$\sin^2\theta_{23}^{\rm comb} = 0.467$$

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

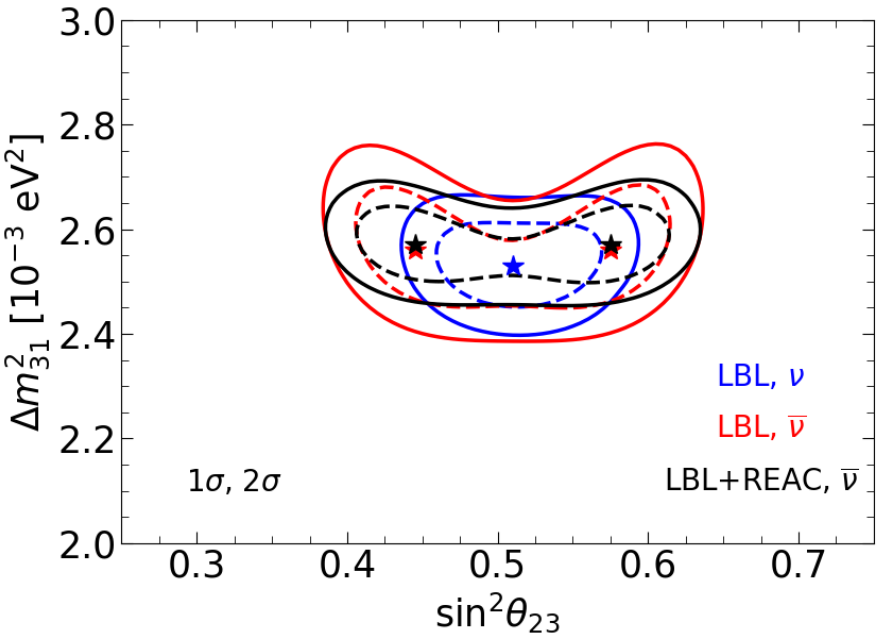


Barenboim, Ternes, Tórtola, 1712.01714, PLB 2018

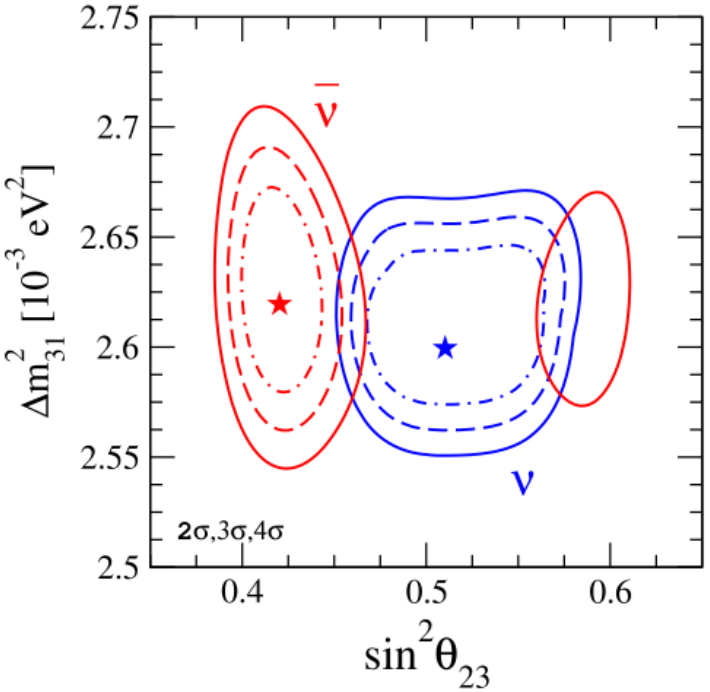
Observing CPT violation

Observing CPT violation

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

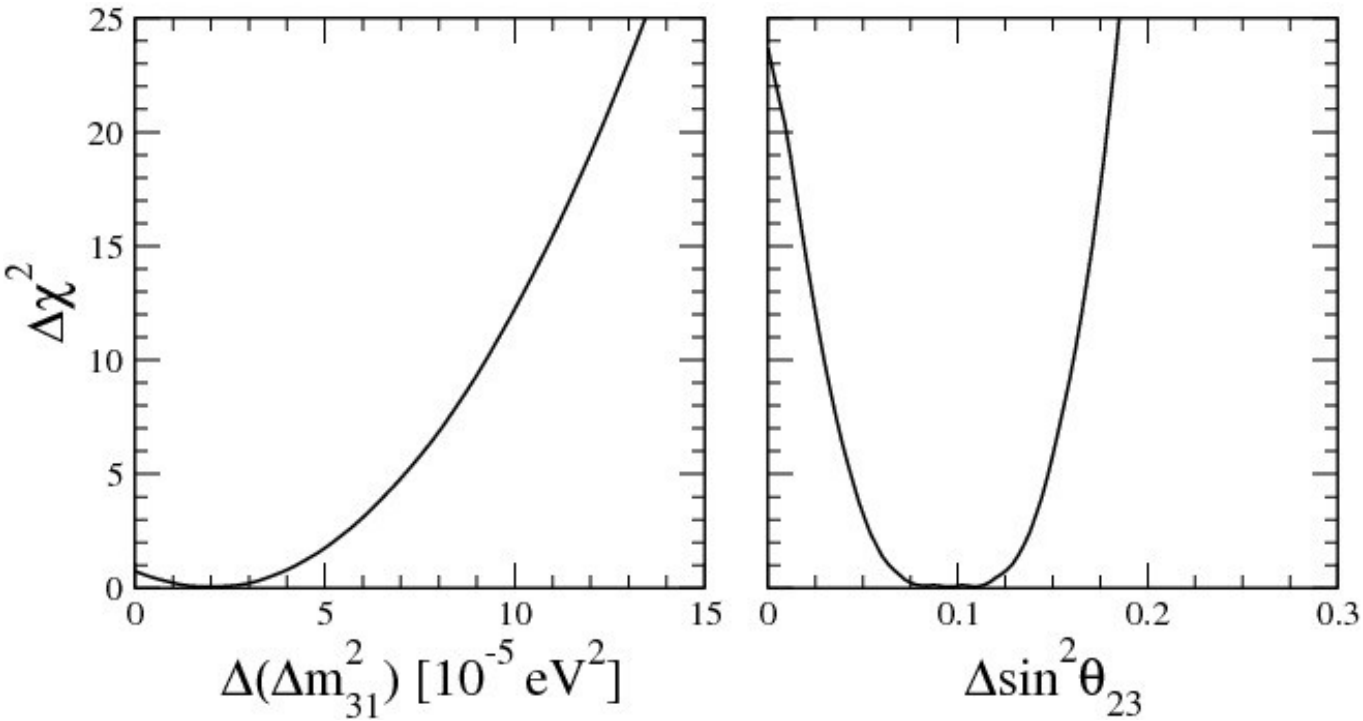


Barenboim, Ternes, Tórtola,
2005.05975, JHEP 2020



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

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

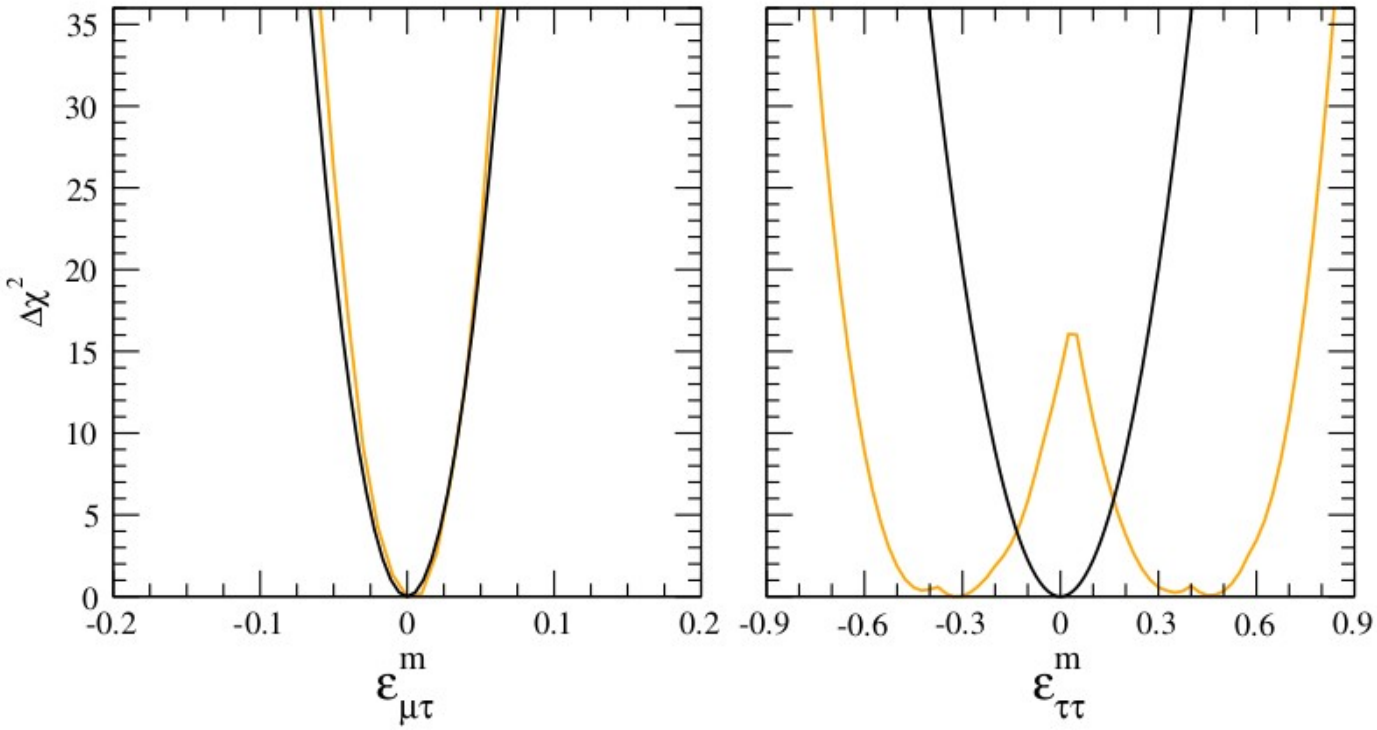
Matter parameters given by

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

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

Barenboim, Ternes, Tórtola, 1804.05842, EPJC 2019

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

Determination of neutrino oscillation parameters worsens when CPT is not conserved

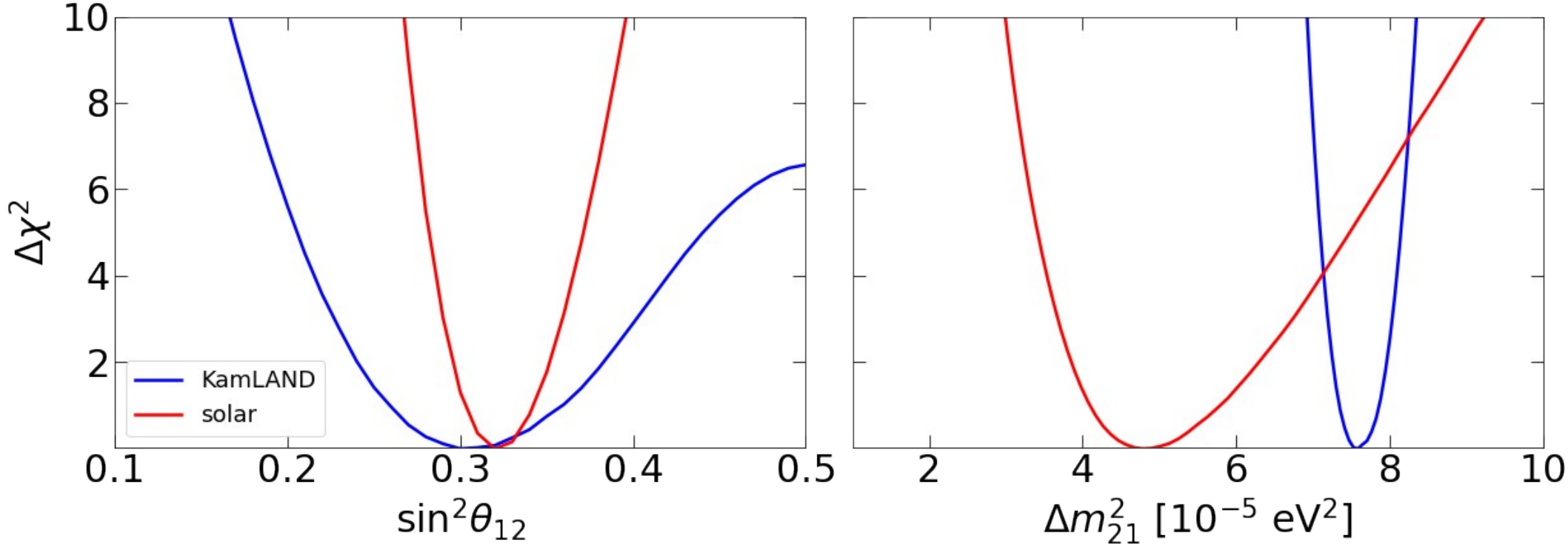
DUNE will improve the current bounds on CPT violation in the neutrino sector

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

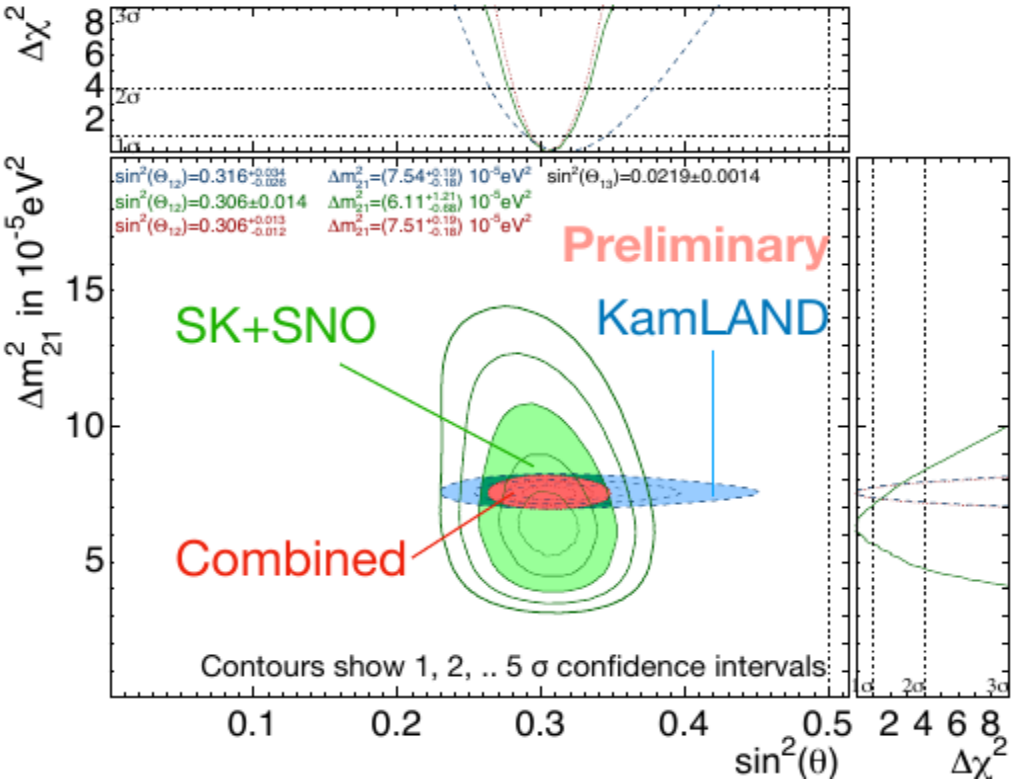
DUNE might distinguish CPT violation from NSI


Thanks!
electron-
neutrino
muon
neutrino
tau-
neutrino

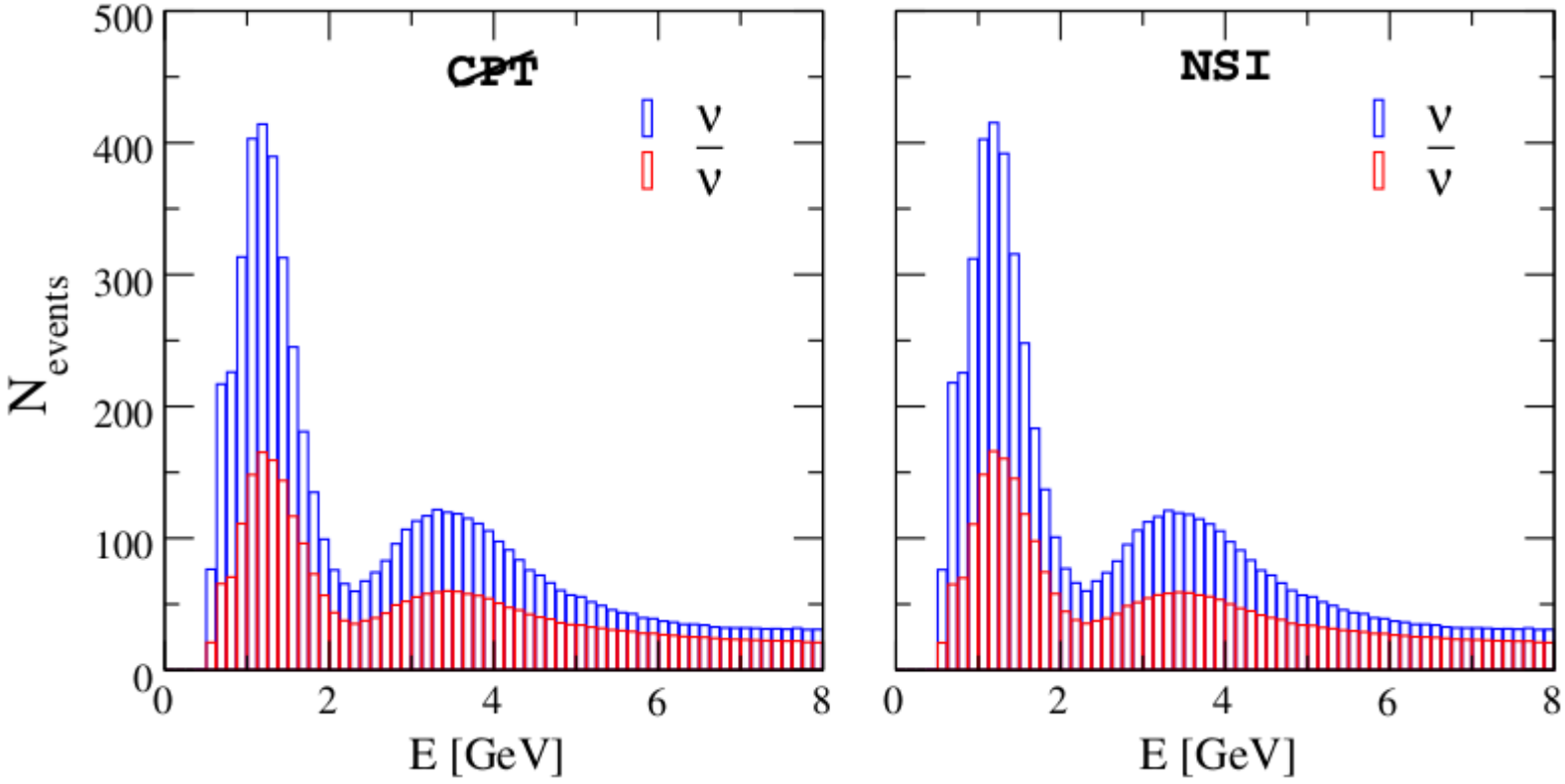
Solar sector



Solar sector



CPT-NSI



CPT-NSI

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

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

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