DUNE and CPT-violating neutrinos

Christoph Andreas Ternes
IFIC, Universitat de València/CSIC

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CPT violation

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  - Assume that neutrinos oscillate due to the PMNS-matrix with parameters $\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta$

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  - 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

Current bounds

Current bounds

- Most stringent bounds come from the neutral kaon system

$$\frac{|m(K^0) - m(\overline{K}^0)|}{m_K} < 0.6 \times 10^{-18}$$

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- Neutrinos might give better bounds

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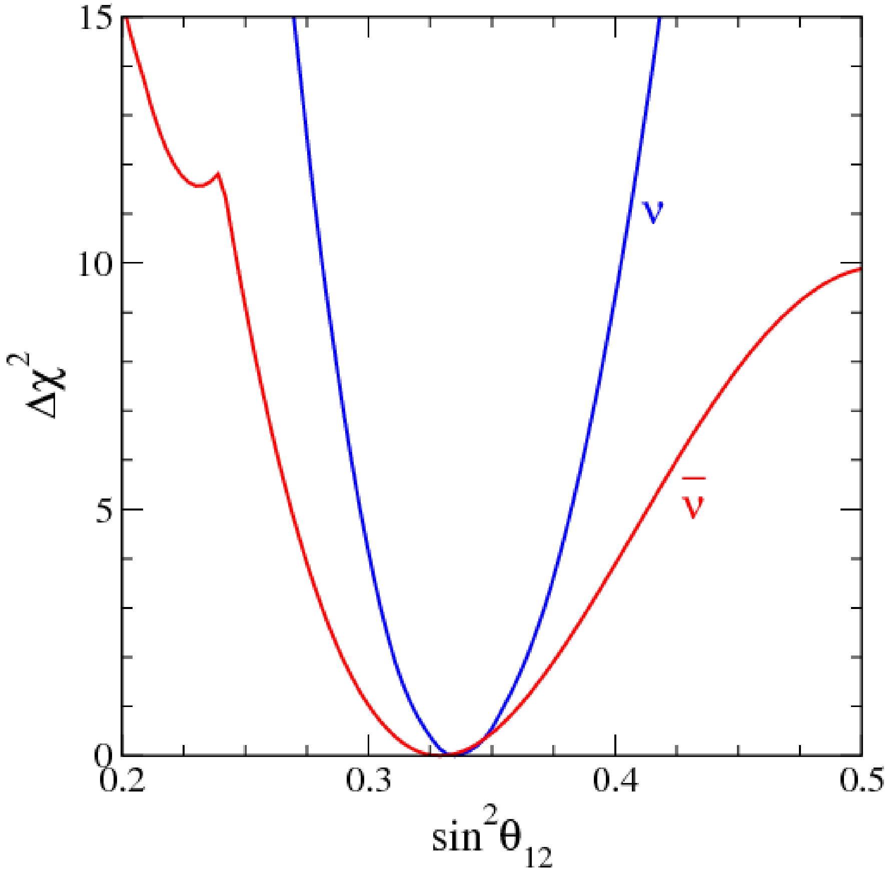
$$\chi^2(\Delta x) = \chi^2(|x - \overline{x}|) = \chi^2(x) + \chi^2(\overline{x})$$

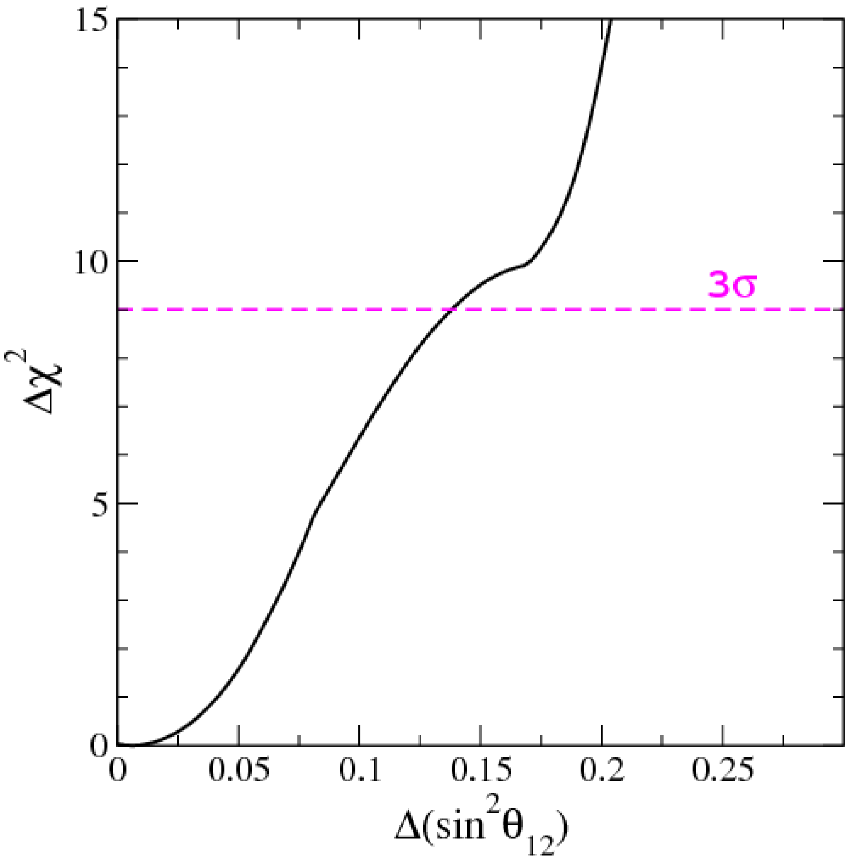
- We use the same data as in the Valencia global fit as of August 2017 (excluding atmospheric experiments)

Phys.Lett. B782 (2018) 633-640, P.F. de Salas, D.V. Forero, CAT, M. Tórtola, J.W.F. Valle
https://globalfit.astroparticles.es/

Current bounds ($\sin^2\theta_{12}$)

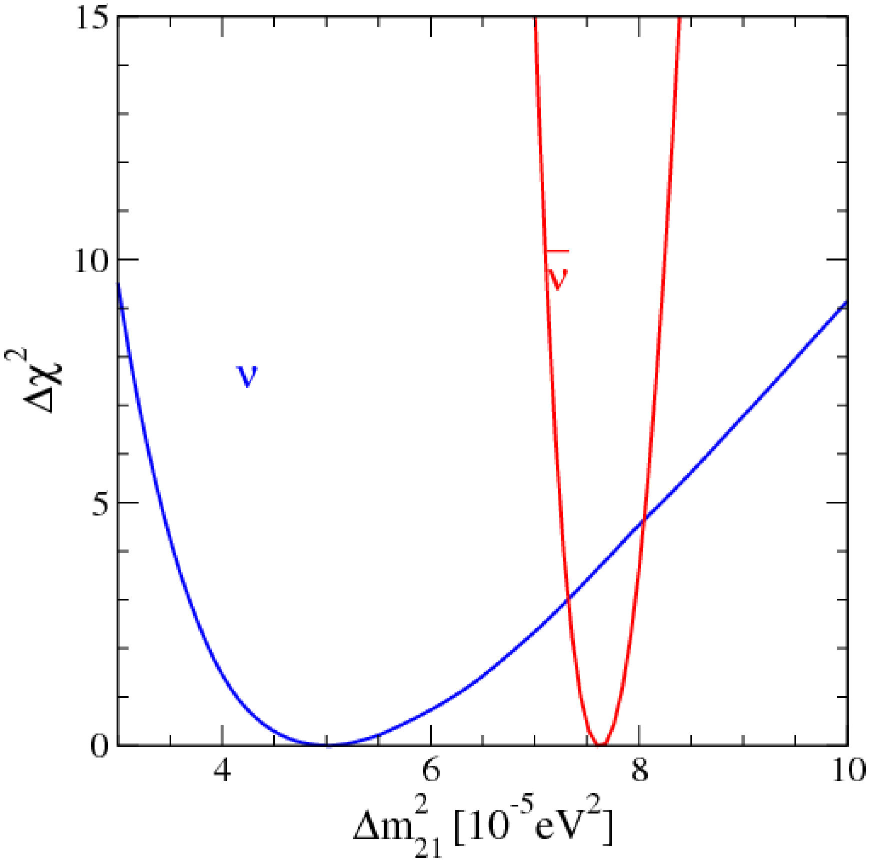
- The solar angle for neutrinos is measured by solar experiments
- The antineutrino counterpart is measured by KamLAND

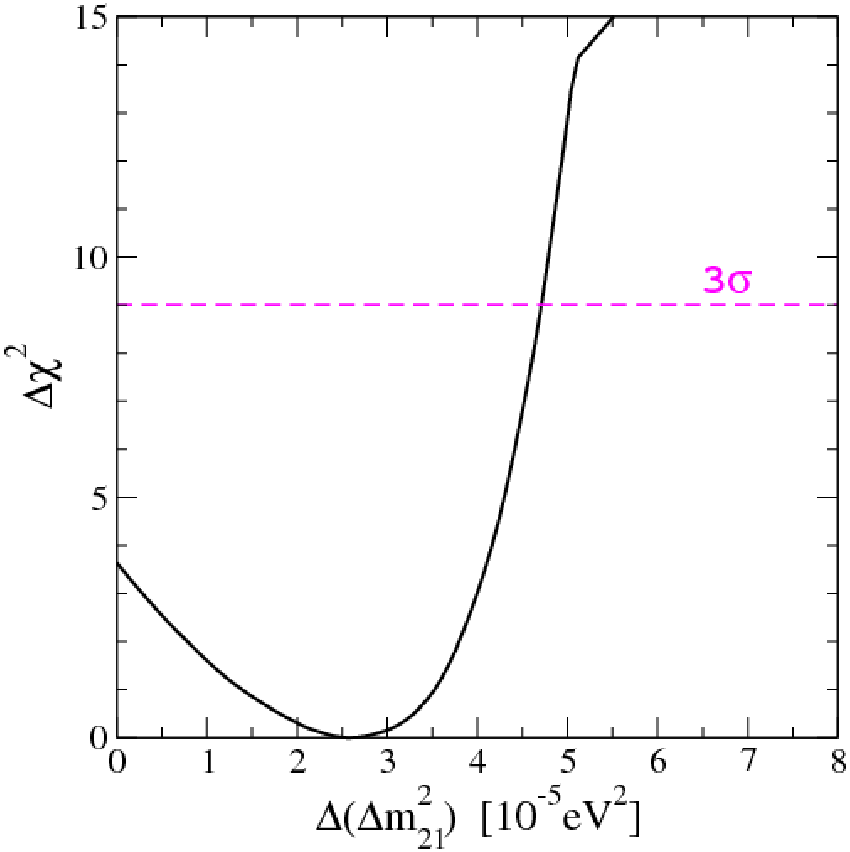




Current bounds (Δm^2_{21})

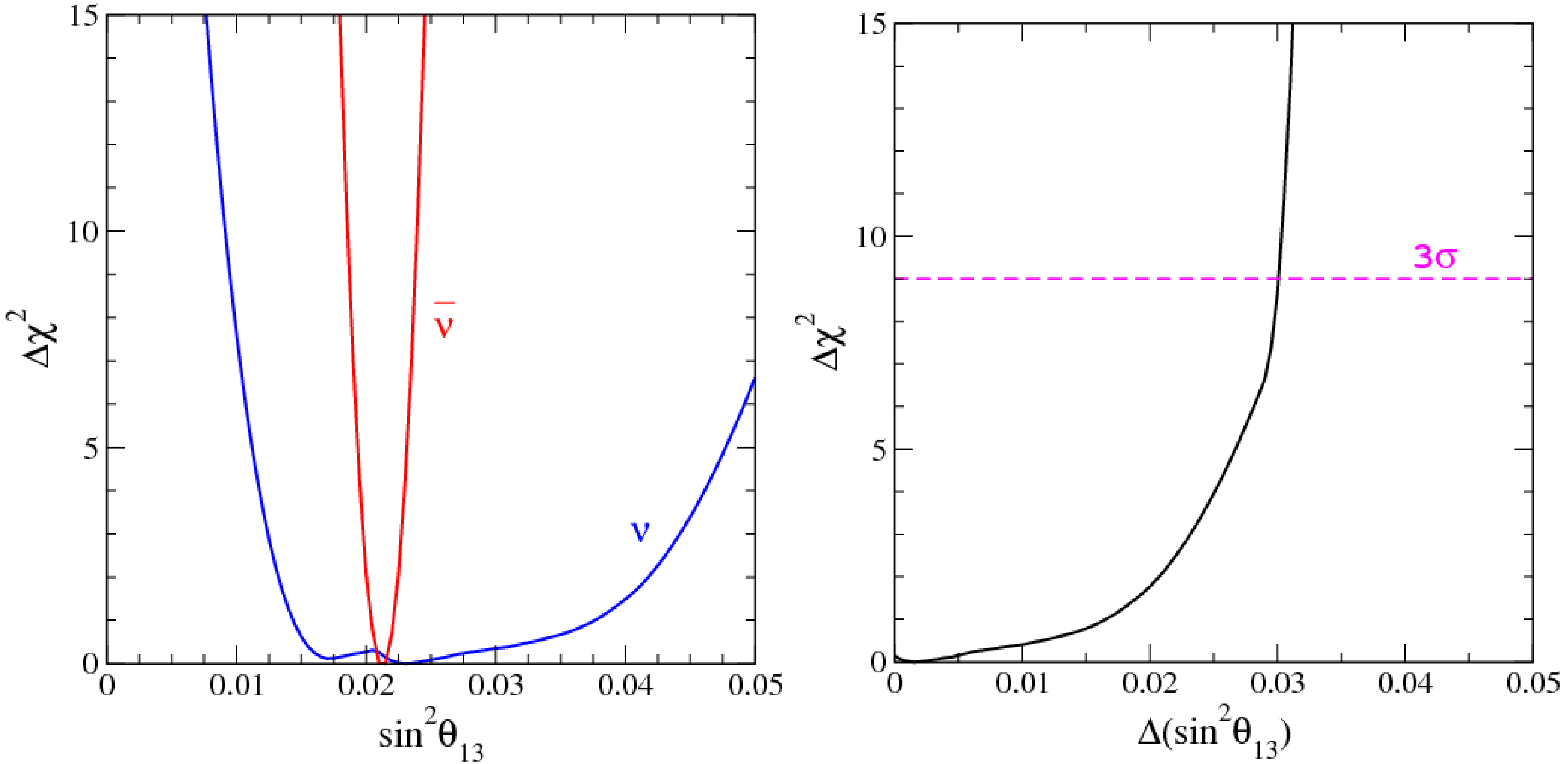
- The same experiments measure the solar mass splittings for neutrinos
- Also in this case the antineutrino part is measured by KamLAND





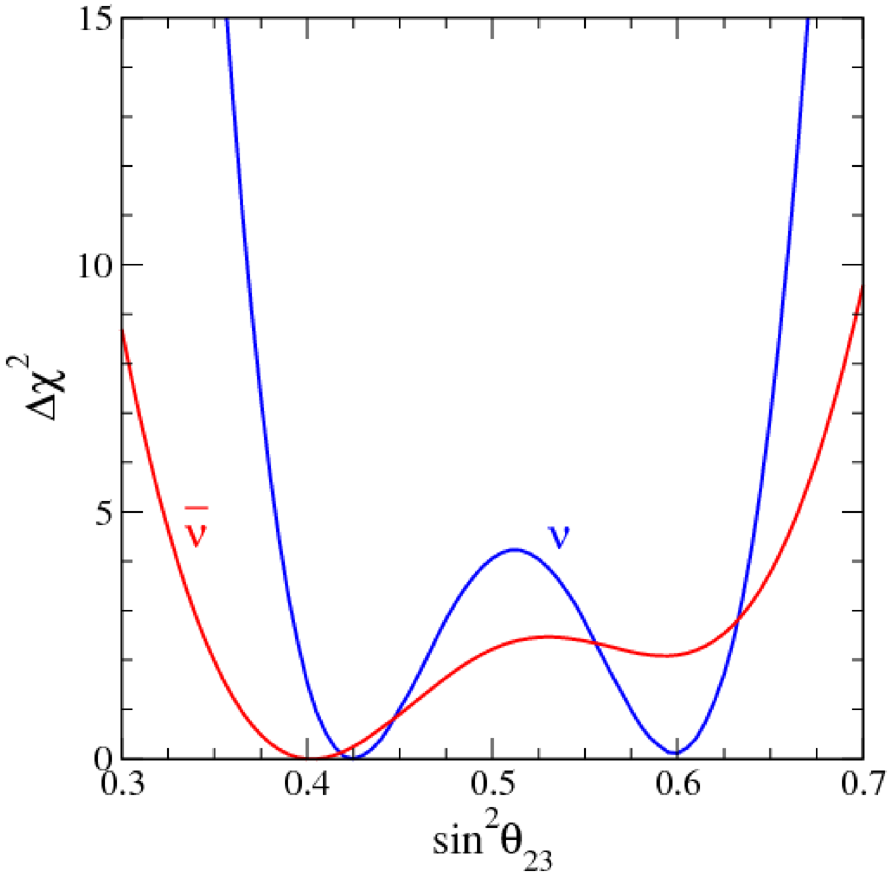
Current bounds ($\sin^2\theta_{13}$)

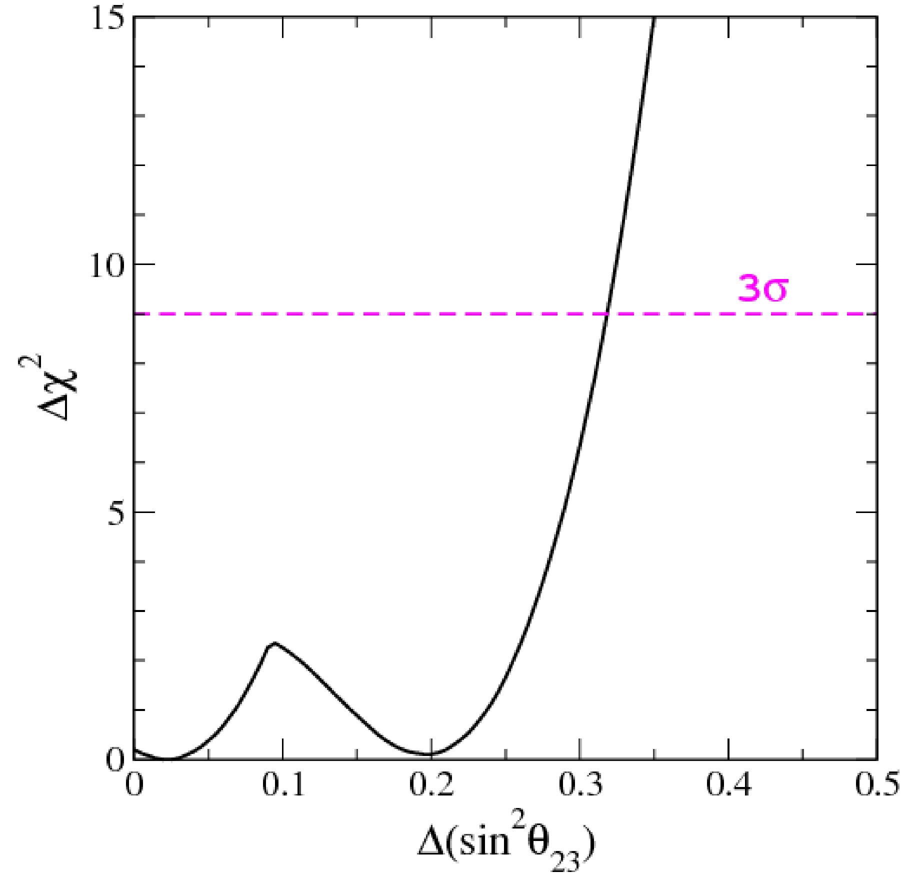
- $\sin^2\theta_{13}$ measured by solar experiments and accelerators (T2K, NOνA, MINOS, K2K)
- Apart from reactor experiments (Daya Bay, RENO, Double Chooz, KamLAND) we include data from T2K and MINOS for $\sin^2\overline{\theta}_{13}$



Current bounds ($\sin^2\theta_{23}$)

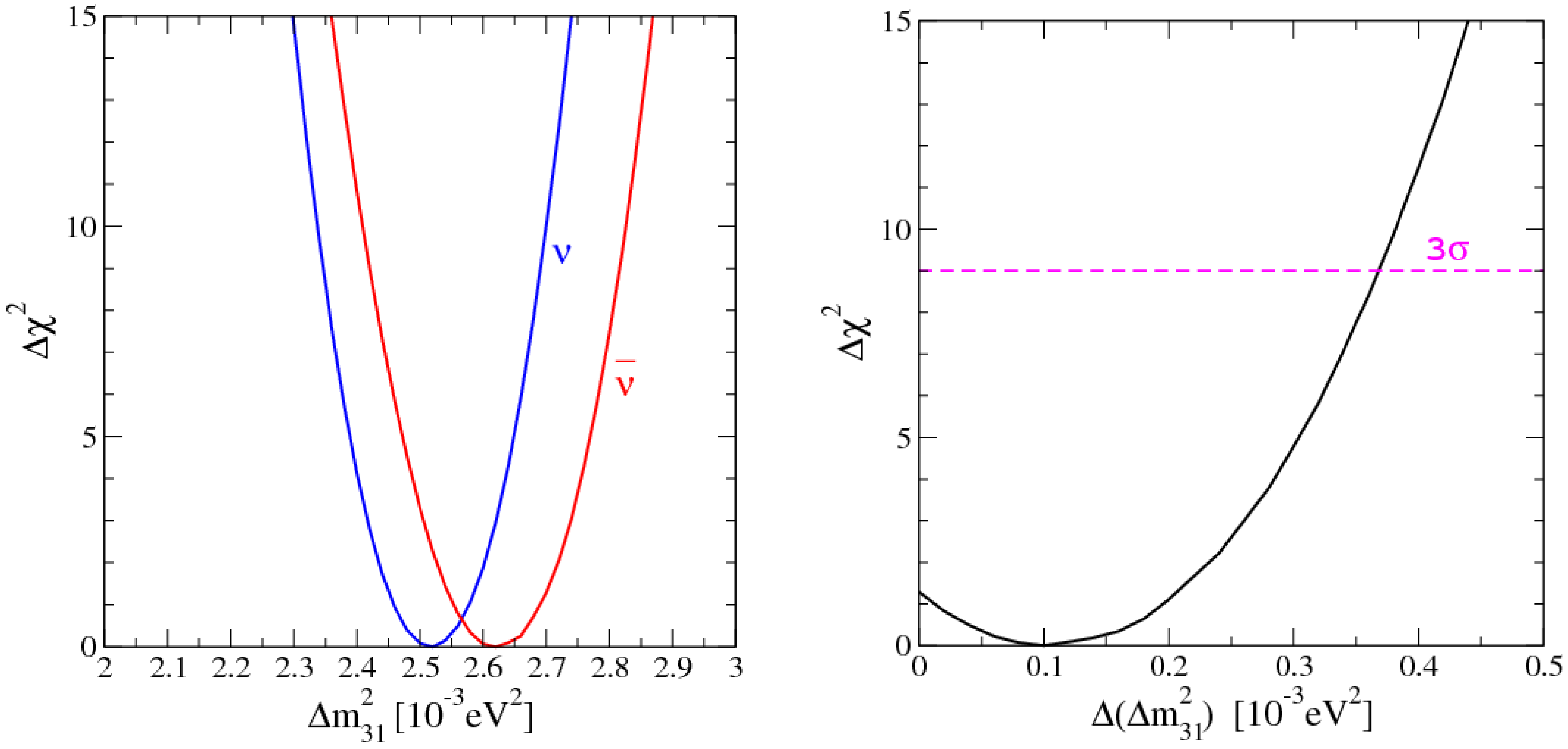
- $\sin^2\theta_{23}$ is measured by all long-baseline accelerators (T2K, NOνA, MINOS, K2K)
- For antineutrinos we use only data from T2K and MINOS (no NOνA antineutrinos in 2017)





Current bounds (Δm^2_{31})

- For the atmospheric mass splitting we use data from all of the LBLs in neutrino mode
- For antineutrinos we use T2K, MINOS and the short baseline reactors



Current bounds

- We obtain the current bounds at 3σ C.L.

$$
\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}| &< 3.7 \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}| &< 0.03, \\
|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| &< 0.32
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Phys.Lett. B780 (2018) 631-637, G. Barenboim, CAT, M. Tórtola

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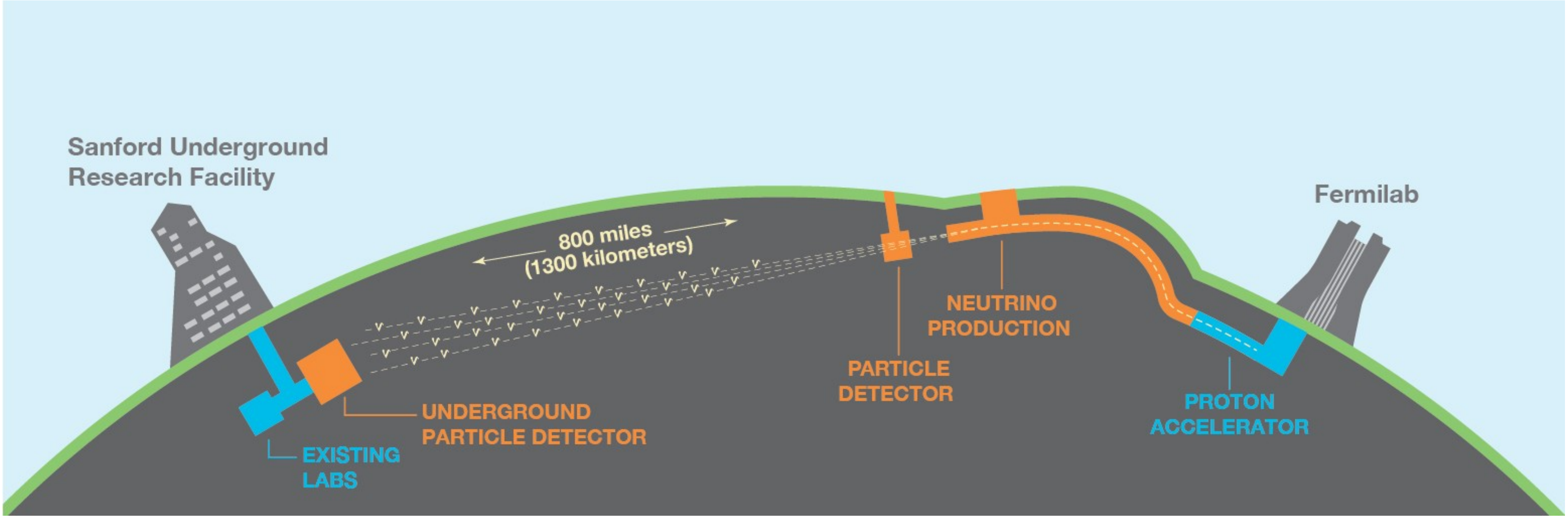
- The bound on both mass splittings is better than the one of the kaons
- We want to see, if DUNE can improve some of these bounds

Phys.Lett. B780 (2018) 631-637, G. Barenboim, CAT, M. Tórtola

Simulation of DUNE



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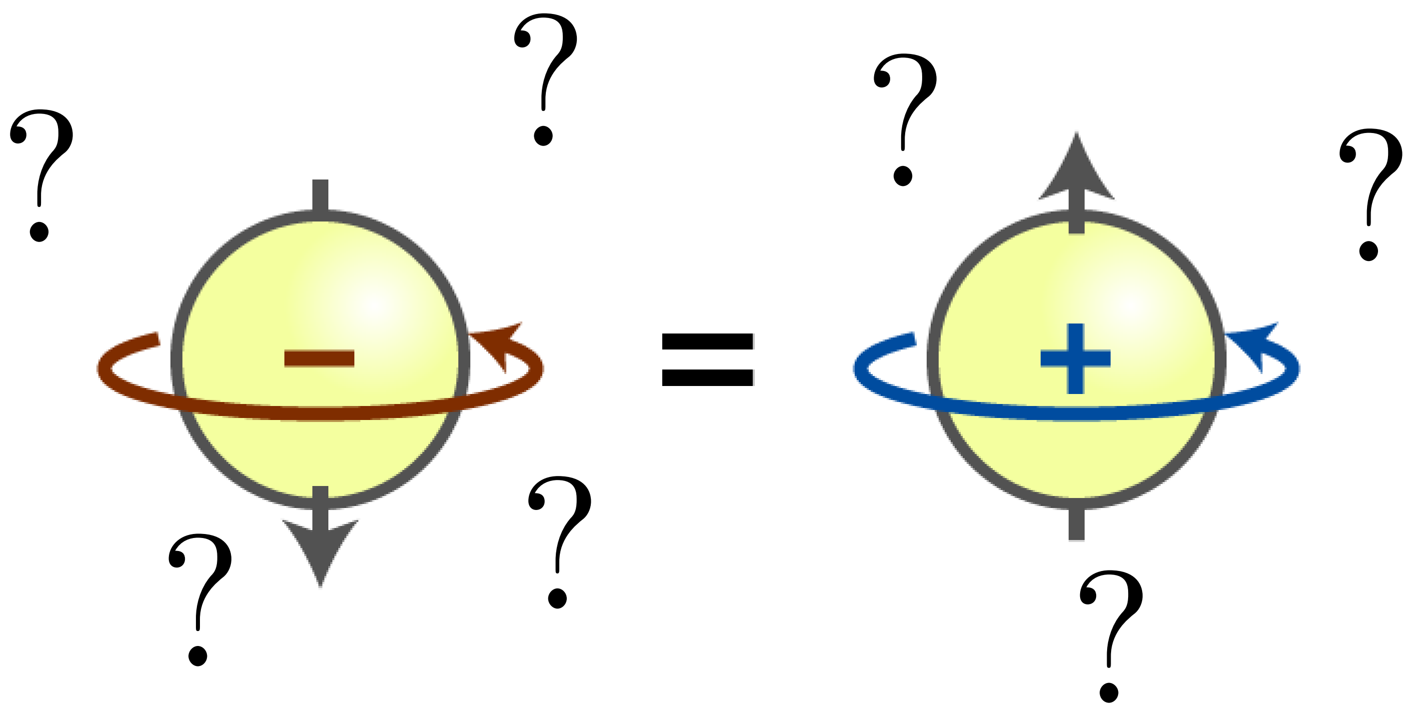
- We use disappearance and appearance channels
- Matter effects are taken into account

Sensitivity to CPT violation



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- To do so we compute as before

$$\chi^2(\Delta x) = \chi^2(|x - \overline{x}|) = \chi^2(x) + \chi^2(\overline{x})$$

being x any of the oscillation parameters

Sensitivity to CPT violation

- The parameters of oscillations to create the data are

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

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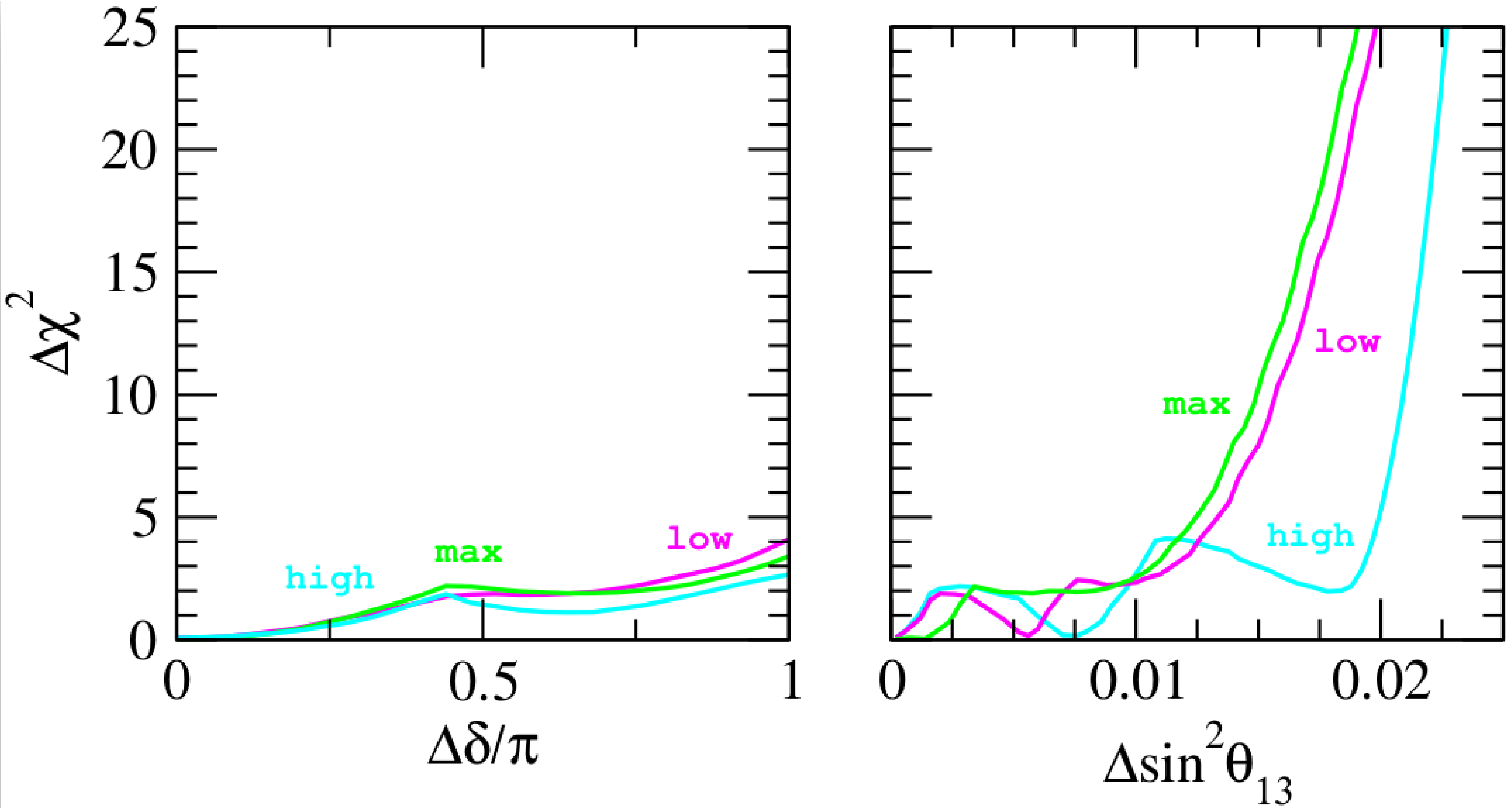
- In neutrino mode $\sin^2\theta_{13}$ is left free, but in antineutrino mode we put a prior on $\sin^2\overline{\theta}_{13}$

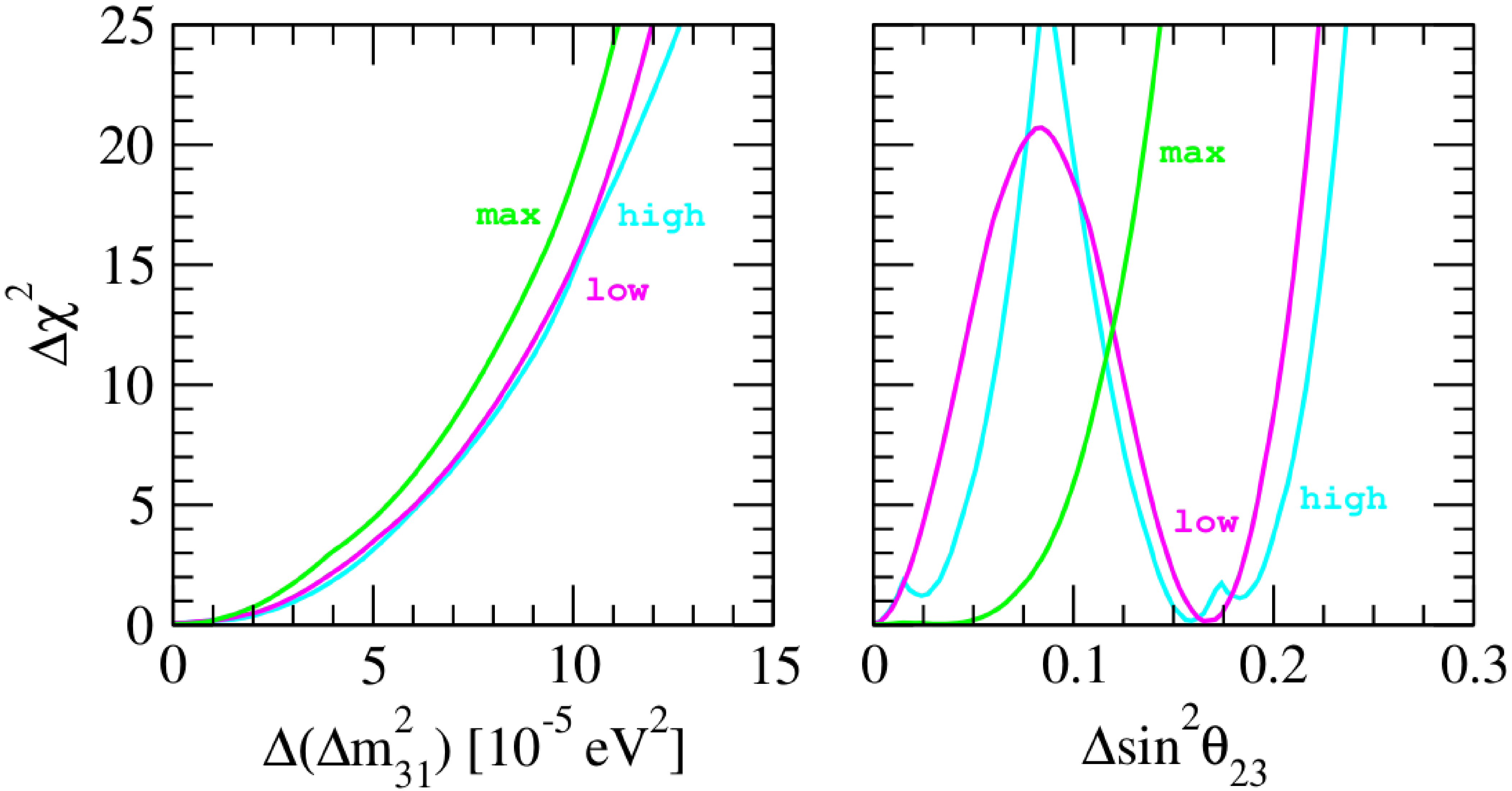
Sensitivity to CPT violation

- There is no sensitivity to $\Delta\delta$ and $\Delta \sin^2 \theta_{13}$



Sensitivity to CPT violation

- This changes in the case of $\Delta(\Delta m^2_{31})$ and $\Delta \sin^2 \theta_{23}$



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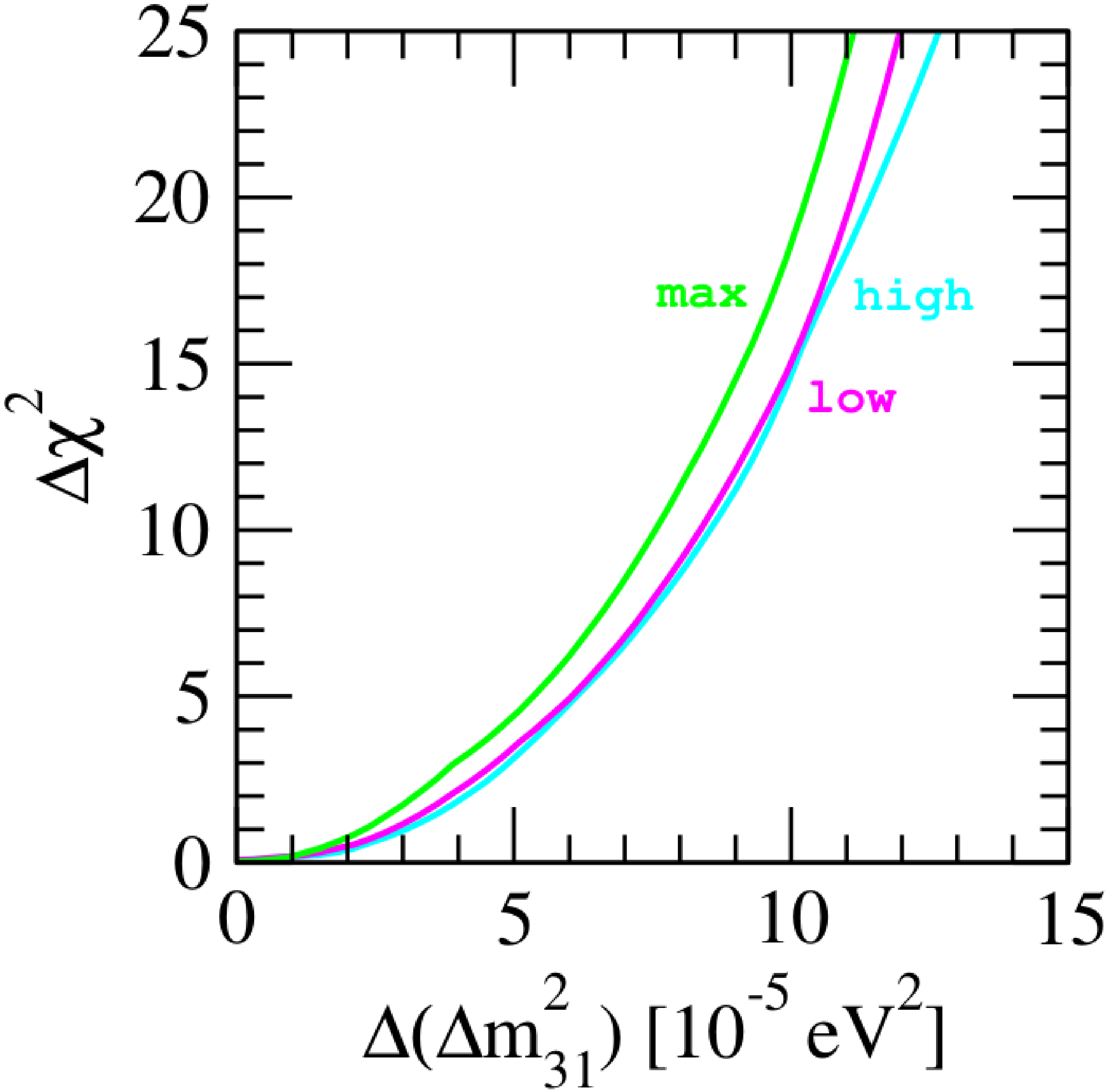

- DUNE has great sensitivity to $\Delta(\Delta m^2_{31})$

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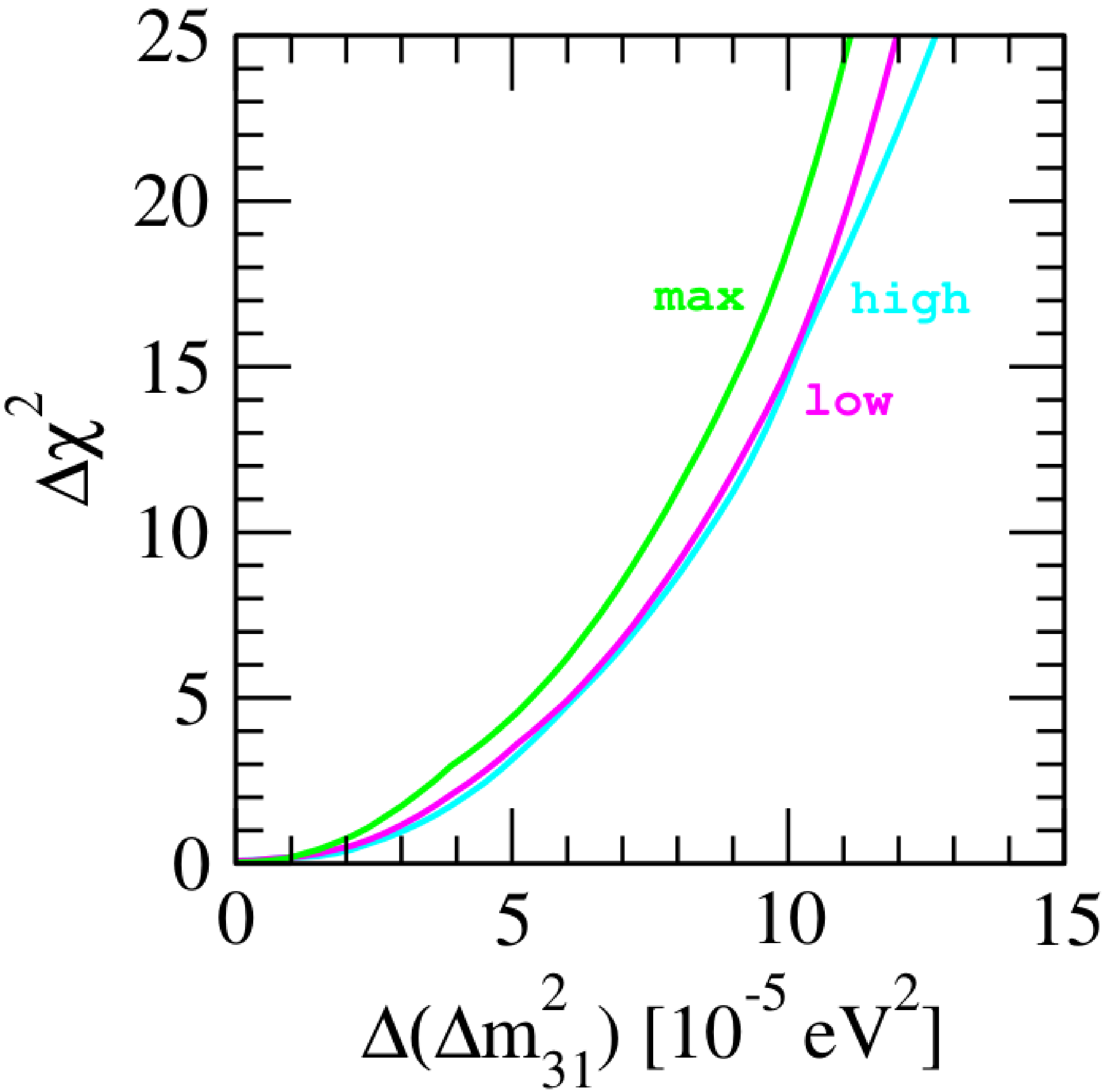

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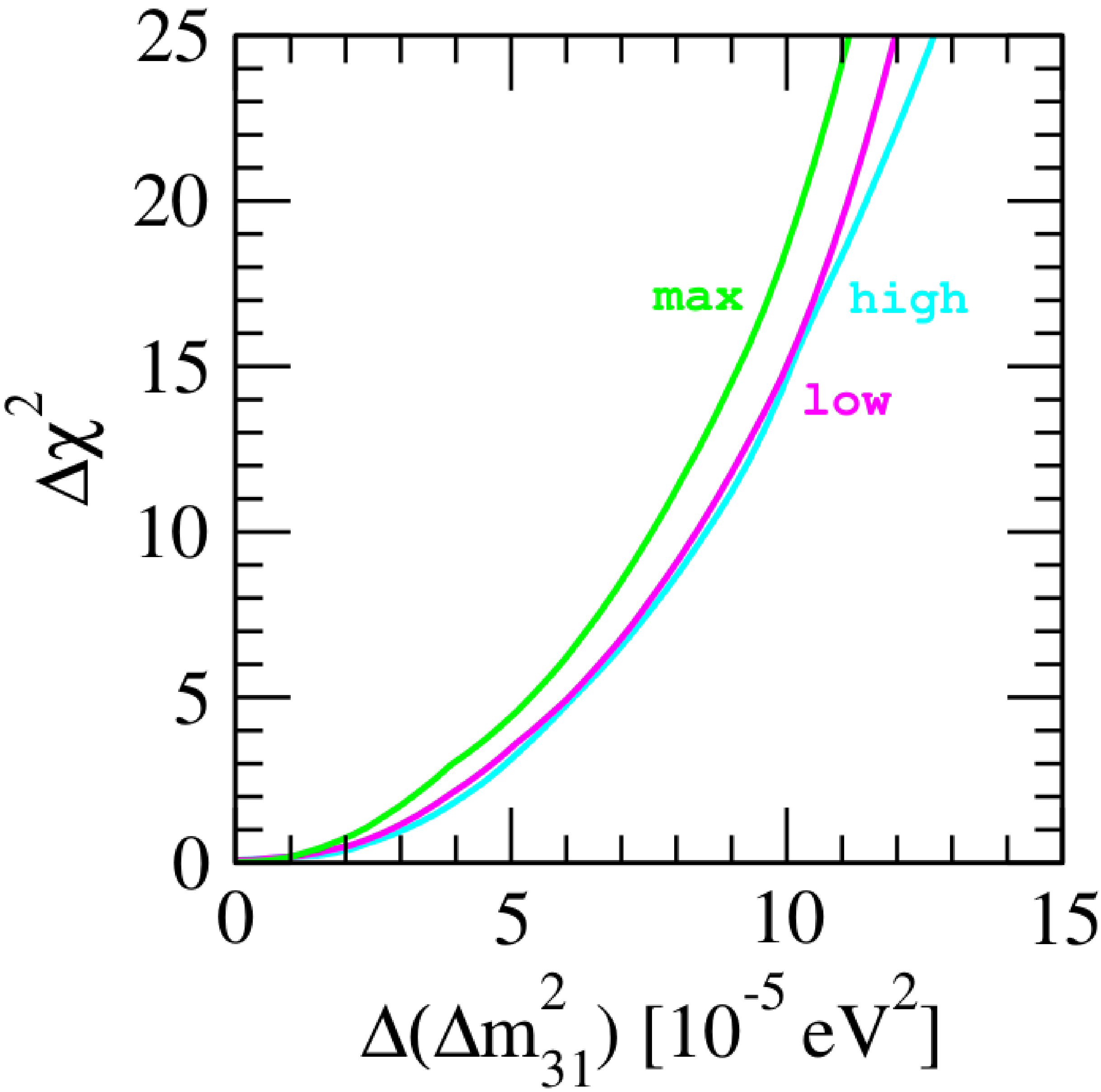
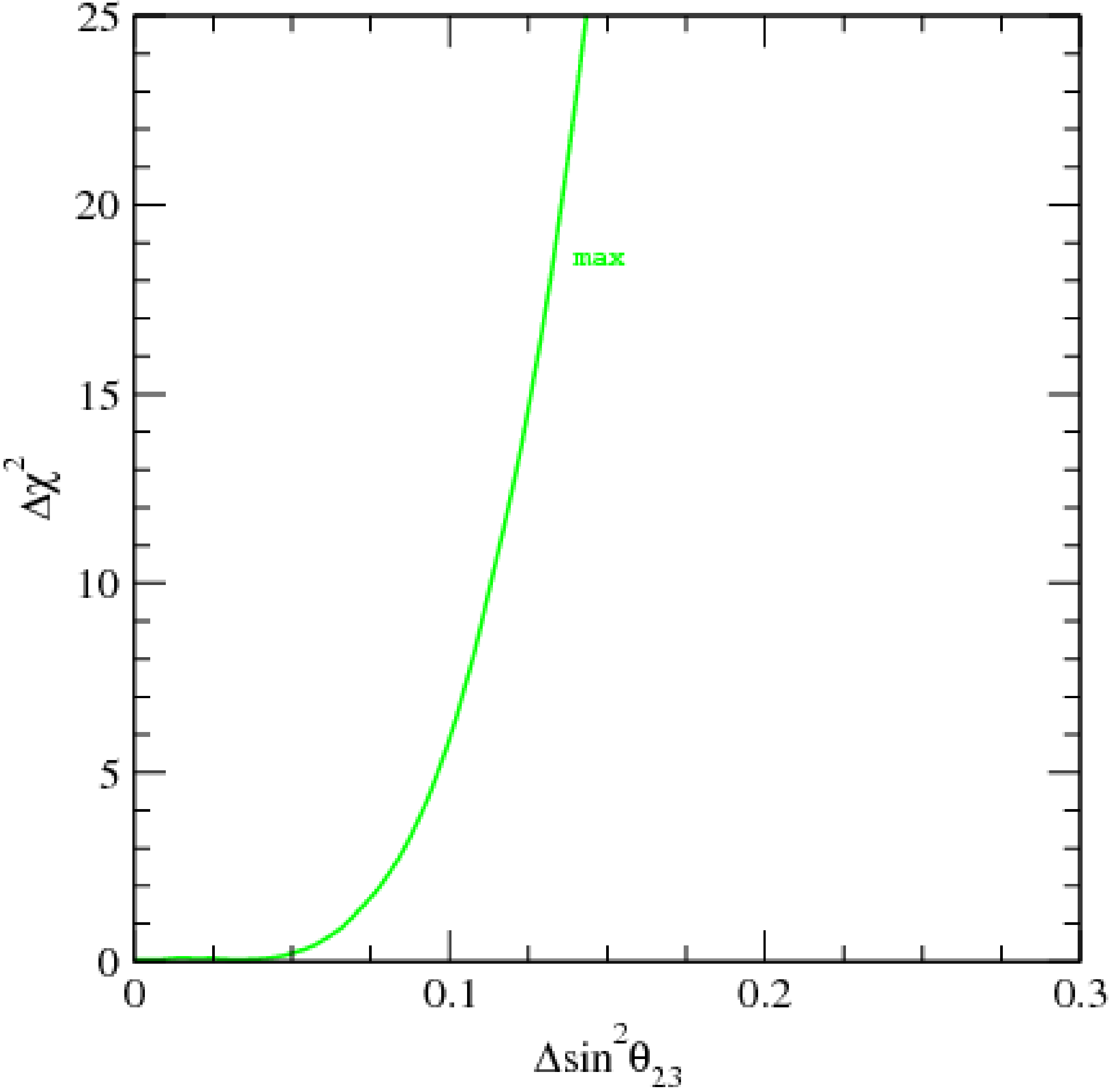


- DUNE has great sensitivity to $\Delta(\Delta m^2_{31})$
- It could improve the current limits by one order of magnitude
- We could obtain

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

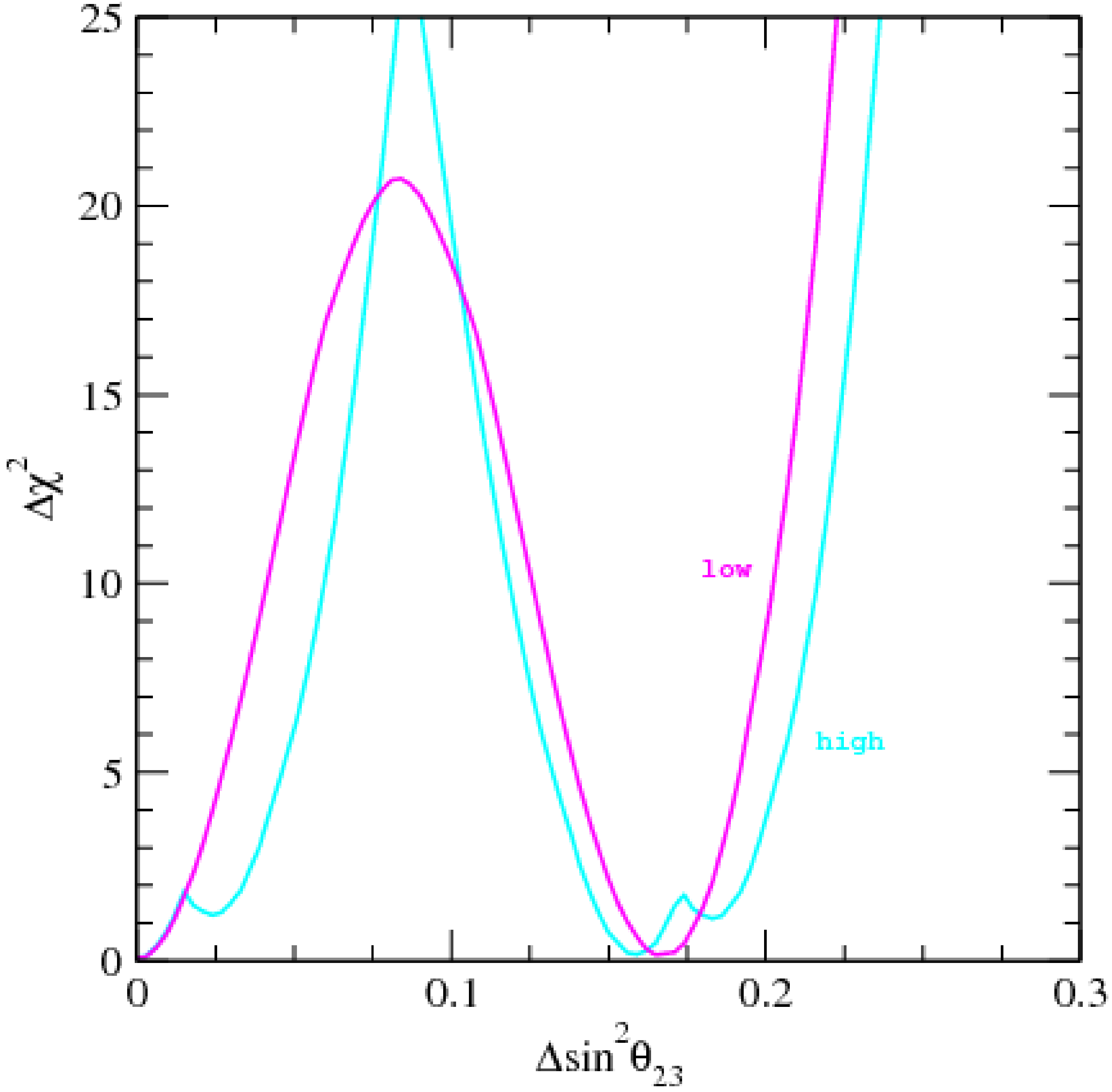
at 3σ C.L.

Sensitivity to CPT violation



- For the atmospheric angle we obtain increasing sensitivity for maximal mixing

Sensitivity to CPT violation



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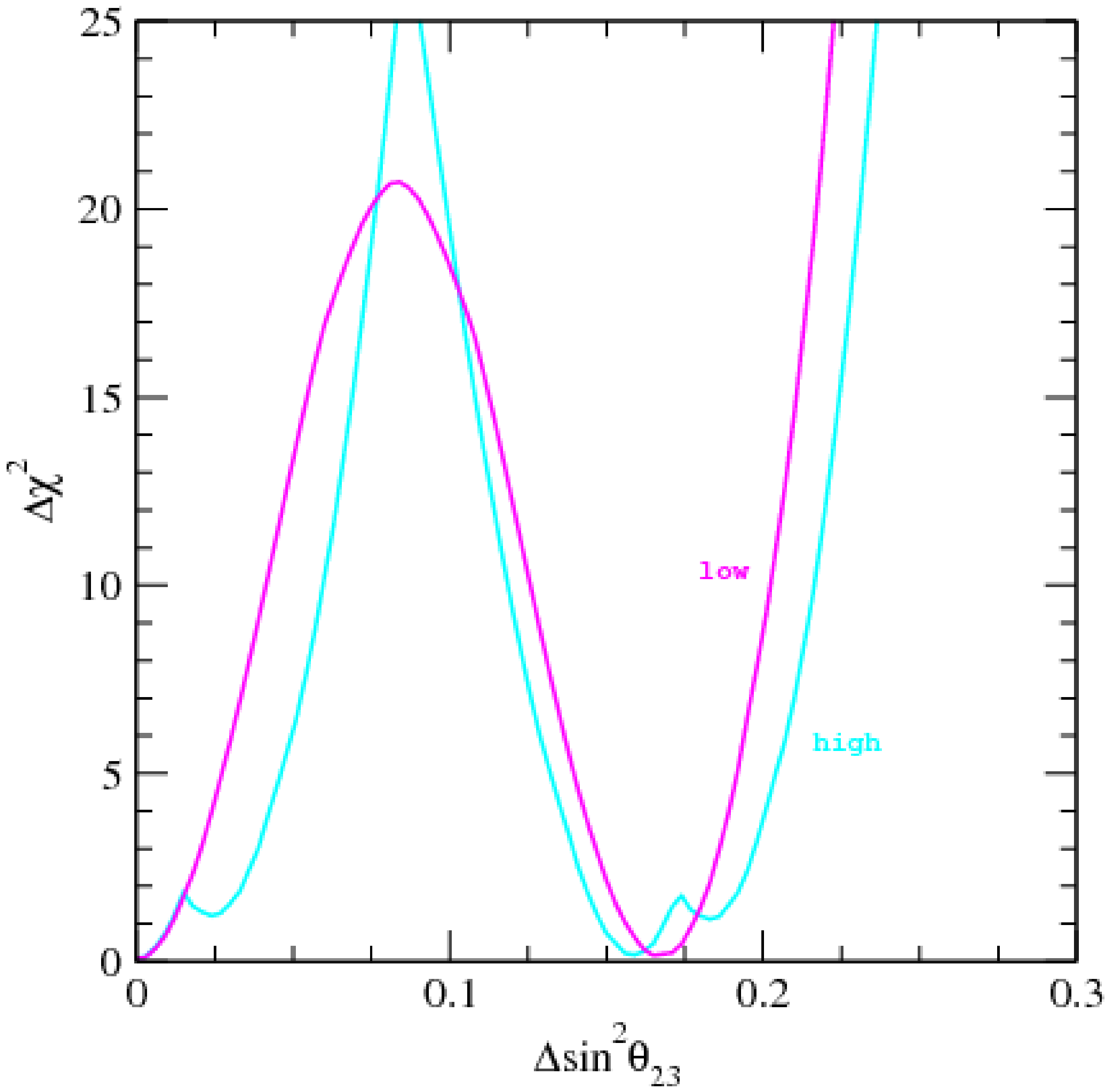
- For the other values instead it increases and then decreases again

Sensitivity to CPT violation



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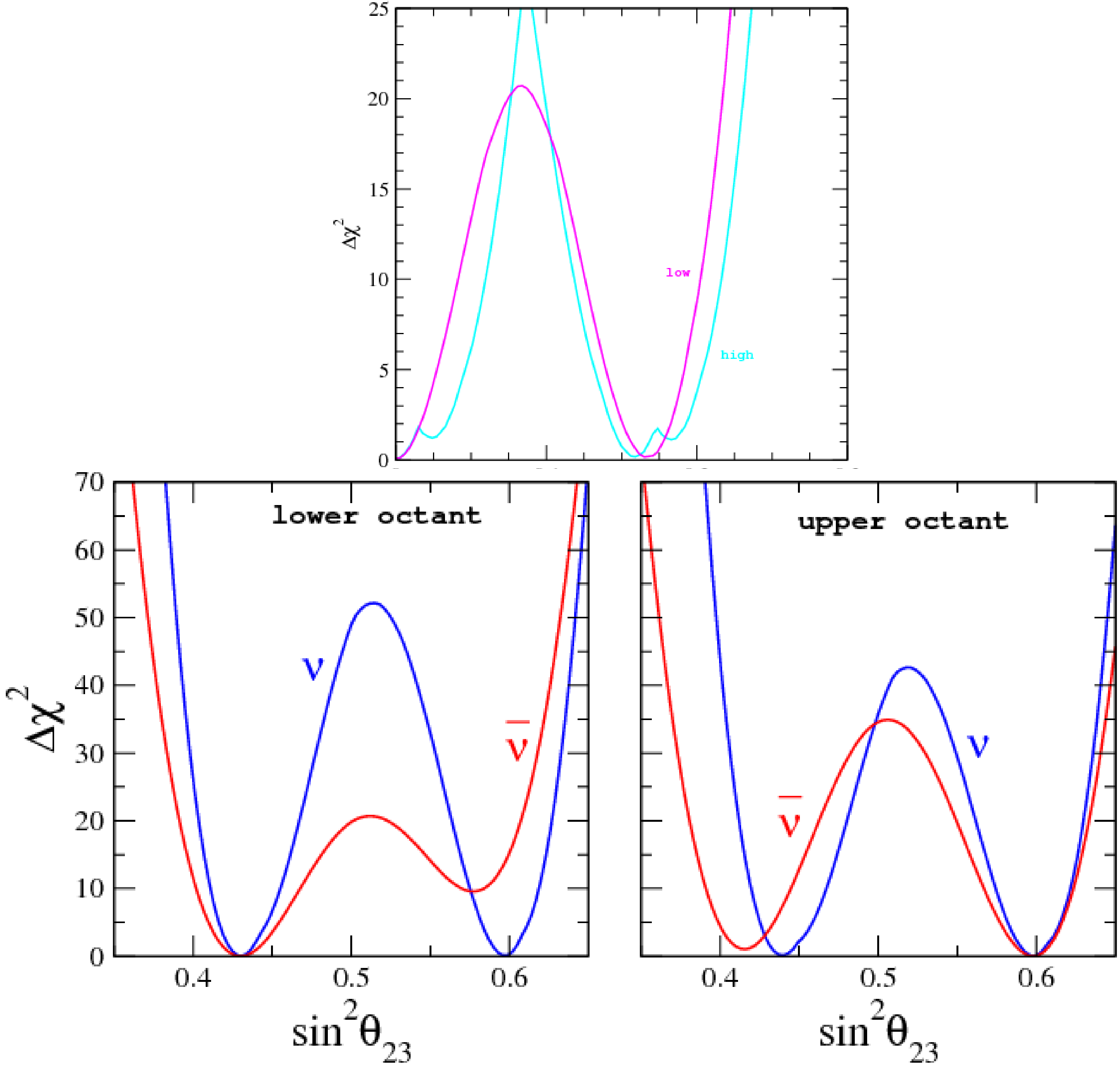
- For the other values instead it increases and then decreases again
- This is due to degenerate solutions

Sensitivity to CPT violation



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- If CPT is not conserved this leads to impostor (fake) solutions in the fits
- To perform the standard fit you would calculate

$$\chi^2_{\mathrm{total}} = \chi^2(\nu) + \chi^2(\overline{\nu})$$

and then minimize this function

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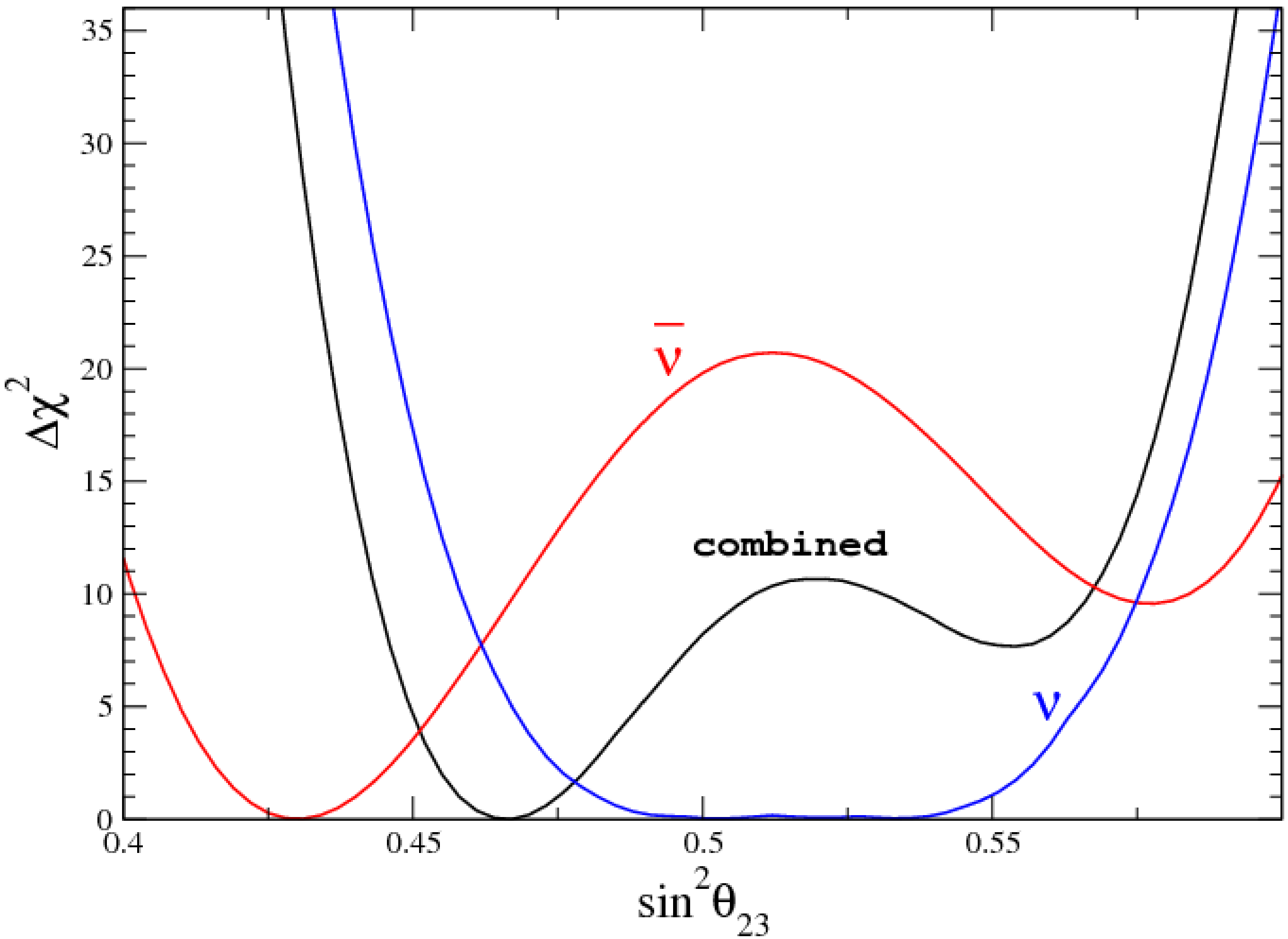

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$$\sin^2\theta_{23}^{\text{comb}} = 0.467$$

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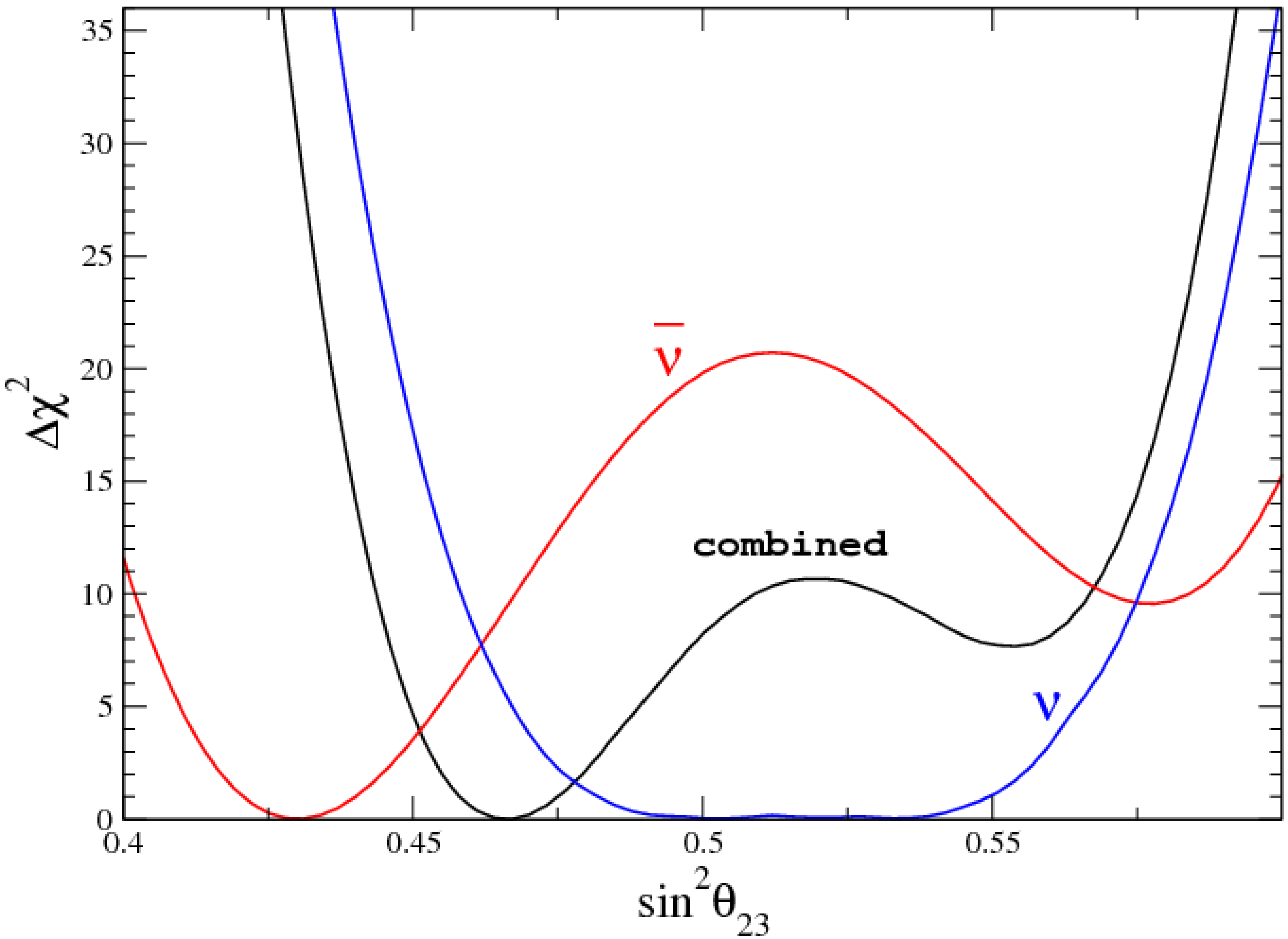

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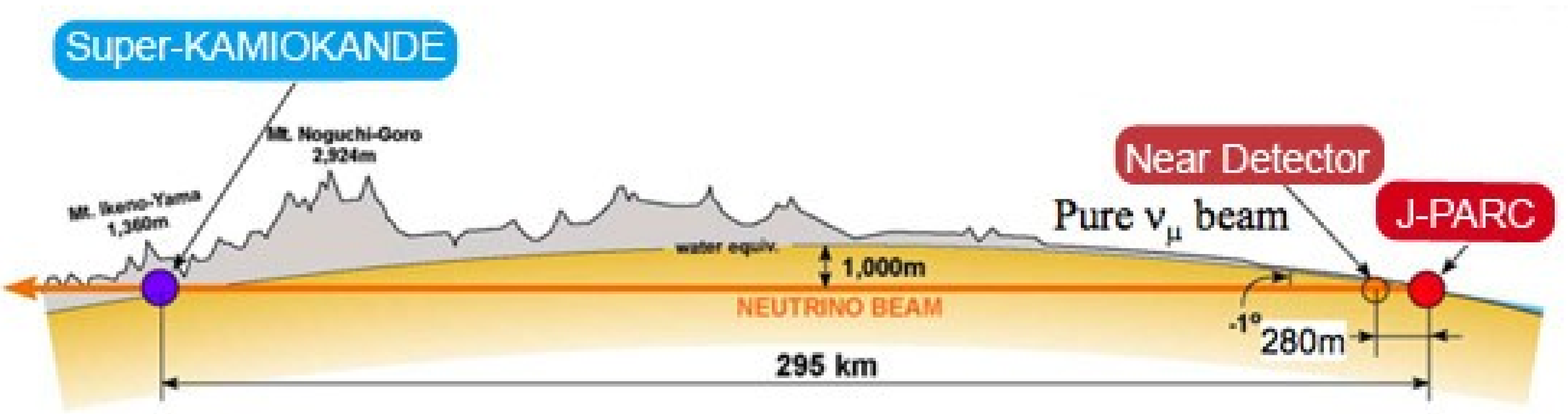
- Real true values are disfavored at close to 3σ and more than 5σ confidence levels

A special case: Probing the T2K results



Probing the T2K results

- T2K studied neutrino and antineutrino oscillations separated

$$\sin^2\theta_{23} = 0.51, \quad \Delta m^2_{32} = 2.53\times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\overline{\theta}_{23} = 0.42, \quad \Delta \overline{m}^2_{32} = 2.55\times 10^{-3}\mathrm{eV}^2$$

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96, 011102(R) (2017)

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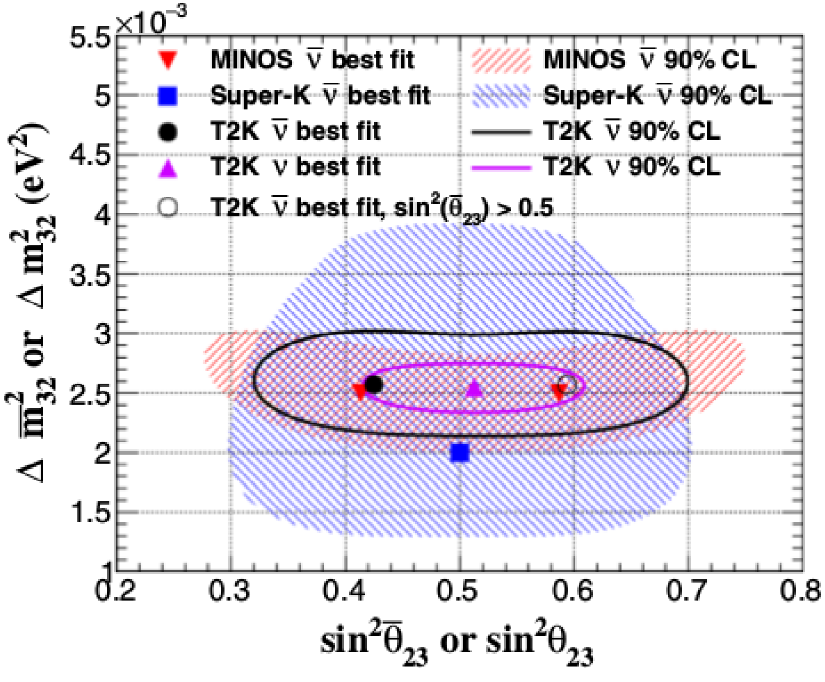
- Results are consistent with CPT conservation



PHYSICAL REVIEW D 96, 011102(R) (2017)

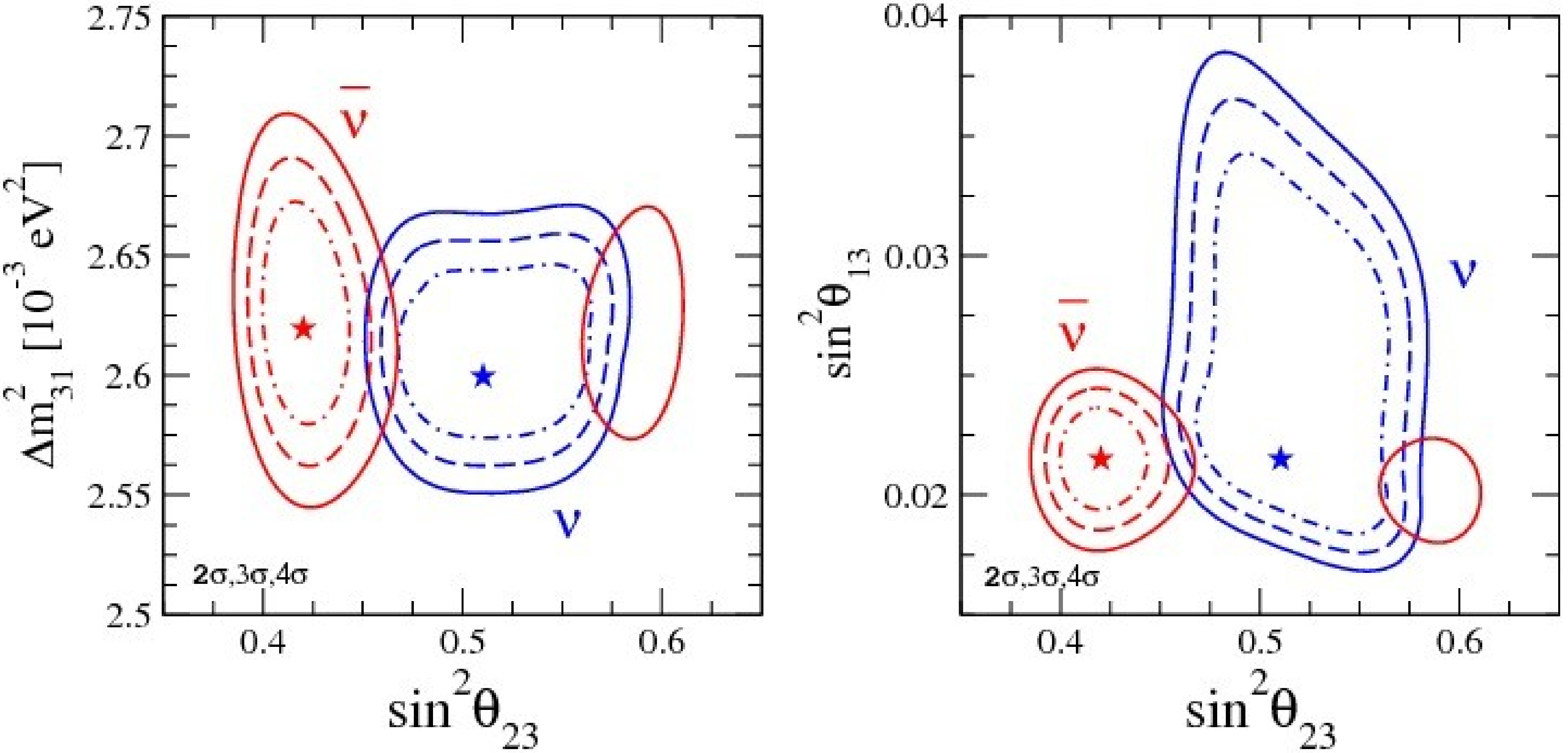
Probing the T2K results

- We assumed these values to be true and simulated DUNE with parameters

parameter	value
Δm^2_{31}	$2.60\times10^{-3}\,\mathrm{eV}^2$
$\Delta\overline{m}^2_{31}$	$2.62\times10^{-3}\,\mathrm{eV}^2$
$\sin^2\theta_{23}$	0.51
$\sin^2\overline{\theta}_{23}$	0.42
$\Delta m^2_{21},\ \Delta\overline{m}^2_{21}$	$7.56\times10^{-5}\,\mathrm{eV}^2$
$\sin^2\theta_{12},\ \sin^2\overline{\theta}_{12}$	0.321
$\sin^2\theta_{13},\ \sin^2\overline{\theta}_{13}$	0.02155
$\delta,\ \overline{\delta}$	1.50π

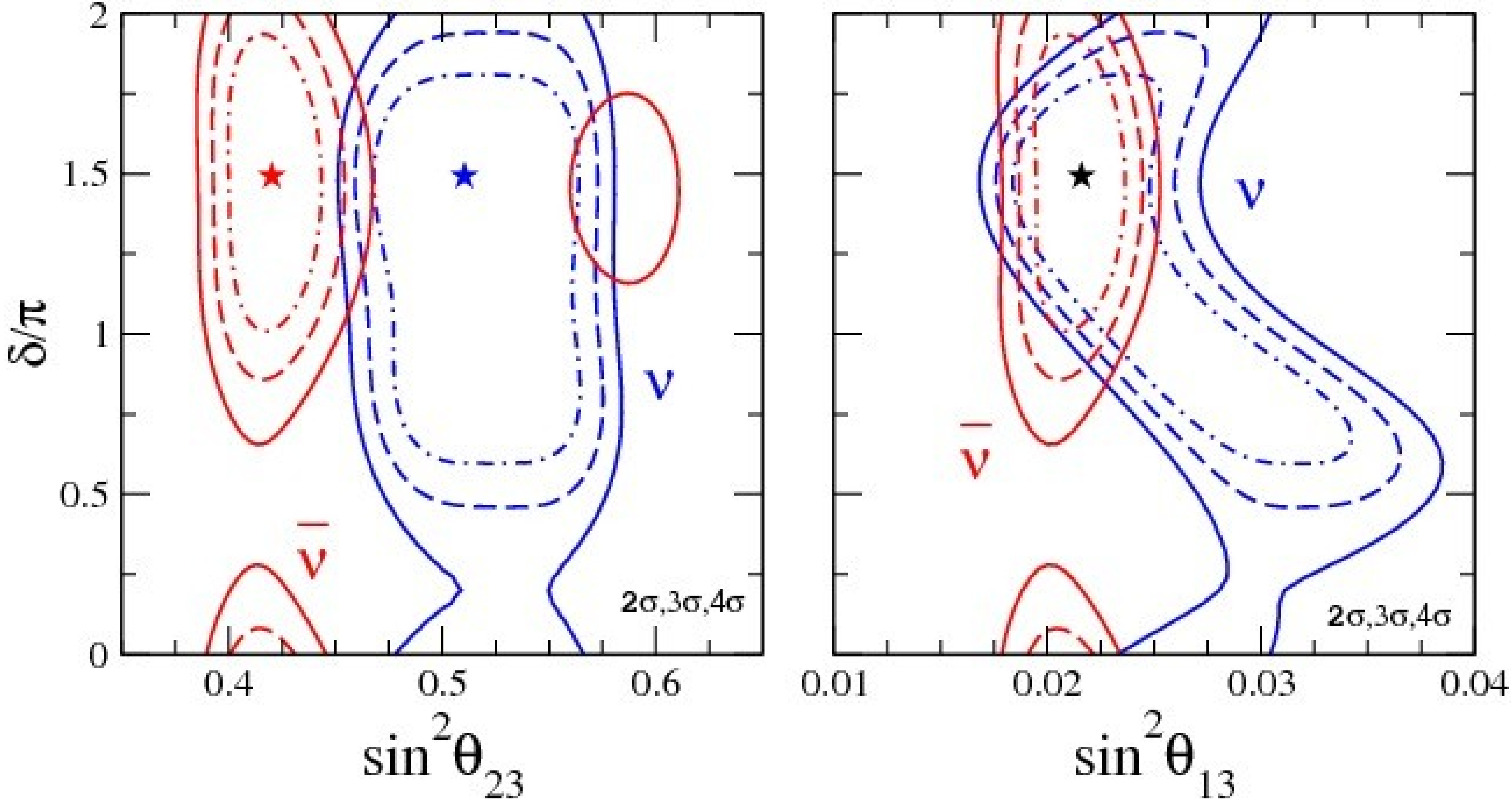
Probing the T2K results

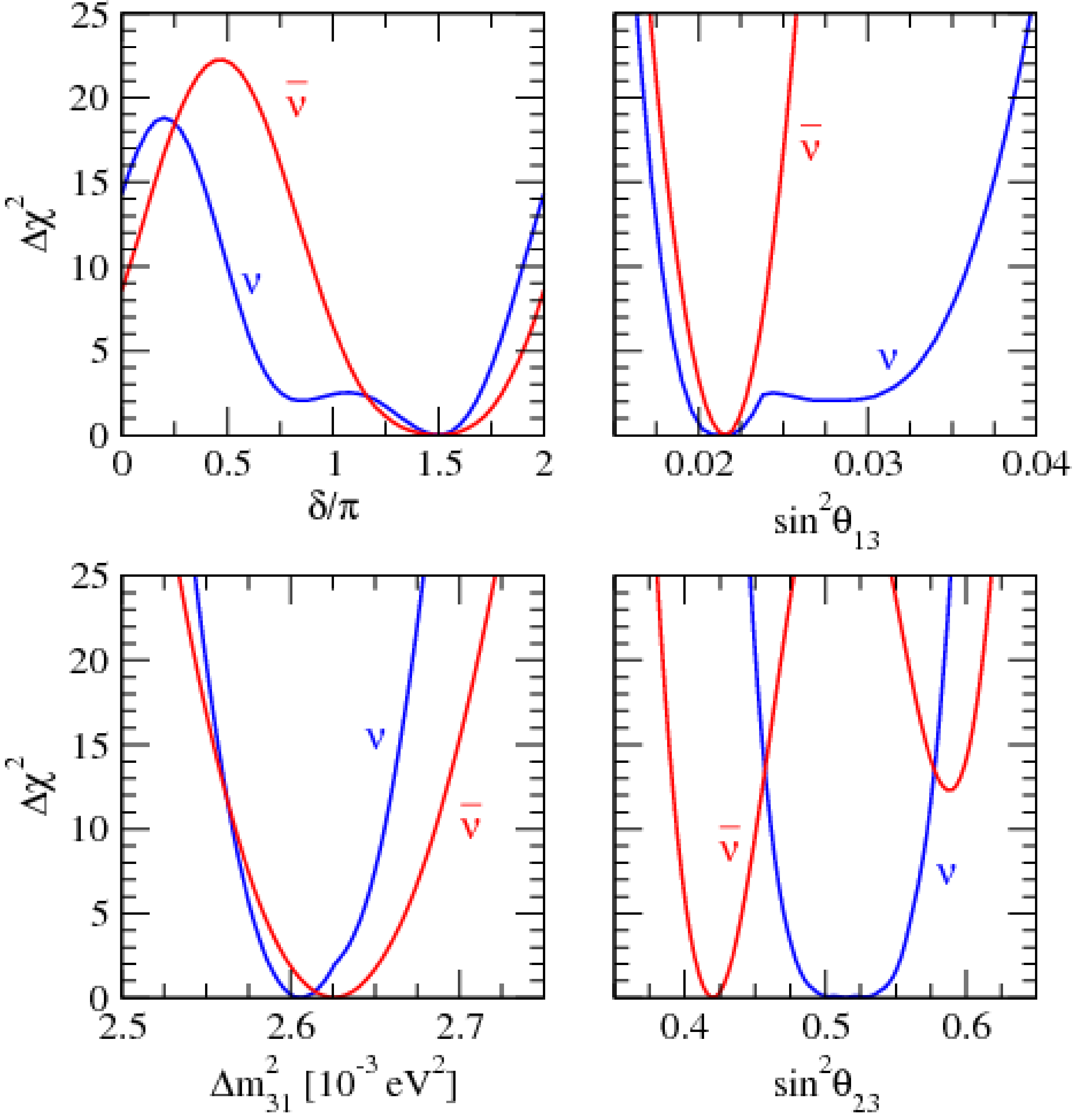
- We find that, if these values turn out to be the true values, DUNE would measure CPT violation at more than 3σ confidence level



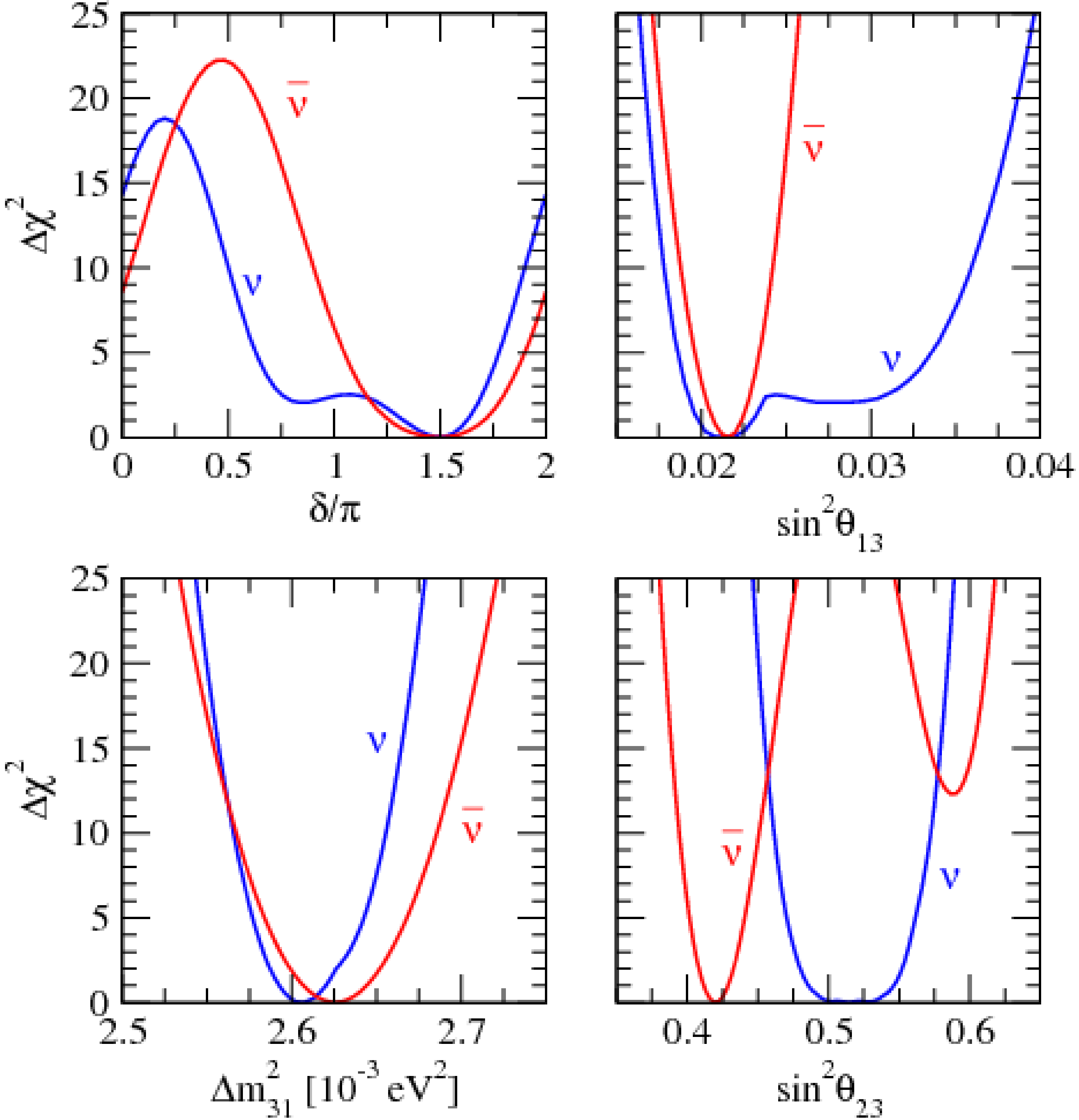
Probing the T2K results

- The good determination of $\overline{\theta}_{13}$ helps in the determination of $\overline{\delta}$





- Indeed, better determination of $\overline{\delta}$ and $\overline{\theta}_{13}$ than δ and θ_{13}



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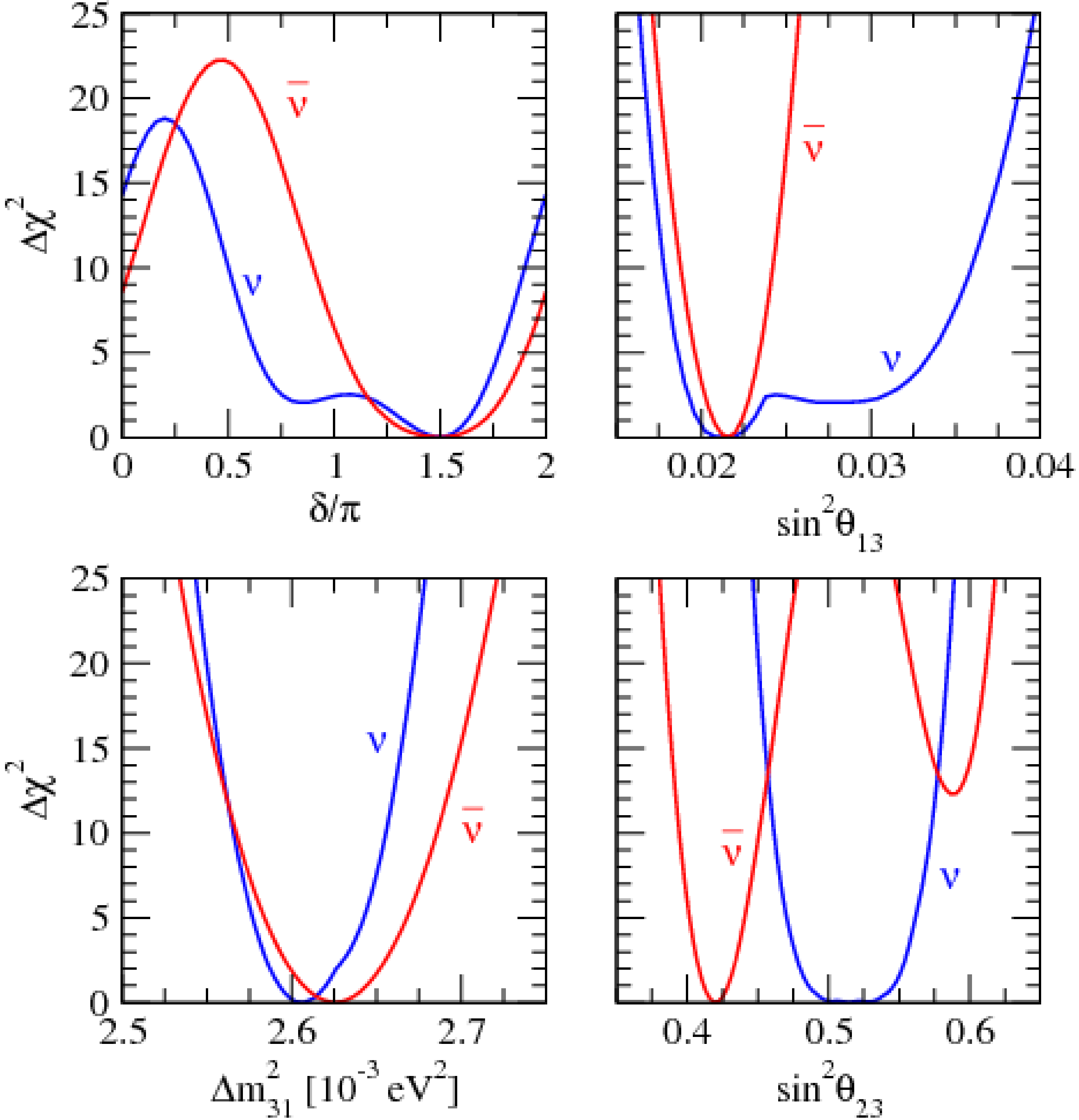

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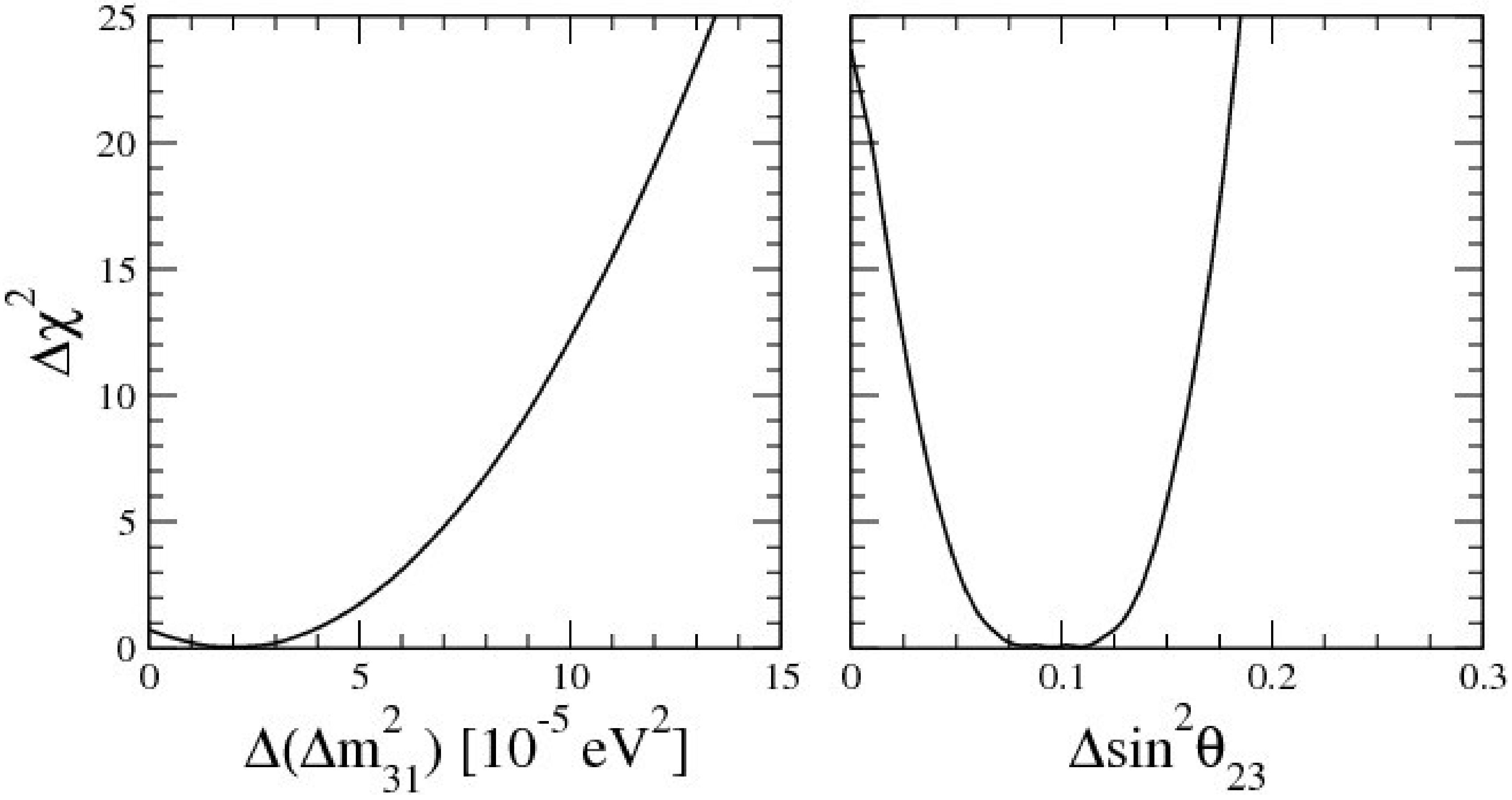
- Octant for antineutrinos is resolved at more than 3σ confidence level

Probing the T2K results

- Projecting into 1-dimensional profiles we obtain



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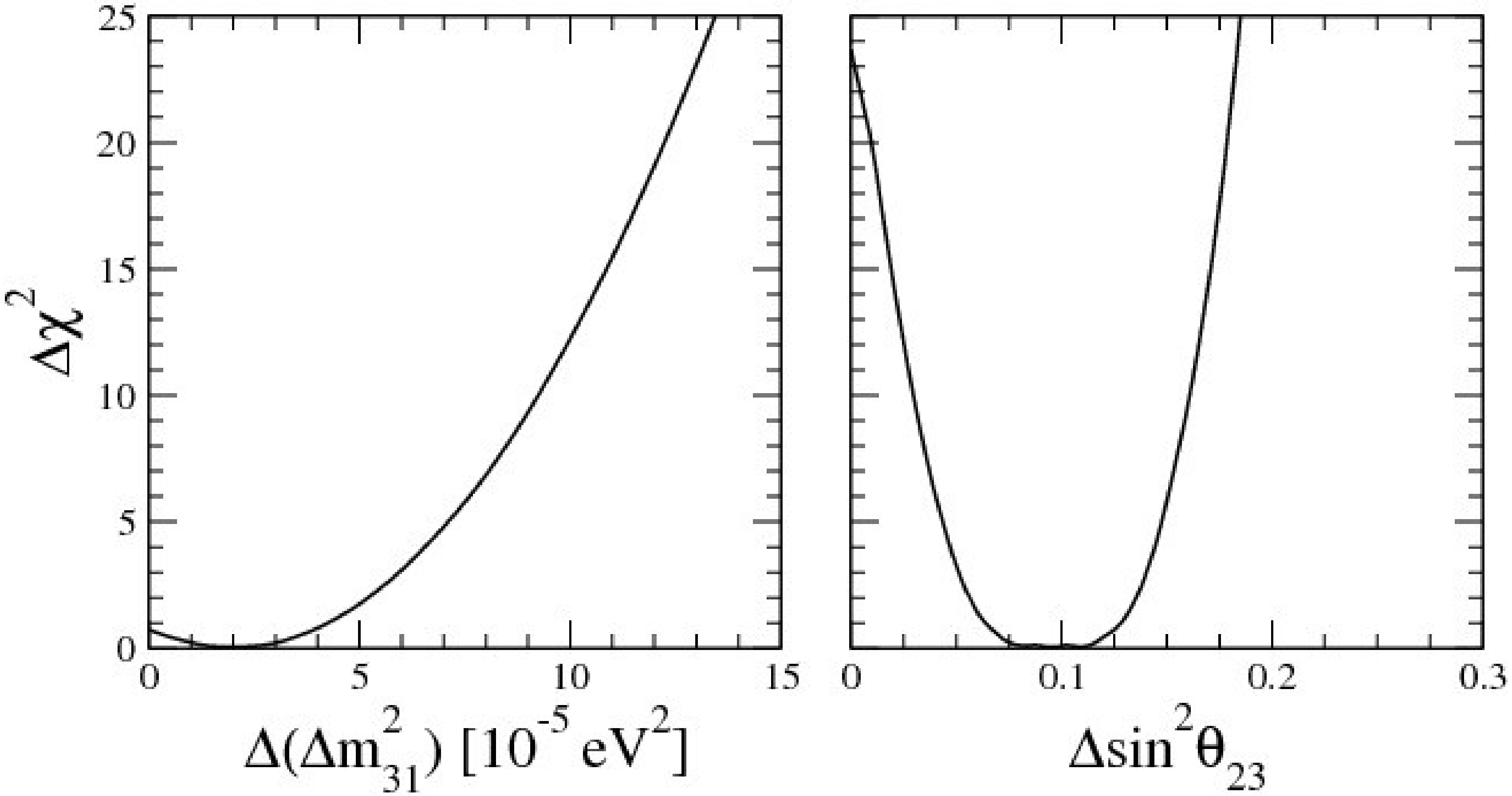

- Mass splittings are consistent with CPT conservation, atmospheric angles are not

Would such a result really indicate a violation of CPT invariance?

CPT versus NSI

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- The survival probability in matter is then

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

CPT versus NSI

- NSI affect different neutrinos and antineutrinos

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

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- The apparent CPT-violating result from T2K might be induced by NSI
- We checked this for DUNE!

CPT versus NSI

- Perform the analysis exactly as before, but add also the two NSI parameters $\epsilon^m_{\mu\tau}, \epsilon^m_{\tau\tau}$

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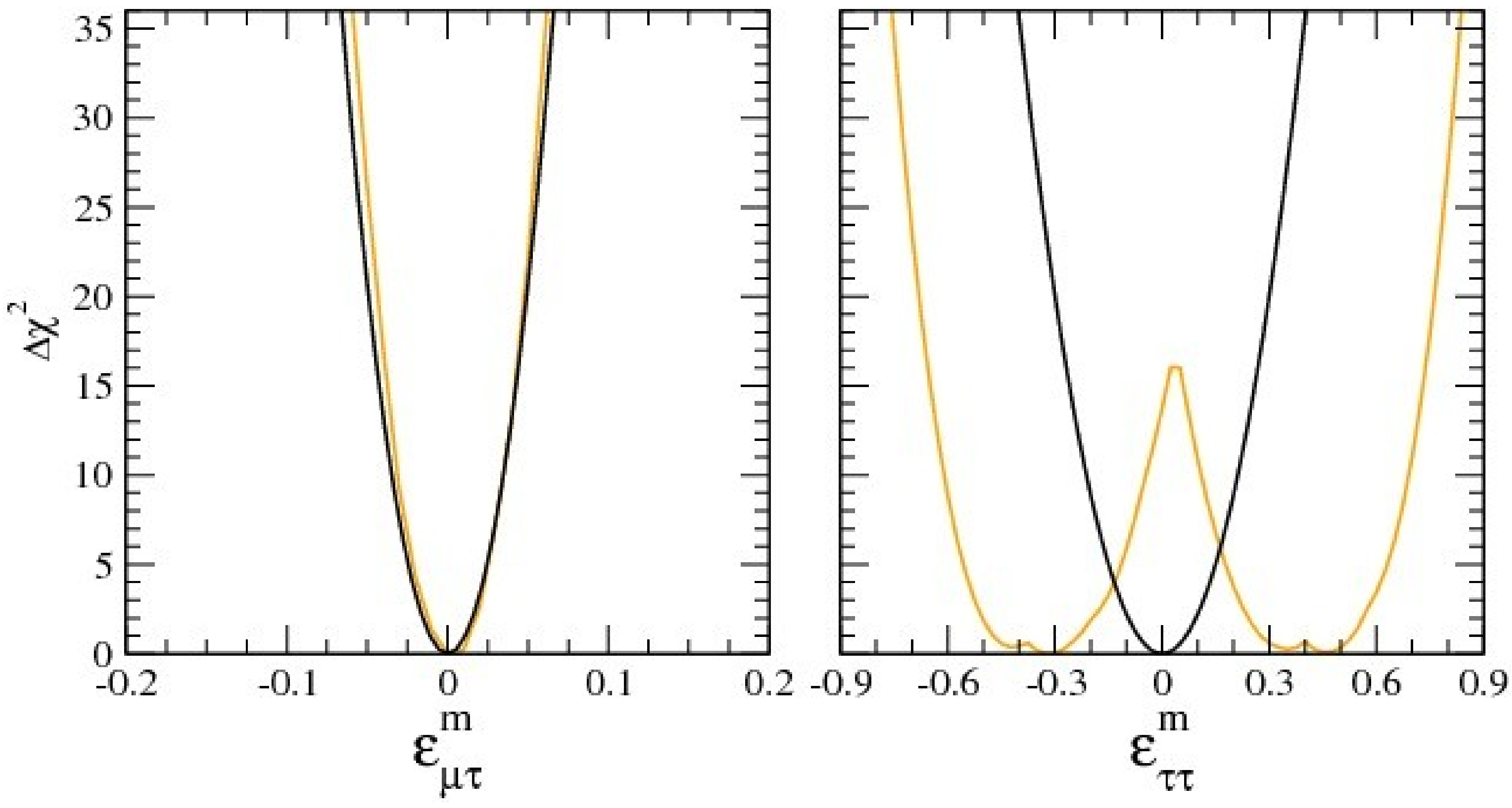
- This time we include only the disappearance channel
- At the end sum the χ^2 grids and marginalize over all parameters, except the ones of interest

arXiv:1804.05842, G. Barenboim, CAT, M. Tórtola

CPT versus NSI

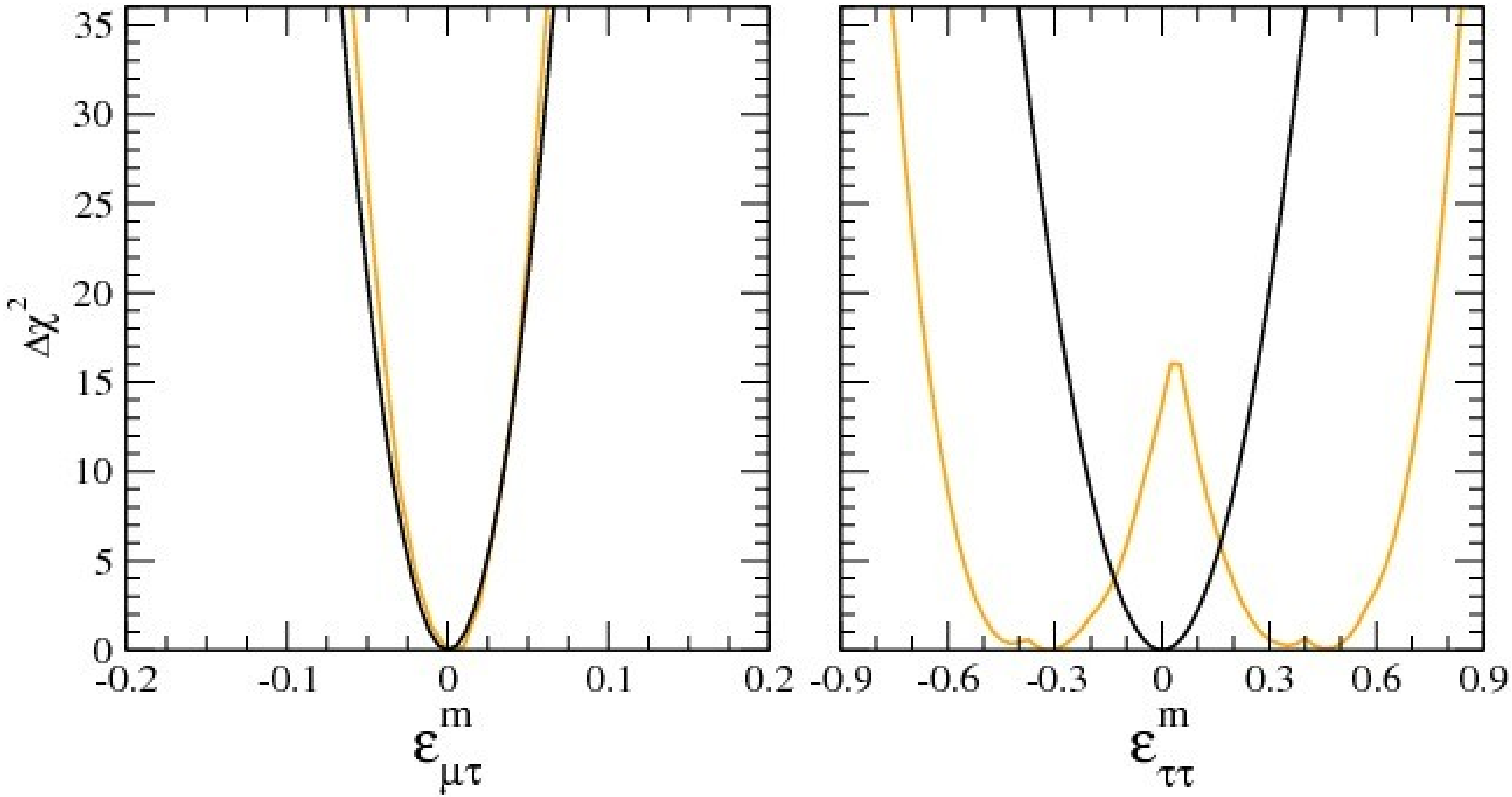
- We obtain the profiles below



arXiv:1804.05842, G. Barenboim, CAT, M. Tórtola

CPT versus NSI

- We obtain the profiles below
- Nothing special in the case of $\epsilon^{m}_{\mu\tau}$



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CPT versus NSI

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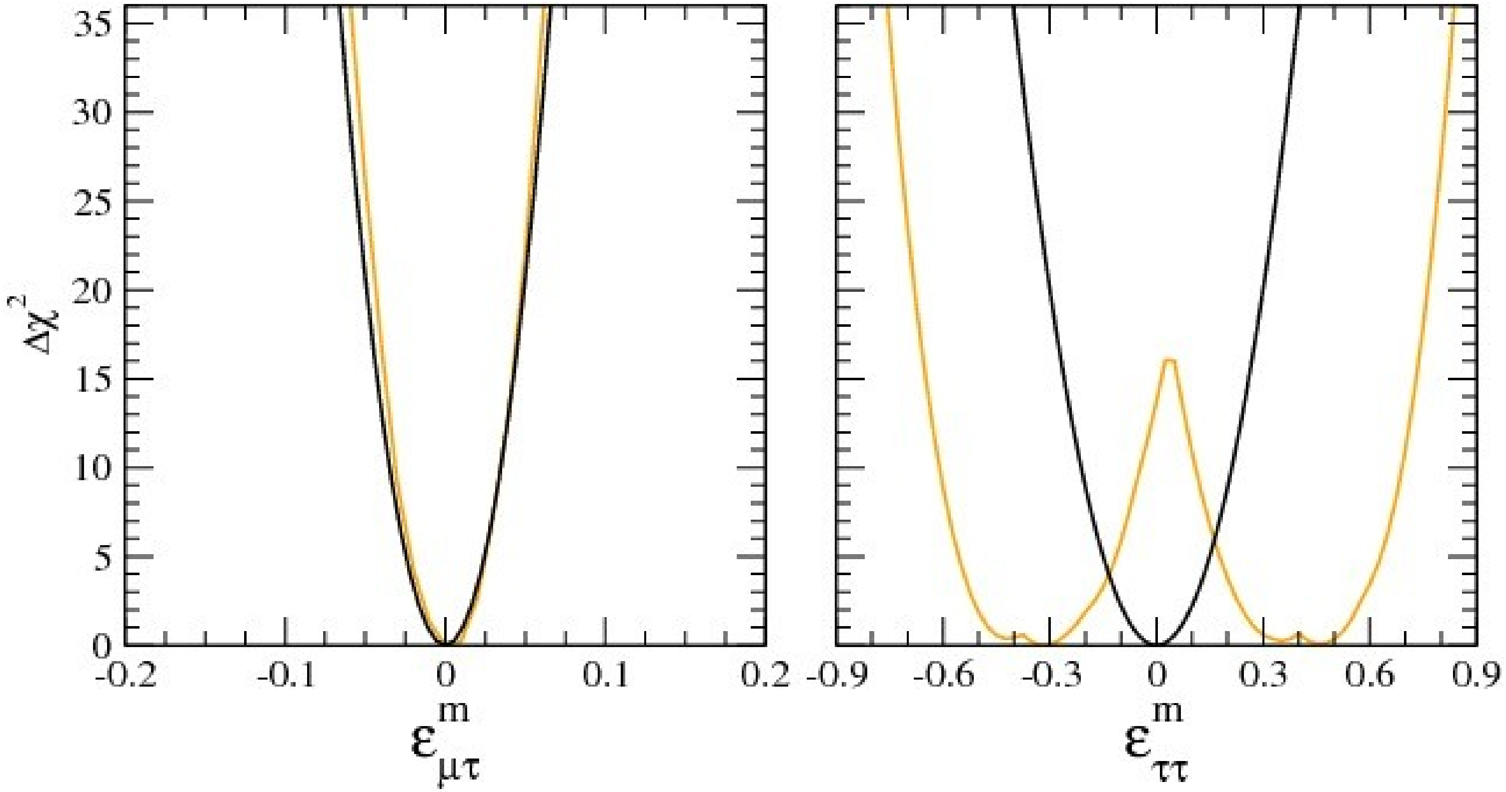

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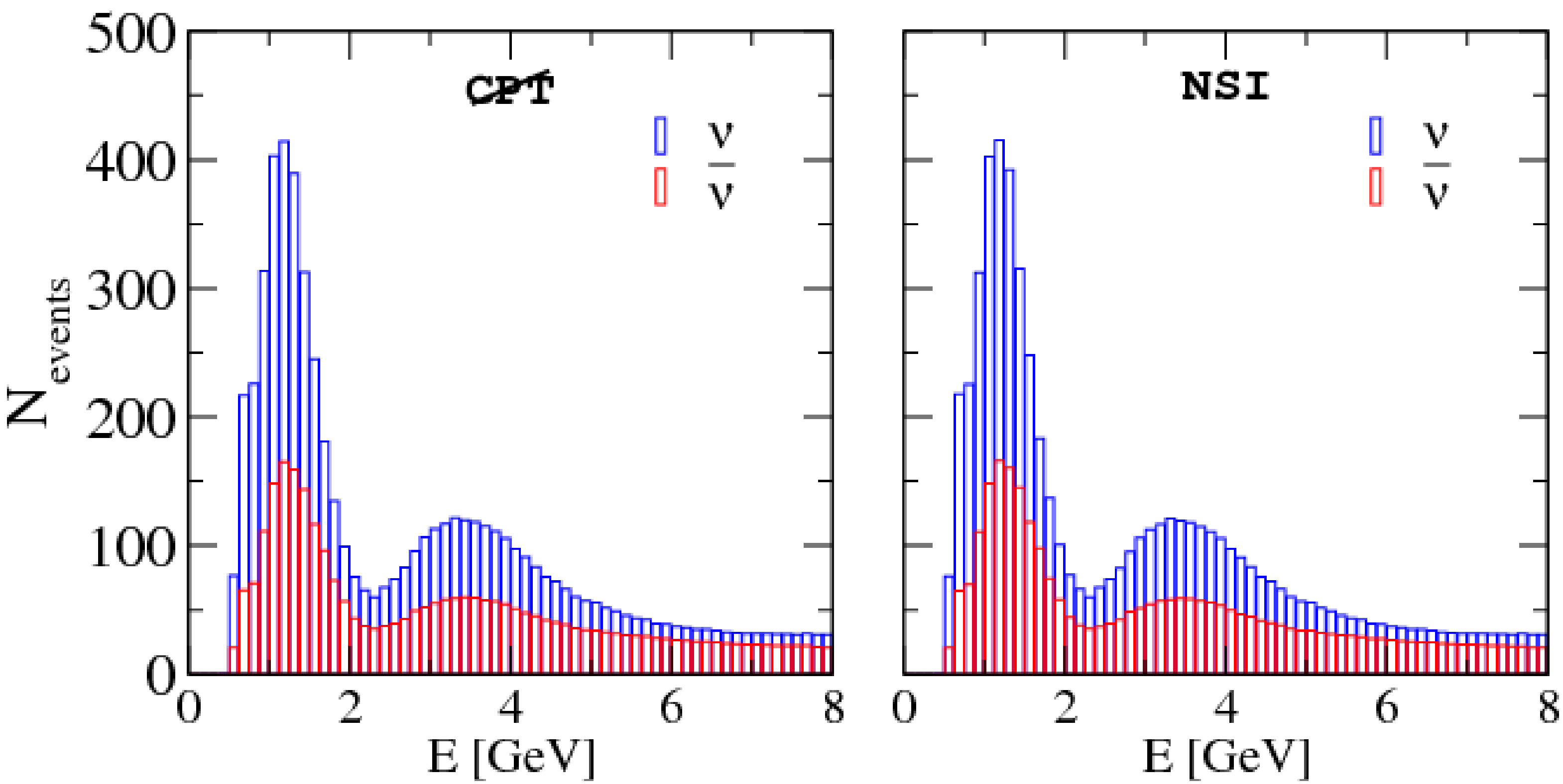

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CPT versus NSI

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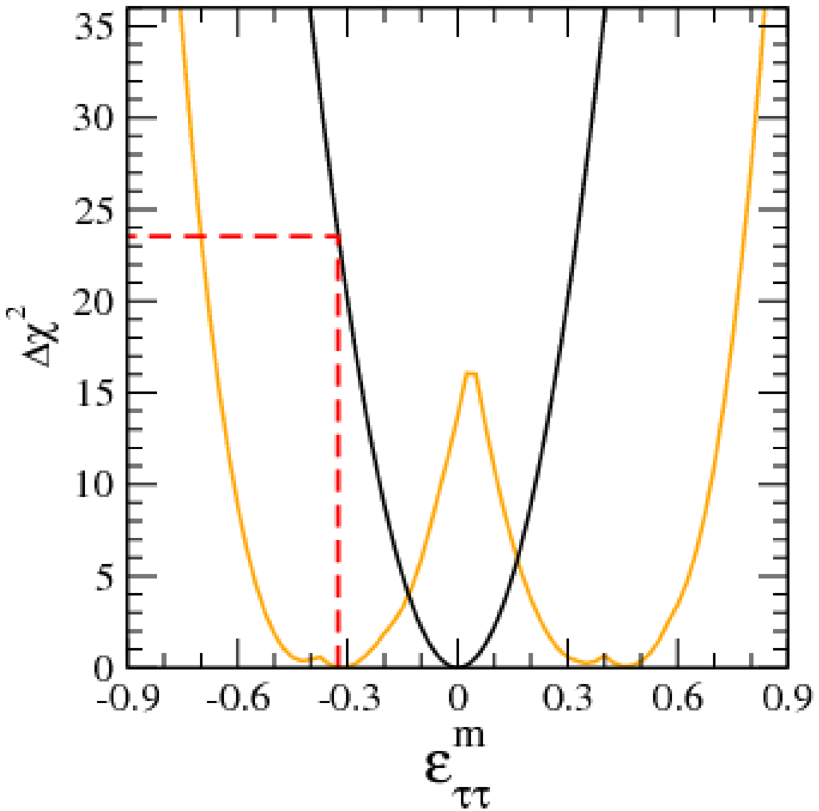
- Anyway, this value is excluded at close to 5σ



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Conclusions

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- If CPT is violated in nature we are committing errors in our analysis by combining neutrino with antineutrino results
- If the results measured by T2K turn out to be true, DUNE would measure CPT violation at more than 4σ
- NSI could not explain the apparent CPT violation measured by T2K


Thank you!
electron-
antineutrino