How robust are the recent CP violation measurements?

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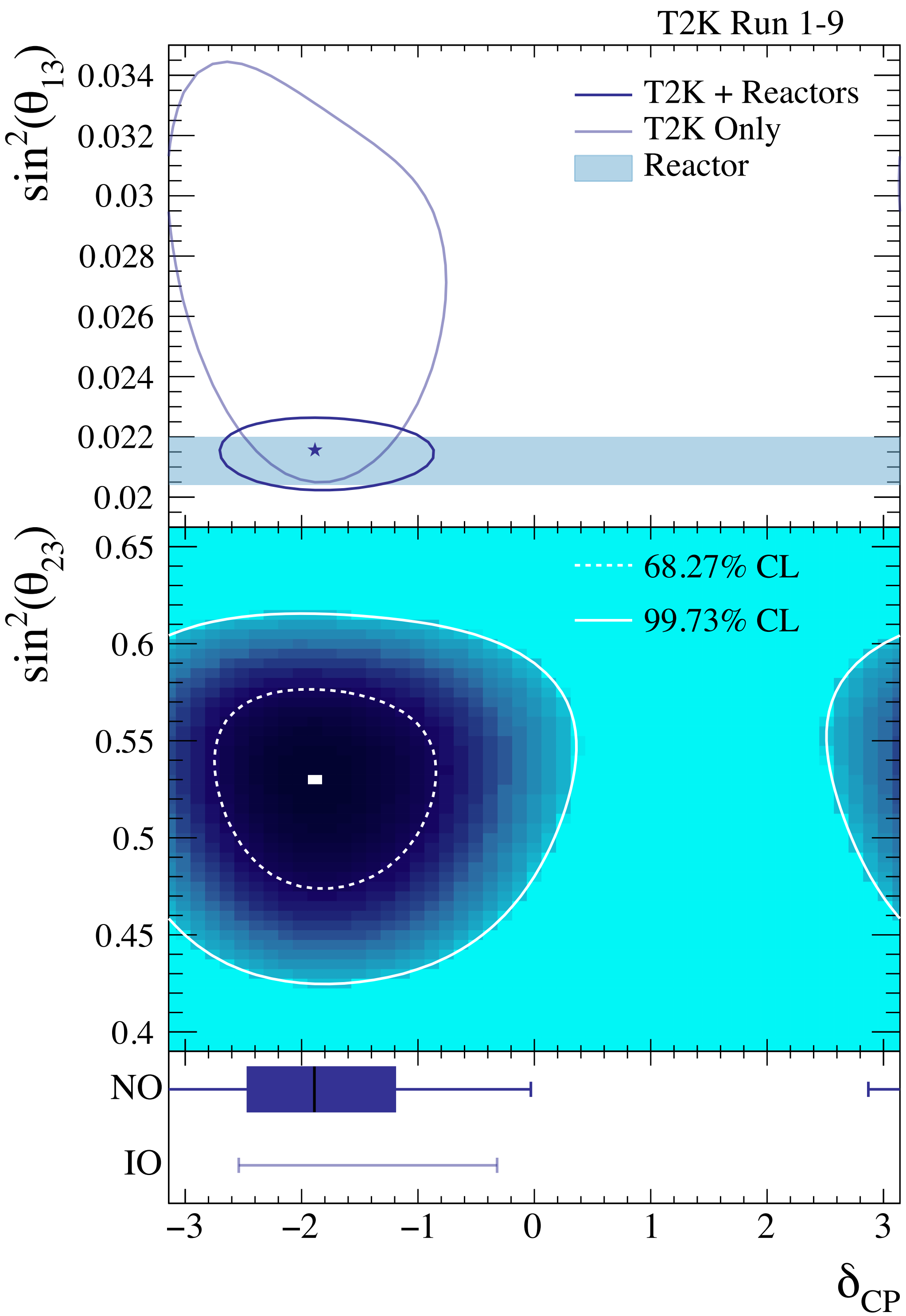
[Based on Barenboim, Ternes, MT, arXiv:2005.05975]

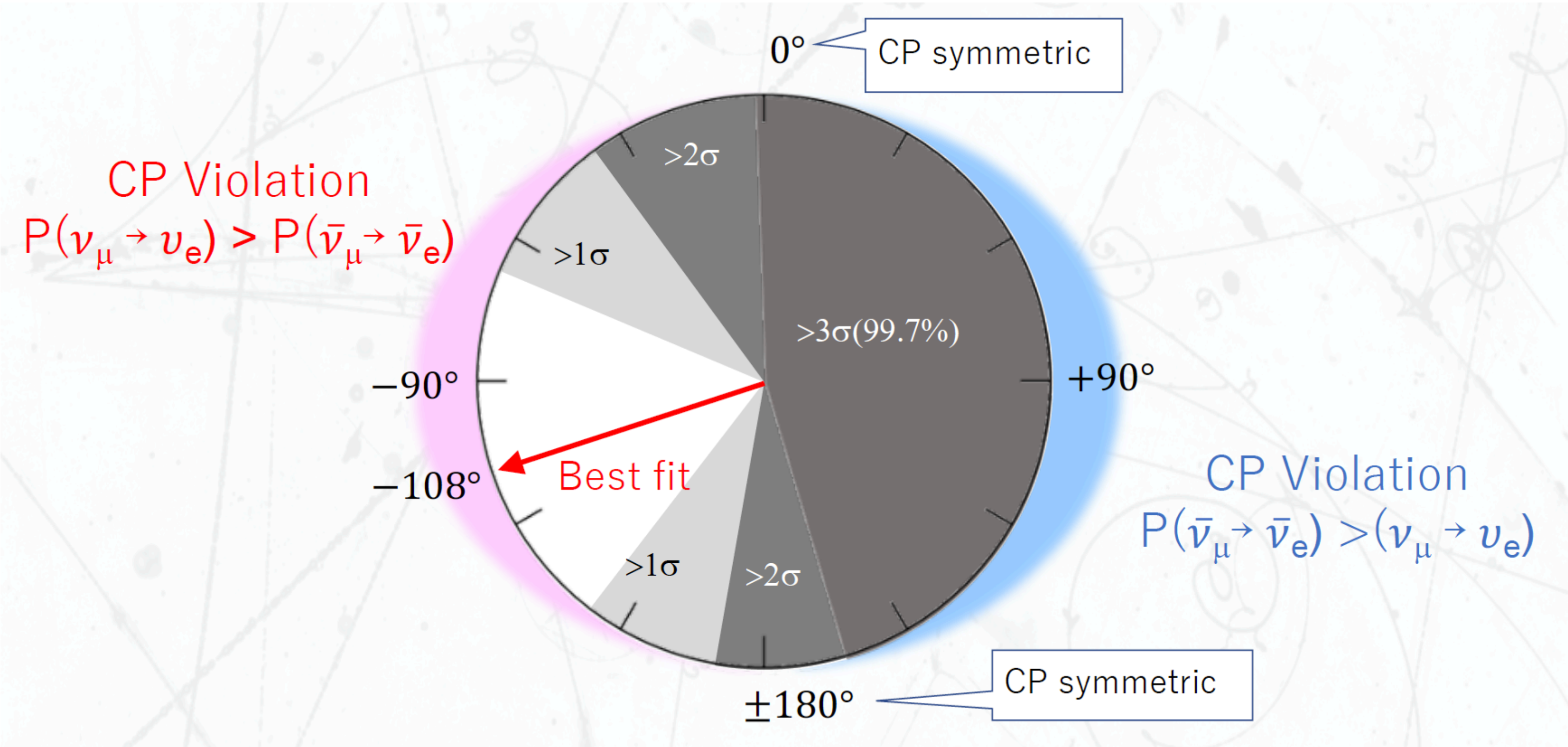
Brookhaven Neutrino Theory Virtual Seminars (BNTVS), June 8th, 2020

T2K constraint on CP violation



T2K Collaboration, Nature 580 (2020) 7803

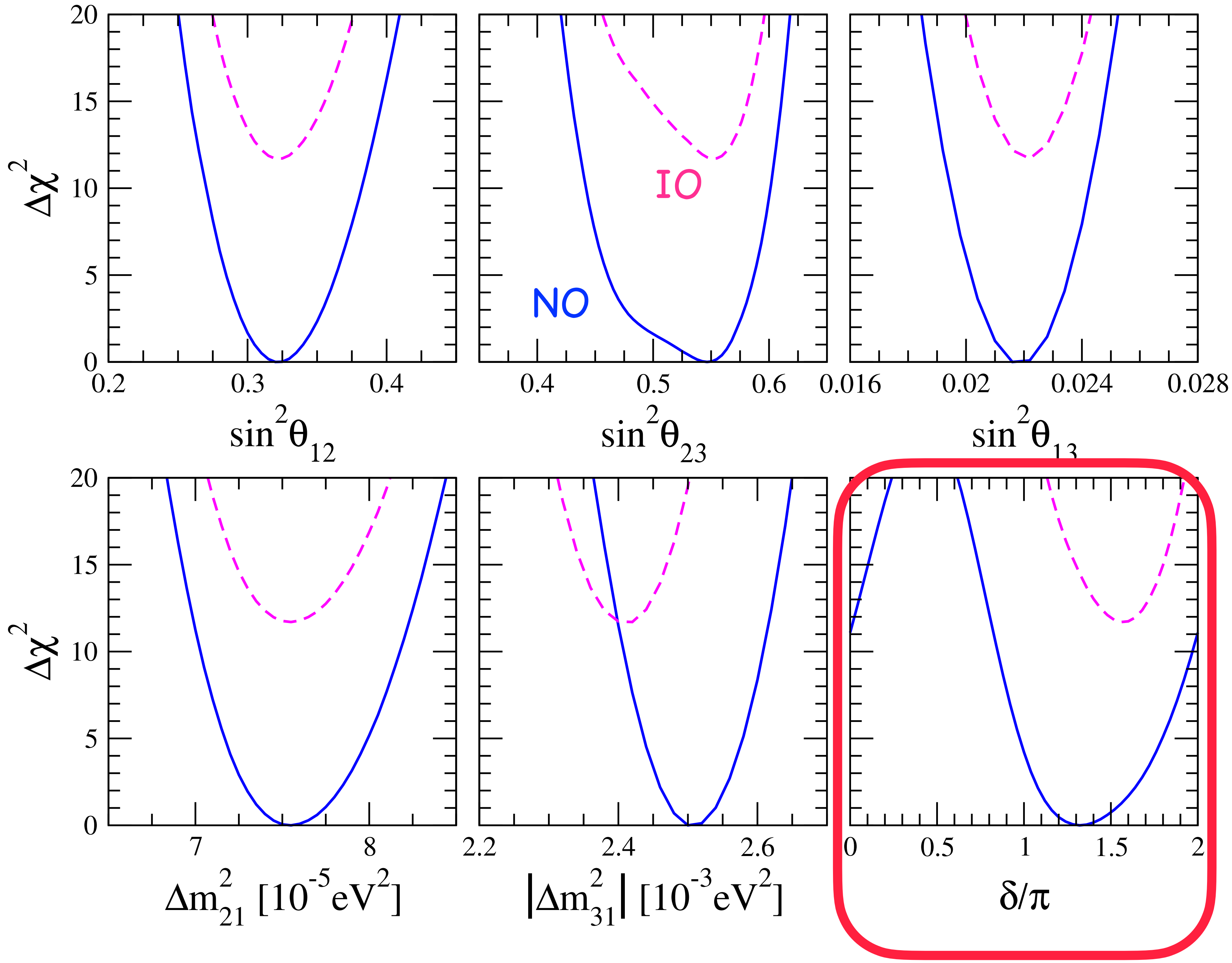
⇒ includes θ_{13} measurement from reactor experiments



F. Sánchez, CERN EP Seminar, 05/05/2020

Global fits to ν oscillation data

de Salas et al, PLB782 (2018) 633

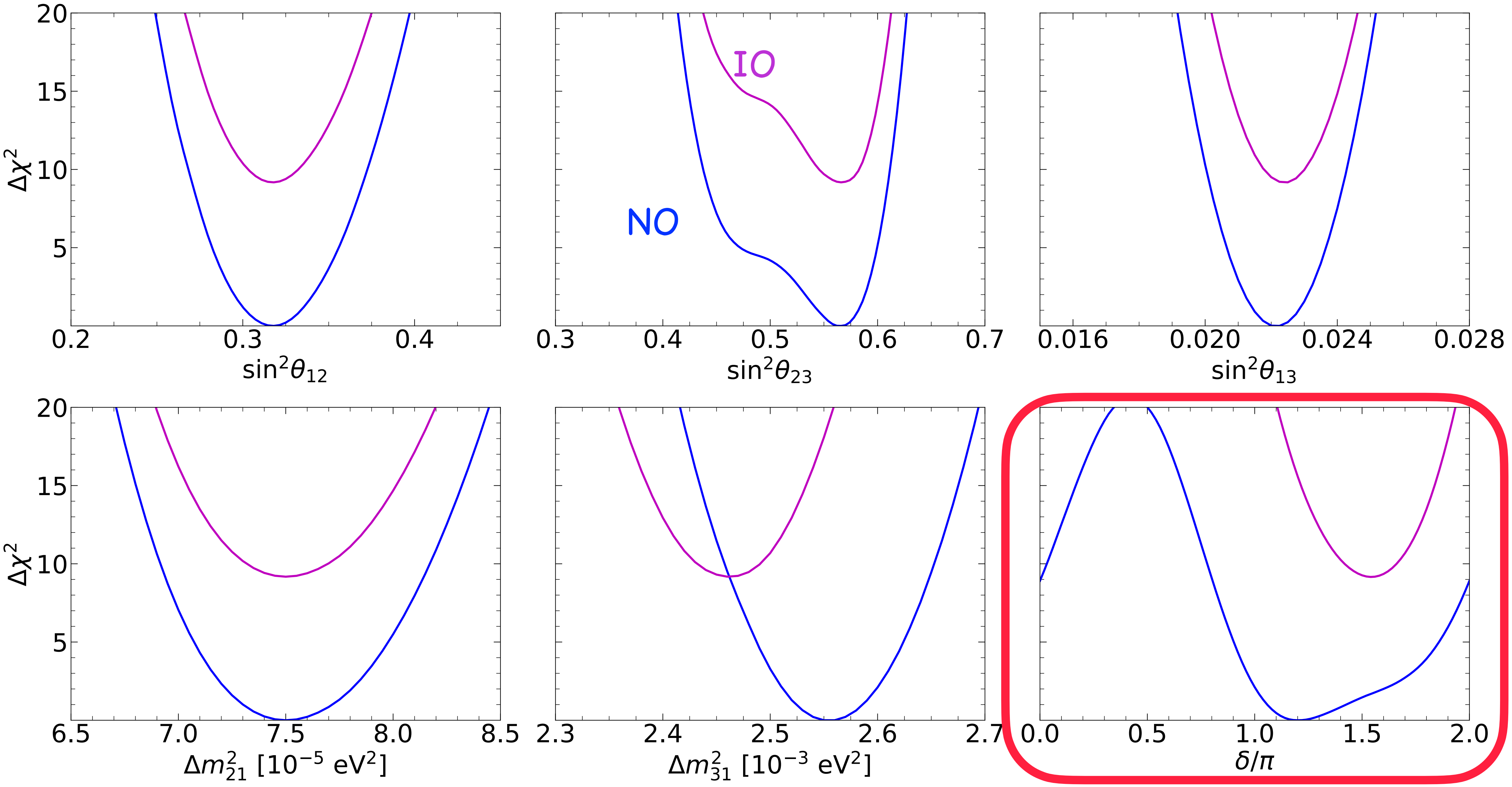


⇒ Best fit value: $\delta = 1.21\pi$ (1.56π) for NO (IO)

⇒ $\delta = \pi/2$ disfavoured at 4.8σ (6.1σ) for NO (IO), $\delta = 0$ at 3.3σ (3.5σ)

Global fits to ν oscillation data

de Salas et al, arXiv:2006.xxxxx



⇒ Best fit value: $\delta = 1.20\pi$ (1.54π) for NO (IO)

⇒ $\delta = \pi/2$ disfavoured at 4.5σ (6.7σ) for NO (IO), $\delta = 0$ at 3.0σ (3.9σ)

The three-flavour picture

neutrino mixing

$$U_{3\times3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- three mixing angles: θ_{12}, θ_{23}, θ_{13}
- three CP phases: 1 Dirac + 2 Majorana
- three masses: m_1, m_2, m_3

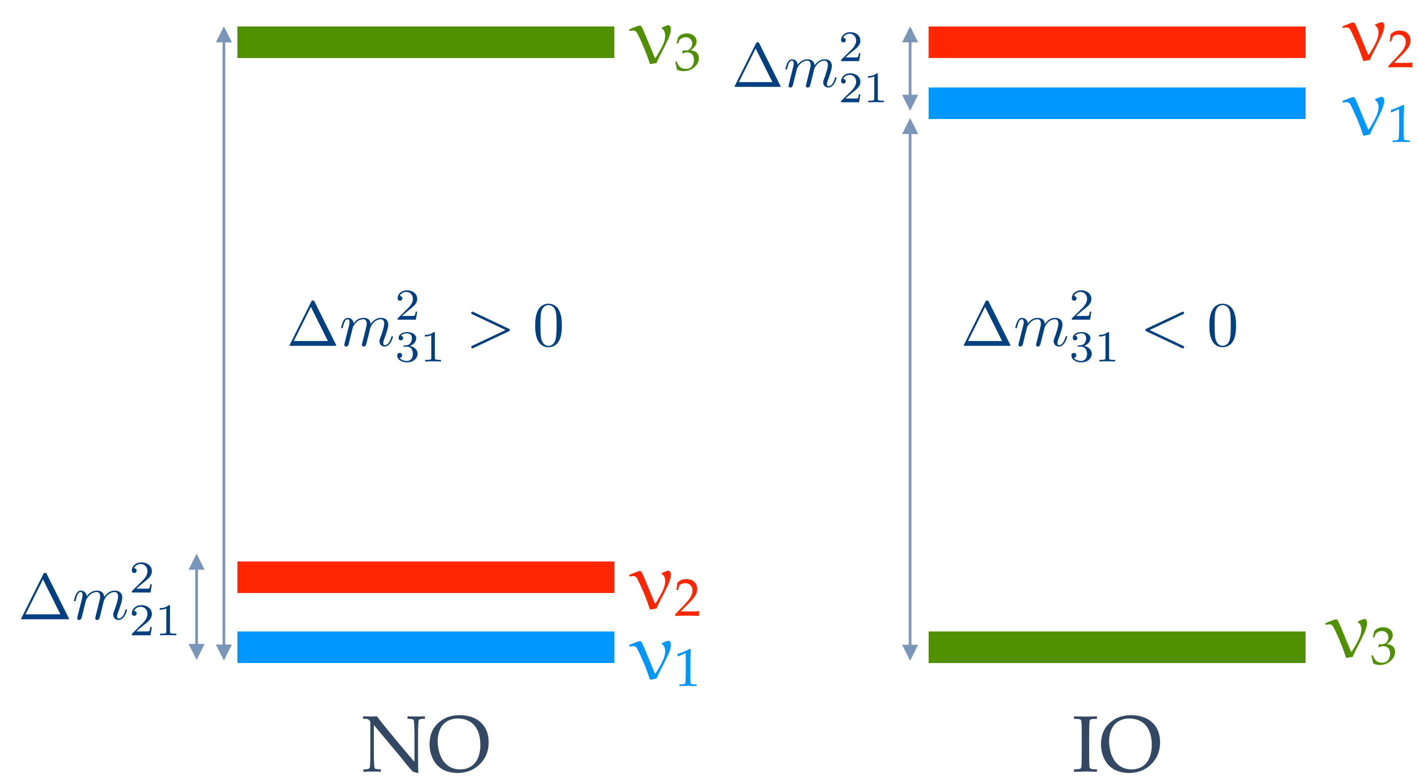
$\Rightarrow$ absolute neutrino mass: m_0

$\Rightarrow$ two mass splittings: $\Delta m^2_{21}, \Delta m^2_{31}$

CPT conservation

same masses and mixings for neutrinos and antineutrinos

neutrino mass spectrum



The three-flavour picture

Many other assumptions are implicit, as the absence of **new physics** (NP) besides neutrino masses

Robustness of CP observations against some NP scenarios has been analyzed

- Non-standard interactions (NSI) — **Esteban et al, JHEP2019**

$\Rightarrow$ CP sensitivity not affected by the presence of NSI

- Non-unitary (NU) mixing

$\Rightarrow$ T2K and NOvA sensitivity on CP

Escrihuela et al, PRD2015, NJP2017

O. Miranda et al, PRL2016

Blennow et al, JHEP2017

Dutta & Ghoshal, JHEP2016

L. Miranda et al, 1911.09398

Breaking of fundamental symmetries

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

Parity violation in weak interactions?

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)

P violated: what about **CP**?

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

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)

Evidence for **CP** violation

What about **CPT**?

CPT tests

- CPT invariance tested in several matter-antimatter systems:

  $\Rightarrow$ neutral kaons

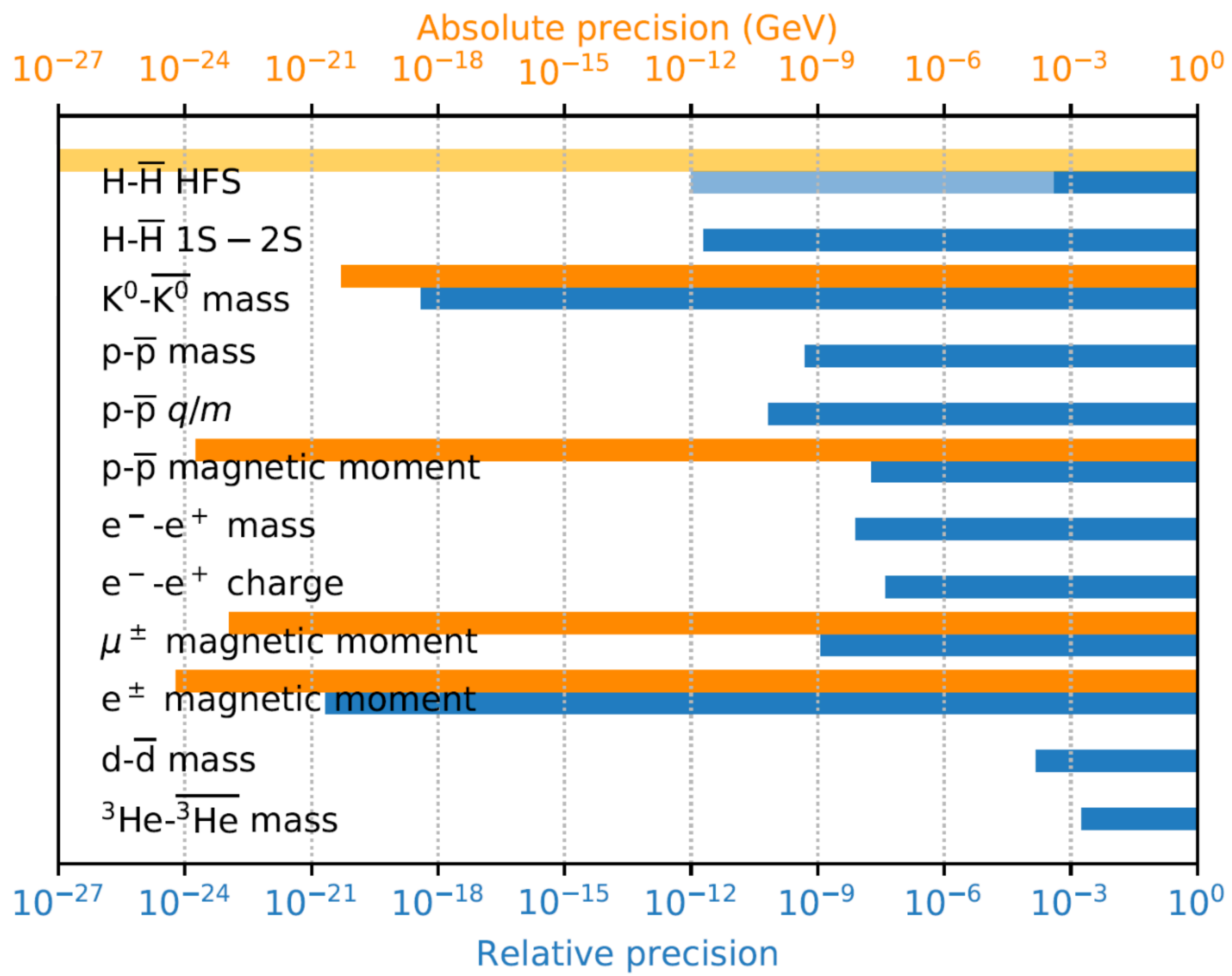
  $\Rightarrow$ electron/positron

  $\Rightarrow$ proton/antiproton

  $\Rightarrow$ H/anti-H

  $\Rightarrow$ …

- Several experiments at the Antiproton Decelerator and ELENA(Extra Low ENergy Antiproton) @CERN



E. Widmann, IFIC Colloquium 2020

CPT violation in neutrinos

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

- neutrino oscillation results derived under the assumption of CPT conservation should be reconsidered

Barenboim, Ternes, MT, arXiv:2005.05975

- neutrino oscillation data can be used to constrain CPT violation at the neutrino sector

$\Rightarrow$ current data → **Barenboim, Ternes, MT, arXiv:2005.05975**; **Barenboim, Ternes, MT, PLB2018**

$\Rightarrow$ future: DUNE, Hyper-K → **Barenboim, Ternes, MT, PLB2018**; **Gouvea & Kelly PRD2017**

☑ Test hypothesis: neutrino and antineutrino oscillations are ruled by different parameters: $(\Delta m^2_{ji}, \theta_{ij}, \delta)$ **vs** $(\overline{\Delta m}^2_{ji}, \overline{\theta_{ij}}, \overline{\delta})$

☐ For CPT-tests associated to Lorentz invariance violation see:

Kostelecky et al. **Barenboim,Masud,Ternes, MT, PLB2019**

Robustness of oscillation fits results: CP sensitivity

~~C~~PT oscillation analysis

- We reanalyze the results of neutrino fits without assuming CPT conservation.

- The number of oscillation parameters duplicates:

$$(\Delta m^2_{ji}, \theta_{ij}, \delta) + (\overline{\Delta m}^2_{ji}, \overline{\theta}_{ij}, \overline{\delta})$$

$\Rightarrow$ neutrino and antineutrino data can not be directly combined

- Since we want to focus on the sensitivity to CP:

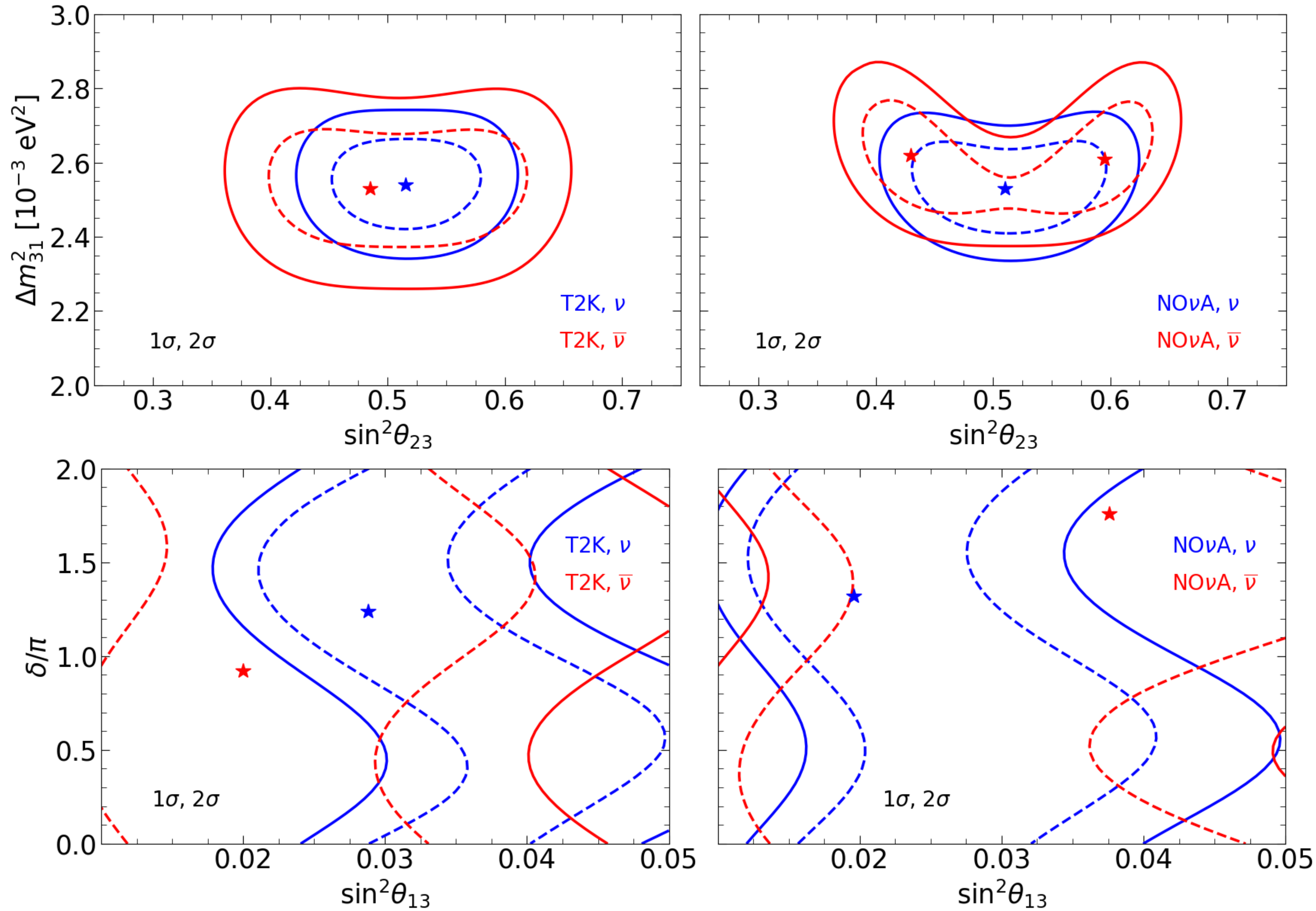
$\Rightarrow$ **neutrino parameters**: T2K & NOvA neutrino channels

$\Rightarrow$ **antineutrino parameters**: T2K & NOvA antineutrino channels + RENO & Daya Bay reactor experiments

Barenboim, Ternes, MT, arXiv:2005.05975

~~CPT~~ oscillation analysis

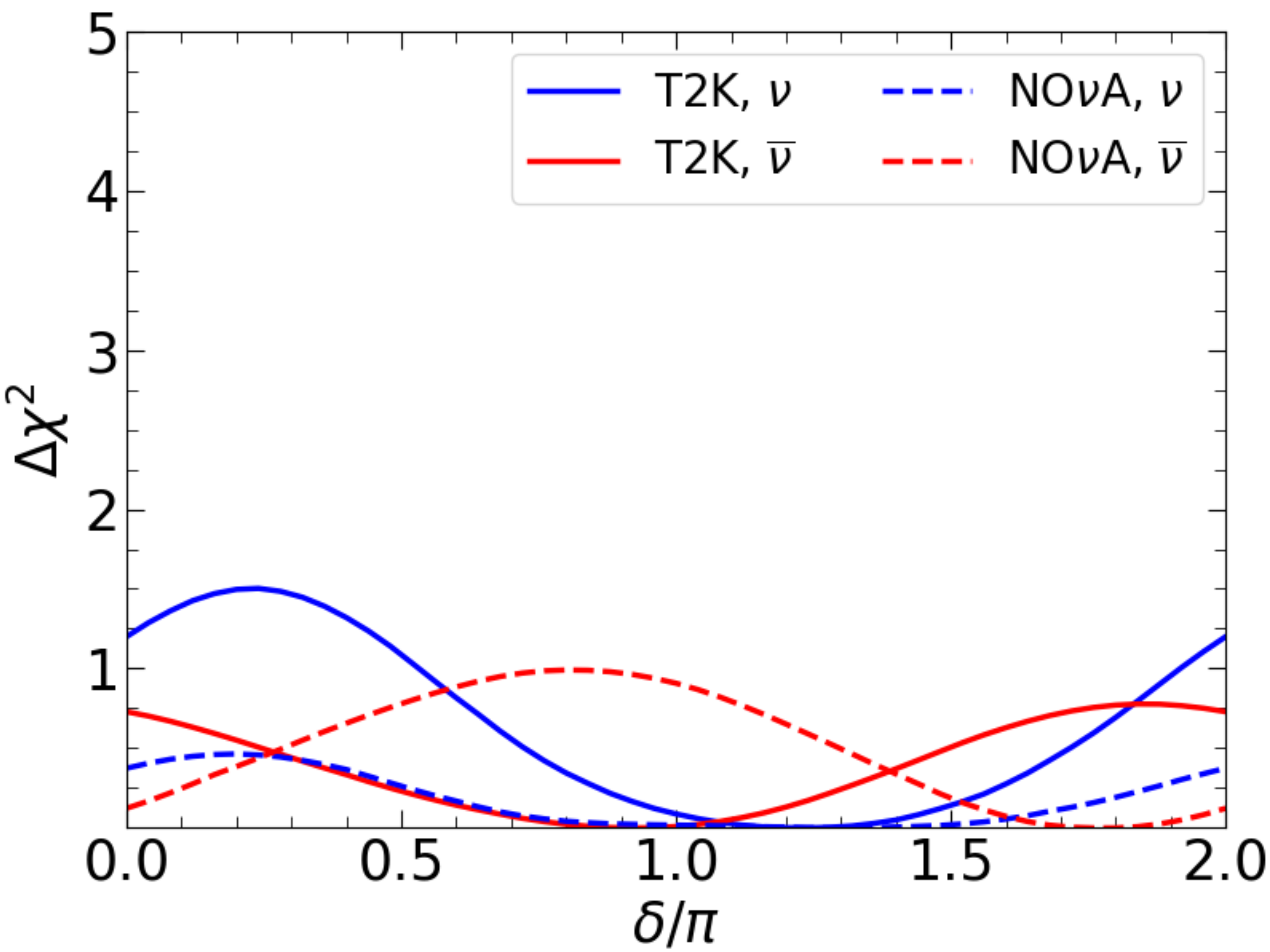
T2K and NOvA reanalysis without CPT invariance
(normal ordering)



Barenboim, Ternes, MT, arXiv:2005.05975

$\cancel{CPT}$ oscillation analysis

T2K and NOvA sensitivity to CP (normal ordering)



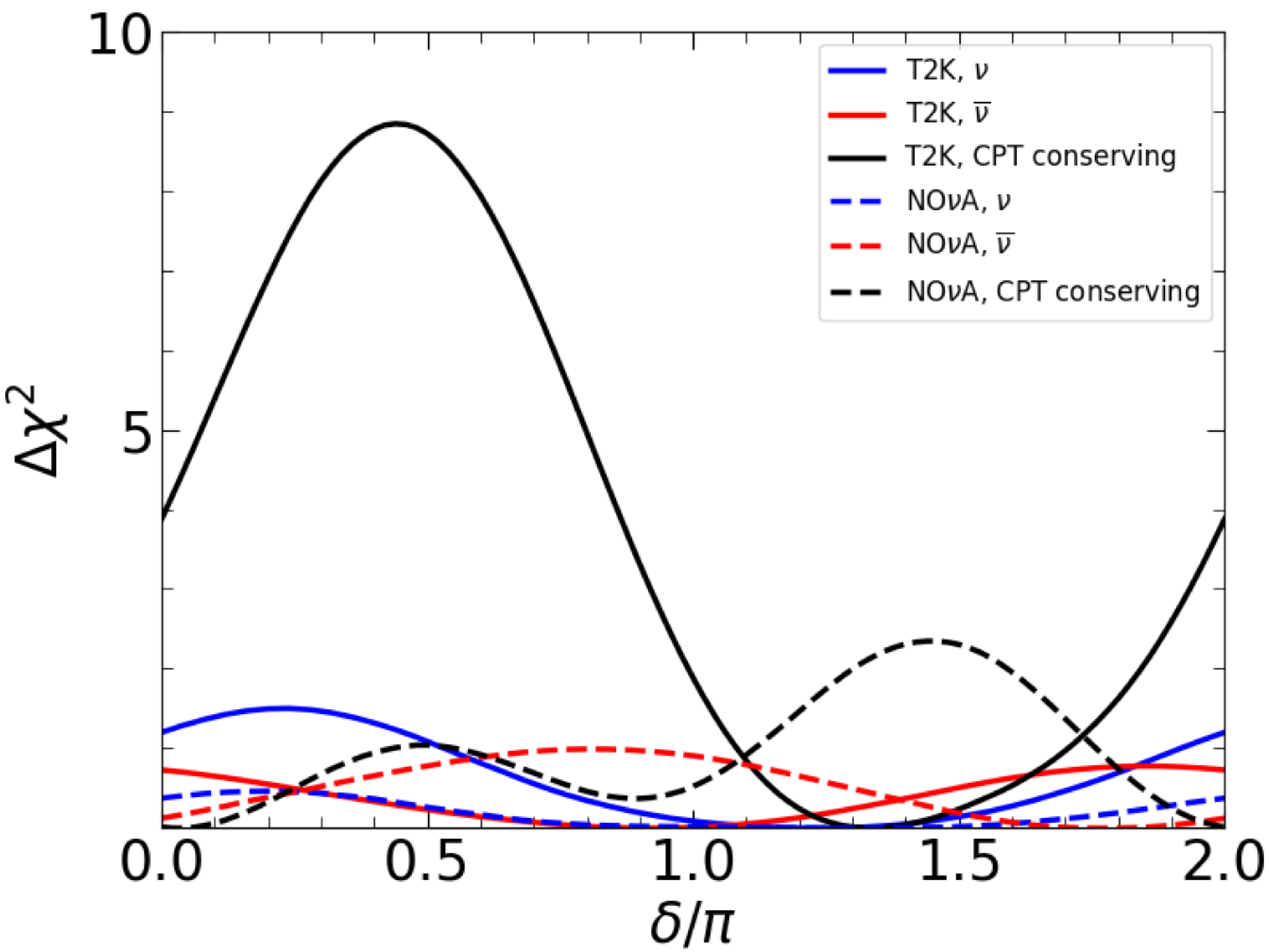
⇒ all values of δ and $\bar{\delta}$ remain allowed at ~ 1σ

⇒ $\theta_{13} \neq \bar{\theta}_{13}$ can account for different behavior in neutrino and antineutrino channels

Barenboim, Ternes, MT, arXiv:2005.05975

~~CP~~T oscillation analysis

T2K and NOvA sensitivity to CP (normal ordering)



⇒ all values of δ and $\bar{\delta}$ remain allowed at ~ 1σ

⇒ $\theta_{13} \neq \bar{\theta}_{13}$ can account for different behavior in neutrino and antineutrino channels

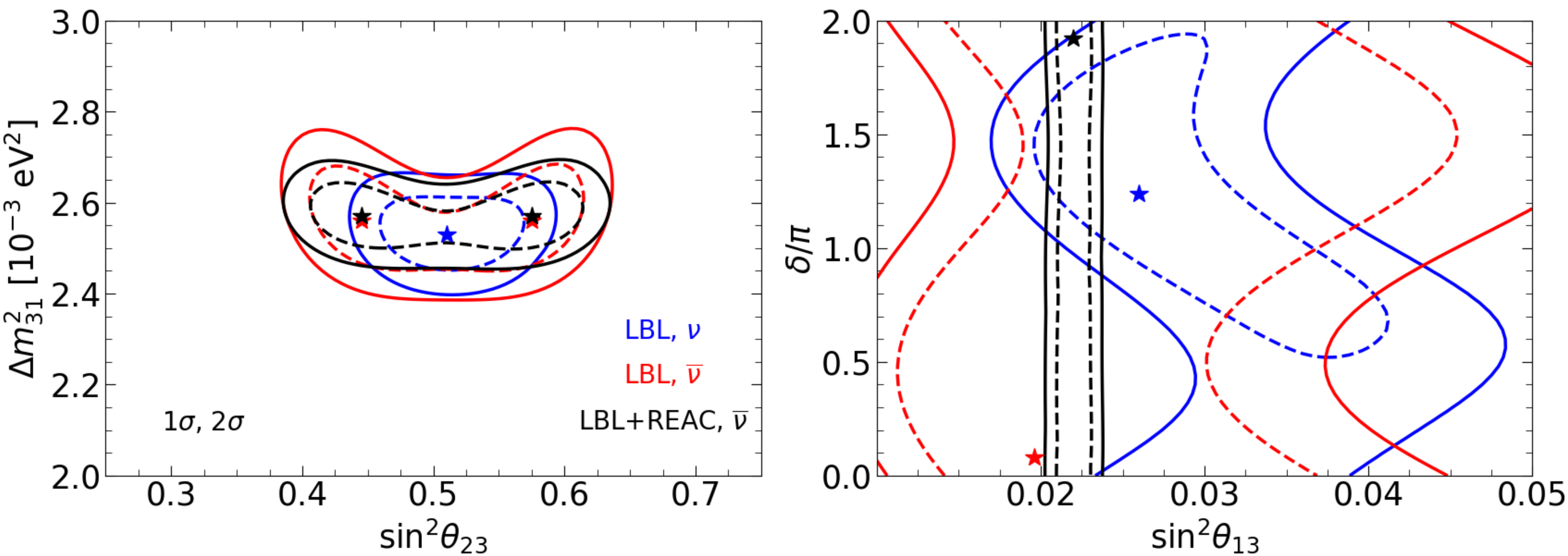
⇒ very poor sensitivity on CP violation compared to CPT-conserving scenario

Barenboim, Ternes, MT, arXiv:2005.05975

~~CPT~~ oscillation analysis

LBL + REAC (DayaBay & RENO) sensitivity to CP
(normal ordering)

Barenboim, Ternes, MT, arXiv:2005.05975



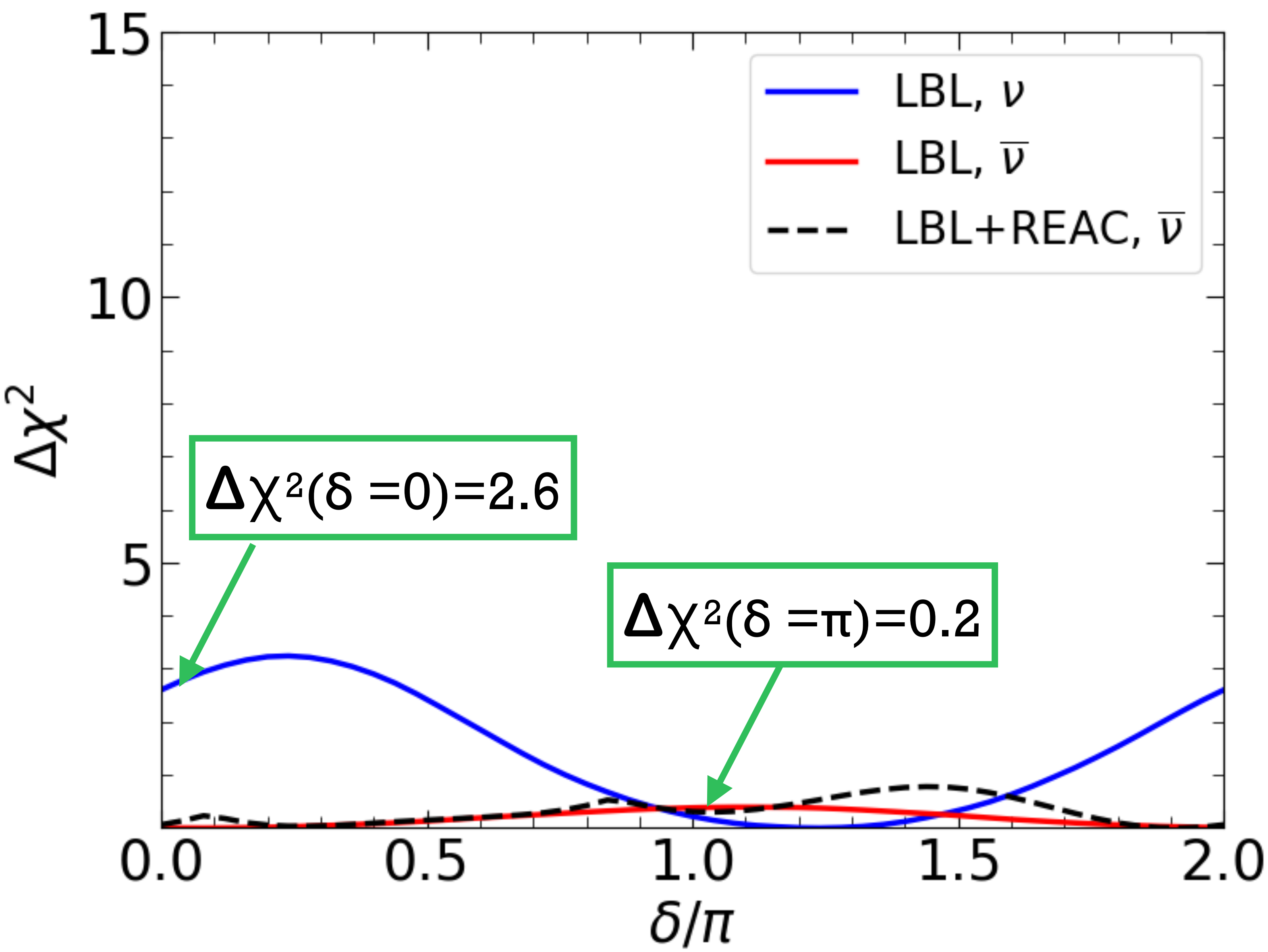
⇒ reactor data improve the sensitivity to $\overline{\Delta m^2_{31}}$

⇒ $\bar{\theta}_{13}$ sensitivity dominated by reactor experiments

⇒ poor sensitivity to θ_{13}, only measured at LBL experiments

~~CPT~~ oscillation analysis

LBL + REAC (DayaBay & RENO) sensitivity to CP
(normal ordering)



- combined LBL analysis:
  - ⇒ improved sensitivity for δ
  - ⇒ reduced sensitivity for $\bar{\delta}$
- LBL +REAC do not improve results for $\bar{\delta}$:

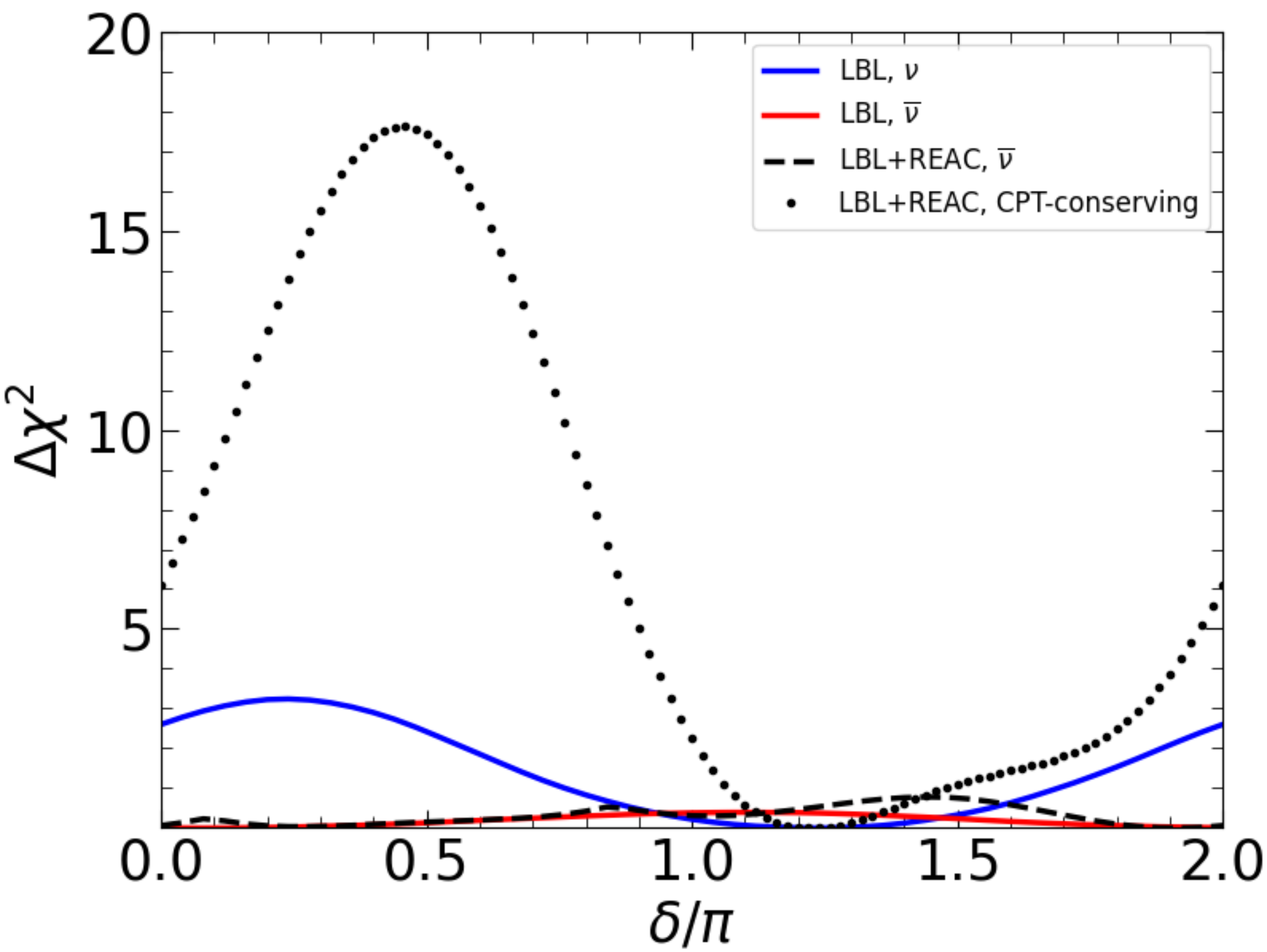
⇒ all values allowed with $\Delta\chi^2 < 1$

- Any value of δ can be excluded above 2σ

Barenboim, Ternes, MT, arXiv:2005.05975

~~CPT~~ oscillation analysis

LBL + REAC (DayaBay & RENO) sensitivity to CP
(normal ordering)



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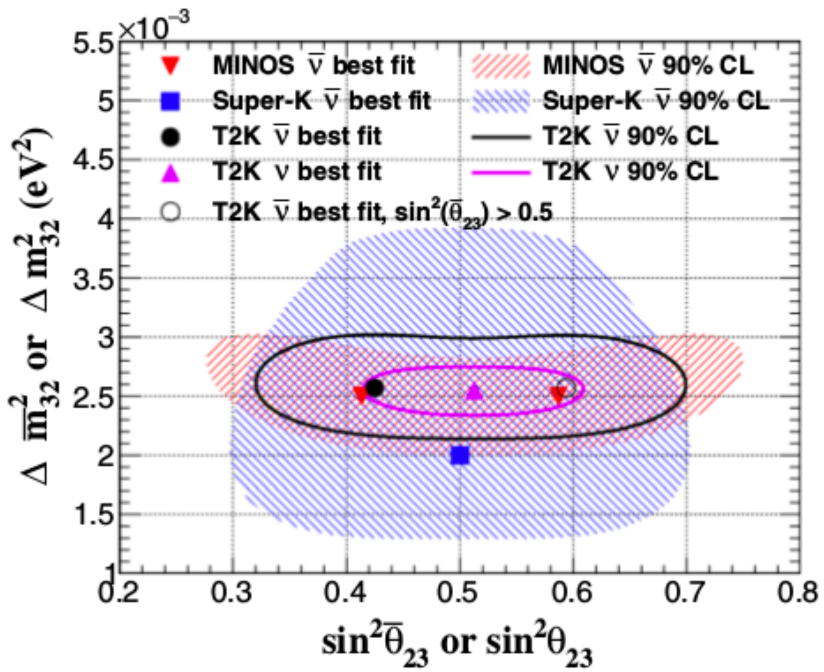
Barenboim, Ternes, MT, arXiv:2005.05975

Constraints on CPT violation

~~CPT~~ in neutrino oscillations

- Most recent experimental test performed by T2K **T2K Coll, PRD2017**



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

→ different best fit values

→ consistent with CPT conservation

- Updated (2018) bounds on CPT violation at 3σ:

Barenboim, Ternes, MT, PLB2018

$$|\sin^2\theta_{12} - \sin^2\bar{\theta}_{12}| < 0.14,$$
$$|\sin^2\theta_{13} - \sin^2\bar{\theta}_{13}| < 0.03,$$
$$|\sin^2\theta_{23} - \sin^2\bar{\theta}_{23}| < 0.32$$

$$|\Delta m^2_{21} - \Delta \overline{m}^2_{21}| < 4.7 \times 10^{-5} \mathrm{eV}^2$$
$$|\Delta m^2_{31} - \Delta \overline{m}^2_{31}| < 3.7 \times 10^{-4} \mathrm{eV}^2$$

For previous results, see: **Ohlsson & Zhou, NPB2015**

$\cancel{CPT}$ in neutrino oscillations

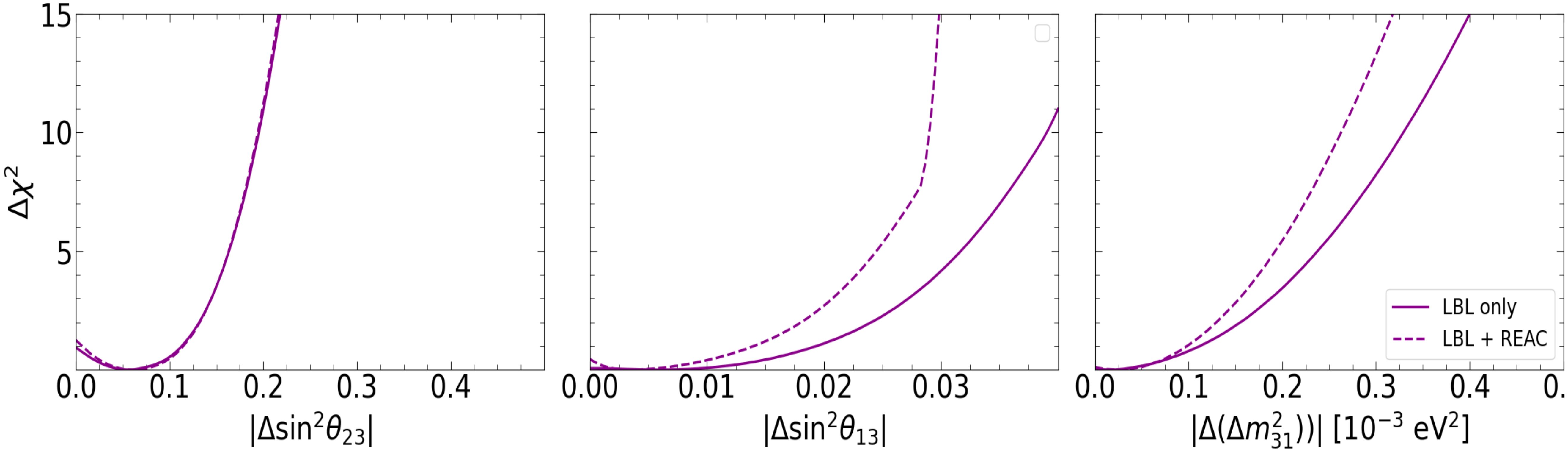
- Updated bounds at 3σ:

$$|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| < 0.14$$
$$|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| < 0.029$$
$$|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| < 0.19$$

$$|\Delta m^2_{21} - \Delta\overline{m}^2_{21}| < 4.7 \times 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m^2_{31} - \Delta\overline{m}^2_{31}| < 2.5 \times 10^{-4}\ \mathrm{eV}^2$$

Barenboim, Ternes, MT, arXiv:2005.05975

$$|\Delta x| = |x - \overline{x}|$$



~~CP~~T sensitivity in DUNE

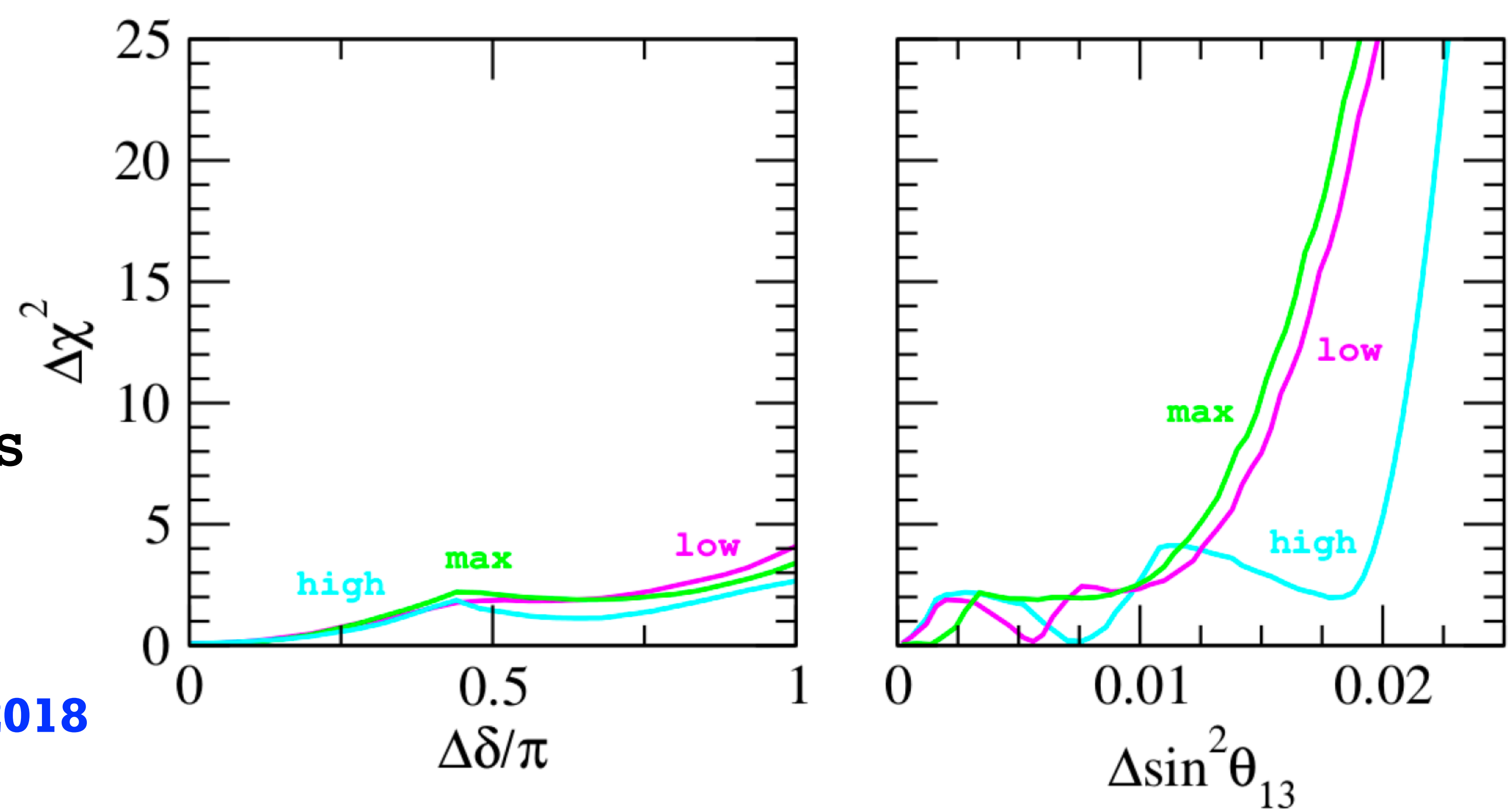
- DUNE's simulation:
  - → disappearance + appearance channels
  - → 3.5 yr neutrino run + 3.5 yr antineutrino run

- Sensitivity to the difference between neutrino and antineutrino params.

$$\Delta x = |x - \overline{x}| \quad \text{for} \quad x \equiv \Delta m^2_{31}\,,\theta_{23}\,,\theta_{13}\,,\delta$$

- Poor sensitivity to differences in CP phase and reactor angle

  → three different values of θ_{23} considered

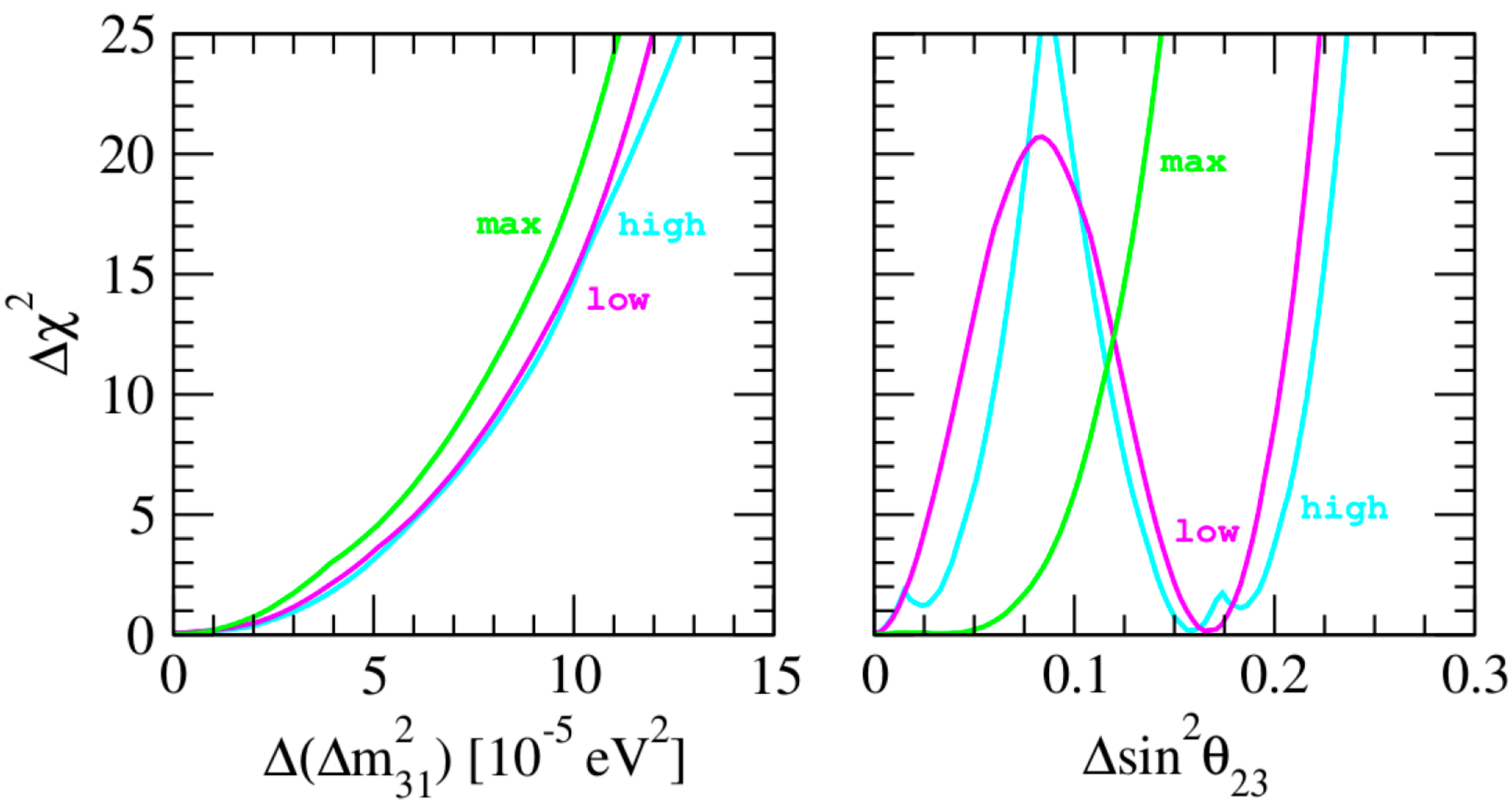


Barenboim, Ternes, MT, PLB2018

~~CPT~~ sensitivity in DUNE

☑ Very good sensitivity to differences in atmospheric parameters

Barenboim, Ternes, MT, PLB2018



→ one order of magnitude improvement:

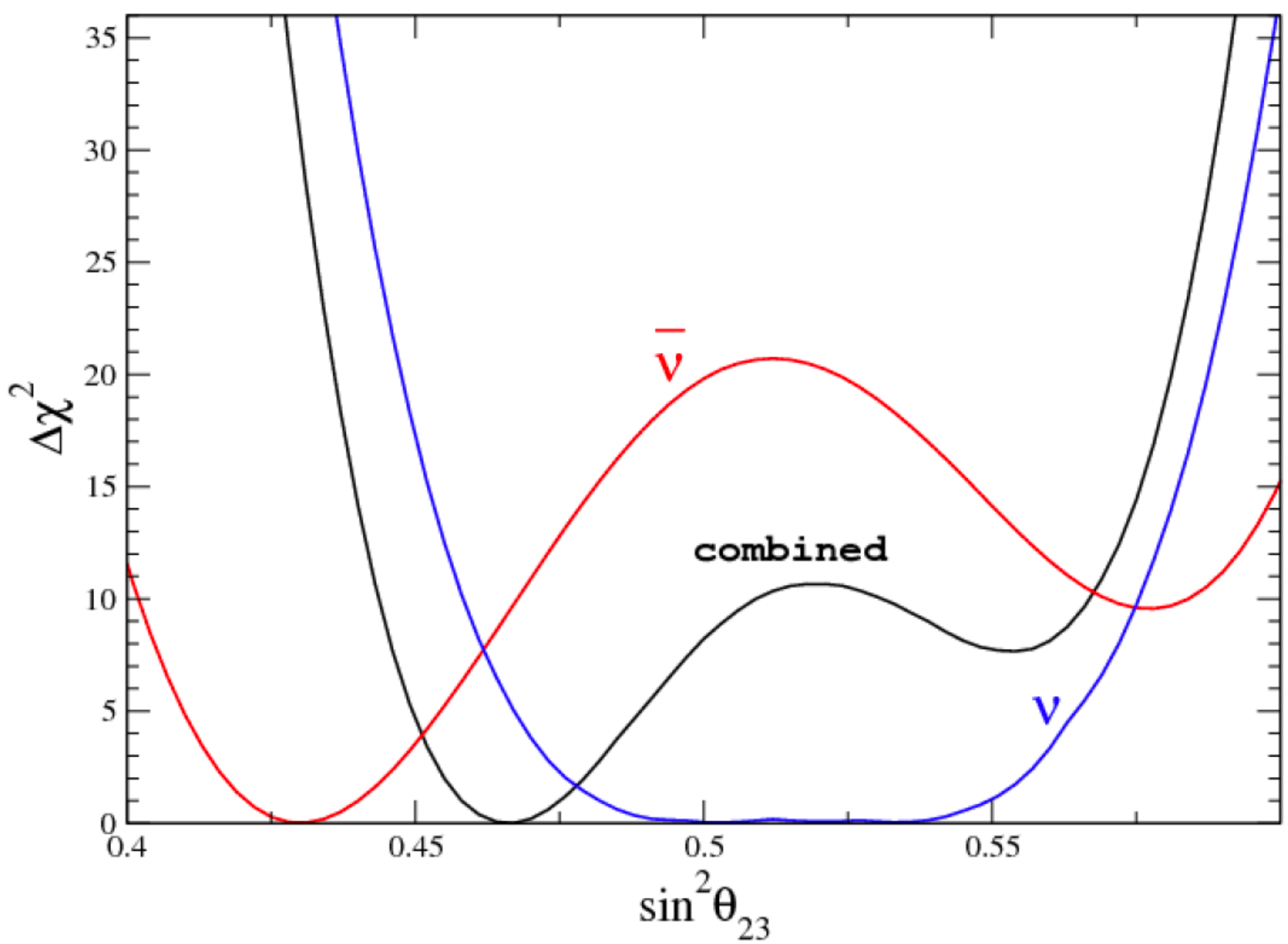
$$\Delta(\Delta m^2_{31}) < 8.1 \times 10^{-5}\mathrm{eV}^2 \quad (3\sigma)$$

→ excellent sensitivity for max mixing

→ oscillating results for high and low octant due to degeneracies

~~CPT~~ oscillations: imposter solutions

- Standard analyses of oscillation data assume CPT conservation
- If CPT is violated one can obtain imposter solutions
- Ex: DUNE neutrino data simulated with $\sin^2\theta_{23} = 0.5\,, \sin^2\overline{\theta}_{23} = 0.43$



→ the combined analysis under CPT conservation gives the best fit value:

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

→ real true values disfavored at close to 3σ (neutrino) and more than 5σ (antineutrino)

Barenboim, Ternes, MT, PLB2018

Summary

- ☑ The increasing precision in neutrino oscillation measurements requires a thorough analysis of the assumptions considered.
- ☑ Precision measurements of neutrino oscillation parameters might be affected by the presence of new physics scenarios.
- ☑ CPT violation at the neutrino sector has not been tested in depth yet.
- ☑ Current neutrino oscillation data can be used to test this hypothesis.
- ☑ Future experiments (DUNE, Hyper-K, JUNO) will improve current bounds on CPT violation in neutrinos.