New physics searches in neutrino experiments

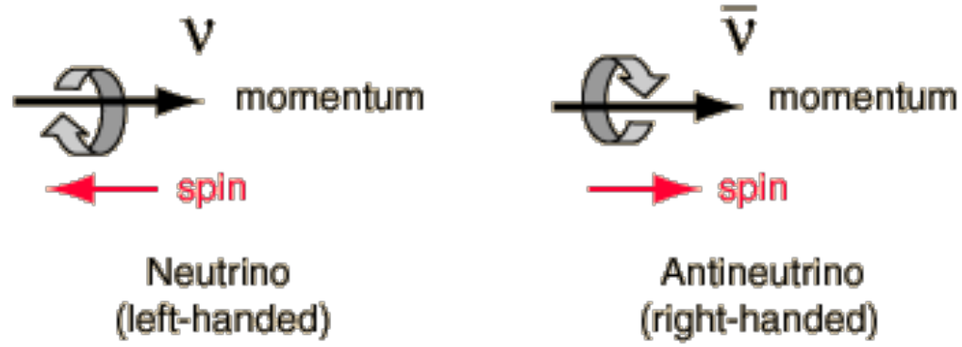
Mariam Tórtola
IFIC, CSIC/Universitat de València

CPNR Workshop 2026
“Neutrinos and Physics Beyond the Standard Model”

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
CSIC Consejo Superior de Investigaciones Científicas
Universitat de València
IFIC Institut de Física Corpuscular
Excelencia Severo Ochoa
Generalitat Valenciana Conselleria d'Educació, Universitats i Ocupació

Neutrinos in the Standard Model

- The SM only contains LH neutrinos (and RH antineutrinos): no $SU(2)_L$ RH neutrinos



- Only neutral fundamental fermion: Dirac or Majorana nature?
- No mass term for neutrinos can be built with the content of the SM:

Dirac mass term

$$m\overline{\nu}_R\nu_L$$

Majorana mass term

$$\frac{1}{2}m\nu_L^T\mathcal{C}^\dagger\nu_L$$

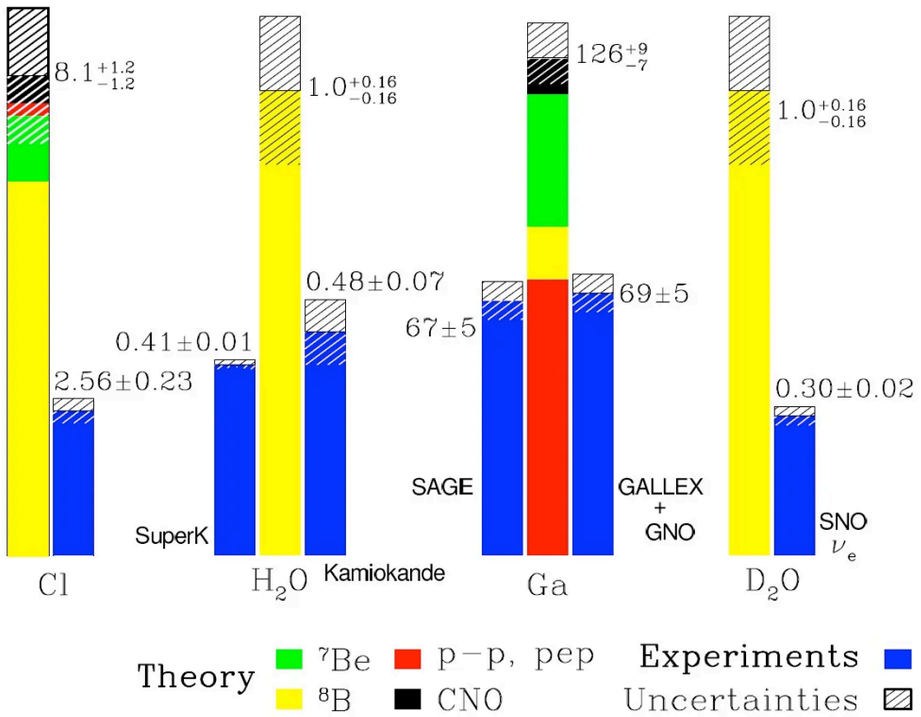
Lowest dim mass term

$$\frac{g}{\Lambda}(L_L^T\sigma_2\phi)\mathcal{C}^\dagger(\phi^T\sigma_2 L_L)$$

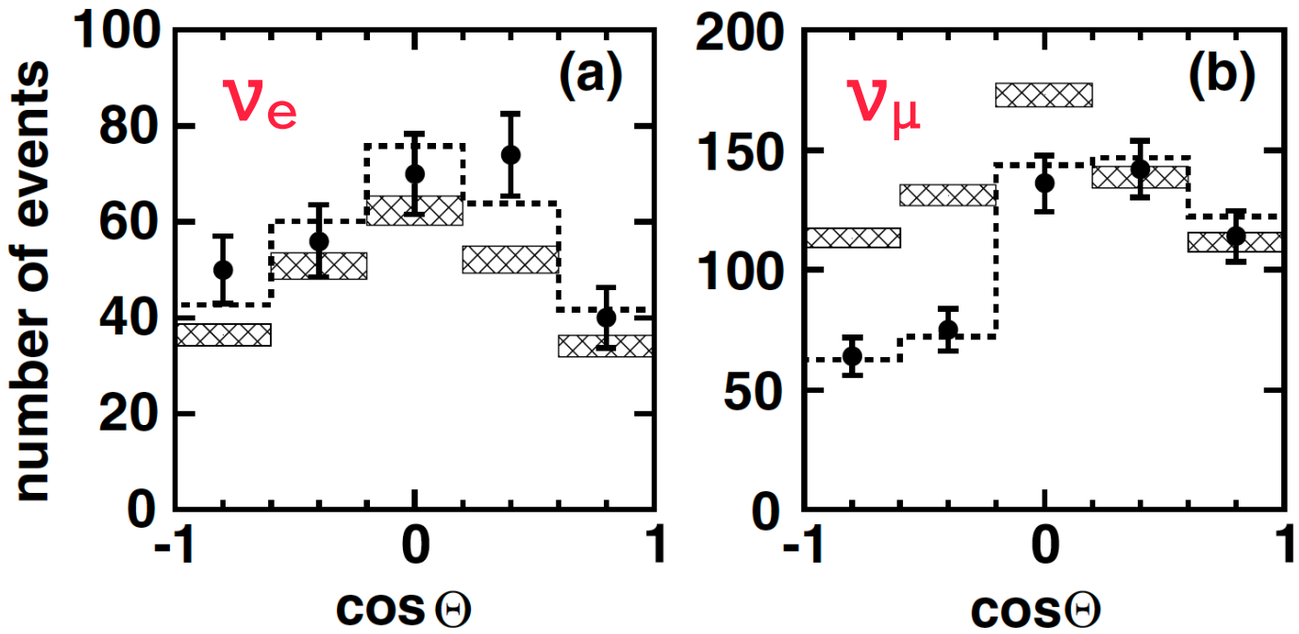
Neutrinos are strictly massless in the Standard Model!

Neutrino anomalies

Solar neutrino problem (60's)

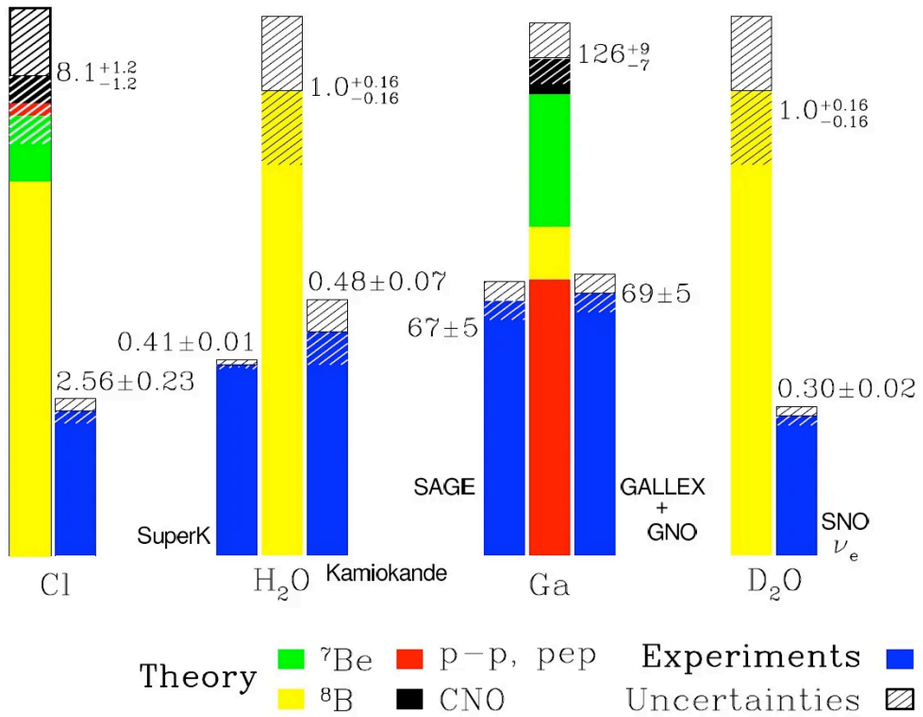


Atmospheric neutrino anomaly (80's)

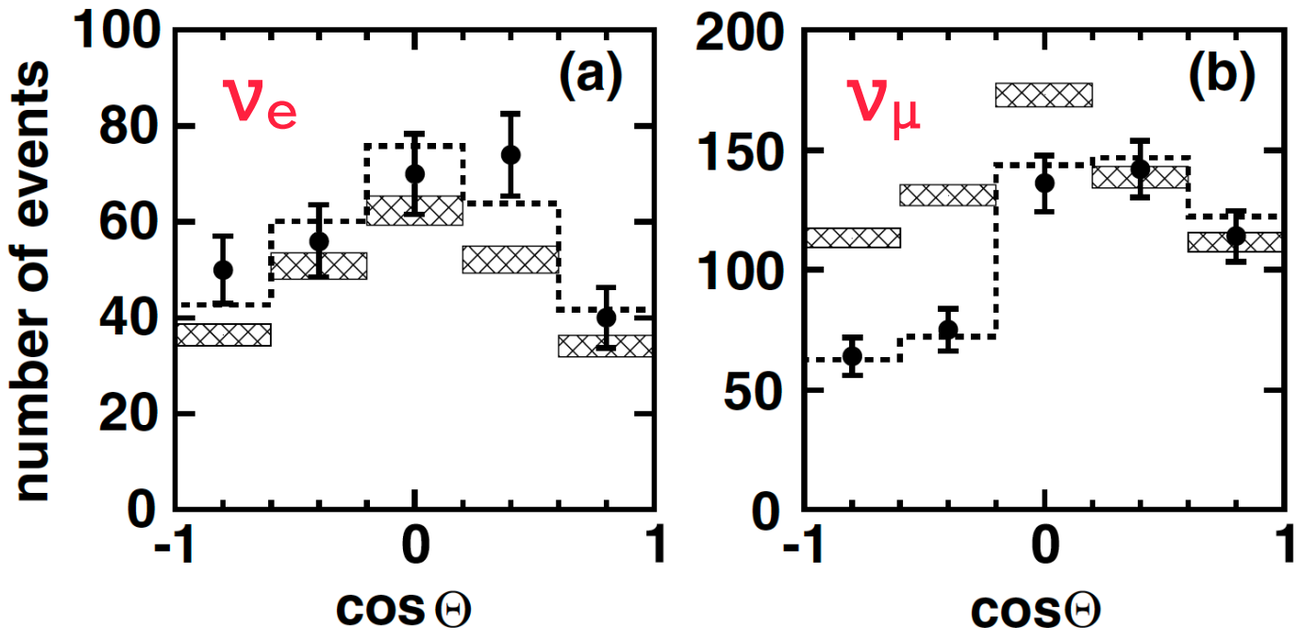


Neutrino anomalies

Solar neutrino problem (60's)



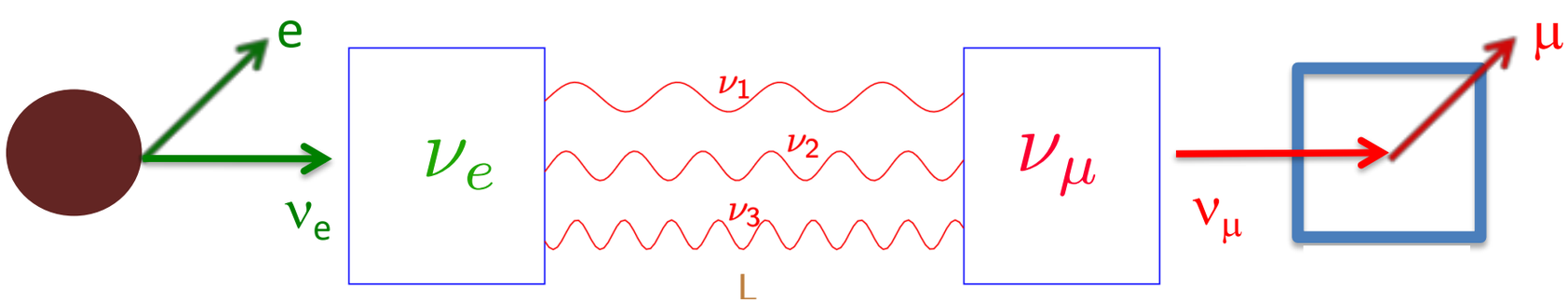
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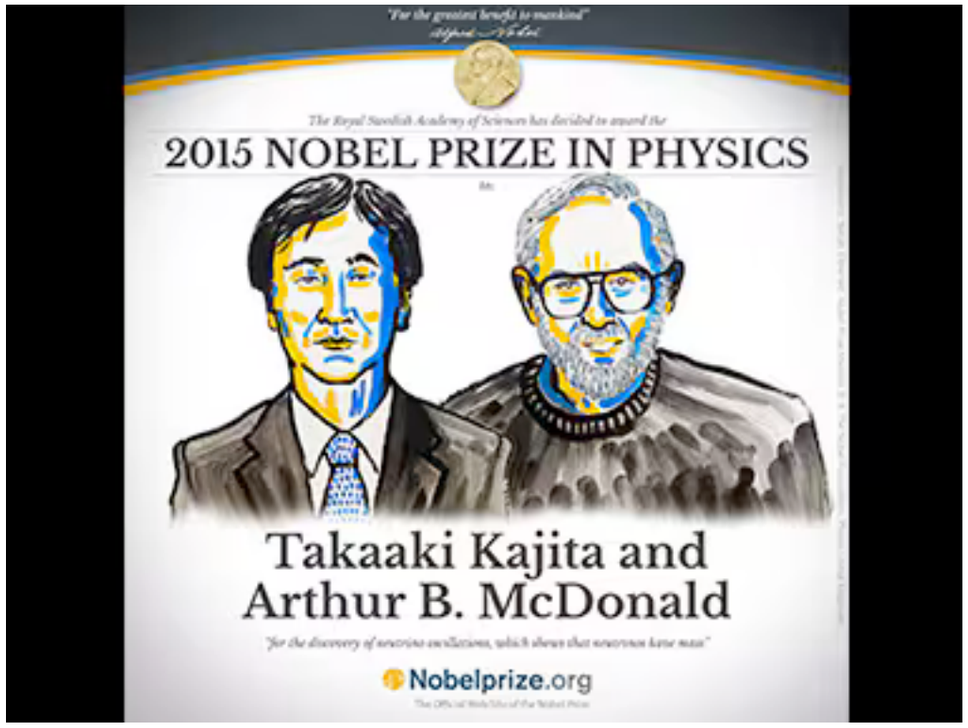


$\nu_e \rightarrow \nu_\mu, \nu_\tau$

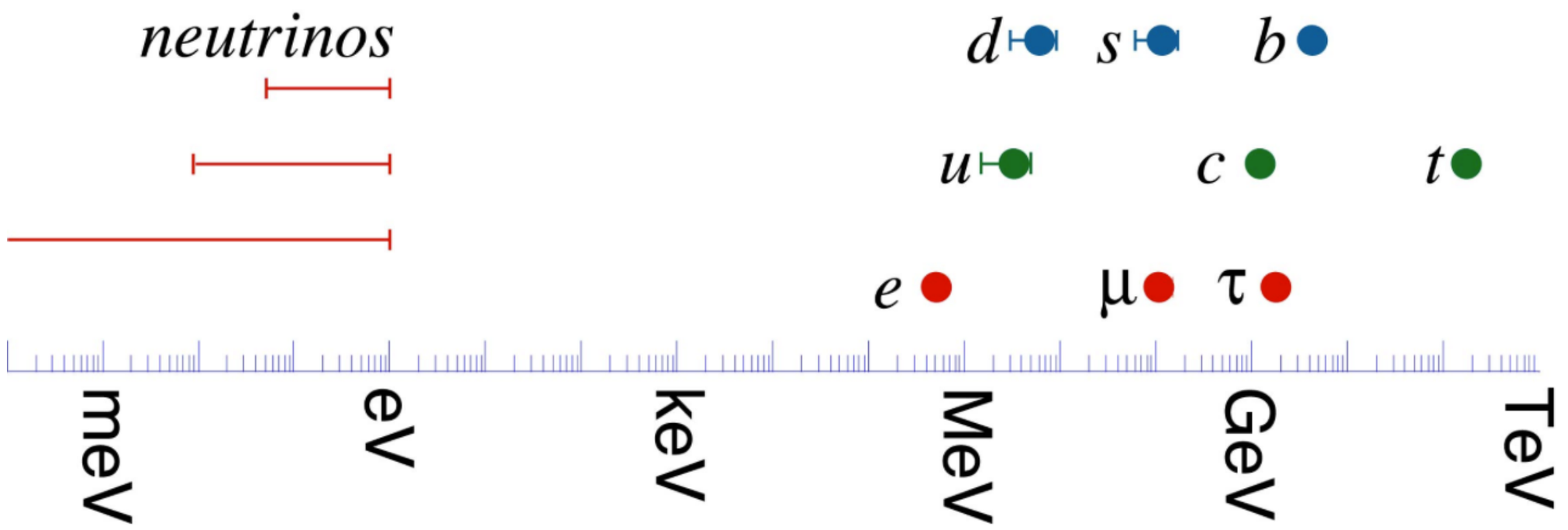
$$\nu_{\alpha L} = \sum_k U_{\alpha k} \nu_{kL}$$

$\nu_\mu \rightarrow \nu_\tau$





"For the discovery of neutrino oscillations, which shows that neutrinos have mass"



The three-flavour ν picture

neutrino mixing

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

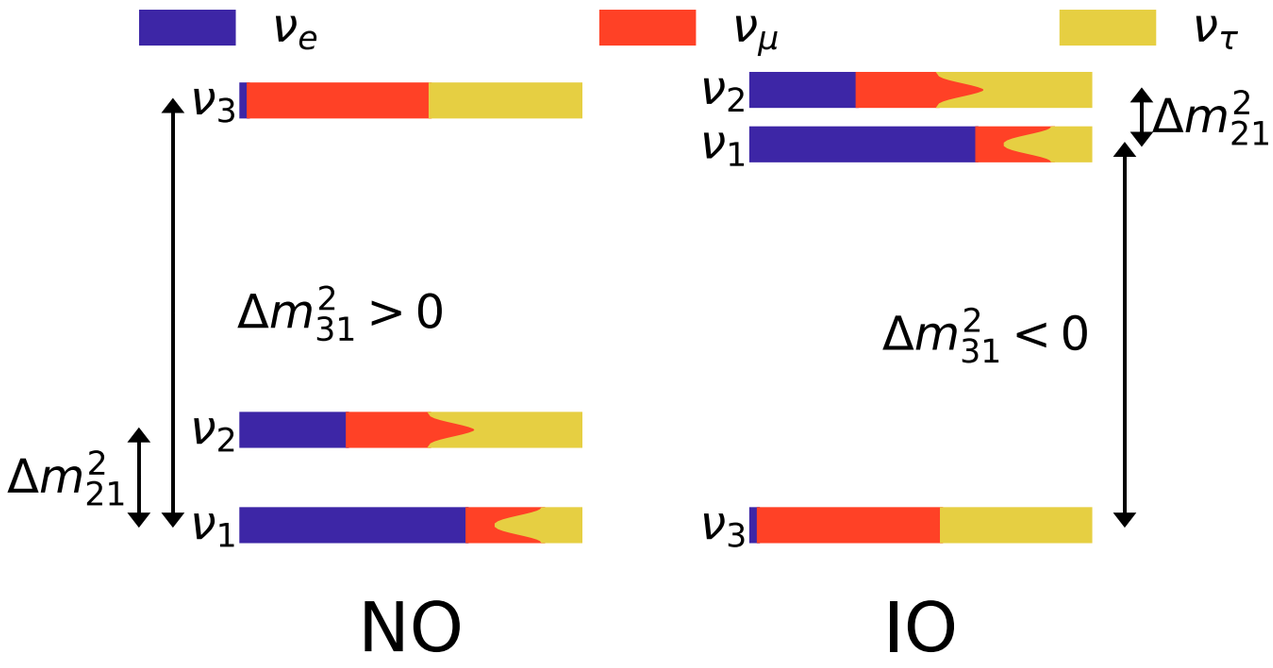
- ✓ 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- ✓ 3 CP phases: 1 Dirac + 2 Majorana
- ✓ 3 masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

$$\Delta m^2_{21}, \Delta m^2_{31}$$

neutrino mass spectrum



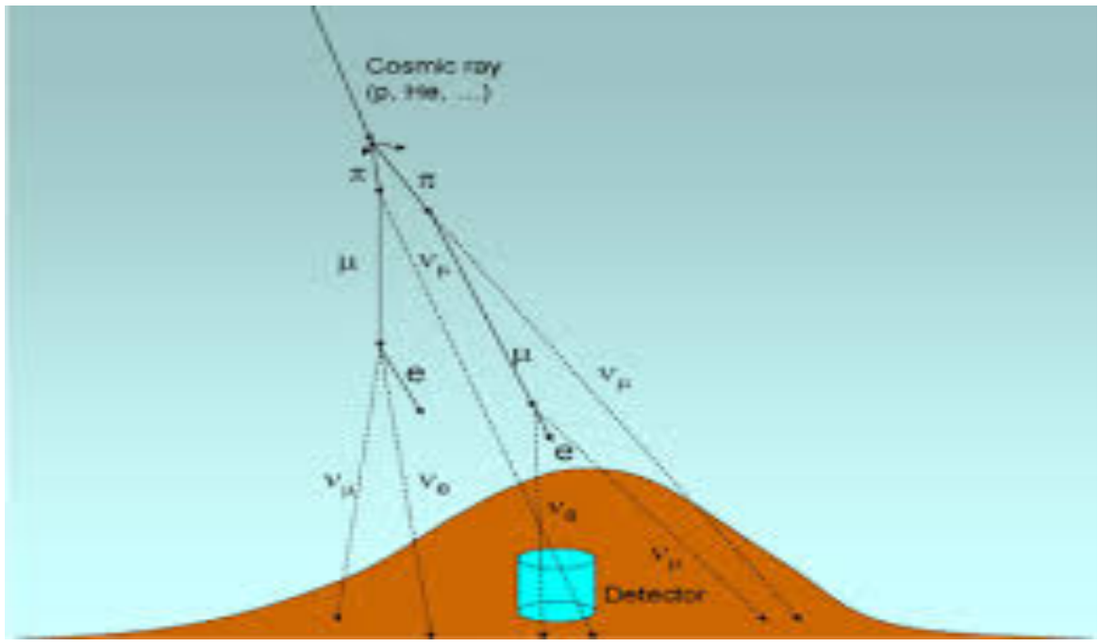
de Salas et al, 2018

Neutrino oscillations

Solar neutrinos



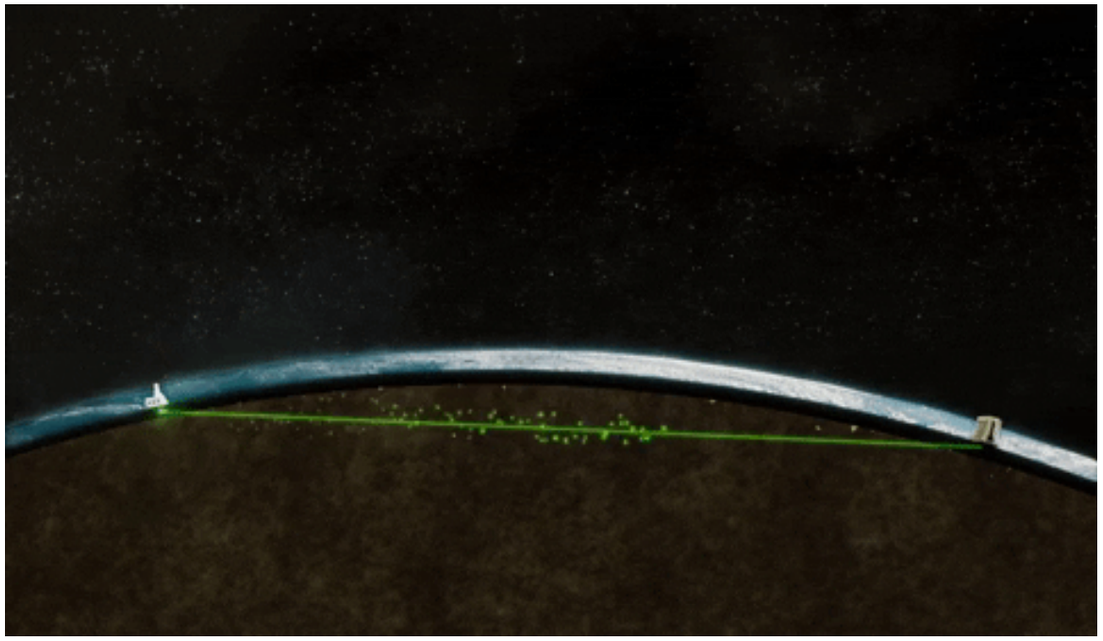
Atmospheric neutrinos



Reactor neutrinos



Accelerator neutrinos

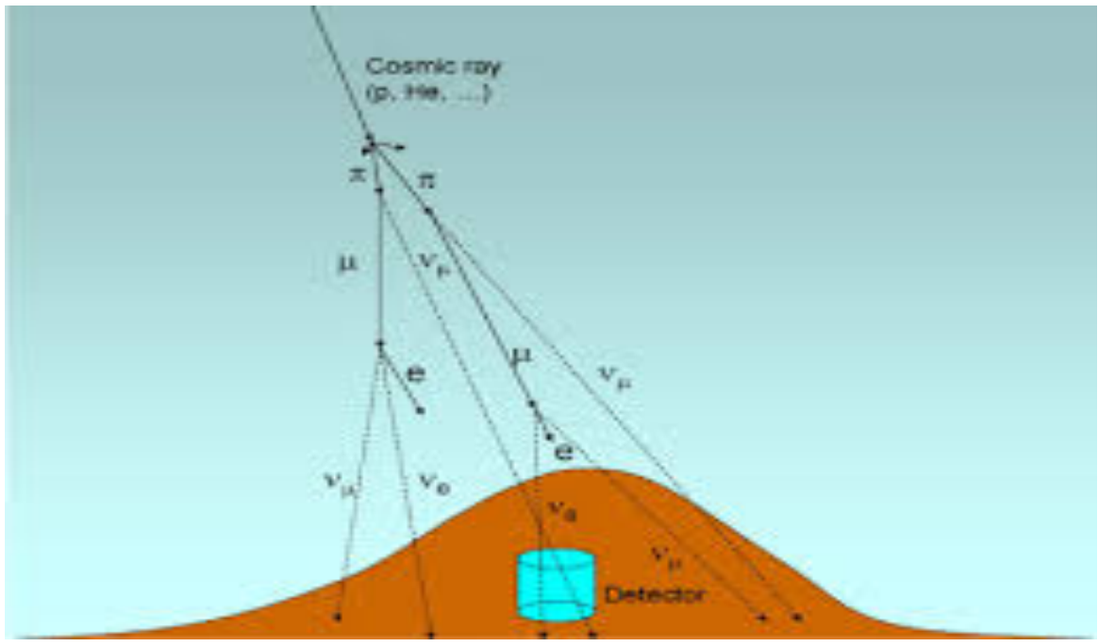


Neutrino oscillations

Solar neutrinos



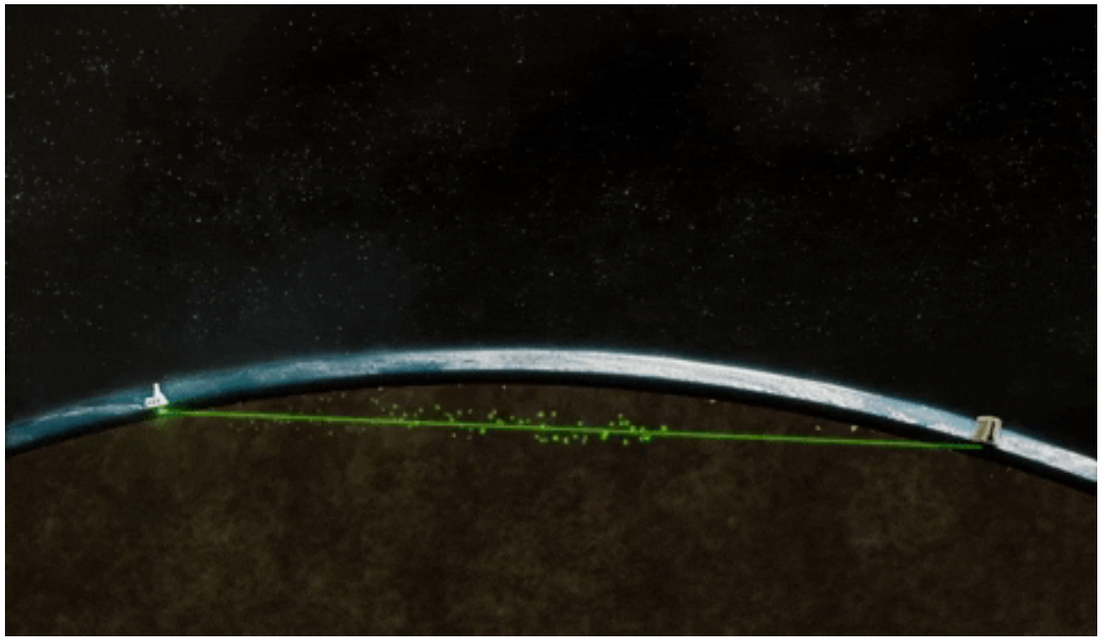
Atmospheric neutrinos



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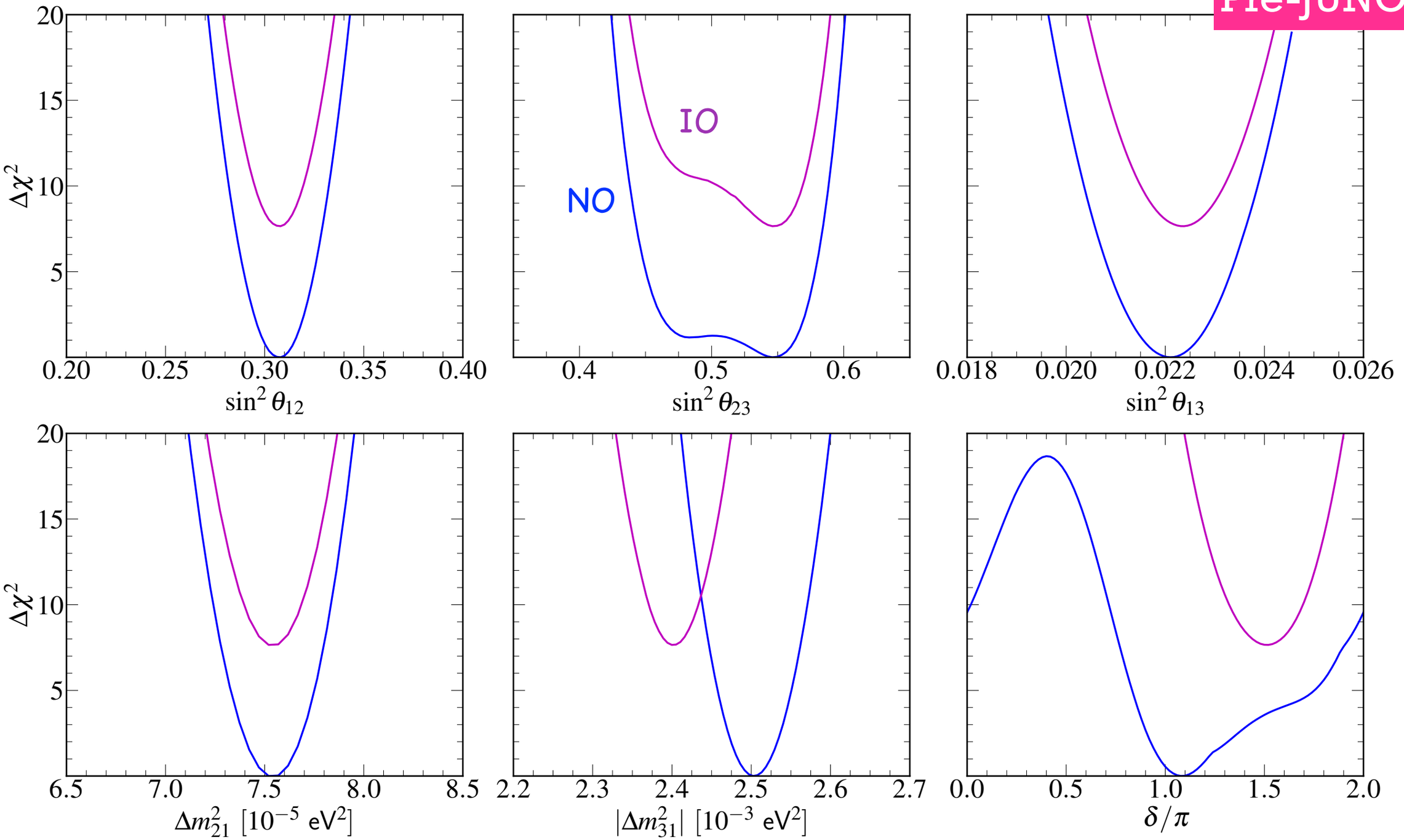
Accelerator neutrinos



Global fit to ν oscillation parameters

Valencia Global Fit https://globalfit.astroparticles.es/

Pre-JUNO 2026



See also NuFIT and Bari analyses

Global fit to ν oscillation parameters

Valencia Global Fit

Pre-JUNO 2026

parameter	best fit ± 1σ	3σ range	relative 1σ uncert	
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.52^{+0.11}_{-0.07}$	7.26–7.82	1.2 %	
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.50 ± 0.02	2.44–2.57	0.9 %	mass ordering?
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	2.40 ± 0.02	2.34-2.46		
$\sin^2\theta_{12}/10^{-1}$	$3.08^{+0.09}_{-0.07}$	2.83–3.31	2.6%	
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.46^{+0.16}_{-0.19}$	4.40–5.87	4.5%	
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.46^{+0.15}_{-0.18}$	4.45–5.84		octant?
$\sin^2\theta_{13}/10^{-2}$ (NO)	2.21 ± 0.05	2.04–2.38	2.5%	
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.24^{+0.05}_{-0.06}$	2.07–2.40		
δ/π (NO)	$1.08^{+0.13}_{-0.11}$	0.74–1.98	8-19%	maximal CP violation??
δ/π (IO)	$1.52^{+0.11}_{-0.13}$	1.15–1.85		

Global fit to ν oscillation parameters

Valencia Global Fit

Pre-JUNO 2026

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Not valid in presence of BSM !

Beyond the 3-neutrino scenario

3ν picture

- Absence of any **new physics** besides neutrino masses
- **CPT conservation**: same masses and mixings for ν and $\bar{\nu}$

HOWEVER…

- Neutrino results suggest the presence of **physics BSM** to explain:
  - ✓ light neutrino masses (mass generation mechanism)
  - ✓ large neutrino mixing compared to quark sector (flavour problem)
  - ✓ short-distance anomalies (LSND, reactor and Ga anomalies)

- Many different **BSM scenarios** analyzed in the literature:

limits on NP

- ✓ Non-standard interactions
- ✓ Non-unitary mixing
- ✓ CPT and Lorentz violation
- ✓ E.m. ν properties
- ✓ Light sterile neutrinos
- ✓ Large extra dimensions

Robustness of 3ν oscillations with NP

CPT violation in the neutrino sector

CPT tests

- CPT invariance tested in several matter-antimatter systems:

  ⇒ neutral kaons

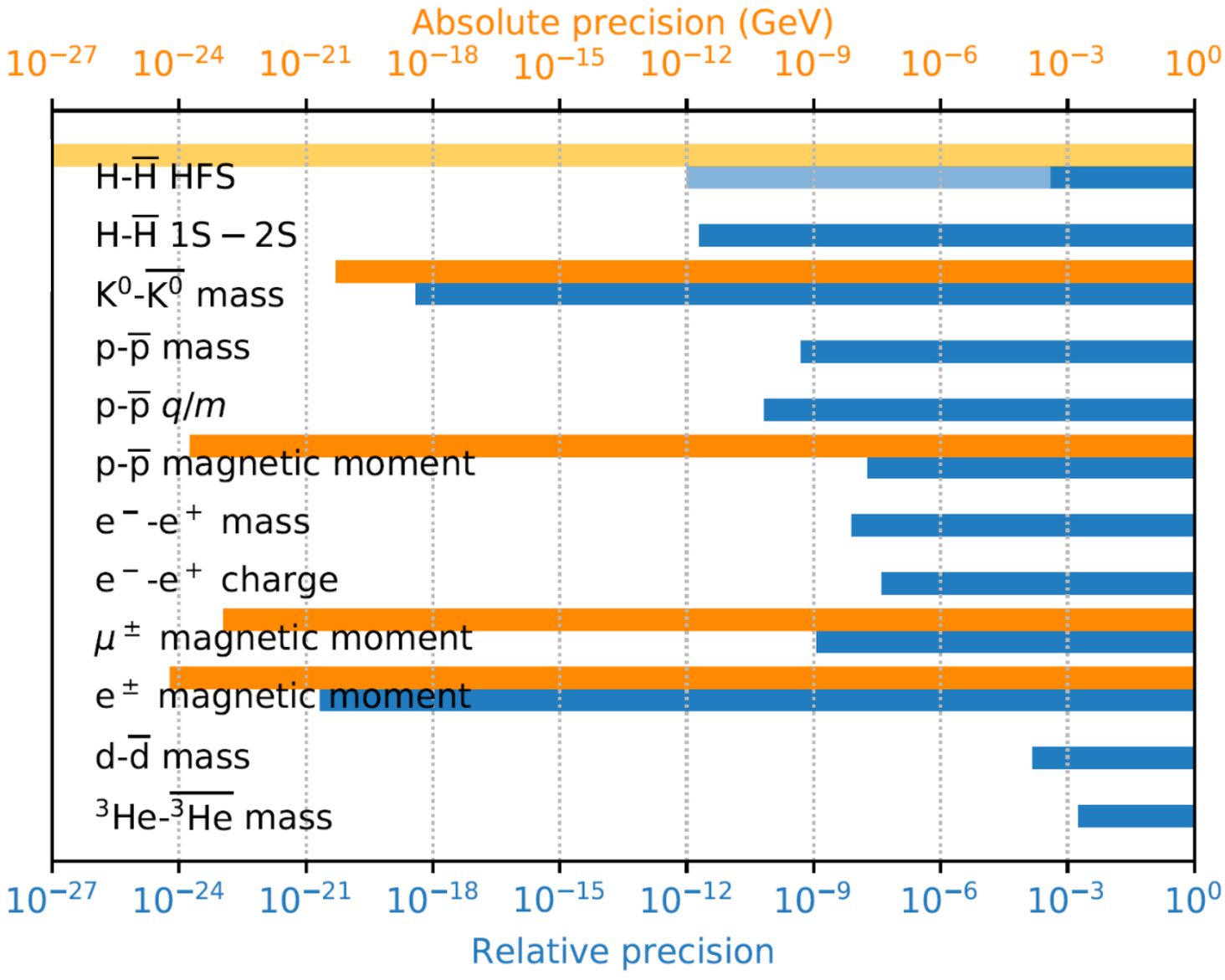
  ⇒ electron/positron

  ⇒ proton/antiproton

  ⇒ H/anti-H

  ⇒ …

- 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, JHEP2020**

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

  ⇒ current data → **Barenboim, Ternes, MT, JHEP2020**, **Barenboim, Ternes, MT, PLB2018**

  ⇒ future: DUNE, Hyper-K → **Gouvea & Kelly PRD2017**

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

Bounds on CPT violation

- Updated bounds at 3σ:

Barenboim, Ternes, MT, JHEP2020

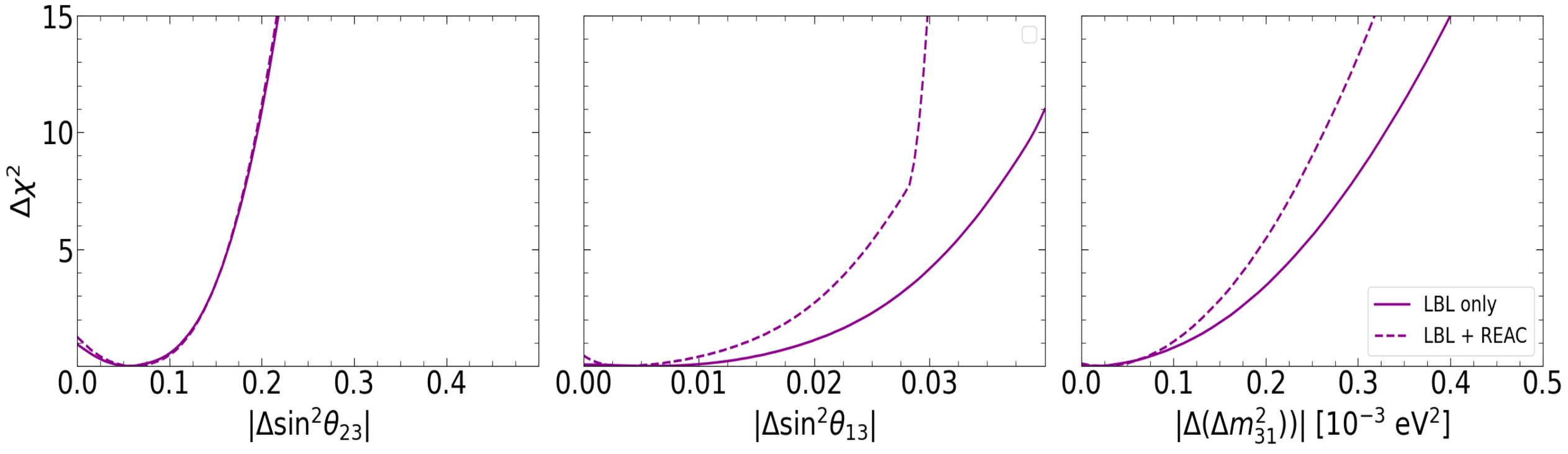
$$|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| < 0.14 \qquad |\Delta m^2_{21} - \Delta\overline{m}^2_{21}| < 4.7\times10^{-5}\ \text{eV}^2$$
$$|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| < 0.029 \qquad |\Delta m^2_{31} - \Delta\overline{m}^2_{31}| < 2.5\times10^{-4}\ \text{eV}^2$$
$$|\sin^2\theta_{23}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

For previous results, see:

Ohlsson & Zhou, NPB2015

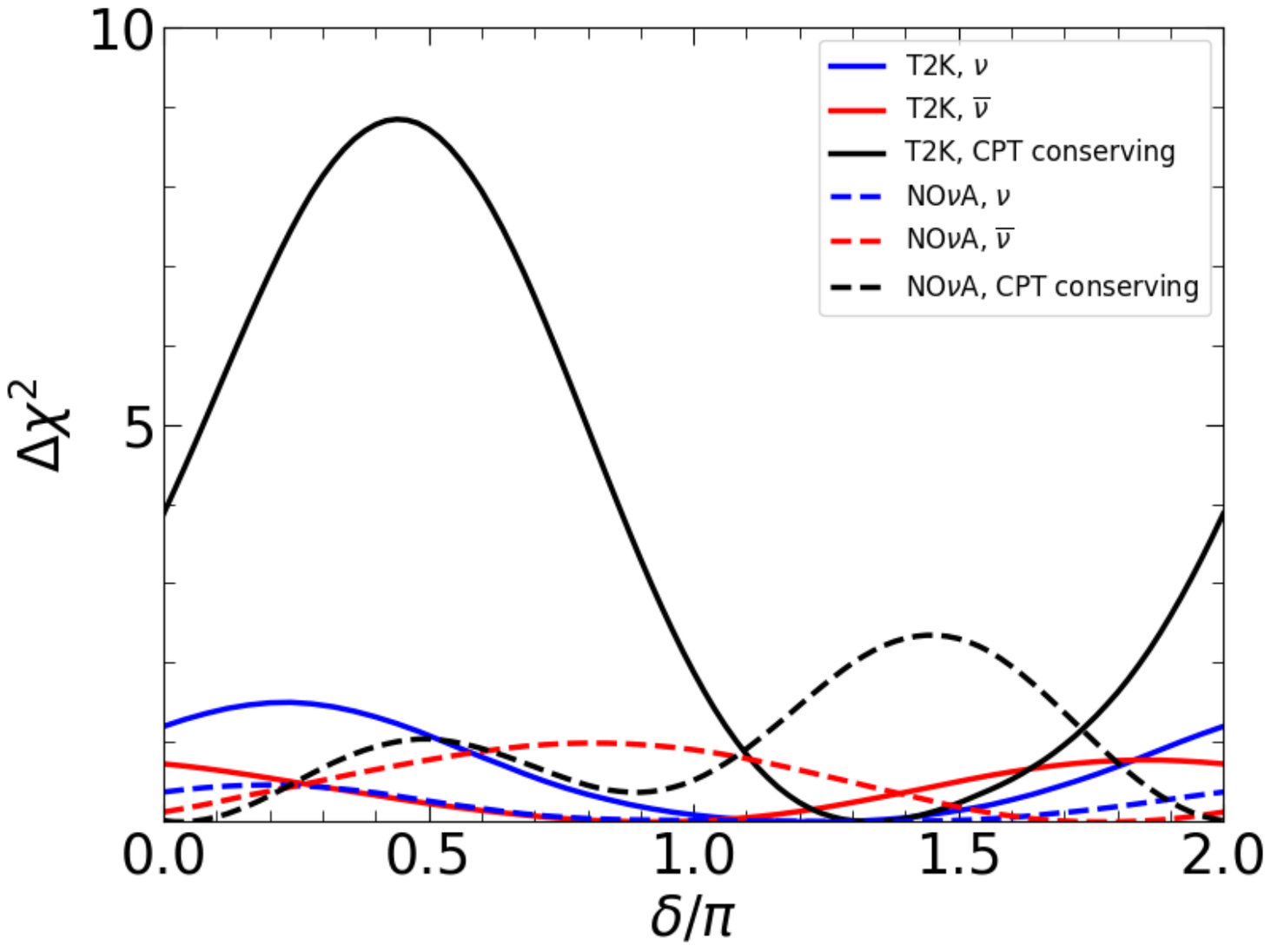
$$|\Delta x| = |x - \overline{x}|$$

Barenboim, Ternes, MT, PLB2018



~~CPT~~ oscillation analysis

T2K and NOvA reanalysis without CPT invariance (NO)



Barenboim, Ternes, MT, JHEP2020

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

✓ $\theta_{13} \neq \bar{\theta}_{13}$ accounts for different behavior in neutrino and antineutrino channels

✓ very poor sensitivity wrt CPT-conserving scenario

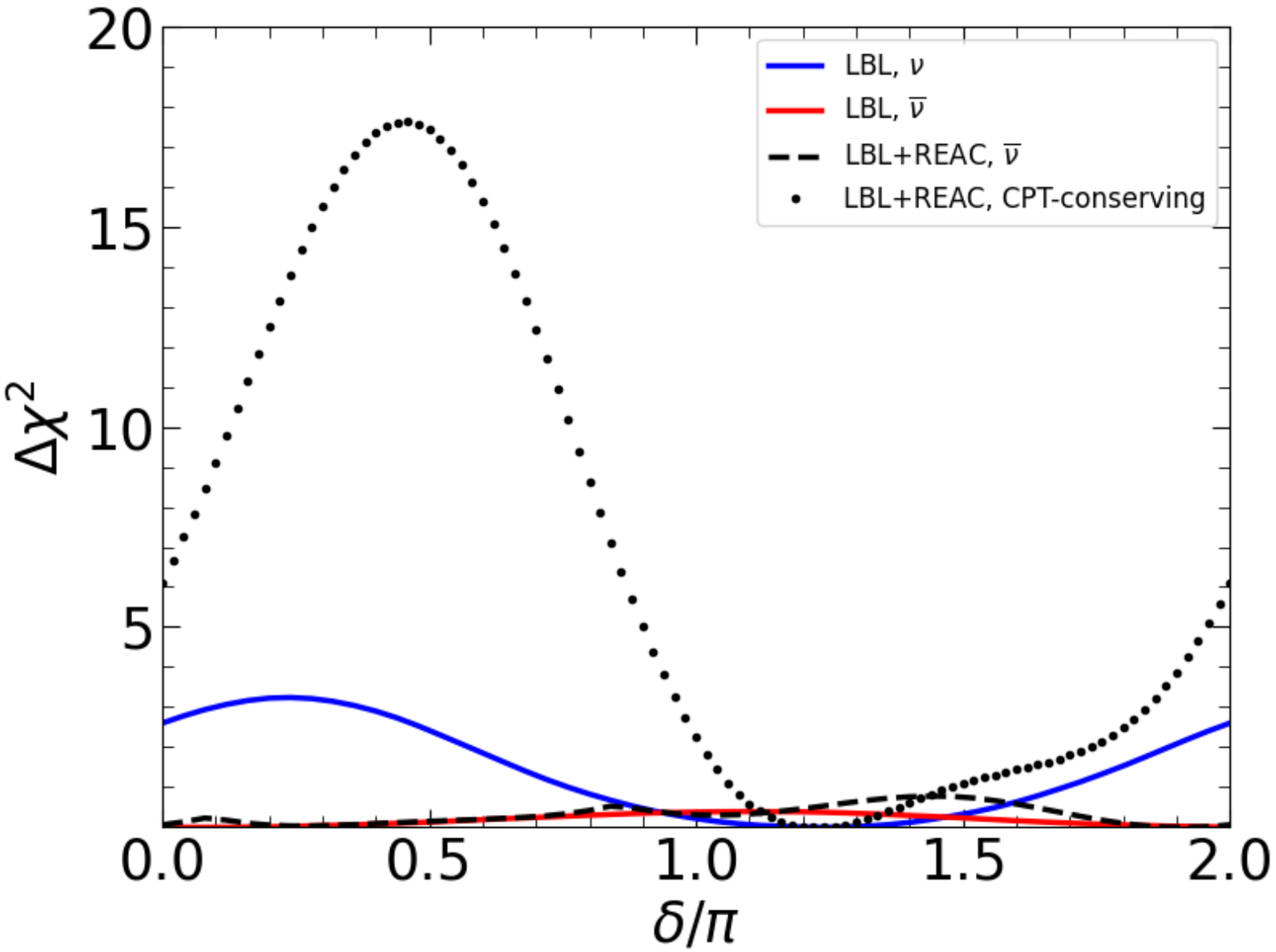
ν channel: good agreement between T2K and NOvA

$\bar{\nu}$ channel: not so good but poor sensitivity to $\bar{\delta}$

~~CP~~T oscillation analysis

LBL + REAC (DayaBay & RENO) sensitivity to CP (NO)

Barenboim, Ternes, MT, JHEP2020



- ✓ combined LBL analysis:
  - ⇒ improved sensitivity for δ
  - ⇒ reduced sensitivity for $\bar{\delta}$
- ✓ LBL +REAC do not improve results for δ
- ✓ Any value of δ is allowed at 2σ

The T2K-NOvA tension in NO disappears

~~CPT~~ 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.

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

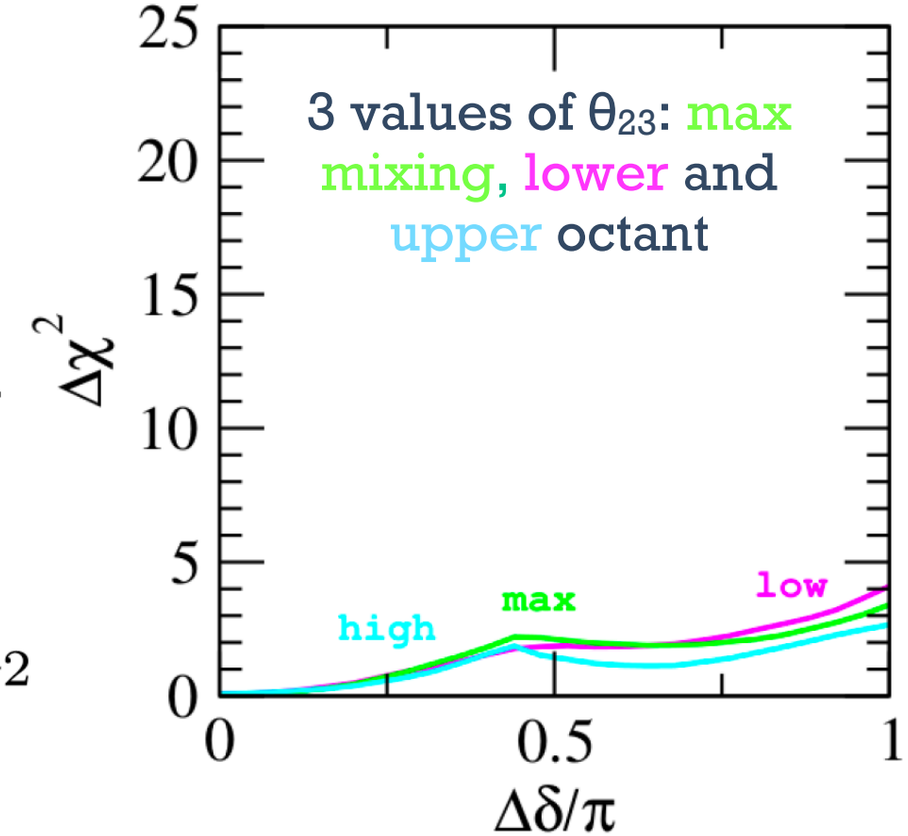
Barenboim, Ternes, MT, PLB2018

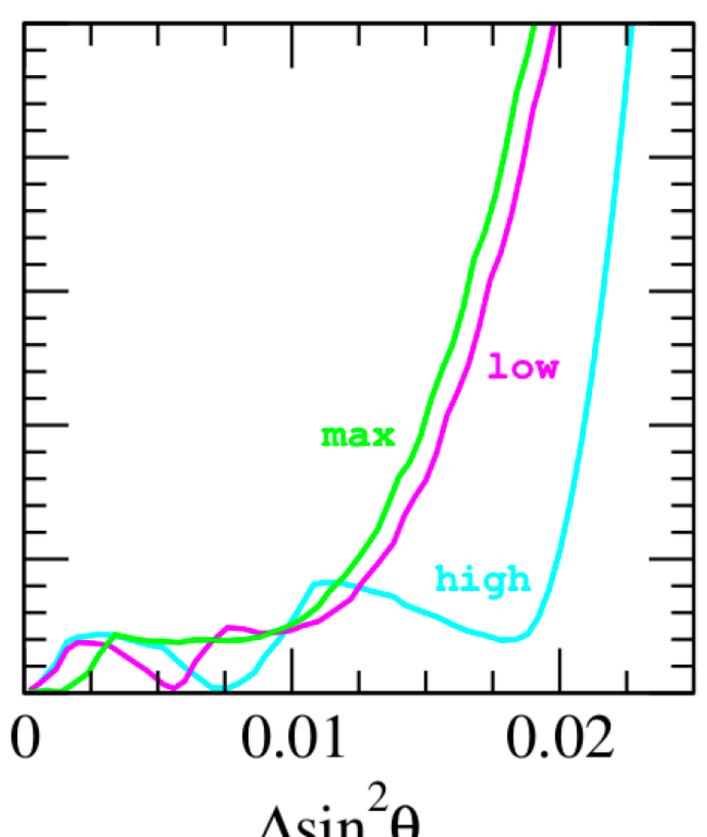
- Poor sensitivity to differences in CP phase and reactor angle

- Factor 3 improvement in atmospheric splitting

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

(3σ)





Light sterile neutrinos

Sterile neutrinos

✦ **sterile neutrino** = singlet fermion of the Standard Model

→ it has no interactions (exceptions: Higgs, mixing and physics BSM)

Motivations: sterile neutrinos can explain...

✦ neutrino oscillation anomalies (m ~ eV)

✦ small neutrino masses (seesaw mechanism, m > TeV-M_{Planck})

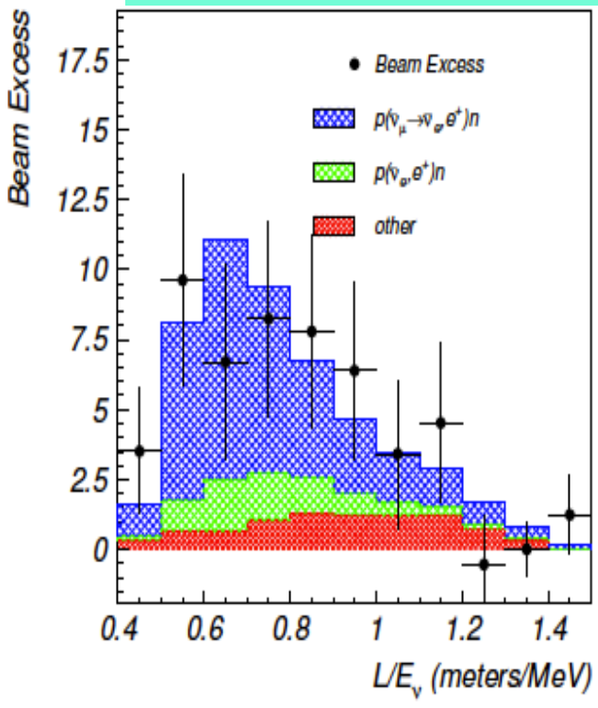
✦ baryon asymmetry of the universe (leptogenesis, m>> 1 GeV)

✦ (part of) the dark matter of the universe.

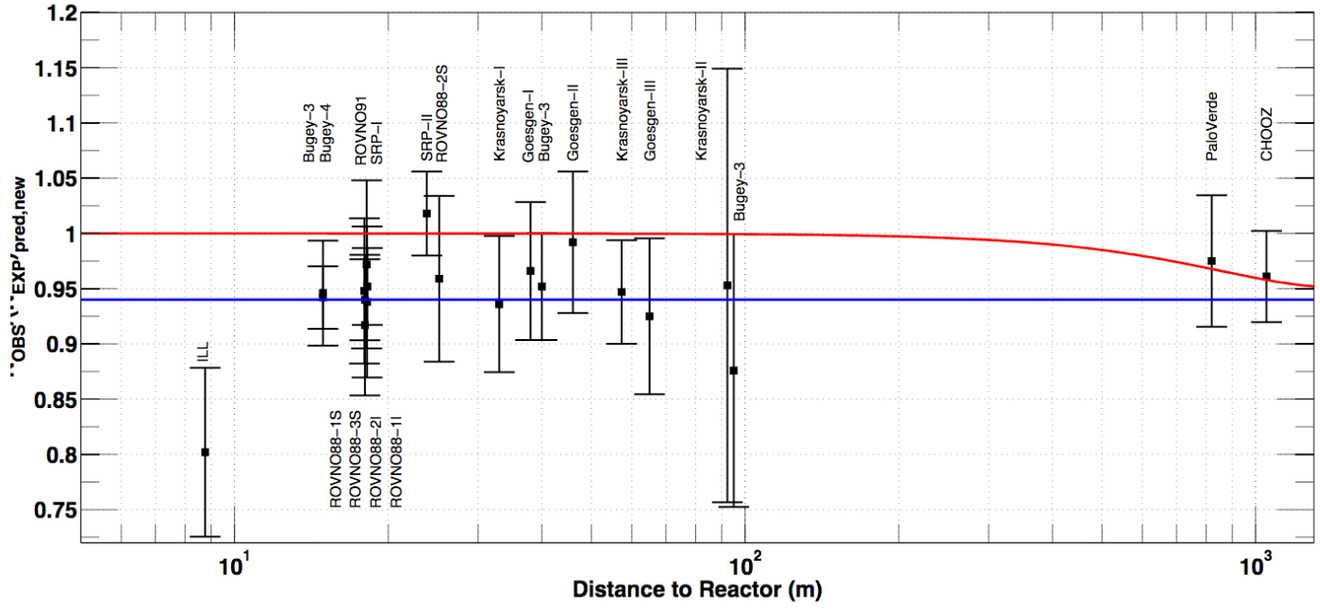
Hints for a light sterile neutrino

Anomalies in neutrino experiments with very short baselines source-detector (10-100 m)

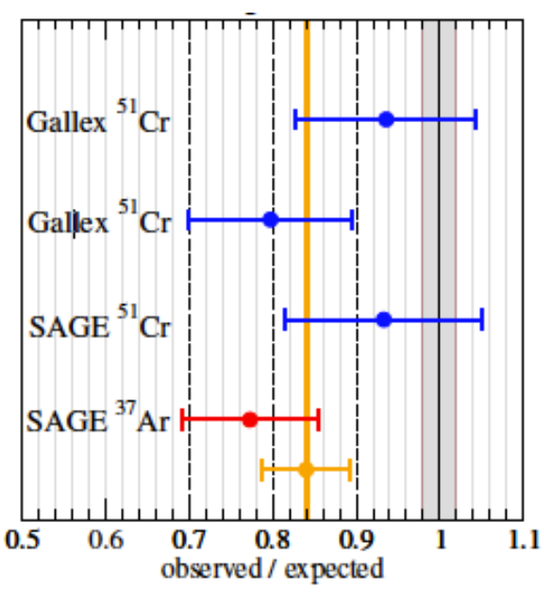
LSND & MiniBooNE



Reactor anomaly



Gallium anomaly

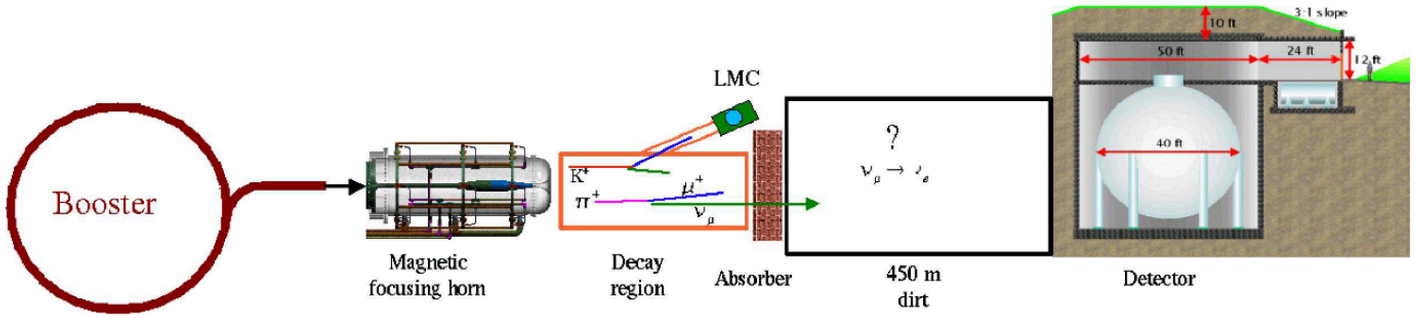


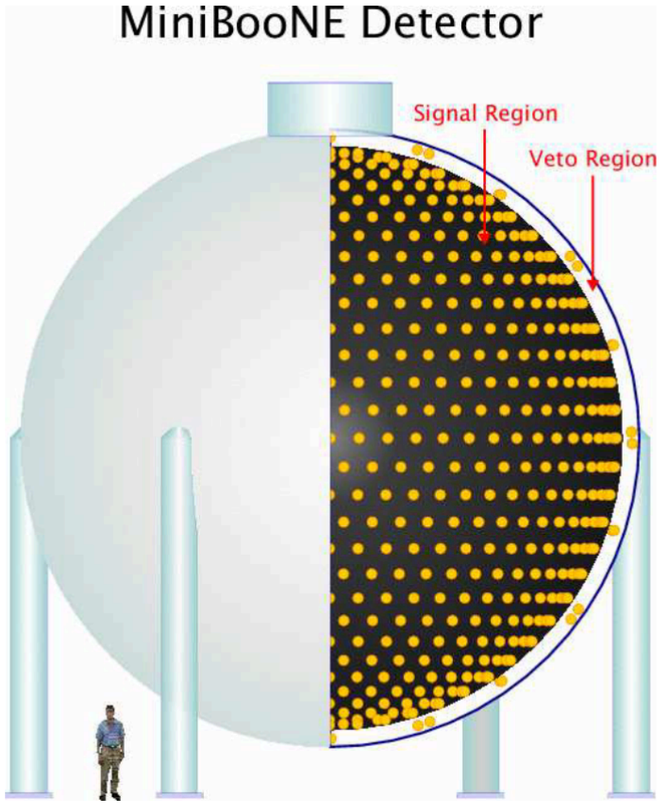
Explained with neutrino oscillations with $\Delta m^2 \sim 1$ eV^2 in the channels:

$$\overline{\nu}_\mu \to \overline{\nu}_e \qquad \overline{\nu}_e \to \overline{\nu}_x \qquad \nu_e \to \nu_x$$

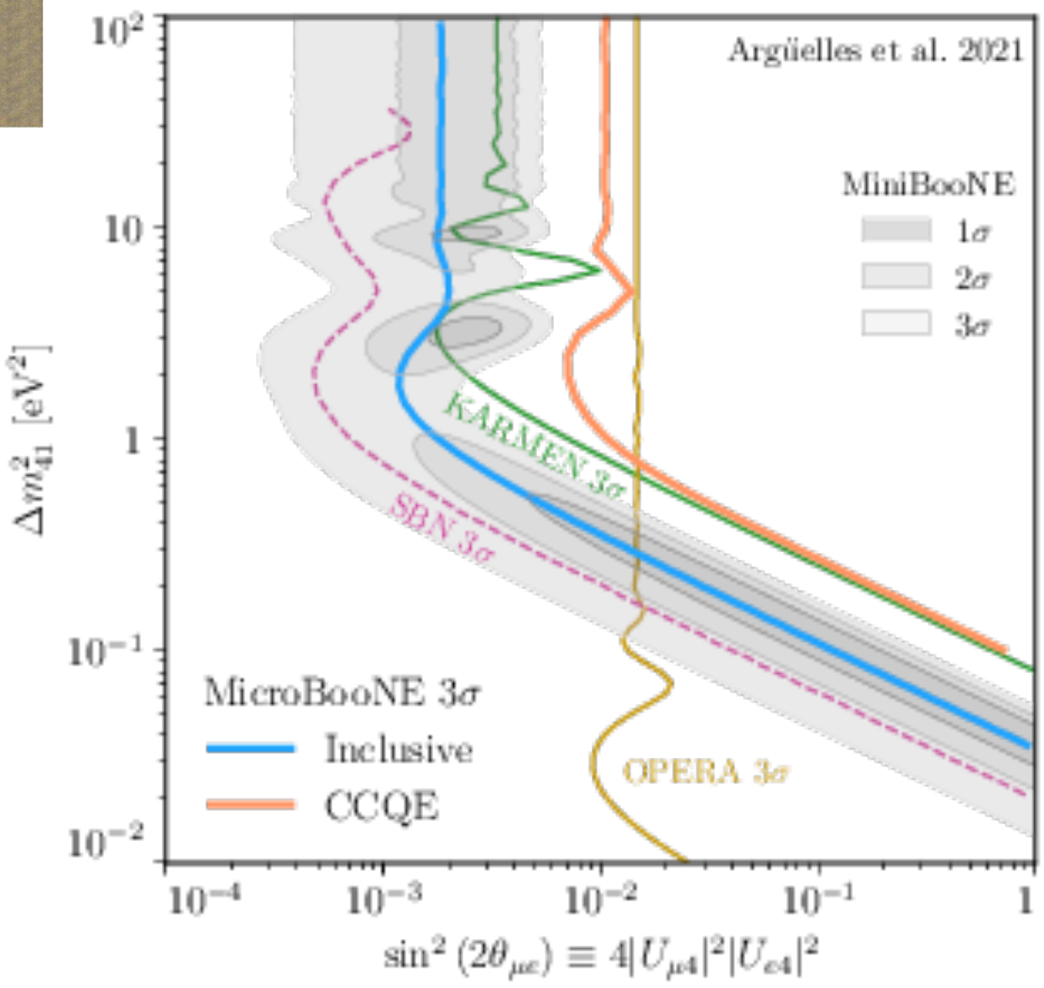
Testing the LSND anomaly

Experiments designed to check LSND signal: **MiniBooNE** & **MicroBooNE**





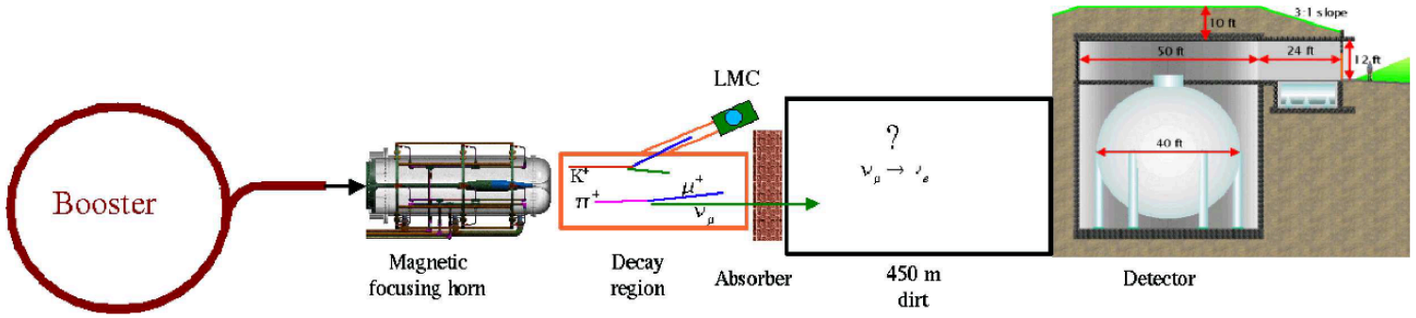
Argüelles et al, 2021

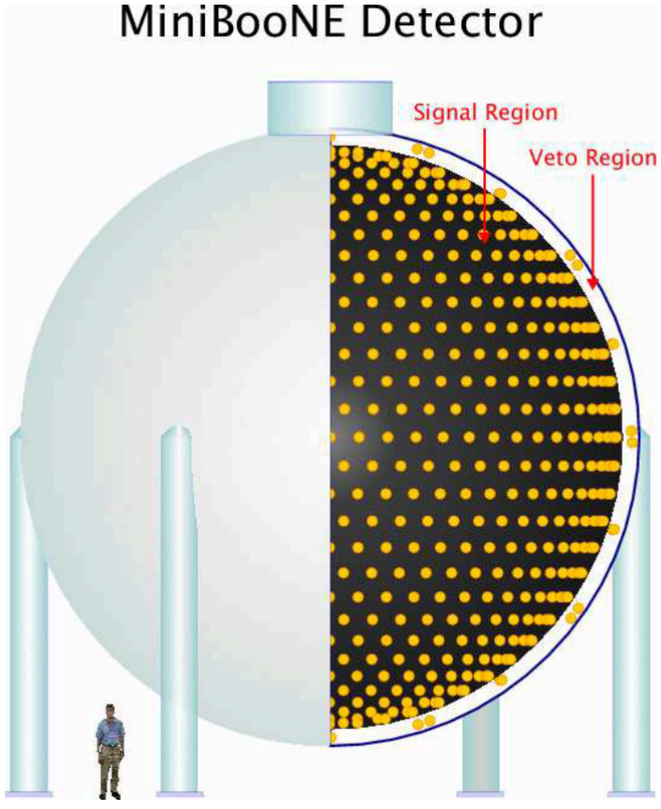


→ Not enough evidences to confirm or rule out the anomaly

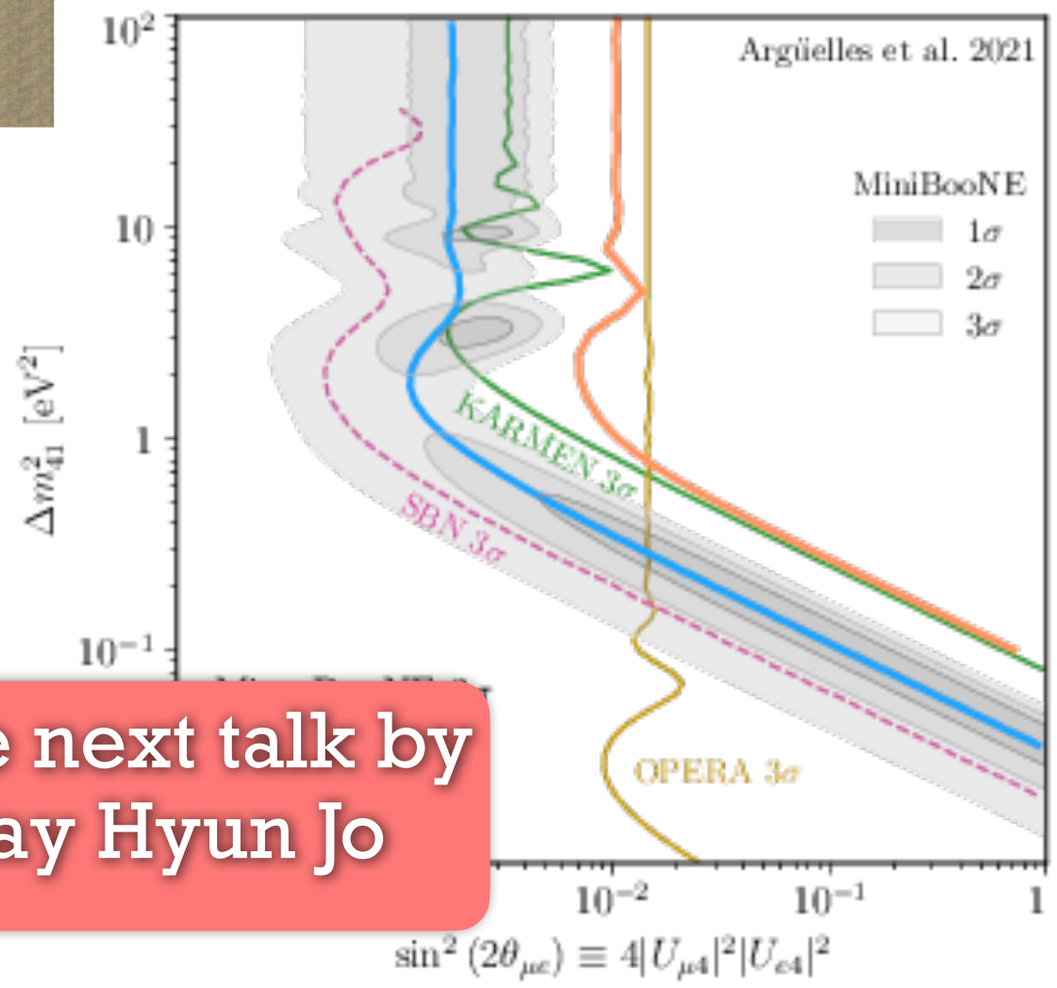
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Argüelles et al, 2021

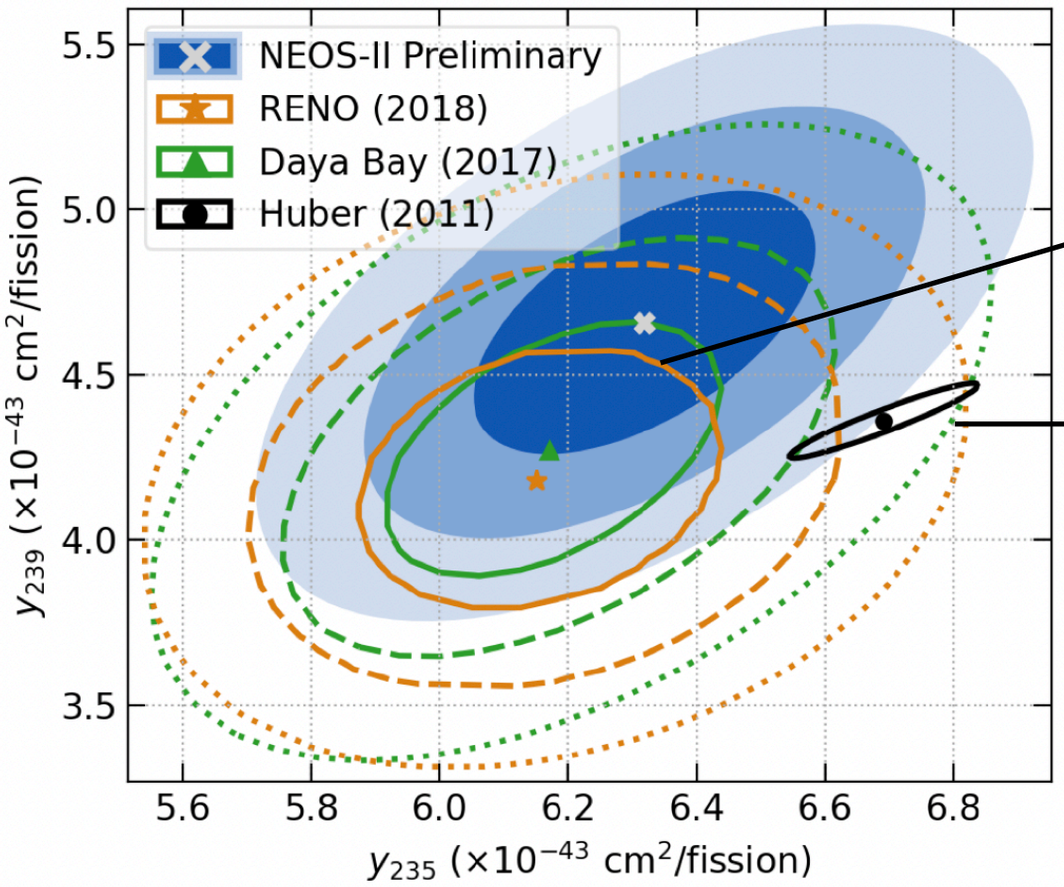


See next talk by Jay Hyun Jo

→ Not enough evidences to confirm or rule out the anomaly

The reactor anomaly

New theoretical models and reactor results indicate that the neutrino flux for ^{235}U should be reduced by 5-10 % with respect to previous estimations



Measurements at reactor experiments NEOS, RENO and DayaBay

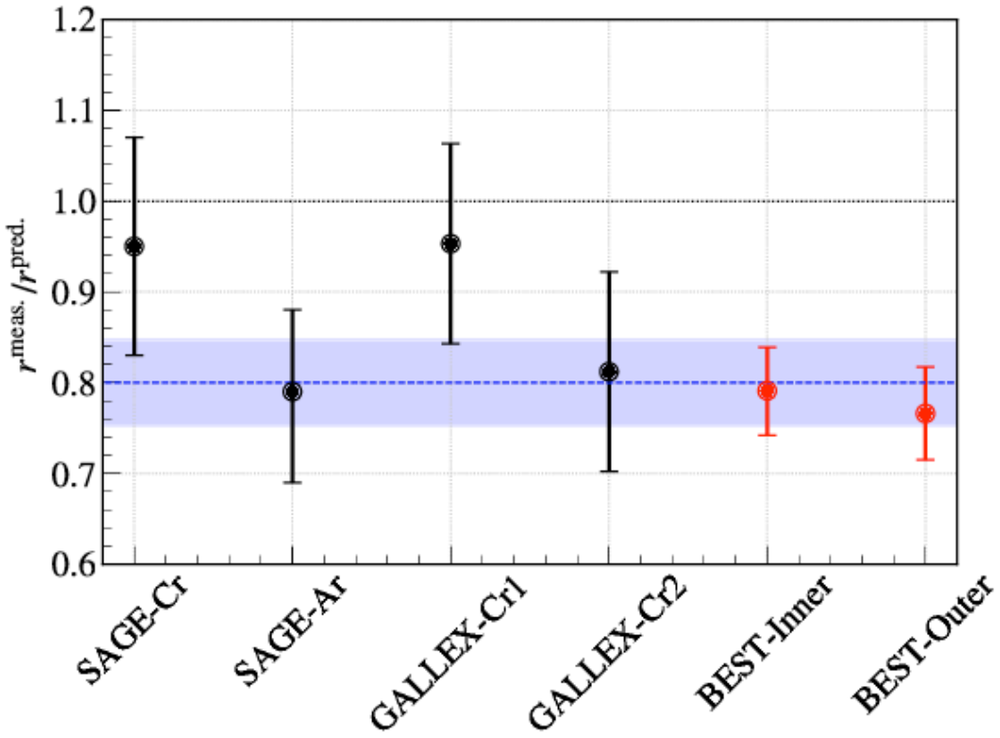
Previous theoretical predictions

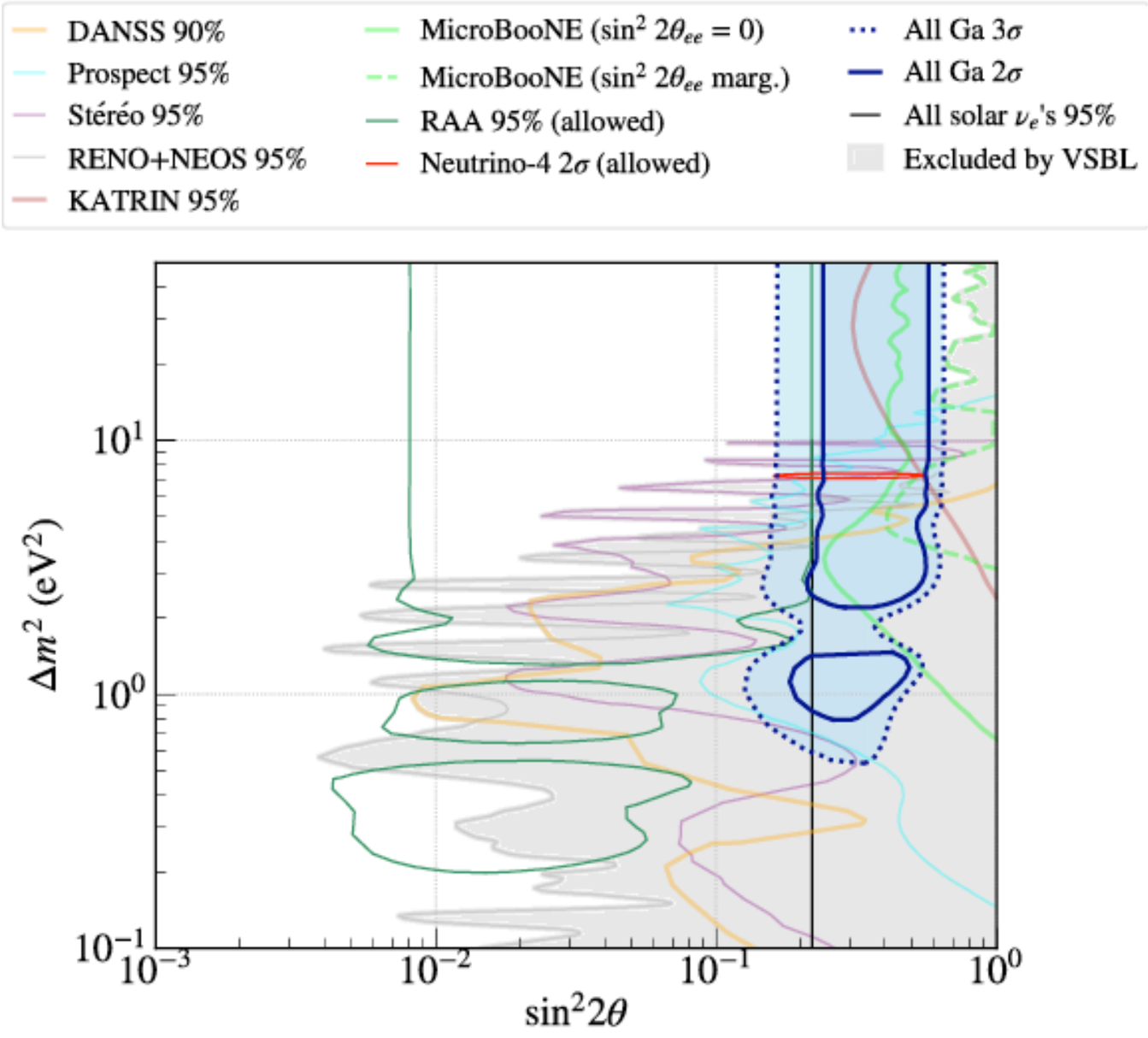
→ this result reconciles experimental data with theoretical predictions, solving the reactor neutrino flux anomaly

P. Vogel, Neutrino 2022

Current status of the Ga anomaly

✦ Recently confirmed by BEST (Baksan Experiment on Sterile Transitions) at 4σ



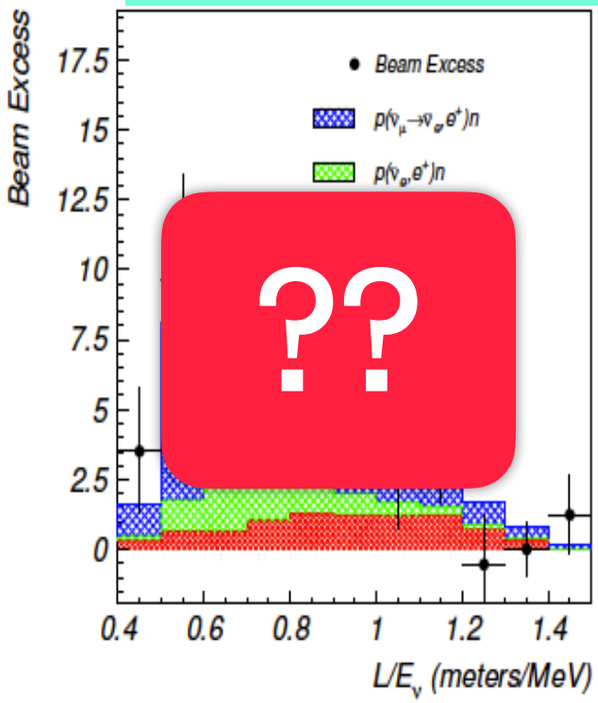


Barinov et al, PRC 2022

Hints for a light sterile neutrino

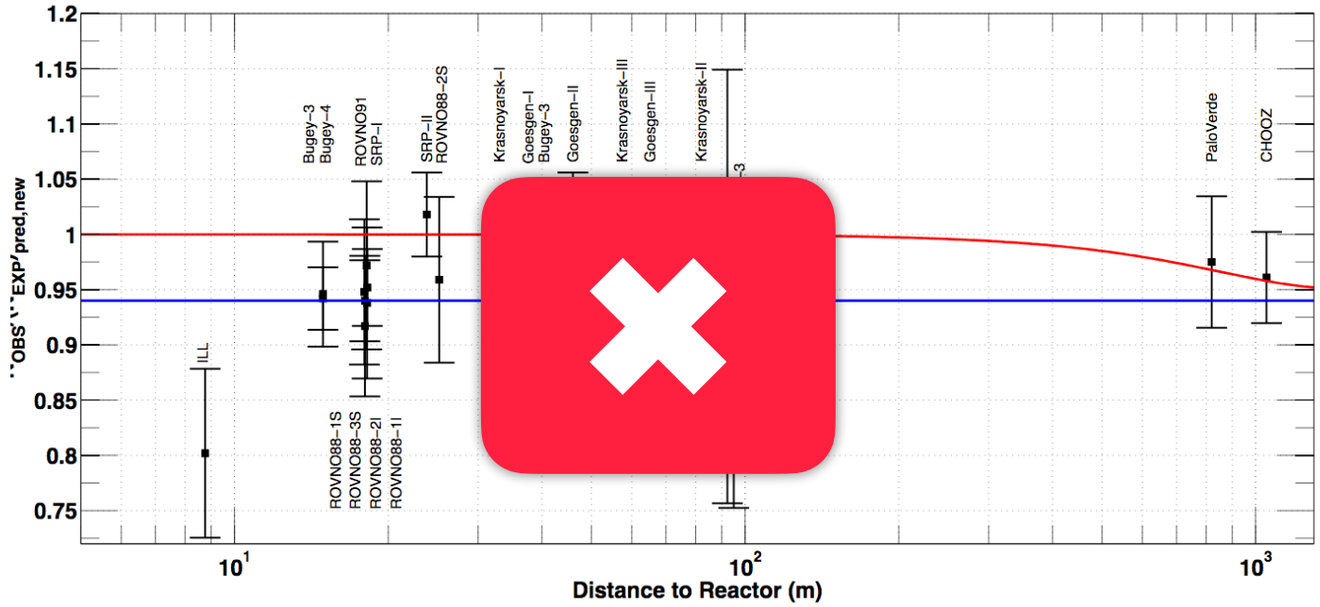
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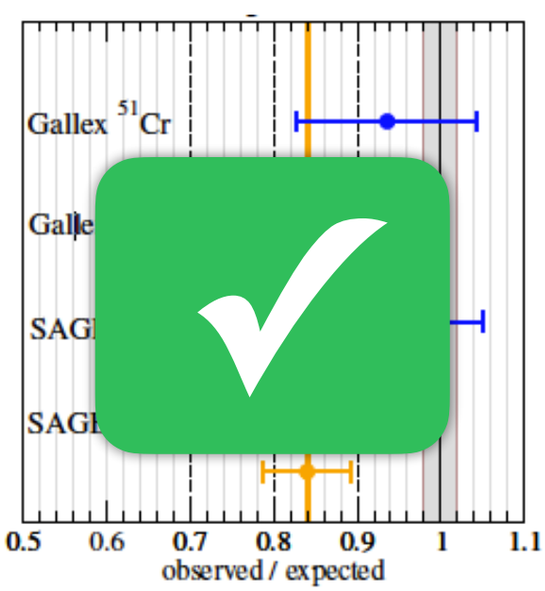


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Reactor anomaly



Gallium anomaly

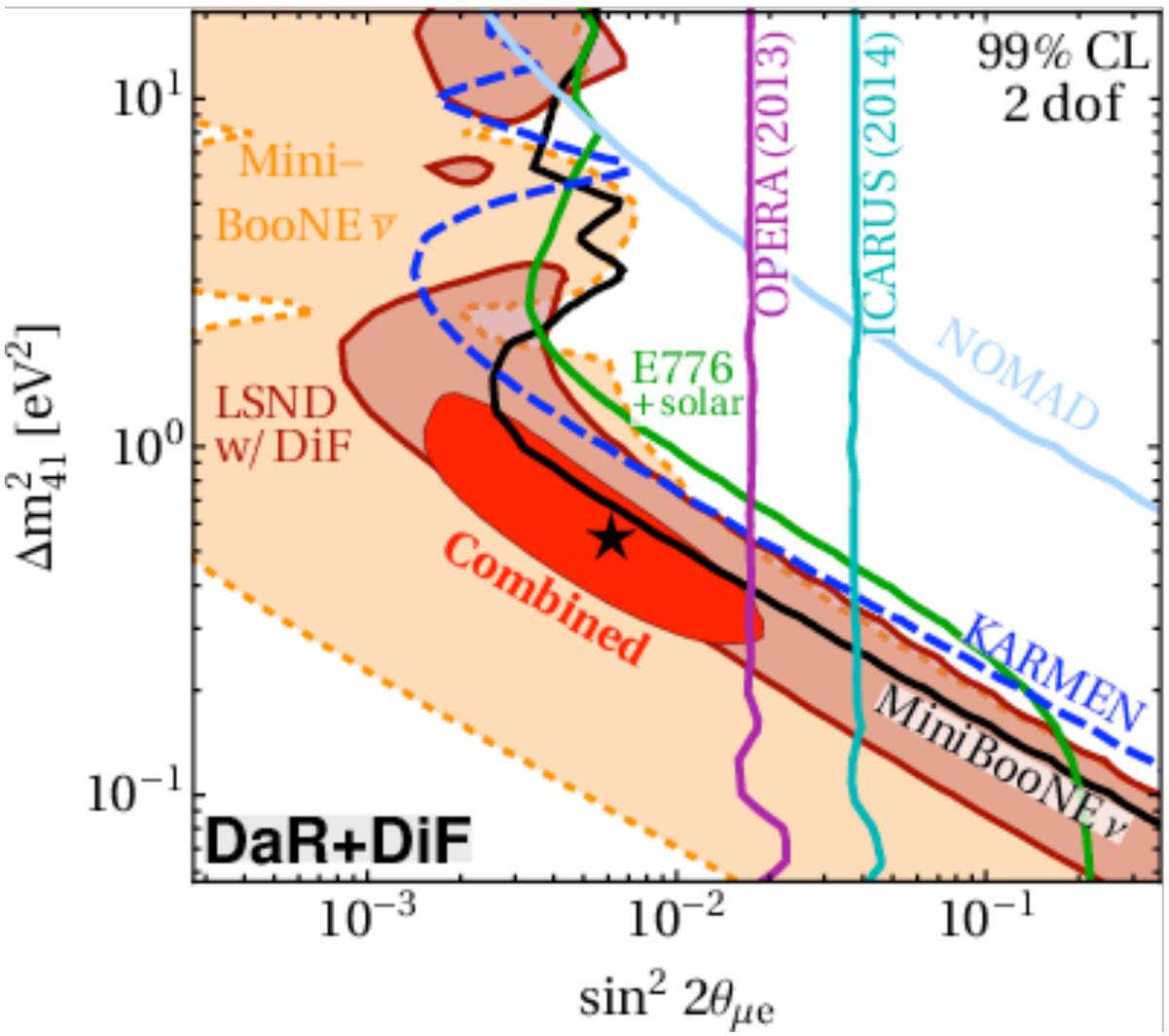


Explained with neutrino oscillations with $\Delta m^2 \sim 1$ eV^2 in the channels:

$$\overline{\nu}_\mu \to \overline{\nu}_e \qquad \overline{\nu}_e \to \overline{\nu}_x \qquad \nu_e \to \nu_x$$

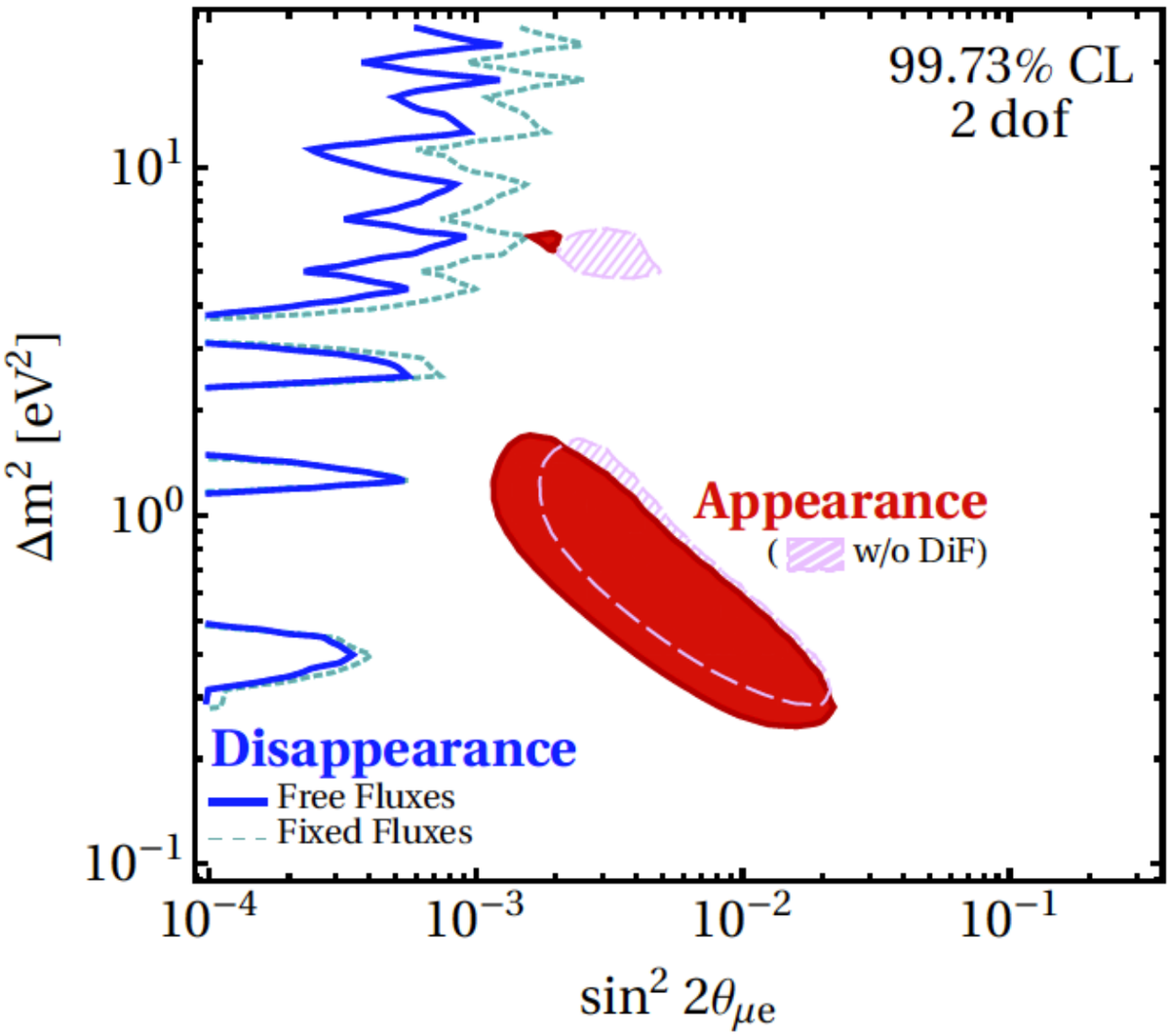
Global fit in 3+1 neutrino scheme

Dentler et al, JHEP 2018 [See also Giunti et al]



⇒ Constraints on short-baseline

$\nu_\mu \to \nu_e$ oscillations



⇒ strong tension between appearance (LSND/MiniBooNE) and disappearance experiments: SK, IceCube, MINOS/+,…

eV-sterile neutrino in Cosmology

- In Cosmology, sterile neutrinos with eV masses contribute to:

  $\Sigma\, m_\nu$ = sum of neutrino masses N_{eff} = relativistic degrees of freedom

- Considering the presence 4th light sterile neutrino:

$$\rightarrow \sum m_\nu \gtrsim 0.05\,\mathrm{eV} + \sqrt{\Delta m^2_{41}} > 1\,\mathrm{eV}$$

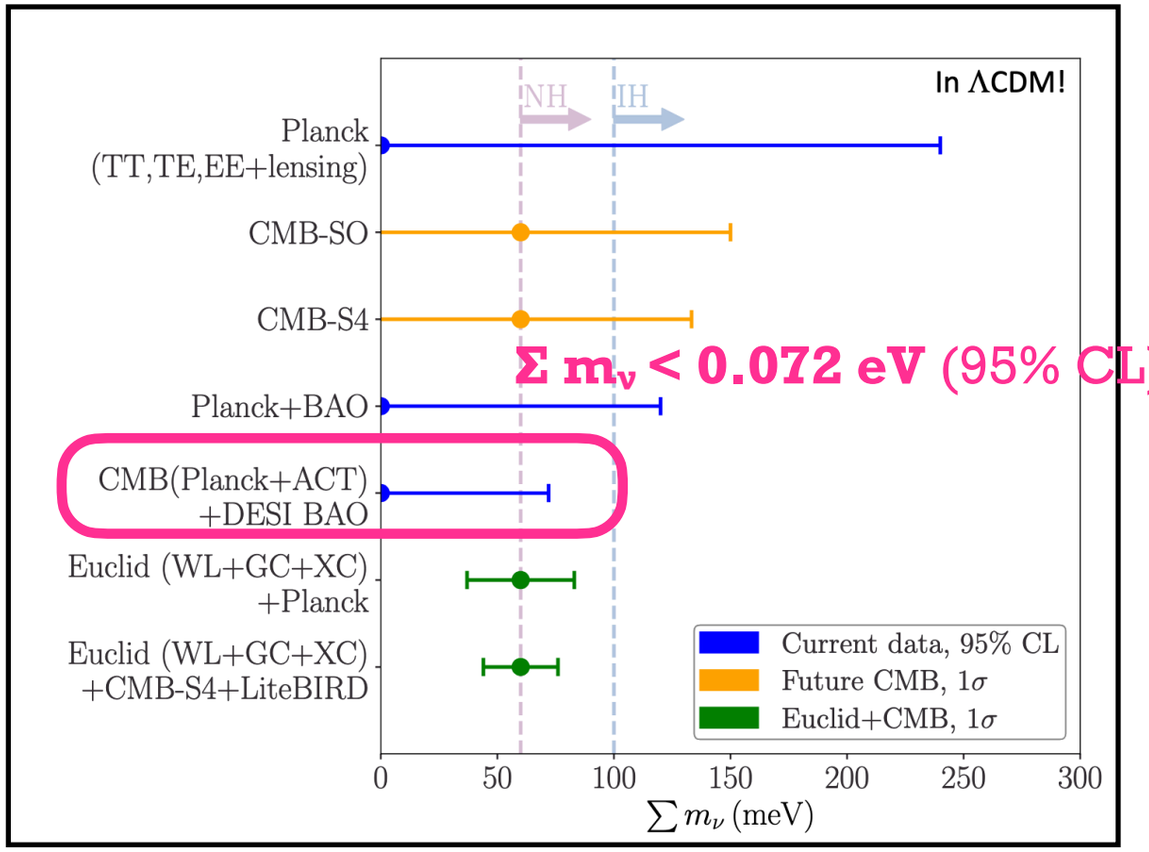
$$\rightarrow N_{eff} \approx 4$$

M. Archidiacono @ Neutrino 2024

- Cosmological constraints:

$$N_{\rm eff} = 2.96^{+0.34}_{-0.33}$$

Strong tension between the eV sterile neutrino hypothesis and cosmology



Non-unitary neutrino mixing

Non-unitary light neutrino mixing

✦ Most models of neutrino masses include **new extra heavy states**

Ex: type I seesaw, inverse seesaw $\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$ $\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$

→ (3x3) light neutrino mixing matrix U is **non-unitary** in general

✦ NxN **non-unitary mixing matrix** described with $2N^2$-(2N-1) parameters

→ 13 parameters are needed to describe a non-unitary (3x3) matrix

→ besides the 4 standard ones (θ_{ij} and δ_{CP}), 9 more parameters are needed

✦ General parameterization for non-unitary NxN mixing matrix

$$U^{n\times n} = \begin{pmatrix} N & W \\ V & T \end{pmatrix} \quad \textbf{with} \quad N = N^{NP}U^{3\times 3} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3\times 3}$$

Escrihuela et al, PRD92 (2015)

See also Xing, PRD2012 for n=6

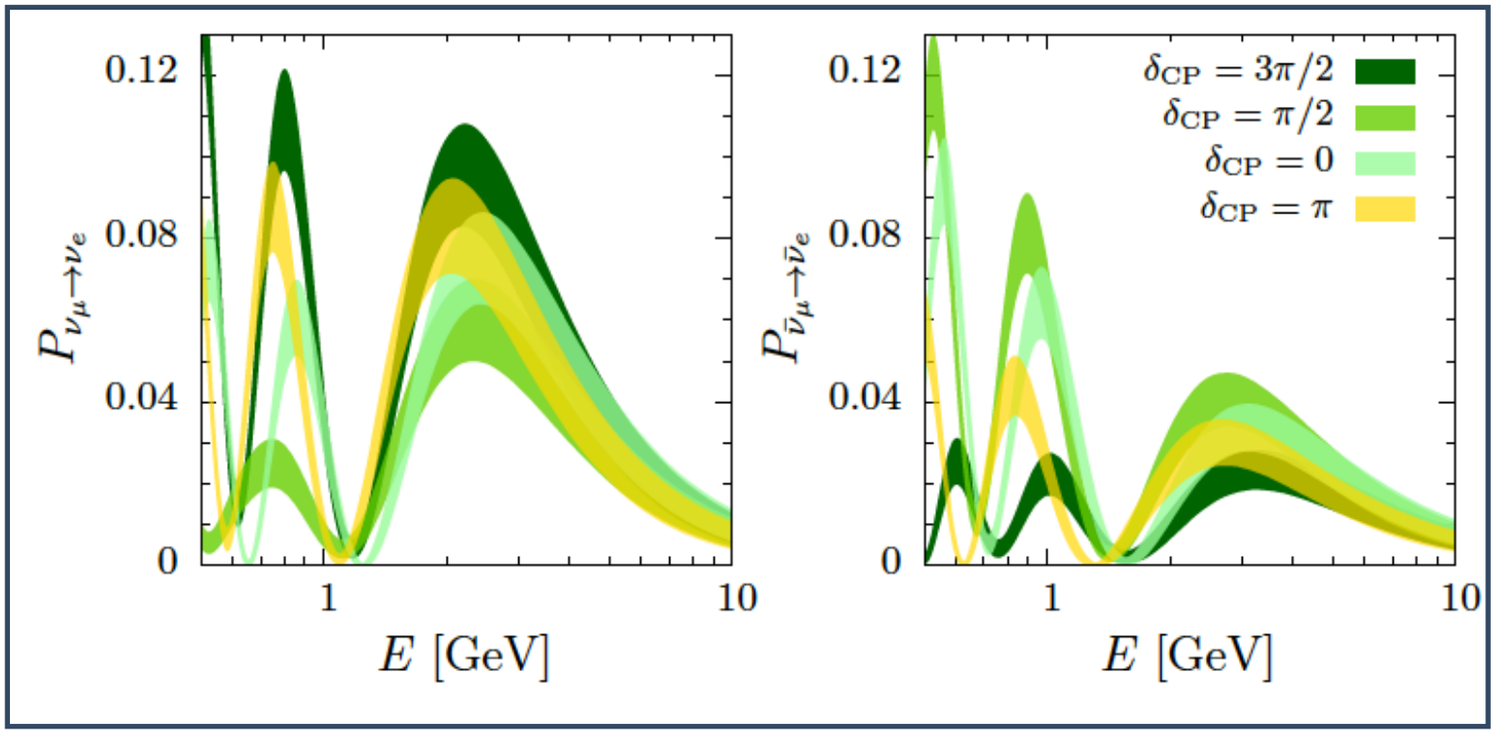
→ α_{ii} real, α_{ij} complex: 9 new parameters

NU neutrino oscillations in DUNE

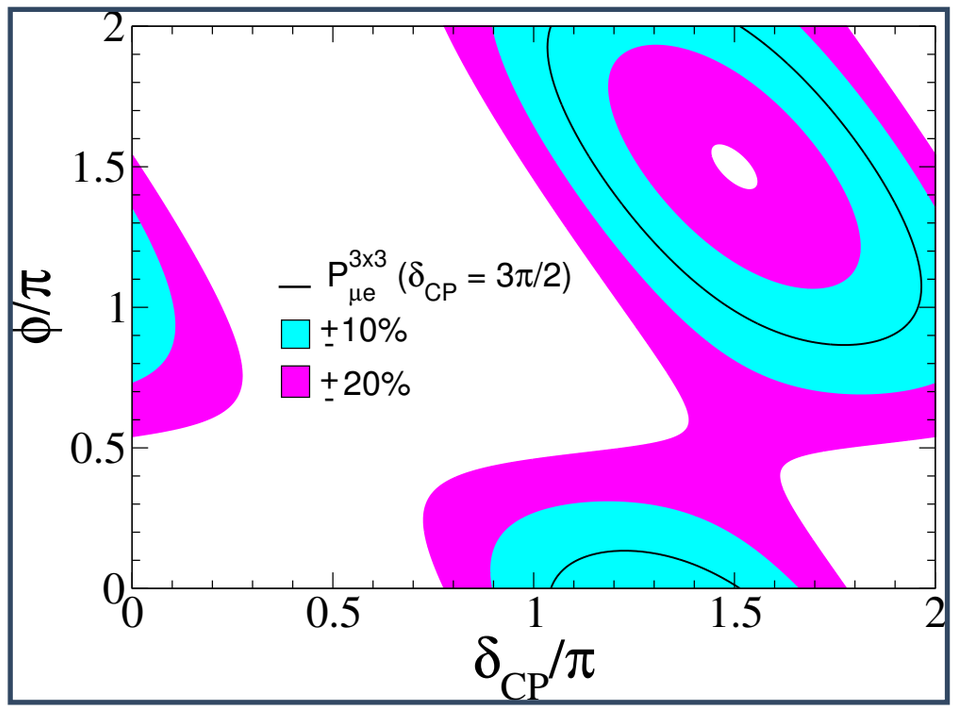
$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P^{3\times3}_{\mu e} + \alpha^2_{11}\alpha_{22}|\alpha_{21}|P^{I}_{\mu e} + \alpha^2_{11}|\alpha_{21}|^2$$

with $P^{I}_{\mu e}(\phi)$

The new phases (ϕ) will modify the standard oscillation picture in LBL experiments, such as DUNE



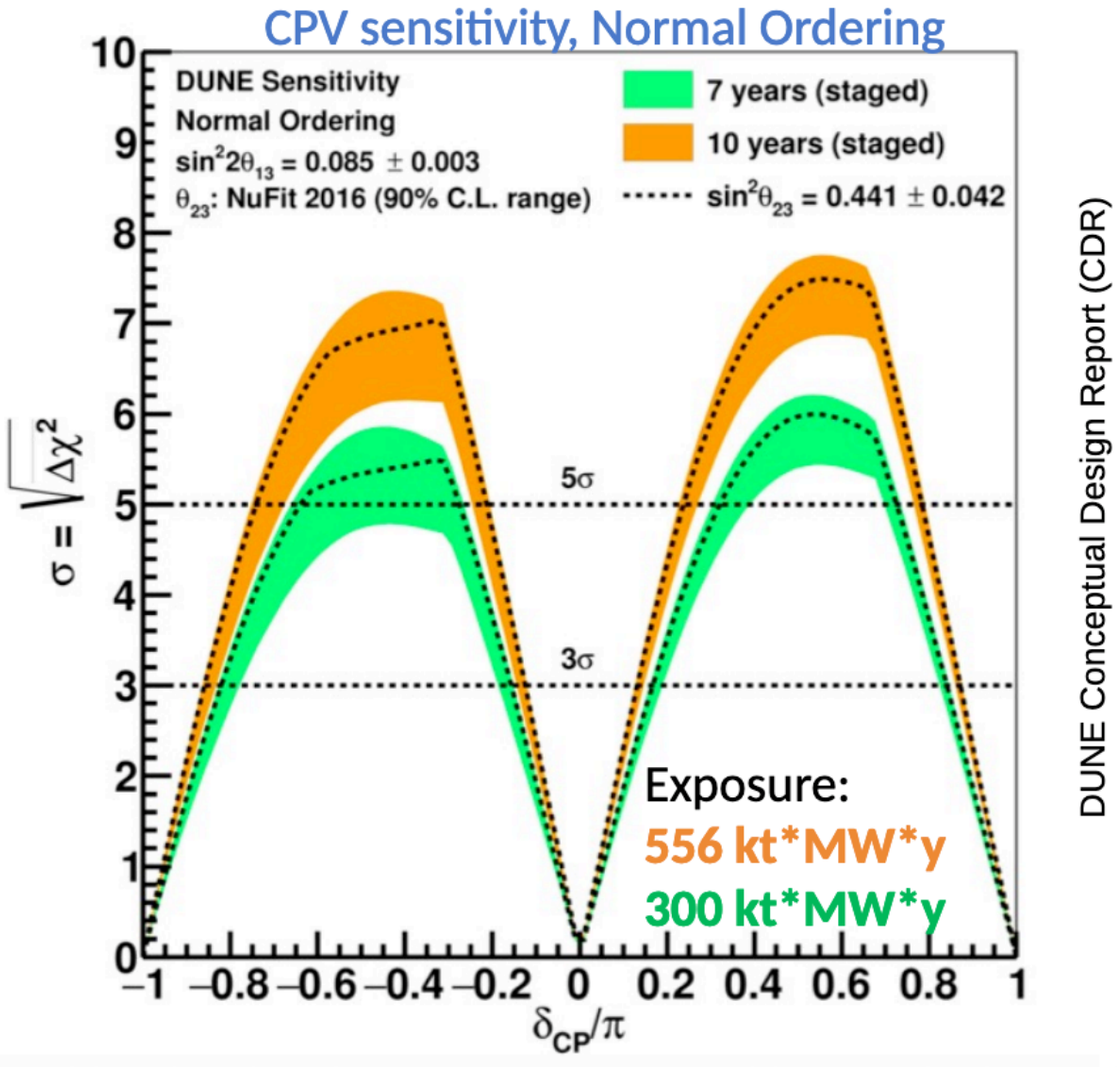
Escrihuela et al, NJP 2017

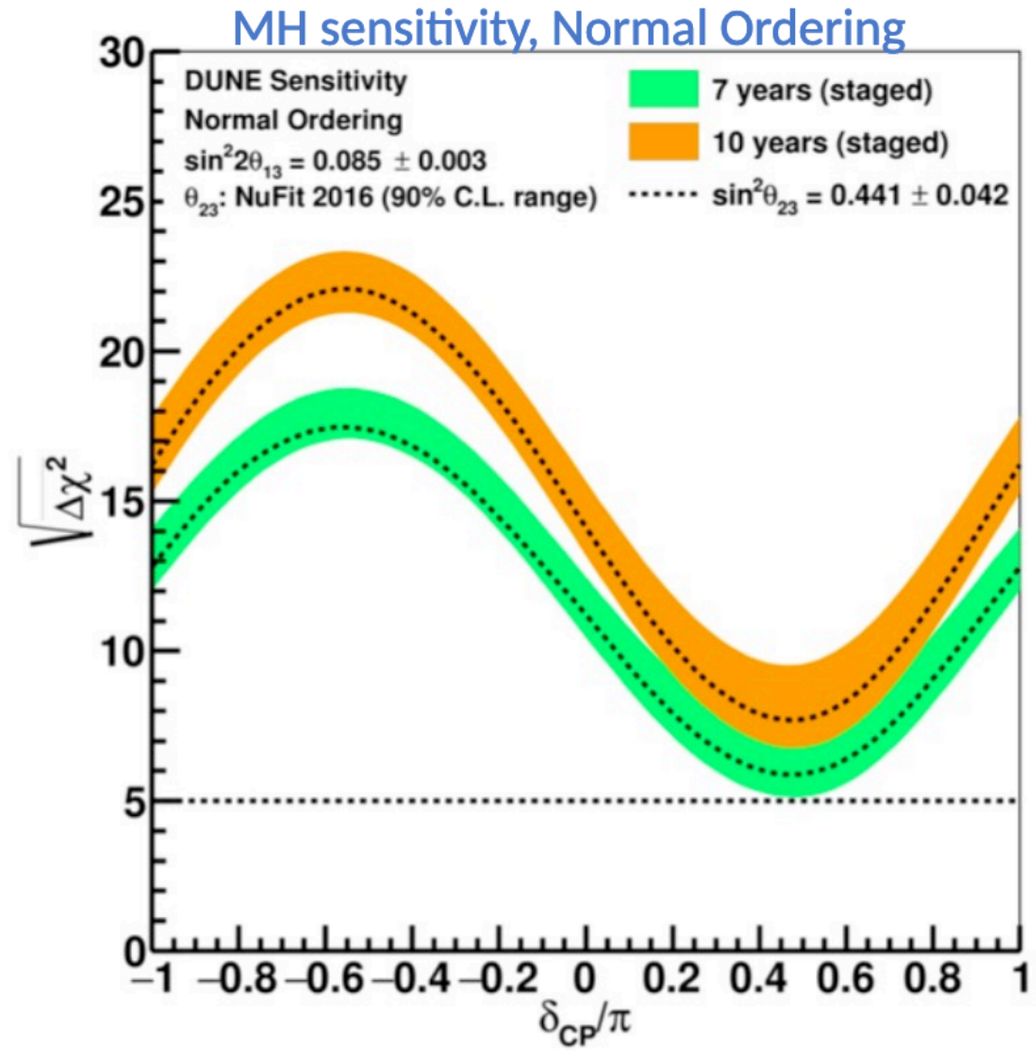


Miranda, MT, Valle, PRL 117 (2016)

→ (δ, ϕ) degeneracies in $P_{\mu e}$ for E≳ 3 GeV affect the sensitivity to δ

Sensitivity to CP-violation and mass ordering in DUNE



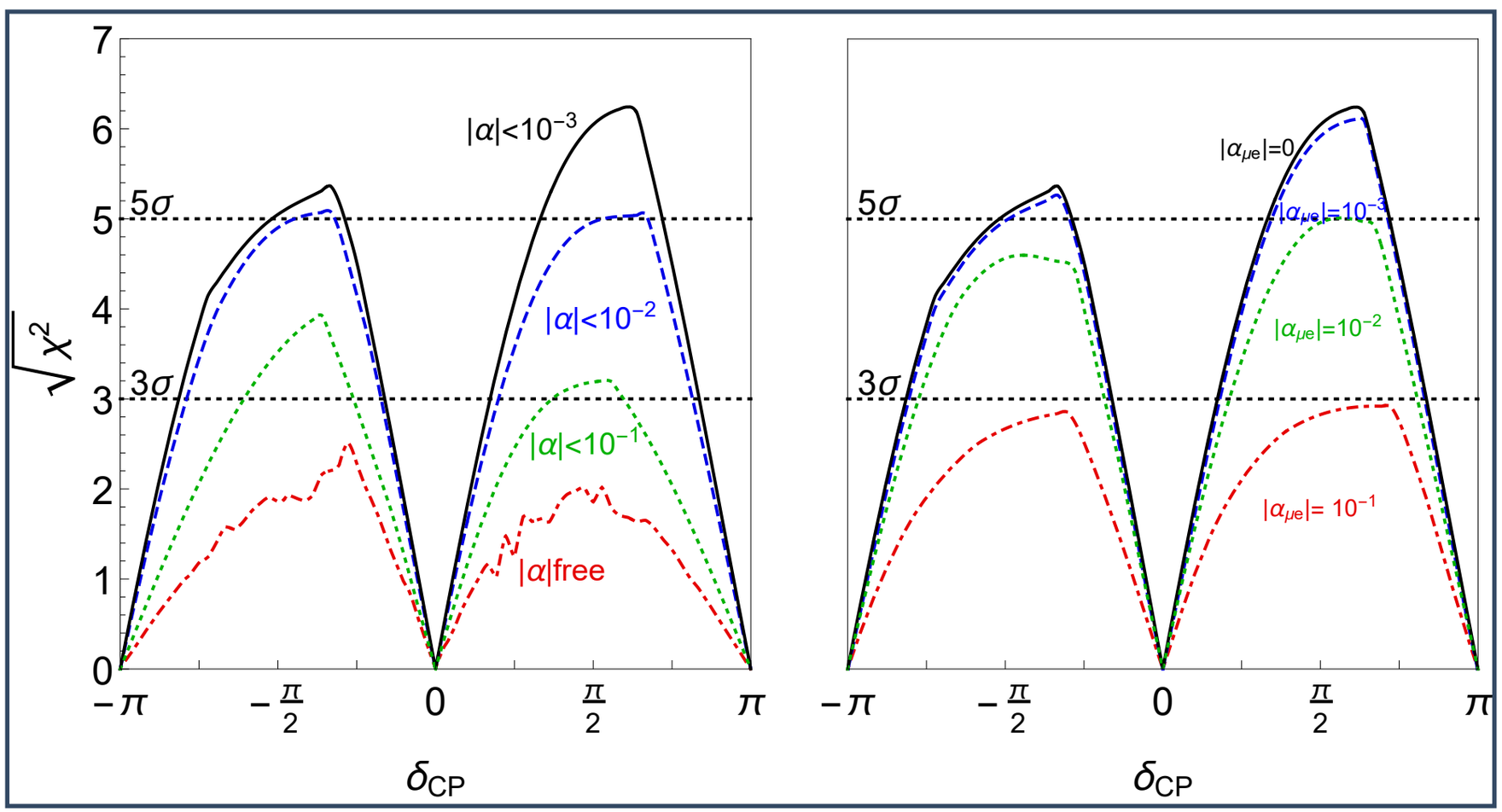


DUNE Conceptual Design Report (CDR)
arXiv:1512.06148

Width of bands indicates variation in possible central values of θ_{23}

>5σ sensitivity for both orderings and the full range of δ_{CP}

DUNE CP sensitivity with NU



Fernández-Martínez et al (DUNE-BSM Working Group)

→ The sensitivity to CP violation might be spoiled in the absence of priors on NU

→ With priors based on current bounds (10^{-3}-10^{-2}), the effect is less dramatic

Bounds on neutrino NU mixing

	One parameter (1 d.o.f.)		All parameters (6 d.o.f.)	
	90% C.L.	3σ	90% C.L.	3σ
Neutrinos + charged leptons				
$\alpha_{11} >$	0.9974	0.9963	0.9961	0.9952
$\alpha_{22} >$	0.9994	0.9991	0.9990	0.9987
$\alpha_{33} >$	0.9988	0.9976	0.9973	0.9961
$\lvert\alpha_{21}\rvert <$	1.7×10^{-3}	2.5×10^{-3}	2.6×10^{-3}	4.0×10^{-3}
$\lvert\alpha_{31}\rvert <$	2.0×10^{-3}	4.4×10^{-3}	5.0×10^{-3}	7.0×10^{-3}
$\lvert\alpha_{32}\rvert <$	1.1×10^{-3}	2.0×10^{-3}	2.4×10^{-3}	3.4×10^{-3}
Neutrinos only				
$\alpha_{11} >$	0.98	0.95	0.96	0.93
$\alpha_{22} >$	0.99	0.96	0.97	0.95
$\alpha_{33} >$	0.93	0.76	0.79	0.61
$\lvert\alpha_{21}\rvert <$	1.0×10^{-2}	2.6×10^{-2}	2.4×10^{-2}	3.6×10^{-2}
$\lvert\alpha_{31}\rvert <$	4.2×10^{-2}	9.8×10^{-2}	9.0×10^{-2}	1.3×10^{-1}
$\lvert\alpha_{32}\rvert <$	9.8×10^{-3}	1.7×10^{-2}	1.6×10^{-2}	2.1×10^{-2}

Escrihuela et al, NJP 2017

✦ Analysis of **short-baseline** and **long-baseline** neutrino experiments:

NOMAD, NuTeV, MINOS, NOvA and T2K.

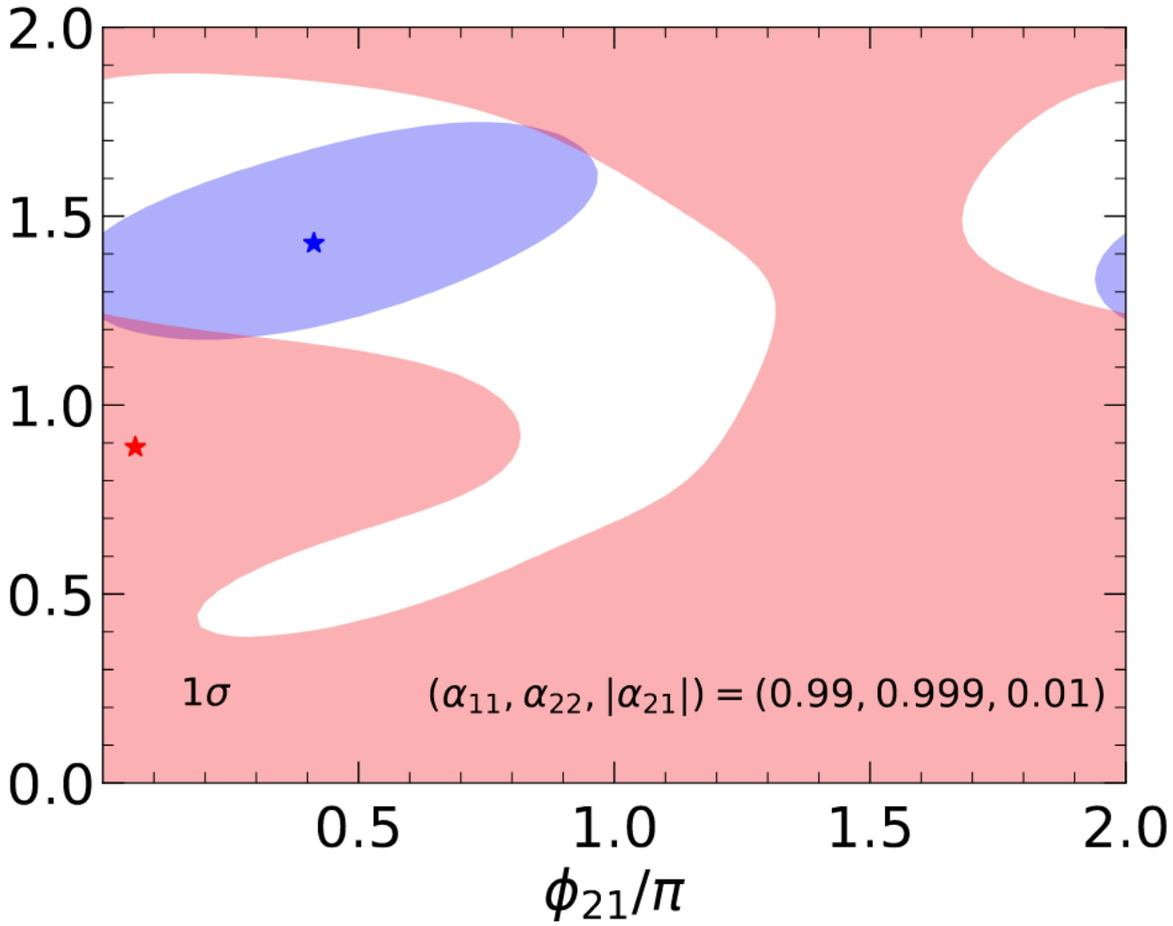
Parameter	90% C.L.	99% C.L.
$1 - \alpha_{11}$	< 0.031	< 0.056
$1 - \alpha_{22}$	< 0.005	< 0.010
$1 - \alpha_{33}$	< 0.110	< 0.220
$\lvert\alpha_{21}\rvert$	< 0.013	< 0.023
$\lvert\alpha_{31}\rvert$	< 0.033	< 0.065
$\lvert\alpha_{32}\rvert$	< 0.009	< 0.017

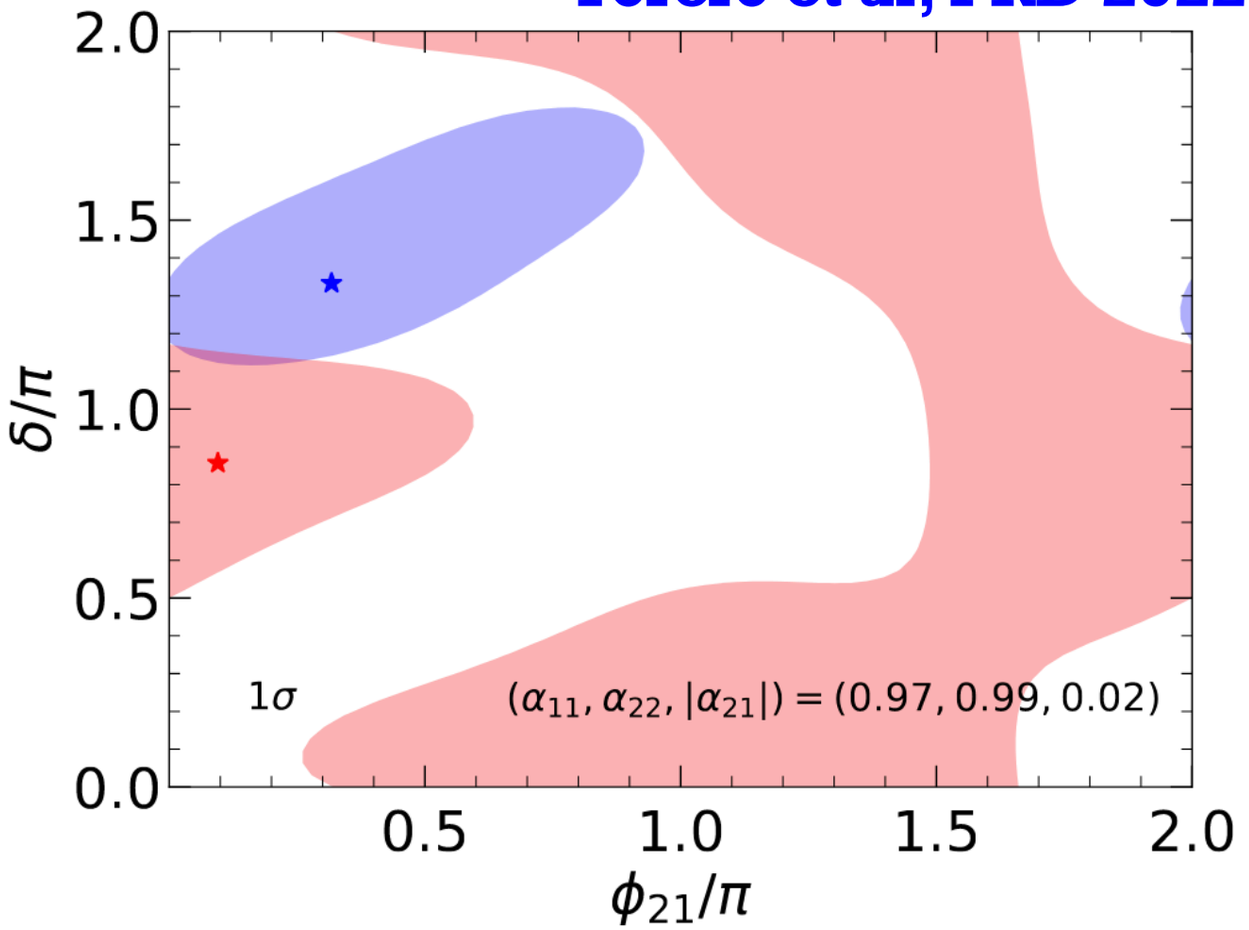
Forero, Giunti, Ternes, Tórtola, PRD 2022

The T2K-NOvA δ_{CP} tension

Non-unitary mixing analysis of T2K and NOvA (NO)

Forero et al, PRD 2022





- NU includes additional sources of CP violation.
- No significant deviation from unitary mixing is found: updated bounds with LBL and SBL ⇒MINOS improves current neutrino limits!

⇒ The tension is not alleviated in the context of NU neutrino mixing

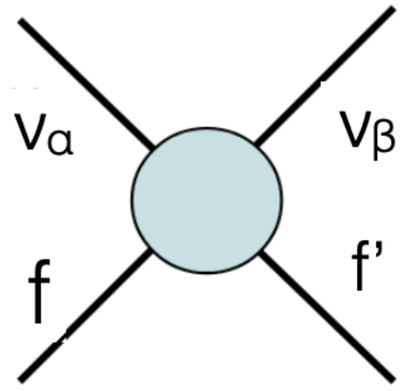
Non-standard neutrino interactions

Non-standard neutrino interactions

- New 4-fermion interactions involving neutrinos

CC-NSI: $$\mathcal{L}_{\rm CC-NSI} = -2\sqrt{2} G_F \, \epsilon^{f f' X}_{\alpha\beta} \left(\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta\right) \left(\bar{f}' \gamma_\mu P_X f\right)$$

$\Rightarrow$ effect on neutrino production and detection



(X= L,R)

NC-NSI: $$\mathcal{L}_{\rm NC-NSI} = -2\sqrt{2} G_F \, \epsilon^{f X}_{\alpha\beta} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{f} \gamma_\mu P_X f\right)$$

$\epsilon_{\alpha\beta} \neq 0 \quad \rightarrow$ NSI violate lepton flavor (FC-NSI)

$\epsilon_{\alpha\alpha} - \epsilon_{\beta\beta} \neq 0 \quad \rightarrow$ NSI violate lepton universality (NU-NSI)

$\Rightarrow$ mainly affecting neutrino propagation in matter:

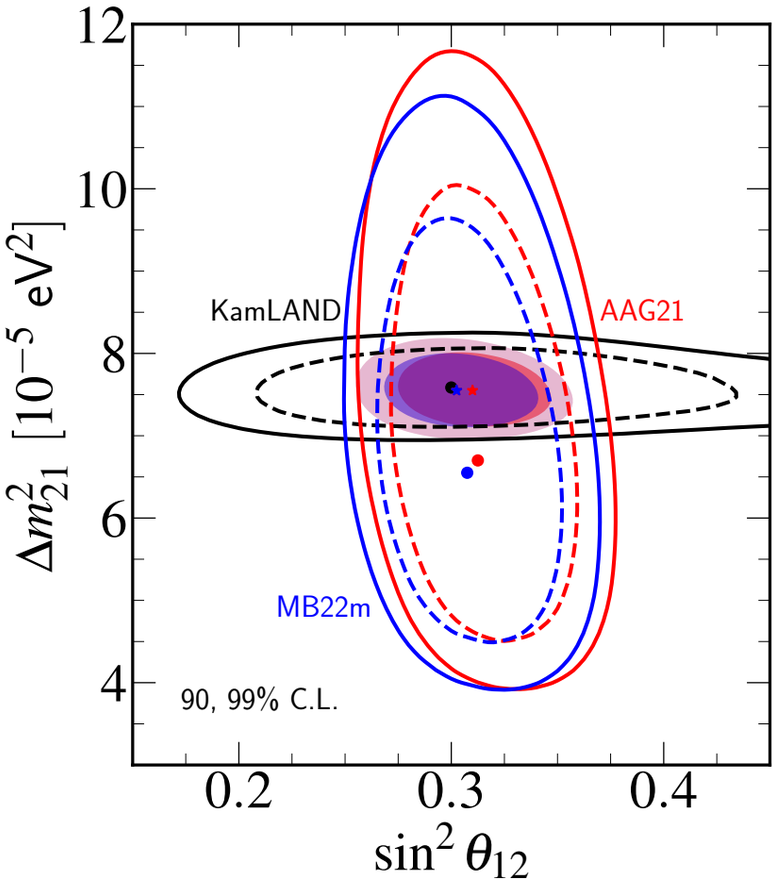
(but also detection, e.g., Super-K and Borexino)

- NSI may affect the 3-neutrino oscillation picture:

$\Rightarrow$ precision measurements at current experiments

$\Rightarrow$ sensitivity reach of upcoming experiments (degeneracies)

NSI in the solar sector



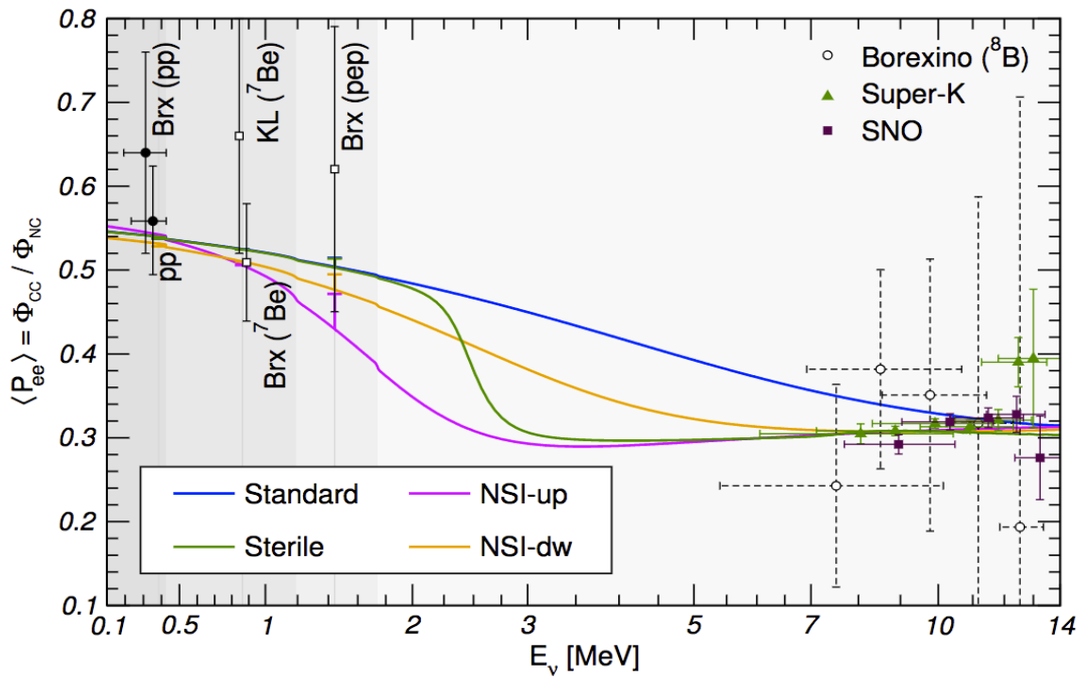
⇒ tension between preferred value of Δm^2_{21} from KamLAND and solar data

⇒ Δm^2_{21} preferred by KamLAND predicts steep upturn and smaller D/N asymmetry

- **NSI** (ε ~0.3) can reconcile both results:

⇒ flatter spectrum at intermediate E-region

⇒ larger D/N asymmetries can be expected



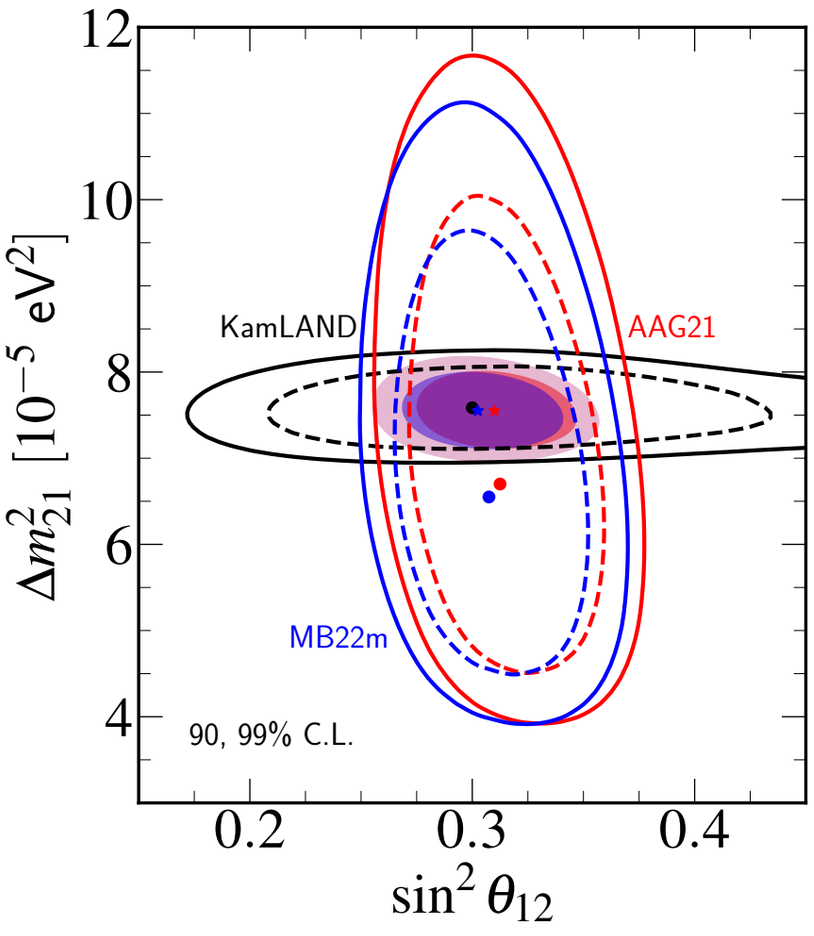
Escrihuela et al, PRD80 (2009); Coloma et al, PRD96 (2017) Maltoni & Smirnov, EPJ 2015

NSI in the solar sector

$$P_{ee} = \frac{1}{2}\left[1 + \cos 2\theta \cos 2\theta_{\rm mat}\right]$$

3ν oscillations

$$\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2} E G_F N_e}{\sqrt{(\Delta m^2 \cos 2\theta - 2\sqrt{2} E G_F N_e)^2 + (\Delta m^2 \sin^2 2\theta)^2}}$$

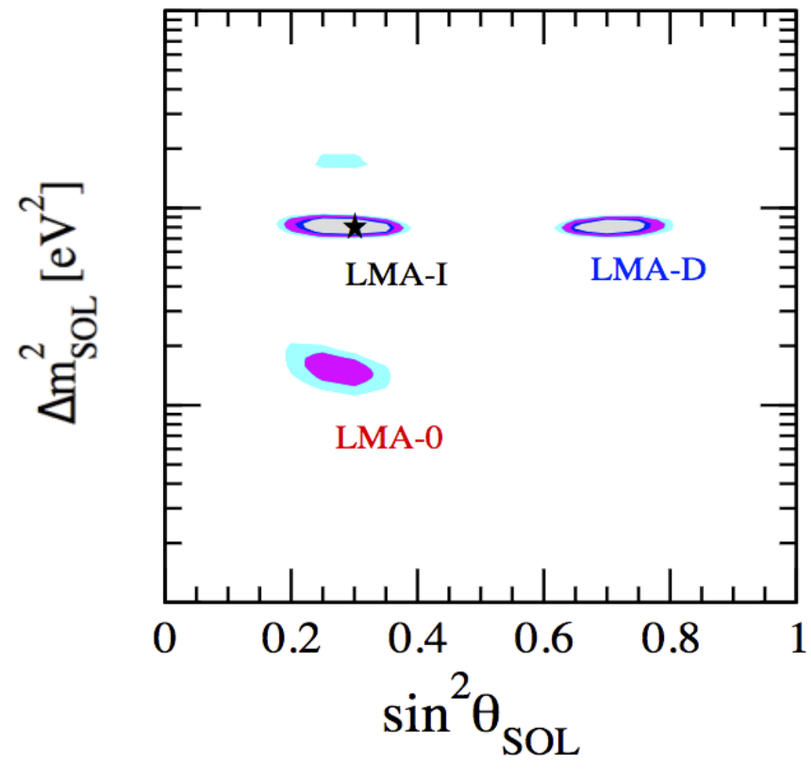


3ν oscillations + NSI:

$$N_e \to N_e + \varepsilon^f_{\alpha\alpha} N_f$$

⇒ **degenerate solution with:**

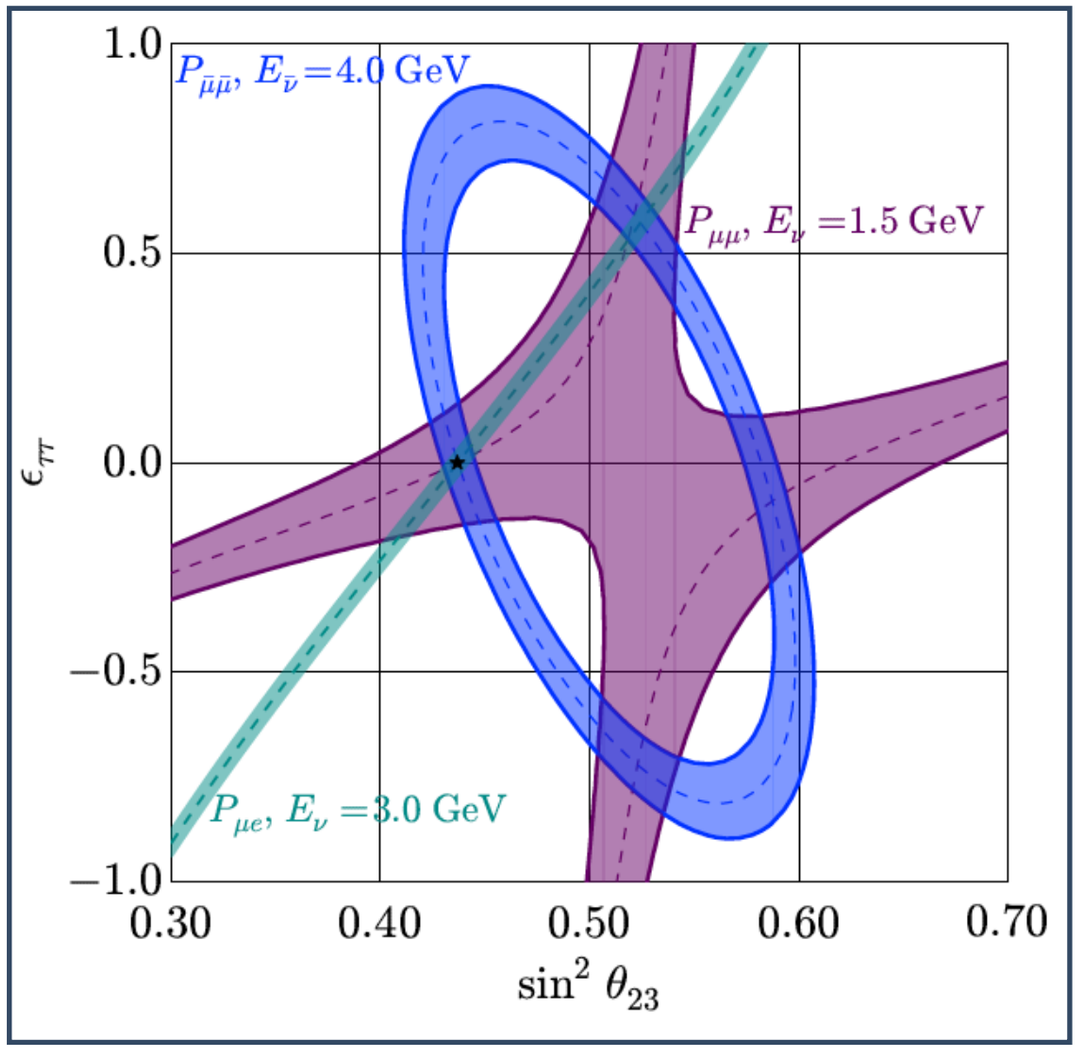
$$\varepsilon^f_{\alpha\alpha} N_f \to -\varepsilon^f_{\alpha\alpha} N_f - 2N_e\,, \quad \theta \to \pi/2 - \theta$$



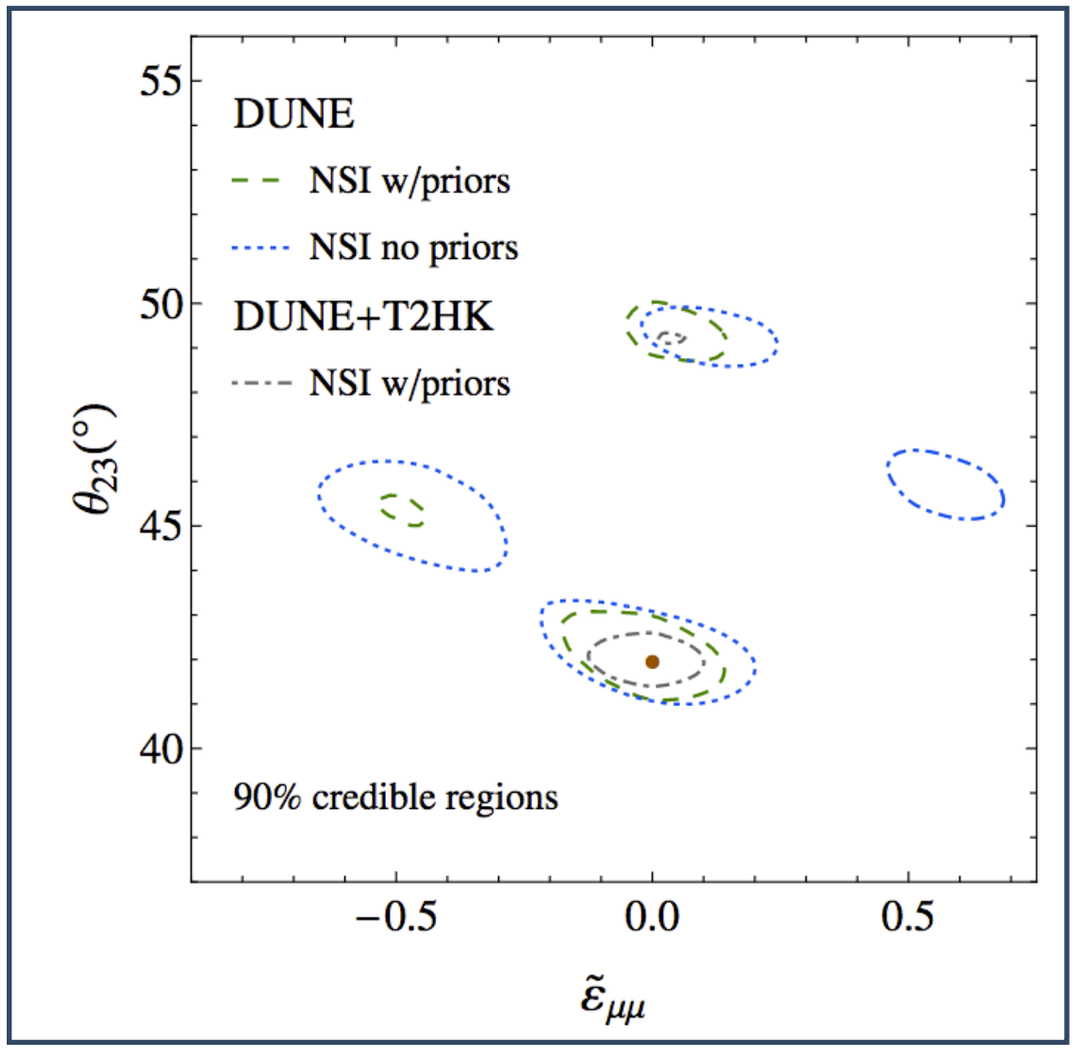
Miranda et al, JHEP 2006

NSI at future LBL experiments

(θ_{23}-$\epsilon_{\tau\tau}$) degeneracy in DUNE



Gouvea and Kelly, NPB 2016

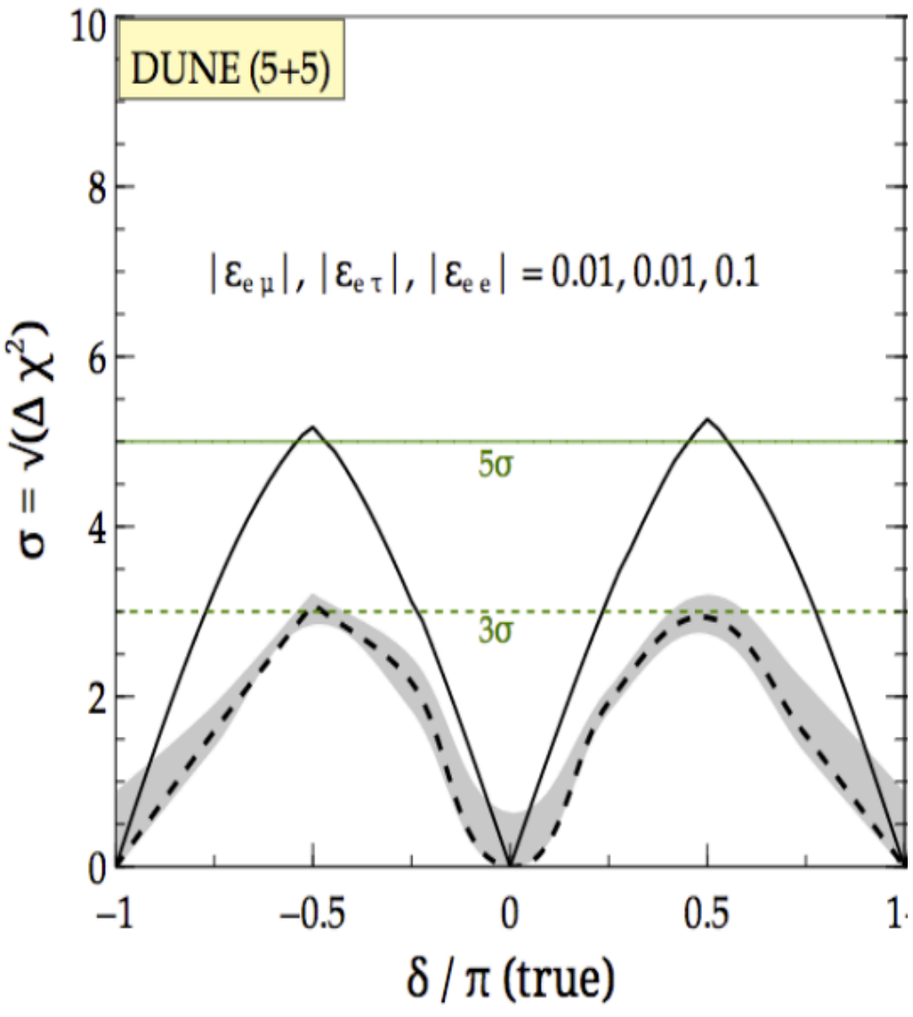


Coloma, JHEP 2016

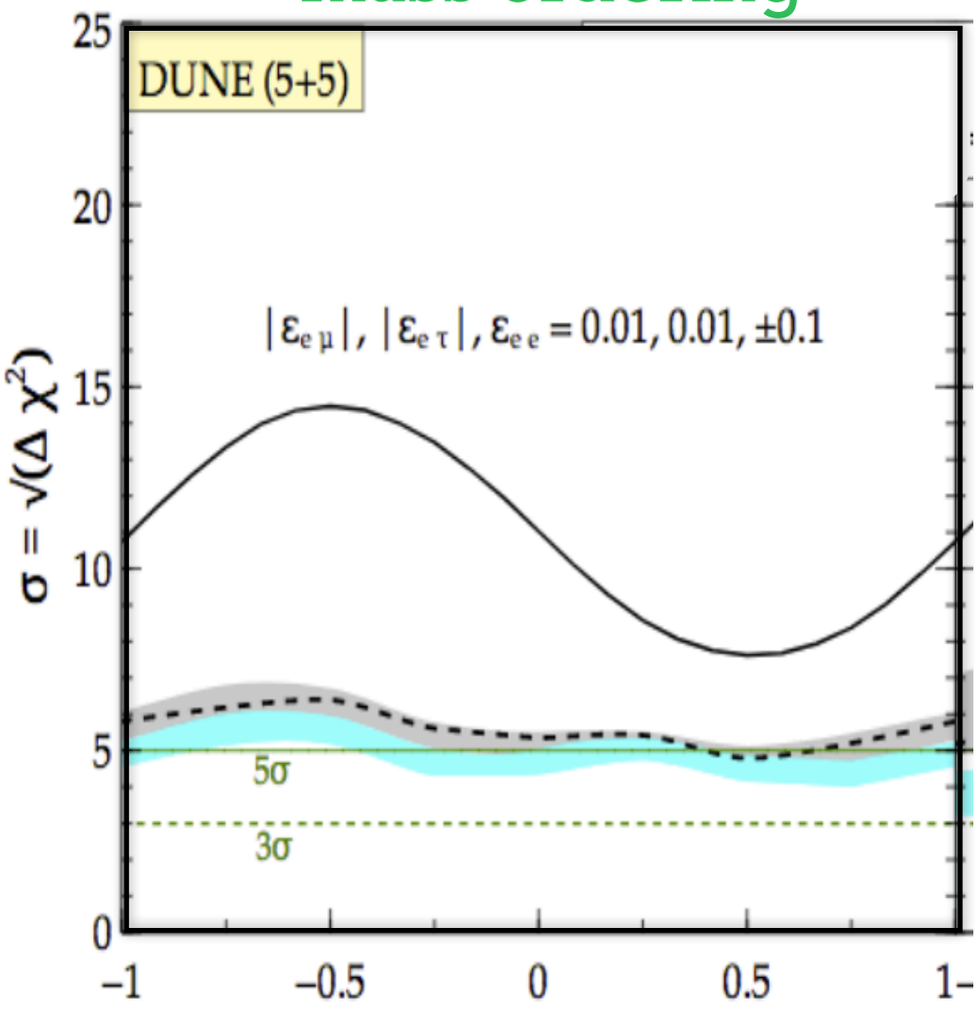
NSI at future LBL experiments

NSI can significantly spoil DUNE's sensitivity to:

CP violation



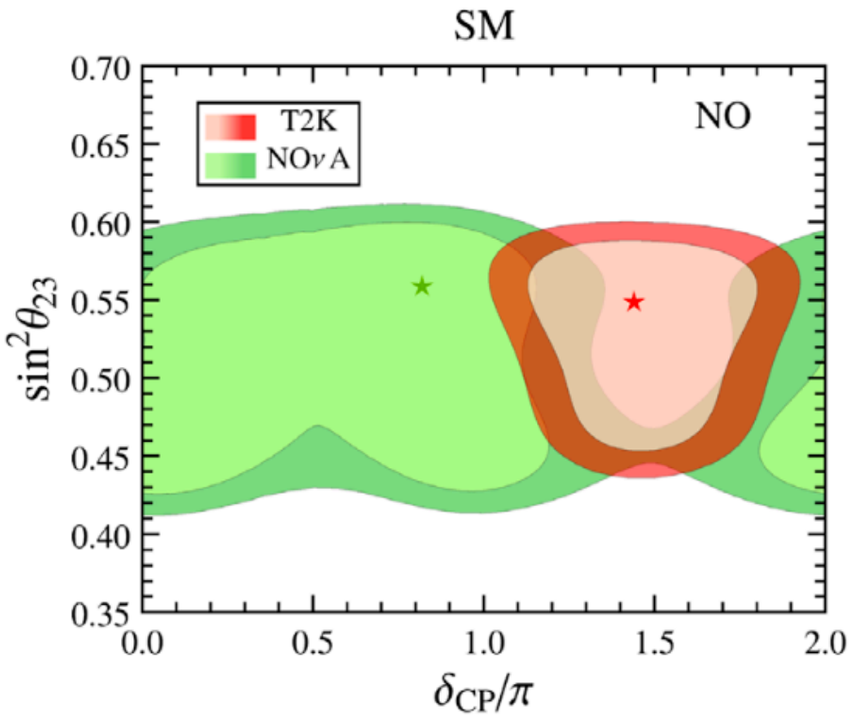
mass ordering

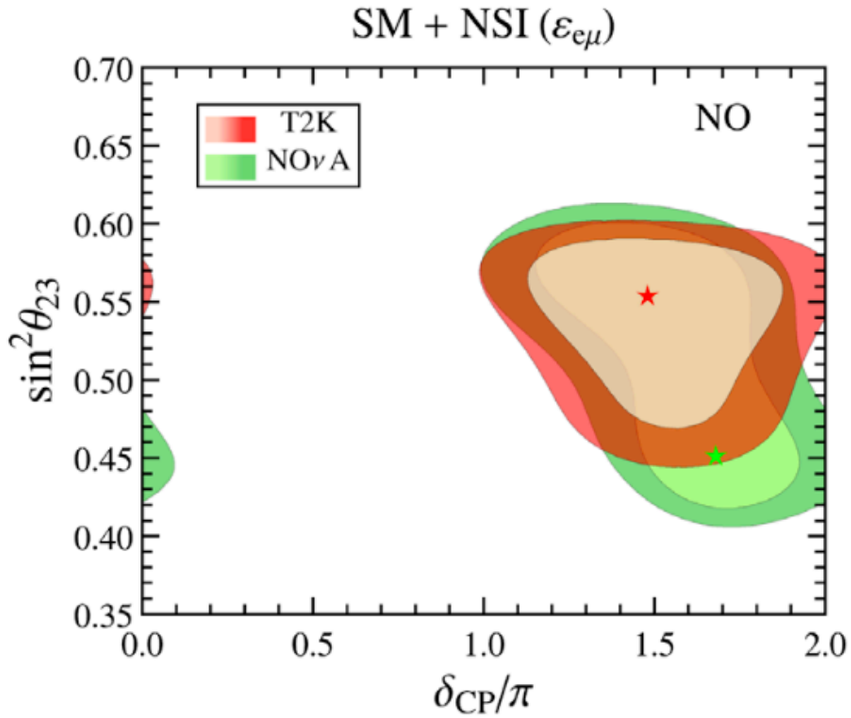


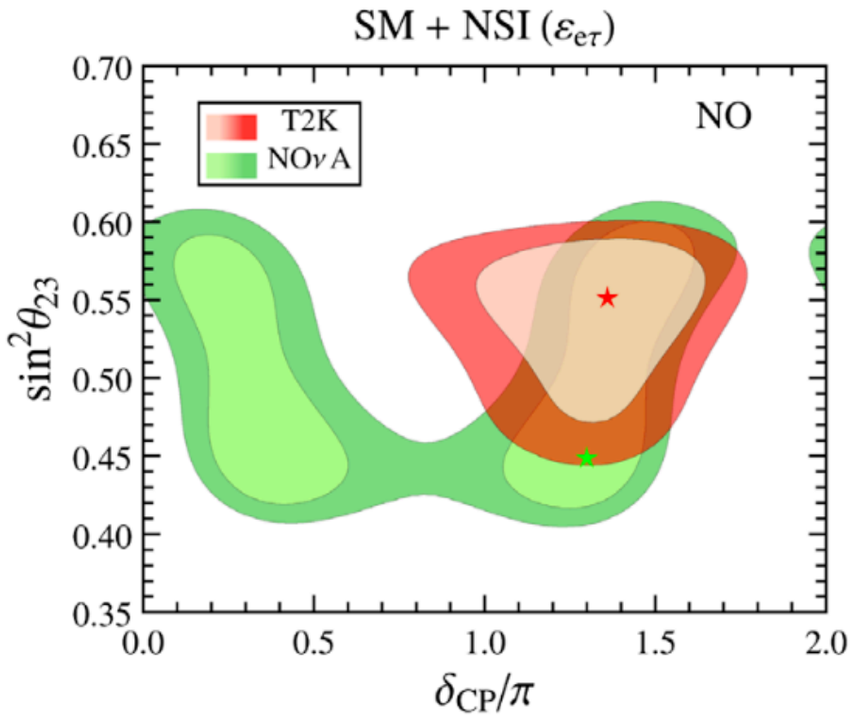
Masud and Mehta, PRD 2016

The T2K-NOvA δ_{CP} tension

- **NSI** may include new sources of CP violation besides δ_{CP}: $\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}| \exp(i\phi_{\alpha\beta})$
- CP-violating NSI with a new complex phase $\phi_{e\mu}$ or $\phi_{e\tau}$ close to maximal with NSI couplings $\varepsilon_{e\mu}$ or $\varepsilon_{e\tau}$ of the order of 0.2 may reconcile T2K and NOvA results.







Chatterjee and Palazzo, PRL 2021

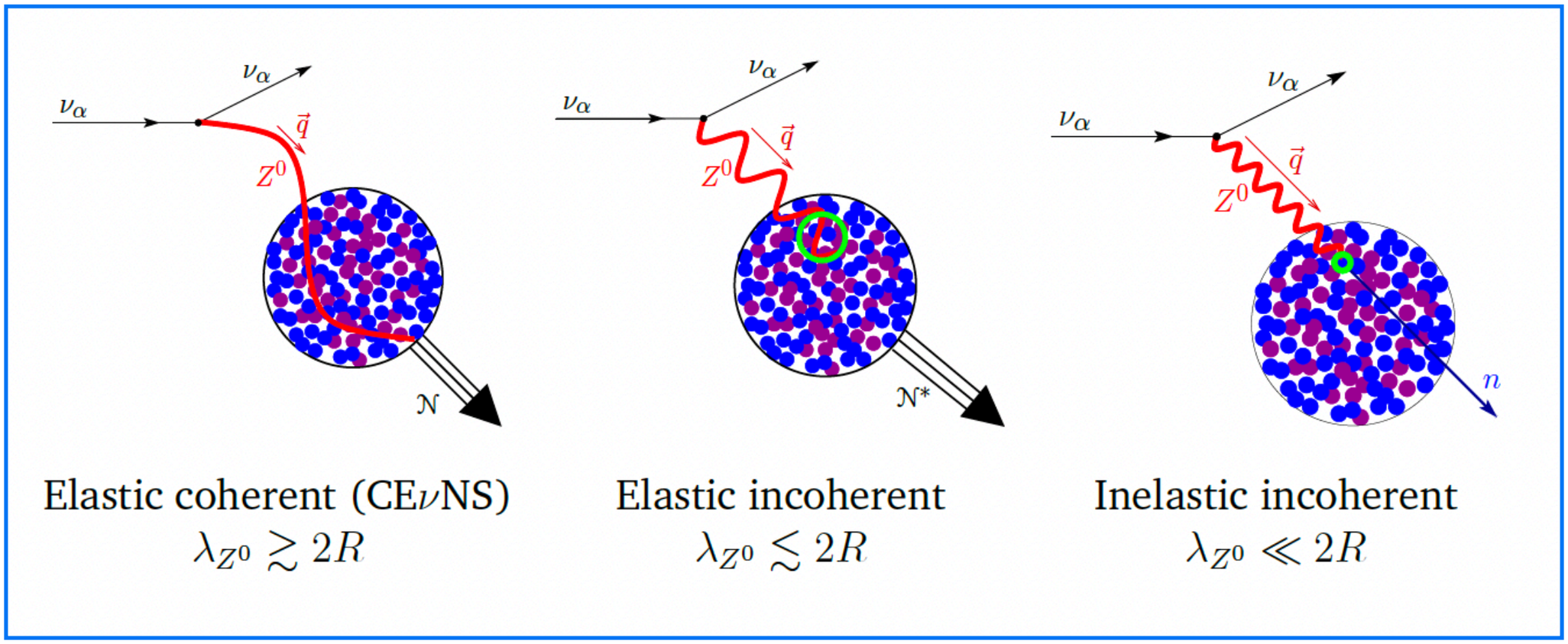
Denton et al, PRL 2021

BSM searches with CEvNS experiments

Coherent Elastic ν Nucleus Scattering (CEvNS)

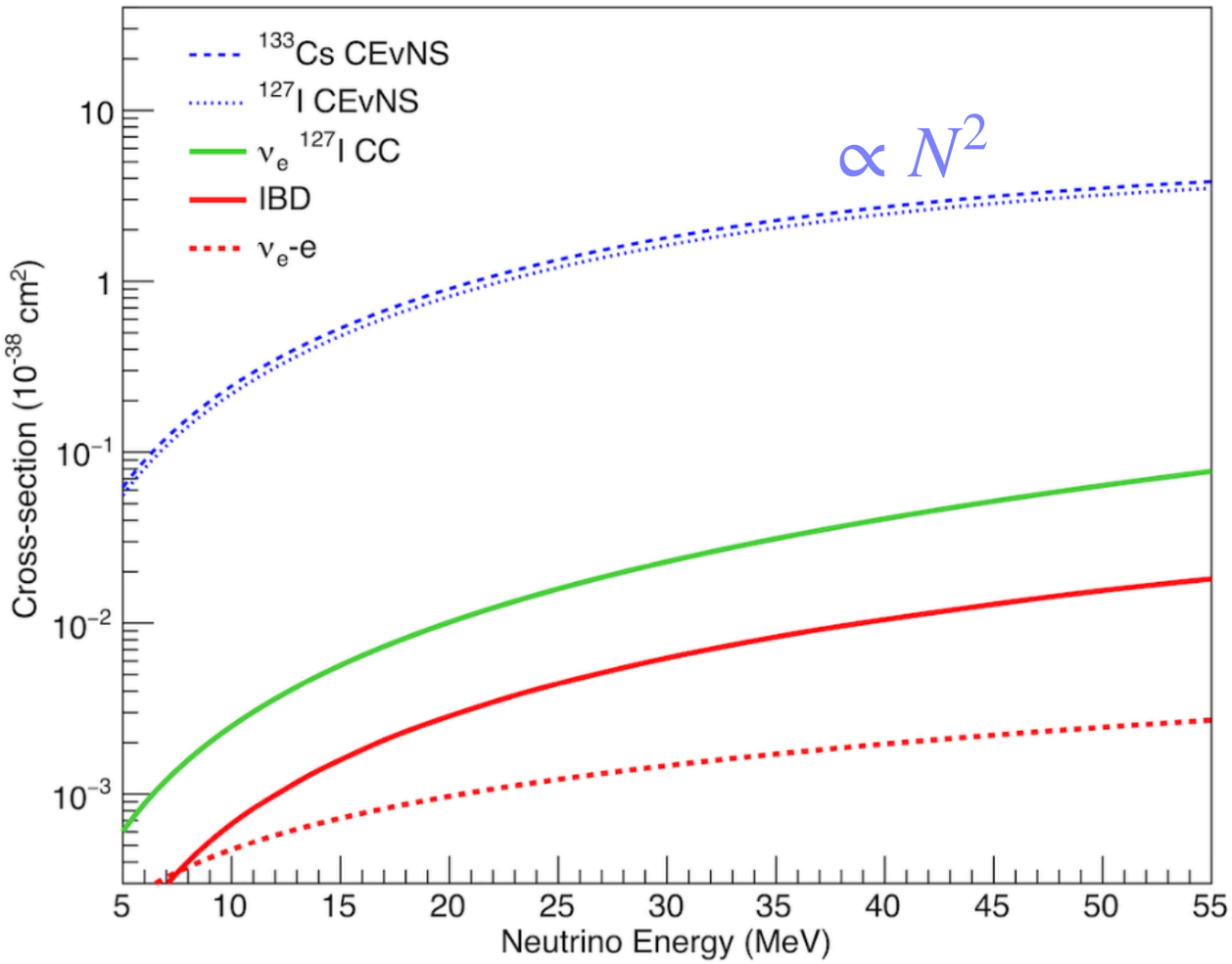
Freedman, PRD 1974

Cadeddu et al, EPL 143.3 (2023)



- If E≲100MeV, nucleon amplitudes sum up coherently:
  - ➡ cross section is enhanced as $(N_{target})^2$
  - ➡ up to 2 times larger than IBD: one can use kg-size detectors!

Coherent Elastic ν Nucleus Scattering (CEvNS)



2017: First observed at the Spallation Neutron Source (Oak Ridge National Lab)



⇒ smaller detectors!

COHERENT Coll. Science 357 (2017) 1123

Physics potential of CEvNS

Freedman, PRD 1974

Barranco et al, JHEP 2005

✦ Standard Model CEvNS cross section:

Nuclear form factor

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu}\right) Q_w^2 \left[F_w(q^2)\right]^2 + \frac{G_F^2 M}{4\pi}\left(1 + \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu}\right) F_A(q^2)$$

Weak nuclear charge

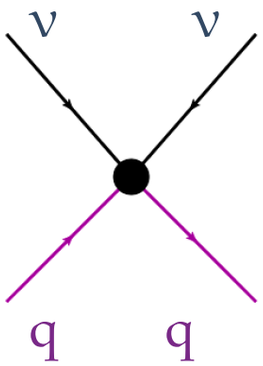
Axial contribution: small for most nuclei, it cancels out for nuclei with even number of p and n

$$Q_W = [Z(1 - 4\sin^2\theta_W) - N]$$

$\sin^2\theta_W \sim 0.23$ → neutron contribution dominates

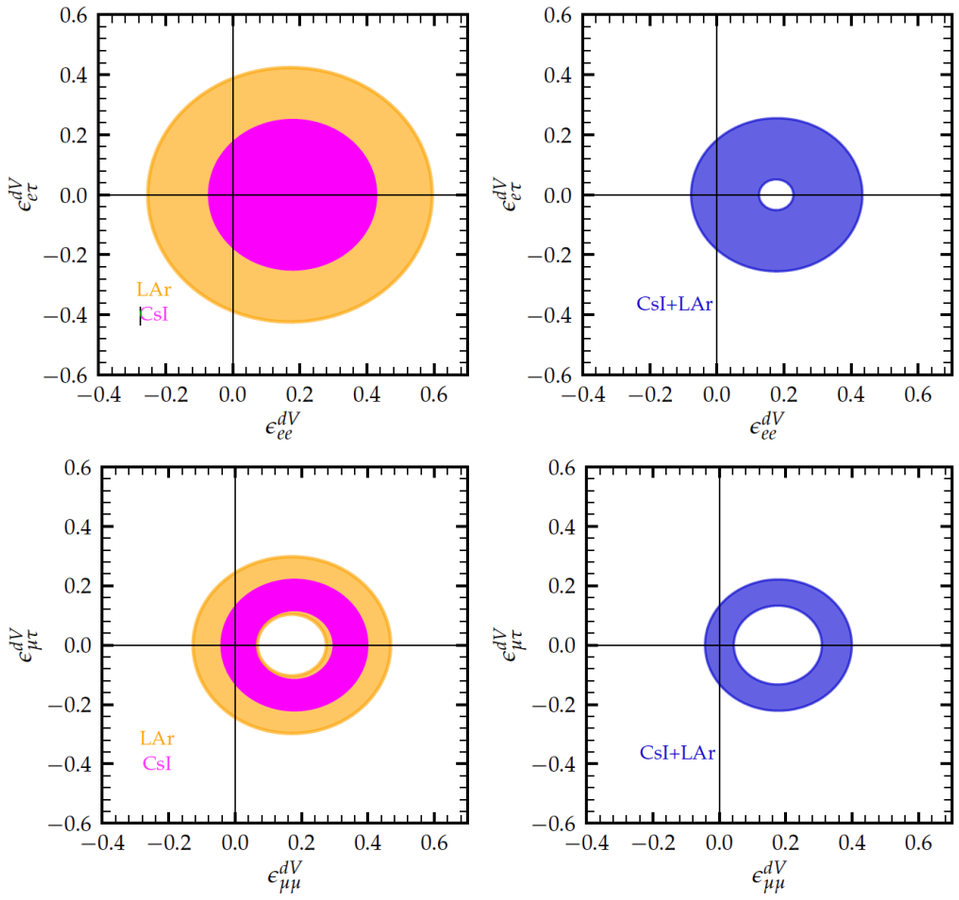
✦ **New physics** may affect the nuclear form factor, weak nuclear charge or add new terms to the cross section

Non-standard interactions

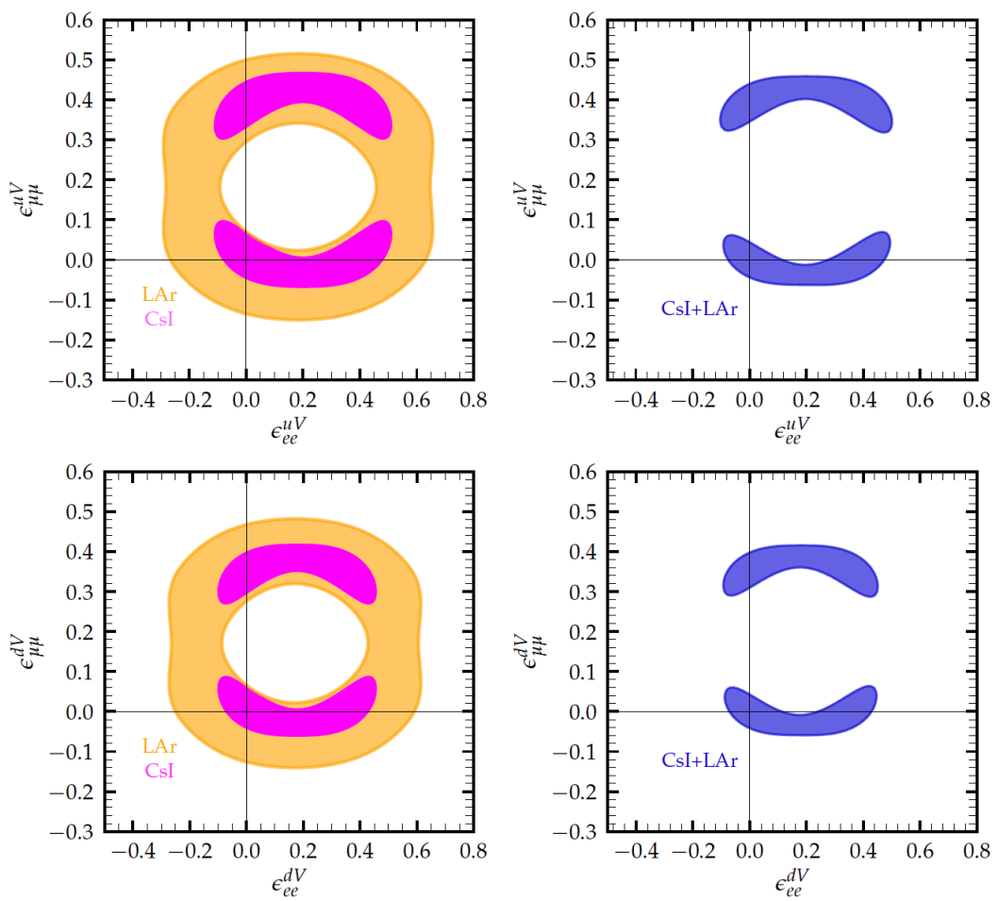


$$Q_V^{\rm NSI} = \left[\left(g_V^p + 2\varepsilon_{\ell\ell}^{uV} + \varepsilon_{\ell\ell}^{dV}\right) Z + \left(g_V^n + \varepsilon_{\ell\ell}^{uV} + 2\varepsilon_{\ell\ell}^{dV}\right) N\right] + \sum_{\ell,\ell'} \left[\left(2\varepsilon_{\ell\ell'}^{uV} + \varepsilon_{\ell\ell'}^{dV}\right) Z + \left(\varepsilon_{\ell\ell'}^{uV} + 2\varepsilon_{\ell\ell'}^{dV}\right) N\right].$$

Flavour-changing NSI



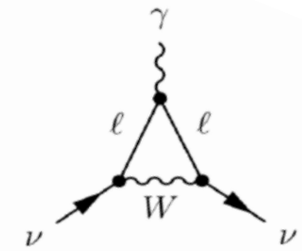
Non-Universal NSI



Data from COHERENT Experiment

De Romeri et al, JHEP 2023

Neutrino charge radius



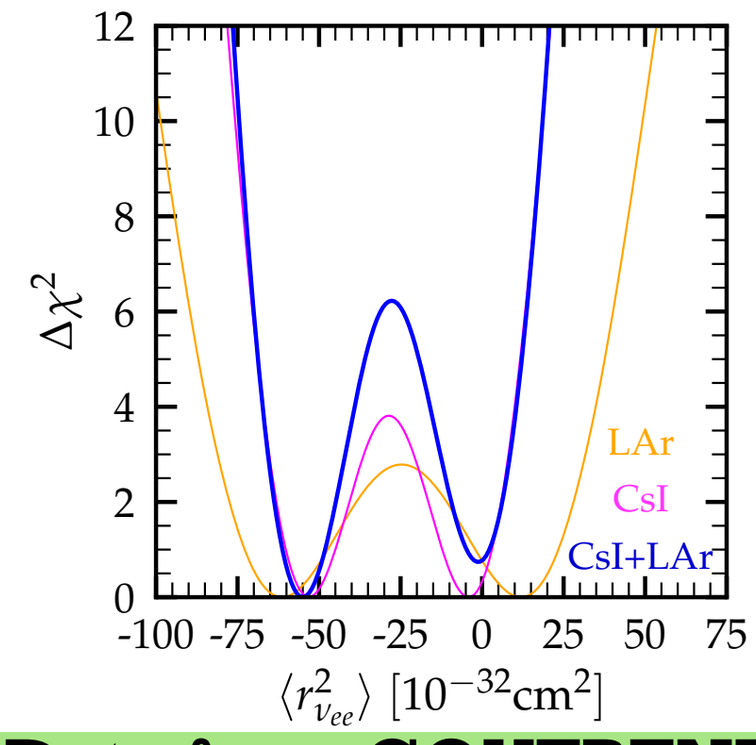
- It is the only EM neutrino parameter that is different from zero in the SM:

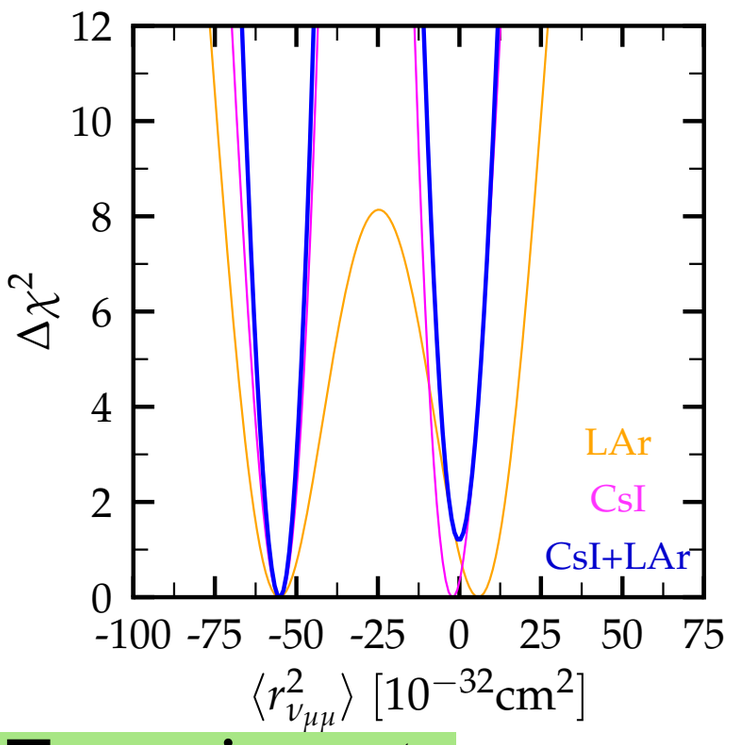
$$\left(\langle r^2_{\nu_{ee}}\rangle, \langle r^2_{\nu_{\mu\mu}}\rangle, \langle r^2_{\nu_{\tau\tau}}\rangle\right) = (-0.83, -0.48, -0.30) \times 10^{-32}\ \text{cm}^2$$ Bernabeu et al NPB 2004

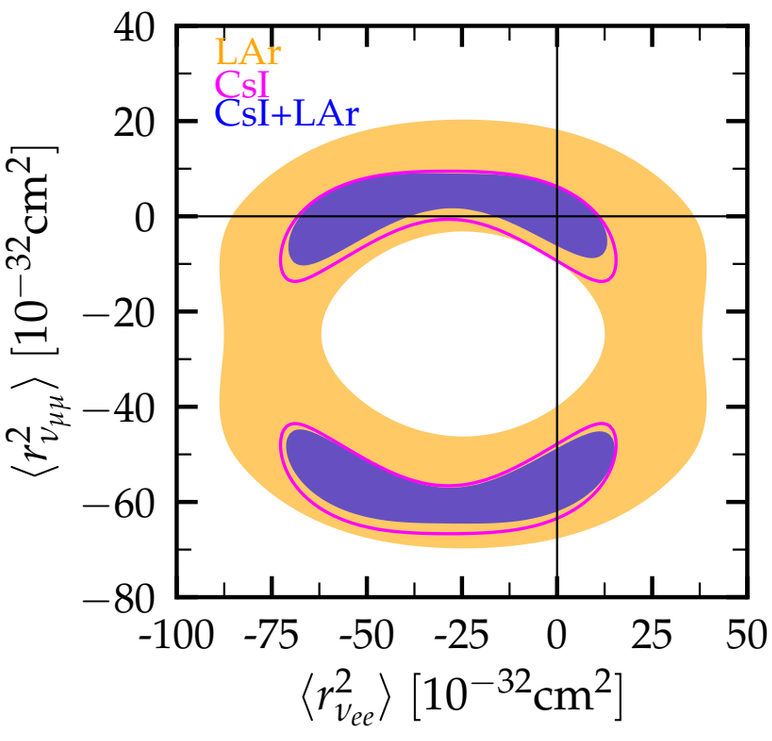
- New contribution to the CEvNS cross section, proportional to

$$Q^{\text{CR}}_{\ell\ell} = \frac{\sqrt{2}\pi\alpha_{\text{EM}}}{3\,G_F}\langle r^2_{\nu_{\ell\ell}}\rangle$$

$$\langle r^2_{\nu_{ee}}\rangle \in [-61.2, -48.2] \cup [-4.7, 2.2] \times 10^{-32}\ \text{cm}^2$$
$$\langle r^2_{\nu_{\mu\mu}}\rangle \in [-58.2, -52.1] \times 10^{-32}\ \text{cm}^2 \quad (1\sigma)$$







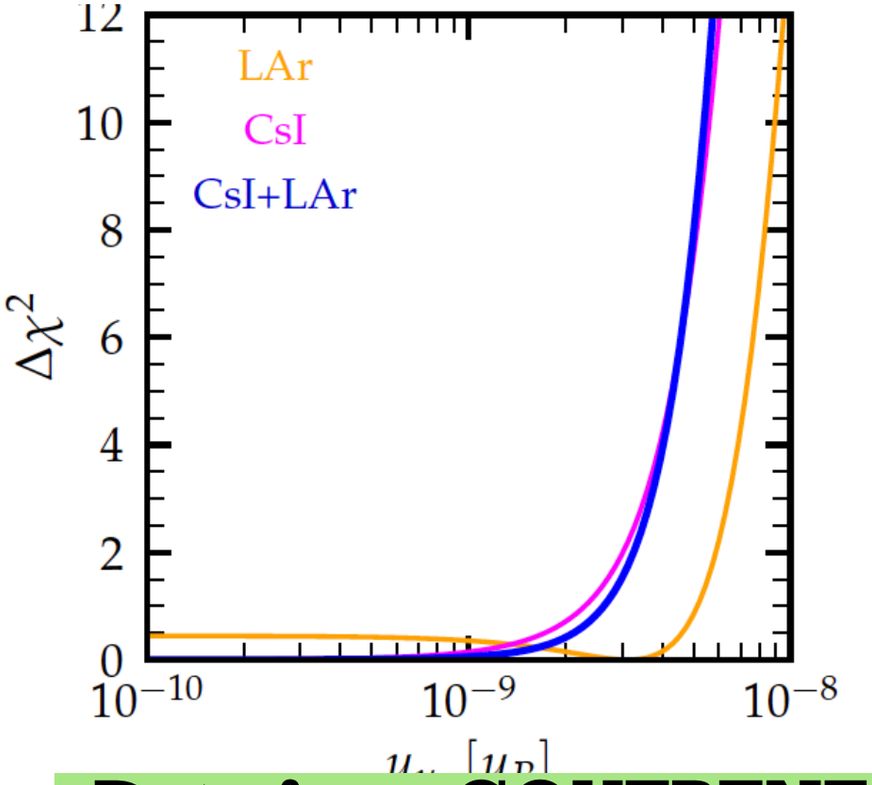
Data from COHERENT Experiment

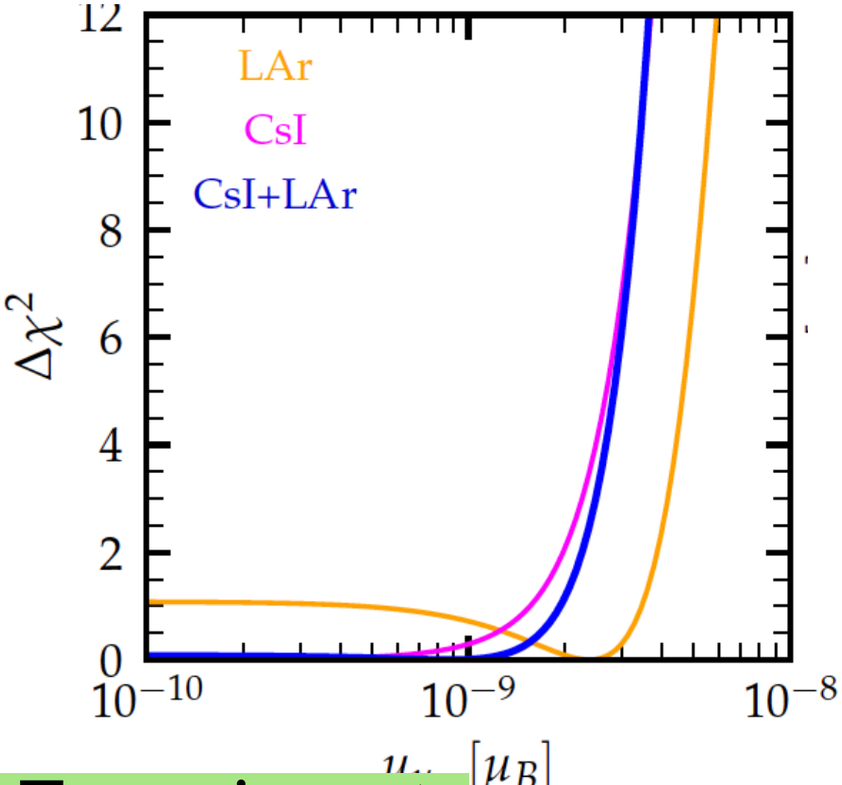
De Romeri et al, JHEP 2023

Neutrino magnetic moment

- Minimal SM extension (with m_ν) predicts $\mu_\nu \simeq 3 \times 10^{-19} \left(\frac{m_\nu}{\mathrm{eV}}\right) \mu_B$ ➡ larger in BSM
- The (effective) neutrino magnetic moment gives extra contribution to CEvNS cross section:

$$\left.\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\mathrm{nr}}}\right|^{\mathrm{MM}}_{\mathrm{CE}\nu\mathrm{NS}} = \frac{\pi \alpha^2_{\mathrm{EM}}}{m_e^2}\left(\frac{1}{E_{\mathrm{nr}}} - \frac{1}{E_\nu}\right) Z^2 F_W^2(|\vec{q}|^2) \left|\frac{\mu_{\nu_\ell}}{\mu_{\mathrm{B}}}\right|^2$$





90% C.L. limits

$$\mu_{\nu_e} < 3.6\ (3.8) \times 10^{-9}\ \mu_B$$
$$\mu_{\nu_\mu} < 2.4\ (2.6) \times 10^{-9}\ \mu_B$$

Data from COHERENT Experiment

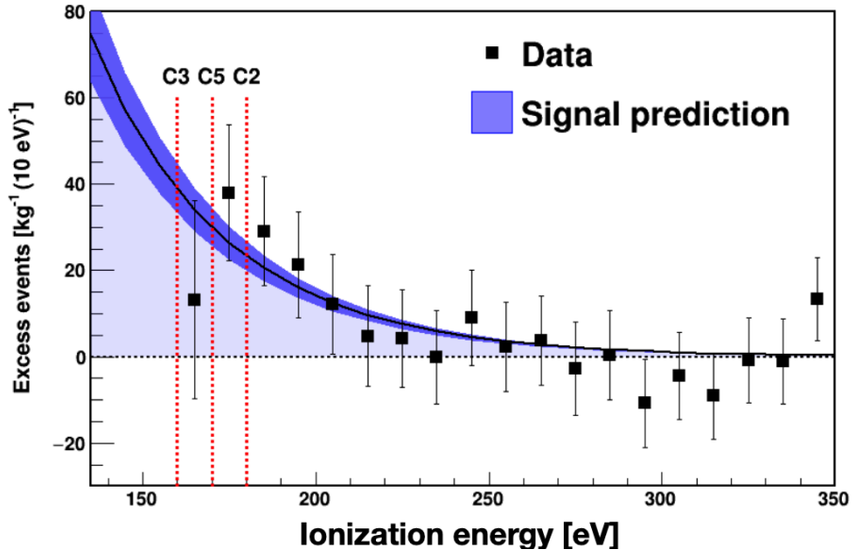
De Romeri et al, JHEP 2023

Limits from reactor CEvNS data

CONUS+ Collaboration, 2501.05206

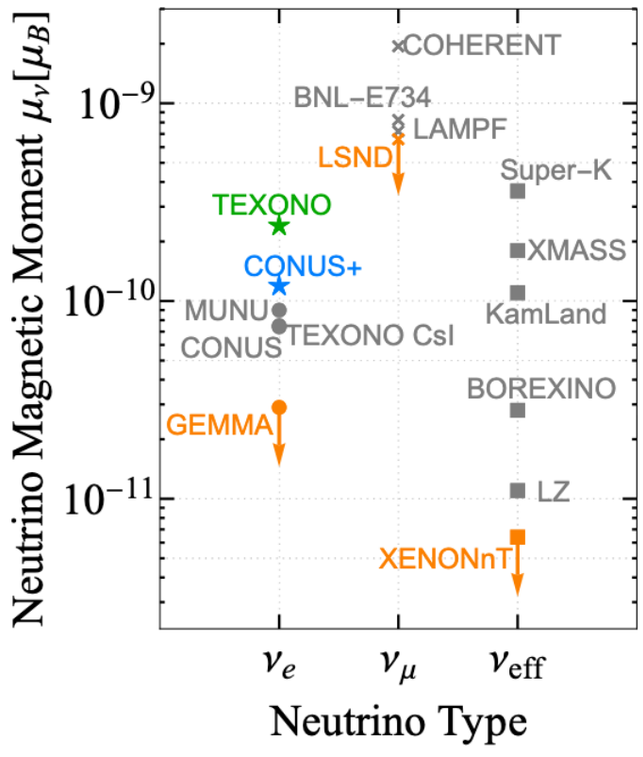
CONUS+





Bounds on neutrino magnetic moment (90% CL)

$$\mu_{\nu_e}^{\text{eff}} \leq 4.78 \times 10^{-10}\ \mu_B \qquad (\text{CE}\nu\text{NS only})\,,$$
$$\mu_{\nu_e}^{\text{eff}} \leq 1.10 \times 10^{-10}\ \mu_B \qquad (\text{CE}\nu\text{NS} + \text{E}\nu\text{ES})$$



De Romeri et al, PRD 2025

Atzori Corona et al, PRD 2025

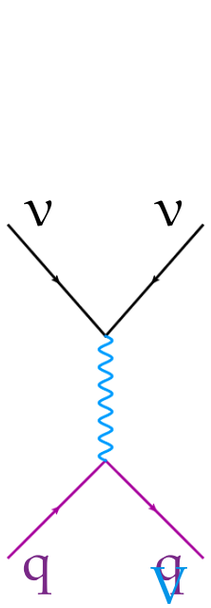
New light mediators

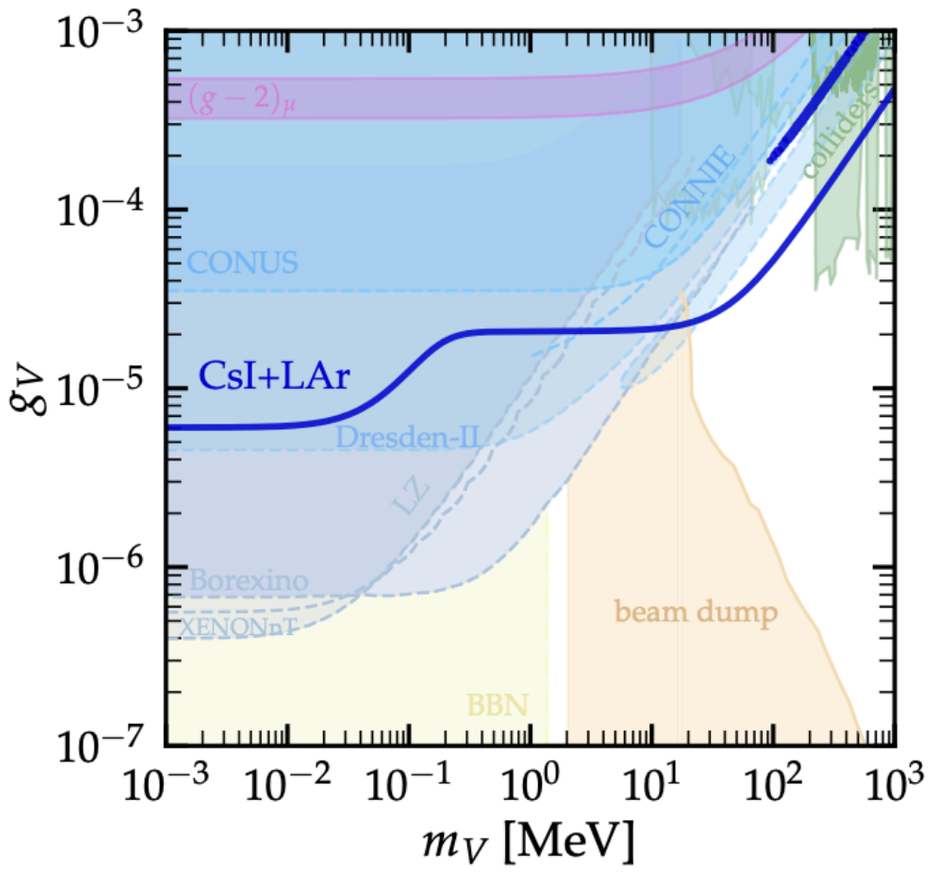
Light-vector mediator

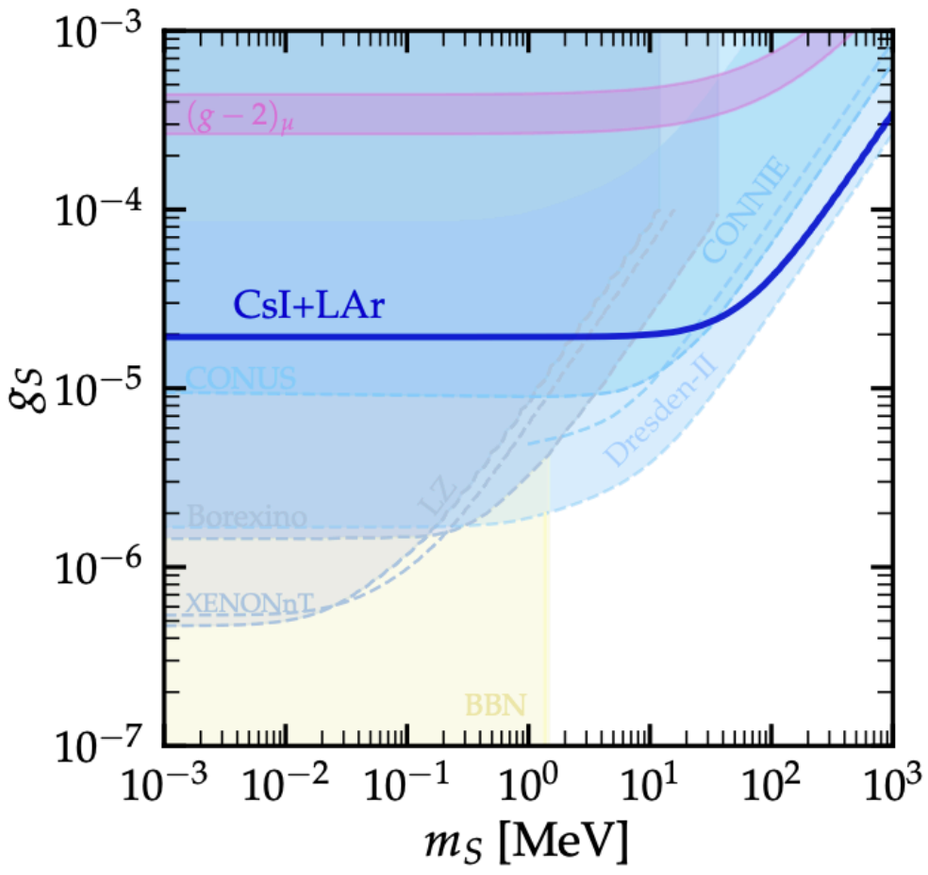
$$\left.\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\rm nr}}\right|^{\rm LV}_{\rm CE\nu NS} = \left(1 + \kappa \frac{C_V}{\sqrt{2} G_F Q_V^{\rm SM} \left(2 m_N E_{\rm nr} + m_V^2\right)}\right)^2 \left.\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\rm nr}}\right|^{\rm SM}_{\rm CE\nu NS}$$

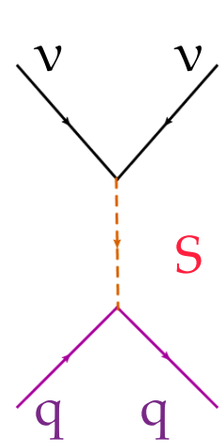
Light-scalar mediator

$$\left.\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\rm nr}}\right|^{\rm LS}_{\rm CE\nu NS} = \frac{m_N^2 E_{\rm nr} C_S^2}{4\pi E_\nu^2 \left(2 m_N E_{\rm nr} + m_S^2\right)^2} F_W^2(|\vec{q}|^2)$$







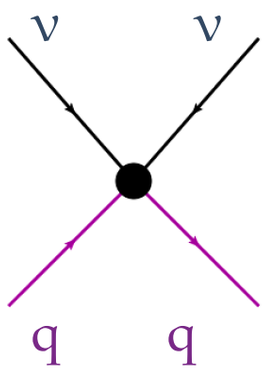


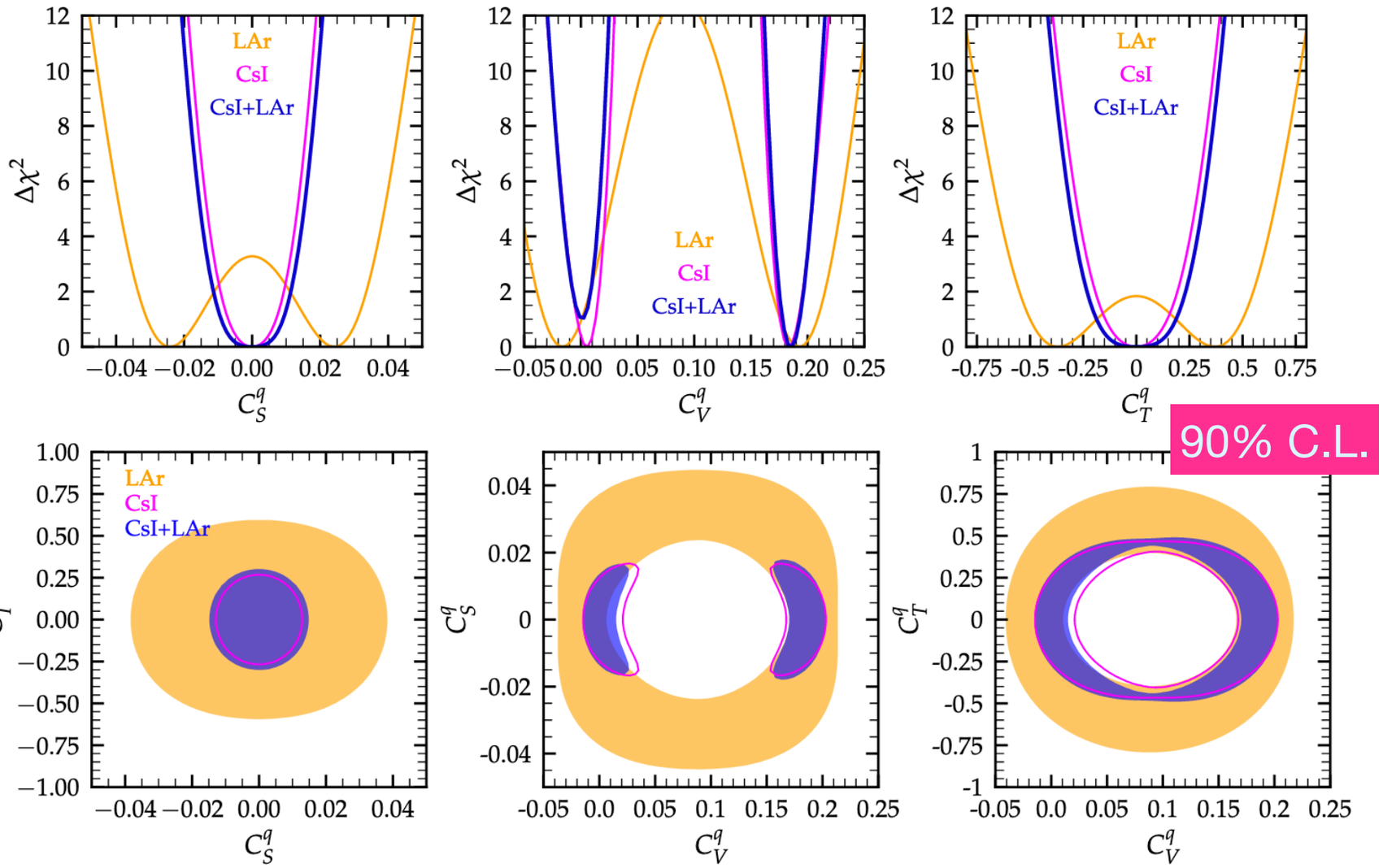
➡ CEvNs provides complementary constraints to other light mediator searches.

De Romeri et al, JHEP 2023

Neutrino generalized interactions (NGI)

NGI includes additional types of Lorentz-invariant interactions involving scalar, vector and tensor terms:





$$\left.\frac{d\sigma}{dE_{\rm nr}}\right|^{\rm NGI}_{\rm CE\nu NS} = \frac{G_F^2 m_N}{4\pi} F_W^2(|\vec{q}|^2)\left\{C_S^2\frac{m_N E_{\rm nr}}{2E_\nu^2} + \left(C_V + 2\,Q_V^{\rm SM}\right)^2\left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2} - \frac{E_{\rm nr}}{E_\nu}\right)\right.$$
$$\left. + 8\,C_T^2\left(1 - \frac{m_N E_{\rm nr}}{4E_\nu^2} - \frac{E_{\rm nr}}{E_\nu}\right) \pm \mathcal{R}\frac{E_{\rm nr}}{E_\nu}\right\}.$$

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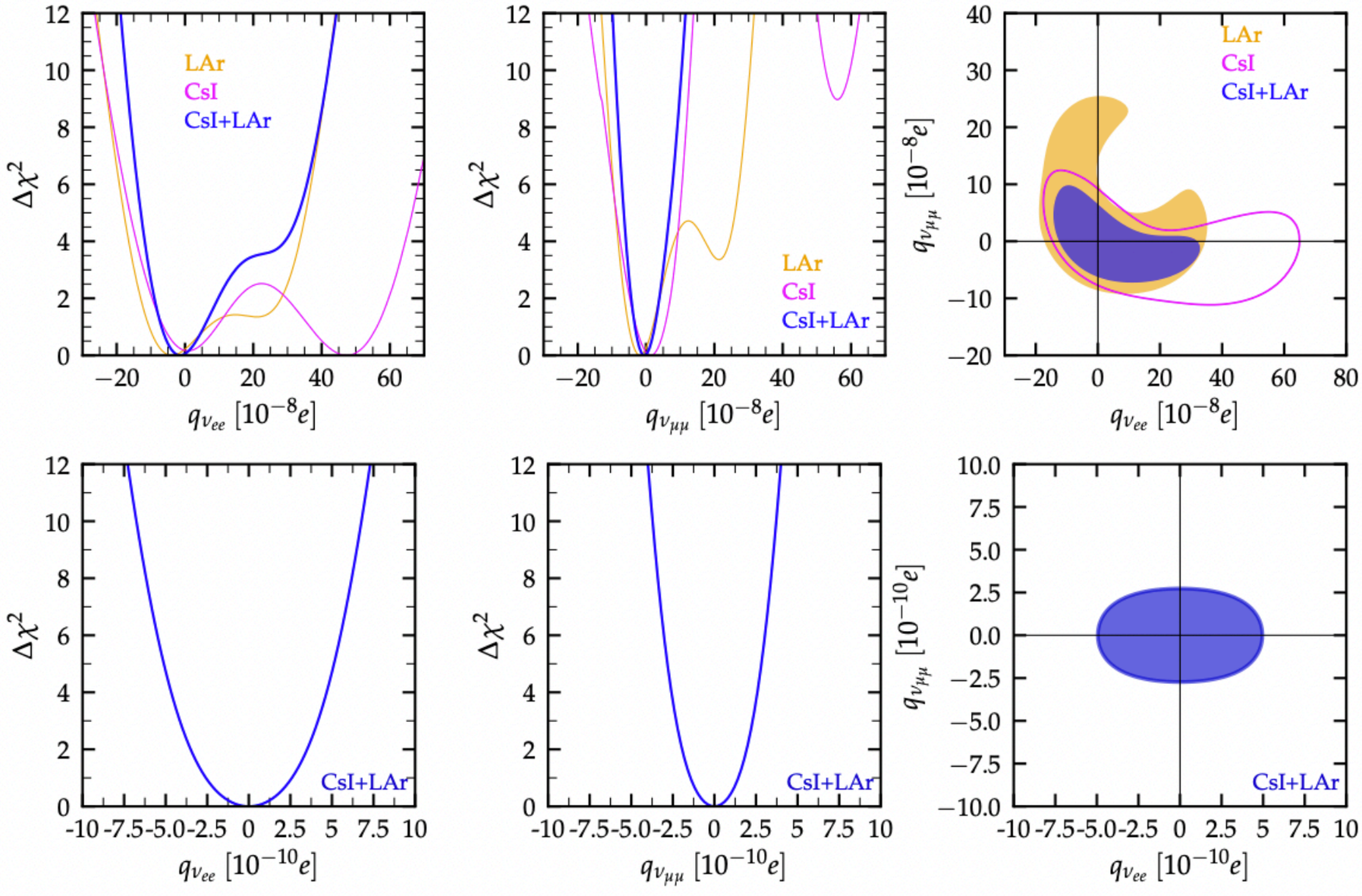
Neutrino electric (milli) charge

- In BSM models, neutrinos can acquire small electric charges: **millicharges**
- This electric charge would generate a new contribution to the CEvNS and ES cross section, proportional to

$$Q_{\ell\ell}^{\rm EC} = \frac{2\sqrt{2}\pi\alpha_{\rm EM}}{G_F q^2} q_{\nu_{\ell\ell}}$$

$q_{\nu_{\ell\ell}}$: neutrino millicharge

q^2: momentum transfered



CEvNS only (1σ)

$$q_{\nu_{ee}} \in [-6.9,\ 5.6] \times 10^{-8}\ e$$

$$q_{\nu_{\mu\mu}} \in [-3.3,\ 2.5] \times 10^{-8}\ e$$

CEvNS +ES (1σ)

$$q_{\nu_{ee}} \in [-2.6,\ 2.6] \times 10^{-10}\ e$$

$$q_{\nu_{\mu\mu}} \in [-1.4,\ 1.4] \times 10^{-10}\ e$$

De Romeri et al, JHEP 2023

Conclusions & Outlook

Neutrinos remain a unique window to new physics

- Oscillation experiments have established a solid picture of ν mixing
- The origin of neutrino masses remains unknown
- New interactions and properties are still largely unconstrained

Precision measurements, complementary probes and new experimental strategies will be essential to uncover physics beyond the Standard Model