Constraining BSM neutrino physics with CEvNS

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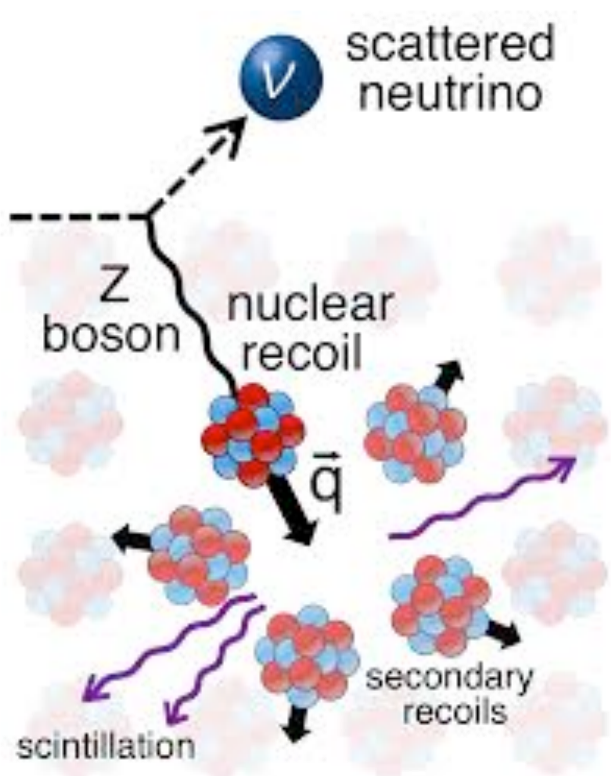
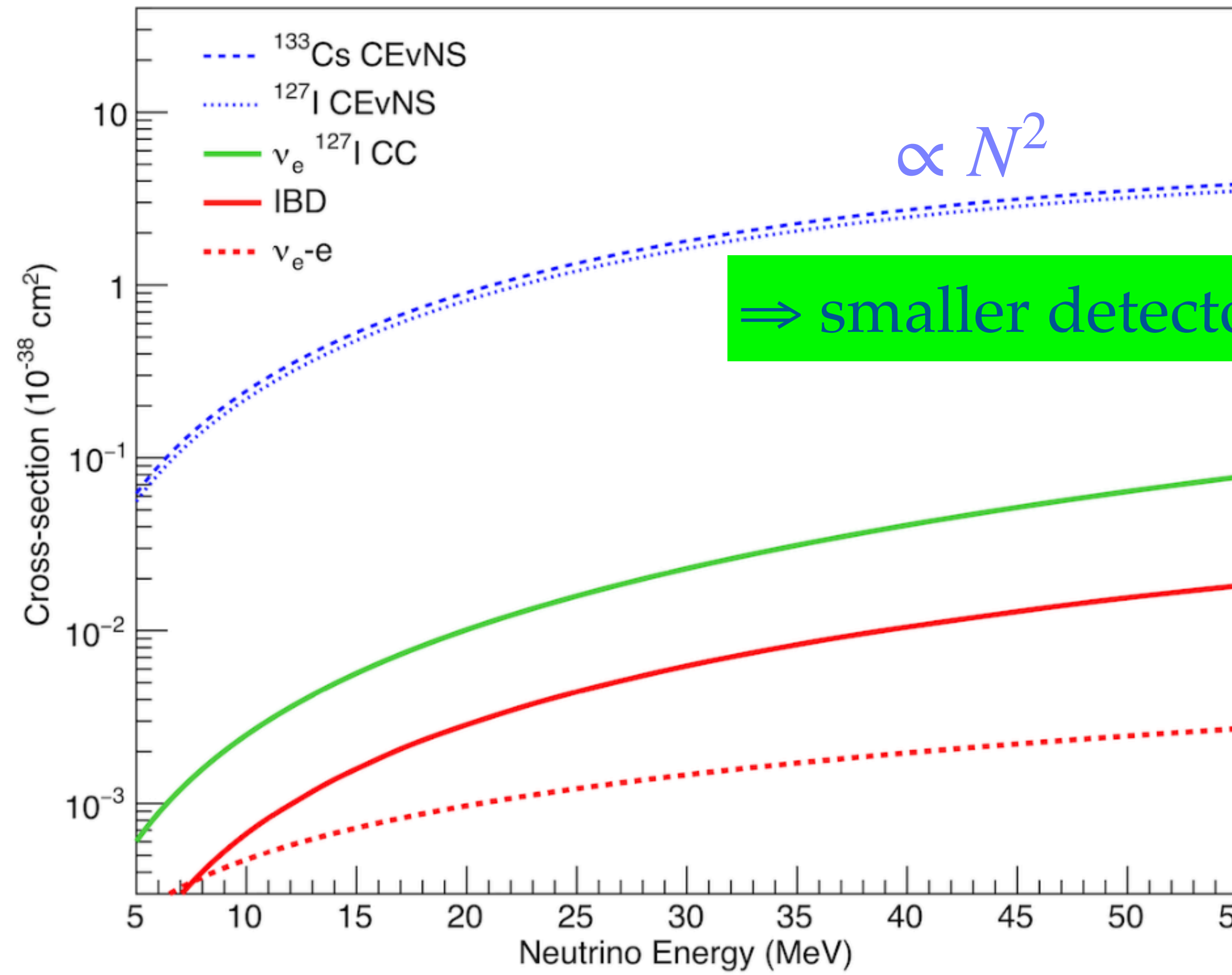
Coherent Elastic ν Nucleus Scattering (CEνNS)



D. Freedman PRD9 (1974) 1389



$\propto N^2$

$\Rightarrow$ smaller detectors!

$$\left.\frac{d\sigma_{\nu N}}{dE_{nr}}\right|_{\rm SM}^{\rm CE\nu NS} = \frac{G_F^2 m_N}{\pi} F_W^2\left(|\vec{q}\,|^2\right)\left(1-\frac{m_N E_{nr}}{2E_\nu^2}\right)\left(Q_V^{\rm SM}\right)^2$$

$$Q_V^{SM} = g_V^p Z + g_v^n N \sim g_V^n N$$

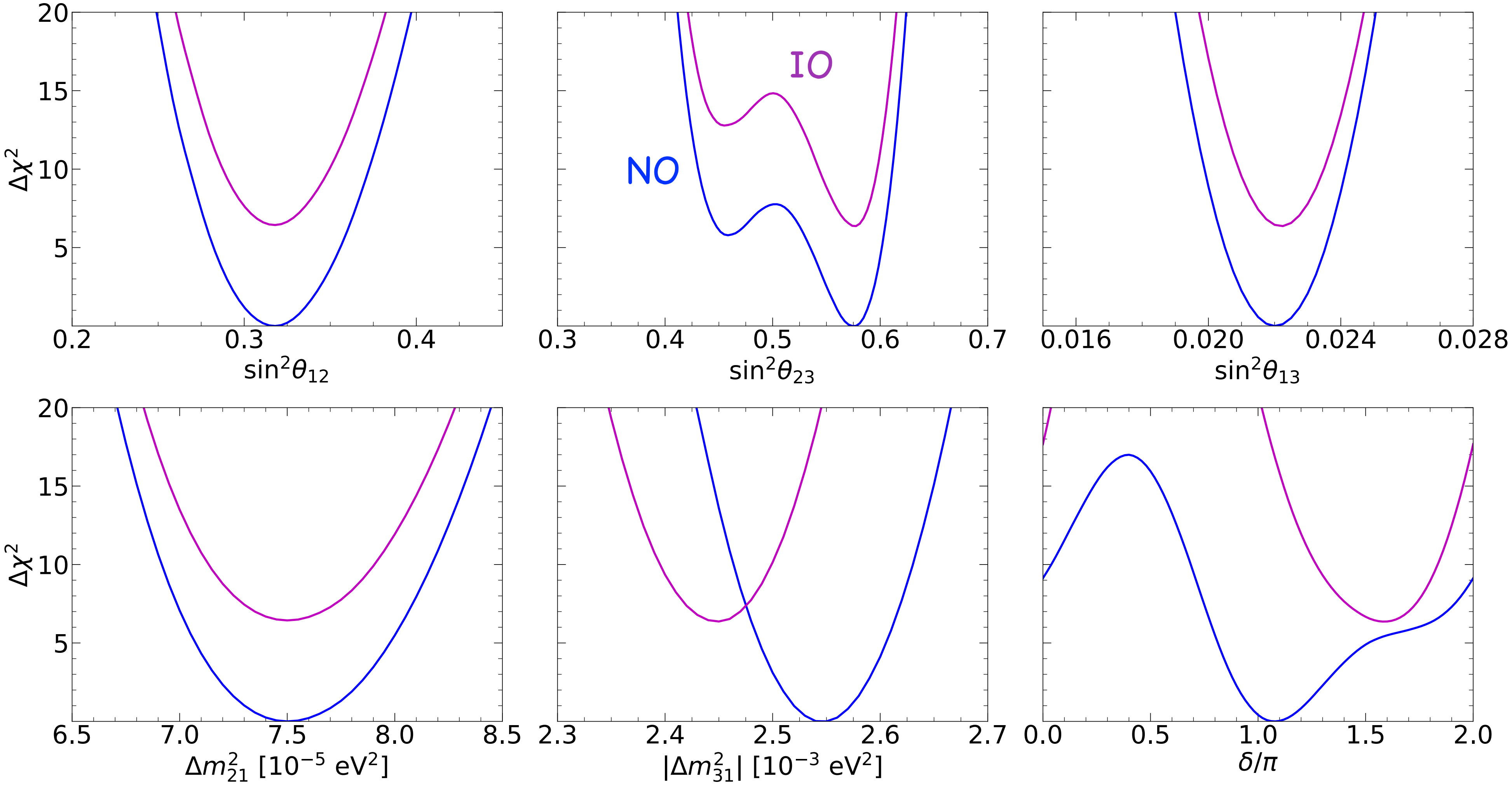
2017: First observed at the Spallation Neutron Source (Oak Ridge National Lab)

COHERENT Coll. Science 357 (2017) 1123

Motivation: why CEvNS?

✦ Our current knowledge of the **neutrino sector**:

✓ Neutrino oscillation parameters: rather well known from **global fits**



Mass ordering: NO or IO?

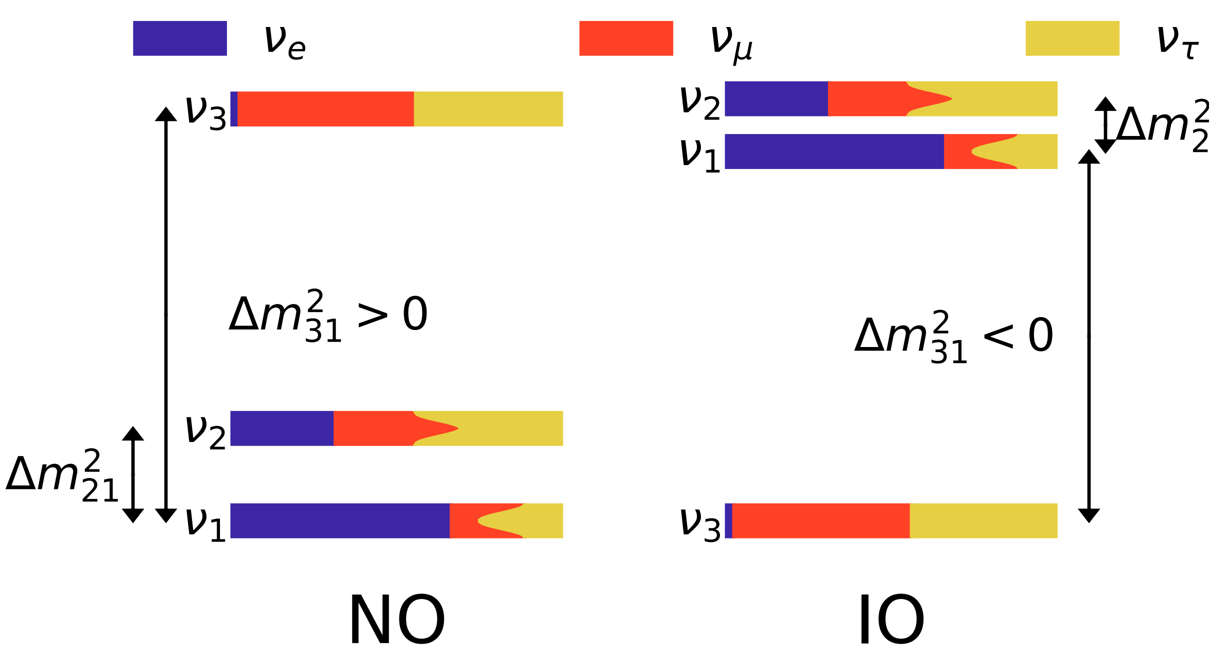
Octant of θ_{23} ?

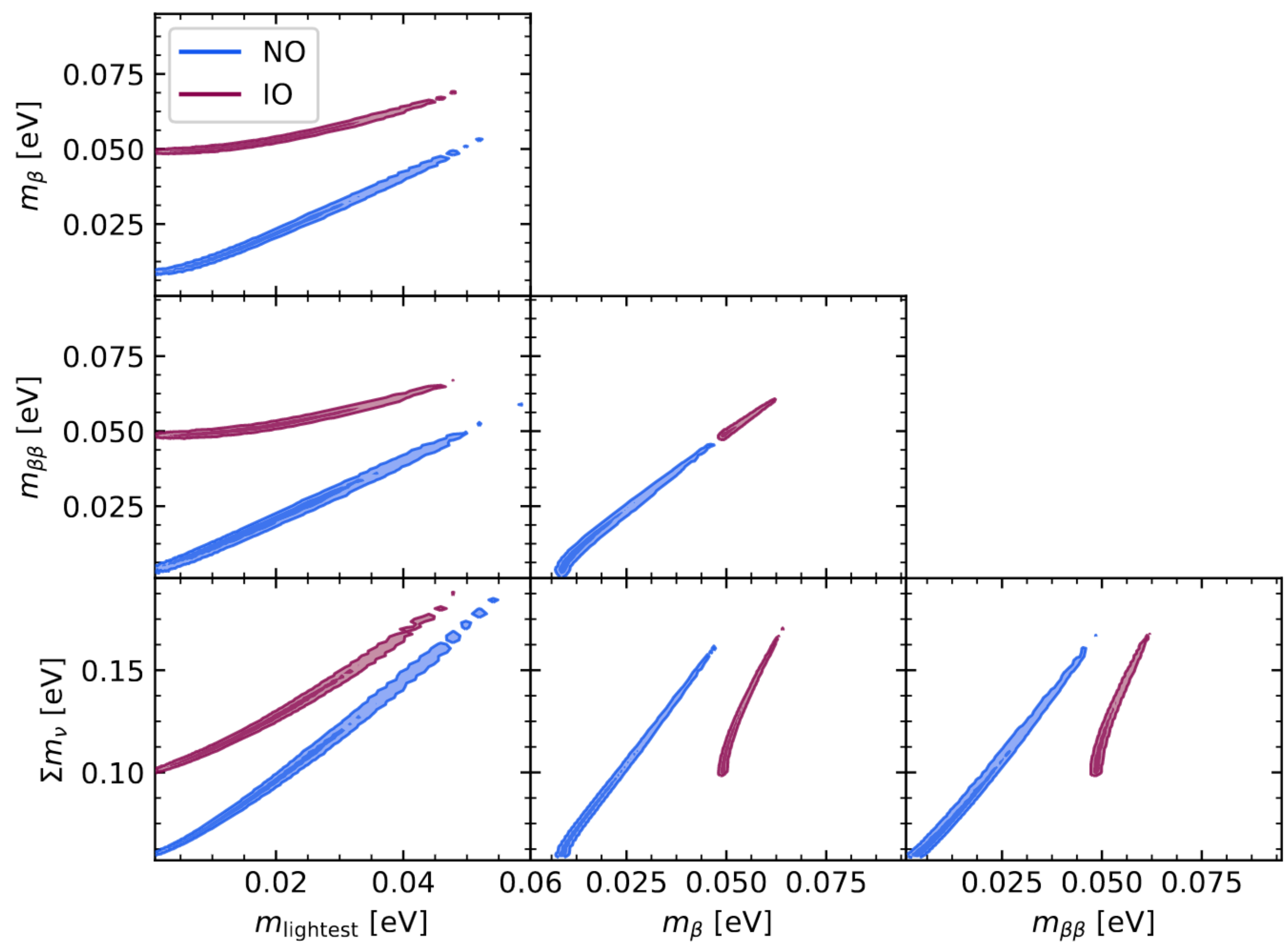
CP violation: maximal?

de Salas et al, **JHEP 02 (2021) 071** https://globalfit.astroparticles.es/

Motivation: why CEvNS?

- Our current knowledge of the **neutrino sector**:
  - ✓ Neutrino oscillation parameters: rather well known from **global fits**
  - ✓ Neutrino **mass scale**: below eV (cosmology + β decay + 0νββ decay)





From oscillations:

$$m_\nu \geq \sqrt{\Delta m^2_{31}(\mathrm{NO})} \gtrsim 0.05\,\mathrm{eV}$$

de Salas et al, JHEP 02 (2021) 071

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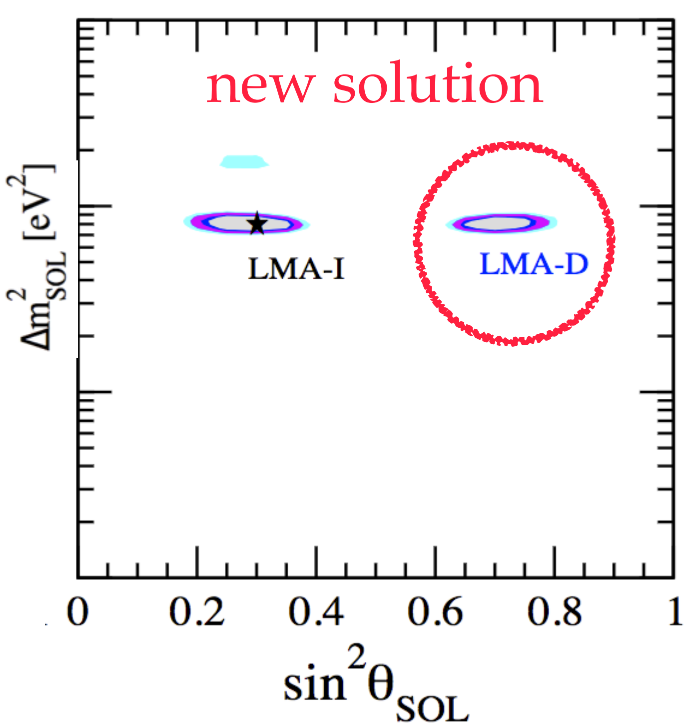
✦ Our current knowledge of the **neutrino sector**:

✓ Neutrino oscillation parameters: rather well known from **global fits**

✓ Neutrino **mass scale**: below eV (cosmology + β decay + 0νββ decay)

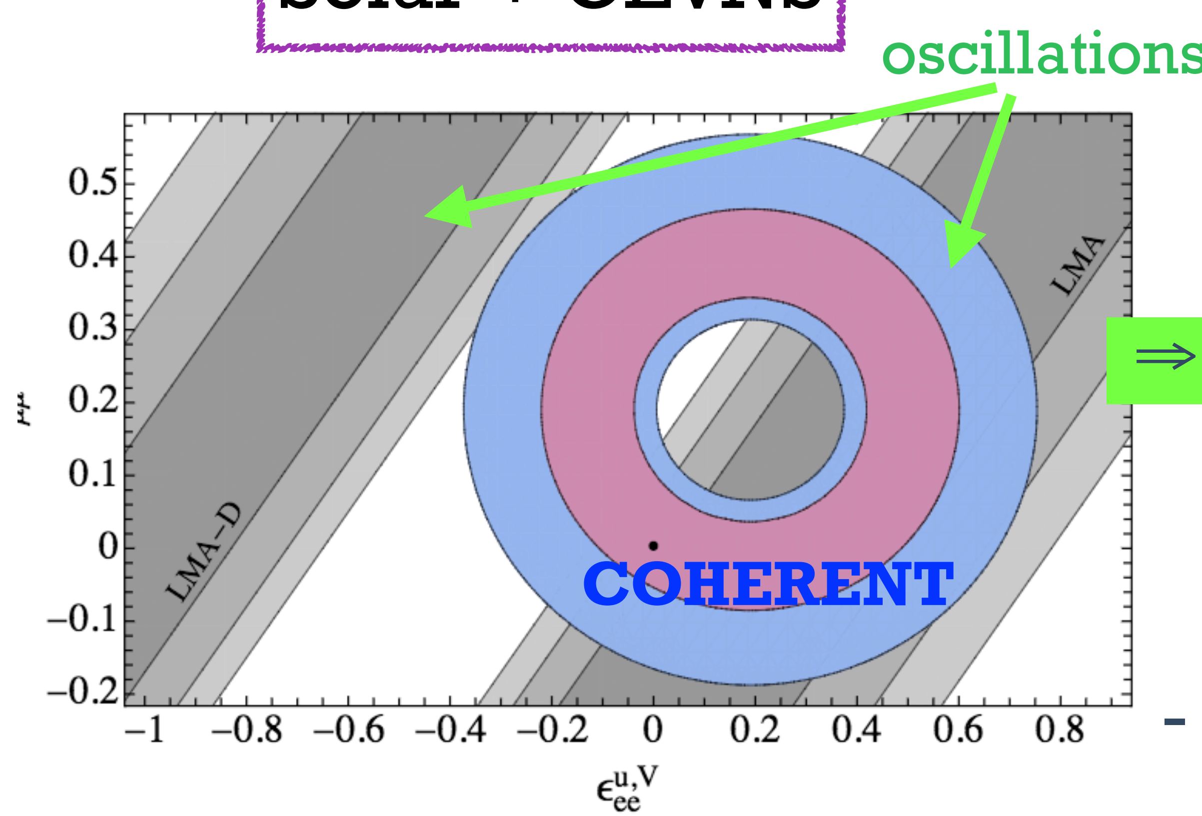
✓ **Neutrino BSM properties** (not observed so far): can affect current picture

Solar (with NSI)



Miranda et al, JHEP 2006

Solar + CEvNS



Coloma et al, PRD 2017
COHERENT Science 2017

⇒ **LMA-D** excluded at 3σ

Relaxed if:

- NSI mediator < 50 MeV
- degeneracies in (ε_d, ε_u)

Physics potential of CEvNS

- **CEvNS** provide a powerful tool to search for **SM** and **BSM physics**:
  - ✓ EW and nuclear physics: weak mixing angle, neutron radius
  - ✓ New neutrino interactions with matter: NSI, NGI, new mediators
  - ✓ Neutrino electromagnetic properties: magnetic moment, charge radius
  - ✓ Light and heavy sterile neutrinos

  [Neutrino sources: **accelerator**, reactor, solar, supernova]

ν e.m. properties

new ν interactions with quarks

$$\frac{d\sigma_{\nu N}^{\rm CEvNS}(E_\nu, E_{nr})}{dE_{nr}} = \frac{G_F^2 m_N}{\pi} F_W^2\left(|\vec{q}\,|^2\right)\left(1-\frac{m_N E_{nr}}{2E_\nu^2}\right)\left(g_V^p\left(\sin^2\theta_W\right) Z + g_V^n N\right)^2 + \dots$$

nuclear physics

EW precision

Based on

JHEP

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Physics implications of a combined analysis of COHERENT CsI and LAr data

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Abstract: The observation of coherent elastic neutrino nucleus scattering has opened the window to many physics opportunities. This process has been measured by the COHERENT Collaboration using two different targets, first CsI and then argon. Recently, the COHERENT Collaboration has updated the CsI data analysis with a higher statistics and an improved understanding of systematics. Here we perform a detailed statistical analysis of the full CsI data and combine it with the previous argon result. We discuss a vast array of implications, from tests of the Standard Model to new physics probes. In our analyses we take into account experimental uncertainties associated to the efficiency as well as the timing distribution of neutrino fluxes, making our results rather robust. In particular, we update previous measurements of the weak mixing angle and the neutron root mean square charge radius for CsI and argon. We also update the constraints on new physics scenarios including neutrino nonstandard interactions and the most general case of neutrino generalized interactions, as well as the possibility of light mediators. Finally, constraints on neutrino electromagnetic properties are also examined, including the conversion to sterile neutrino states. In many cases, the inclusion of the recent CsI data leads to a dramatic improvement of bounds.

Keywords: Neutrino Interactions, Non-Standard Neutrino Properties

ArXiv ePrint: 2211.11905

De Romeri et al,
JHEP 04 (2023) 035

- SM precision tests: weak mixing angle
- Nuclear physics: neutron radius
- New neutrino interactions
  - Neutrino Nonstandard interactions (NSI)
  - Neutrino Generalized interactions (NGI)
  - Light Mediators
- Neutrino electromagnetic properties
  - Neutrino magnetic moment
  - Neutrino charge radius
  - Neutrino millicharge
- Conversion to sterile neutrinos
  - Active-sterile oscillations
  - Active-sterile EM interactions

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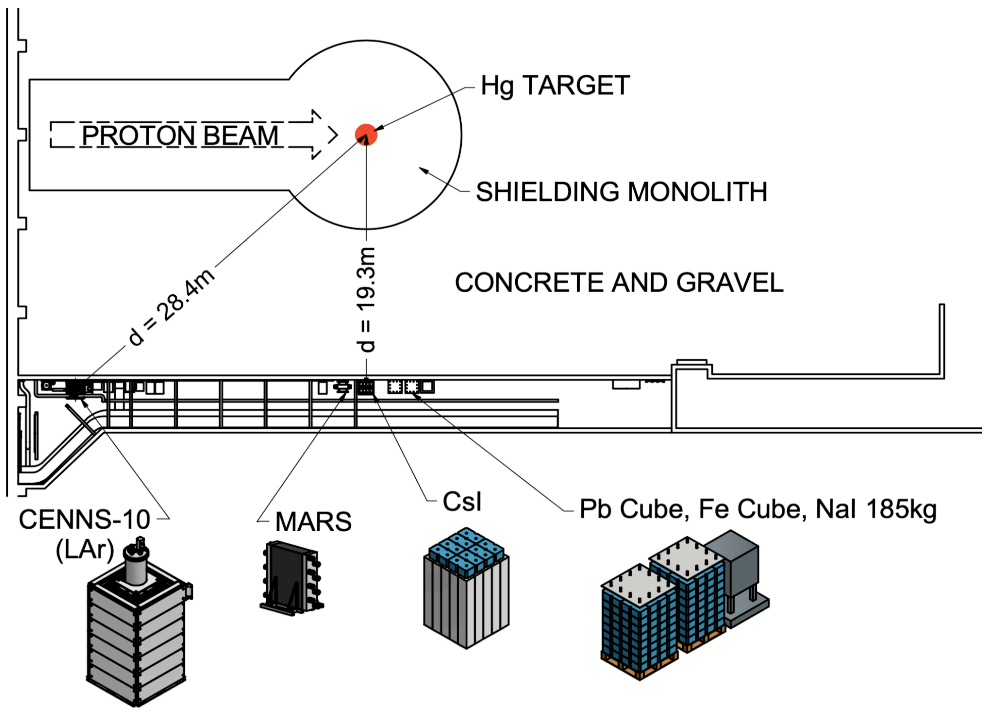
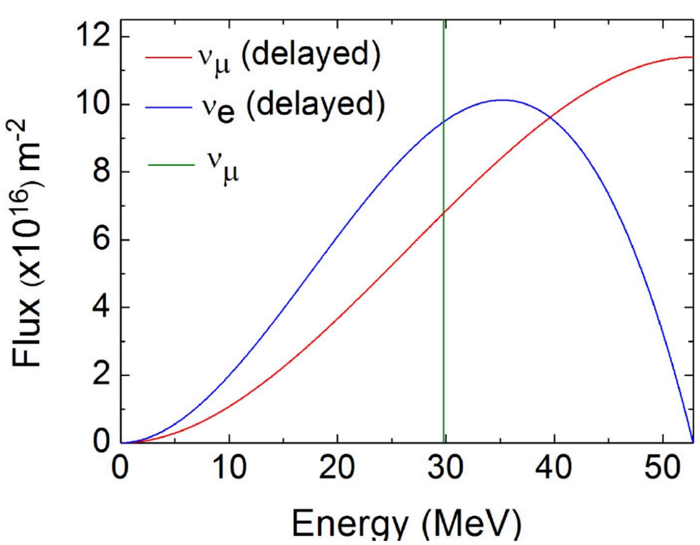
CEvNS data from COHERENT



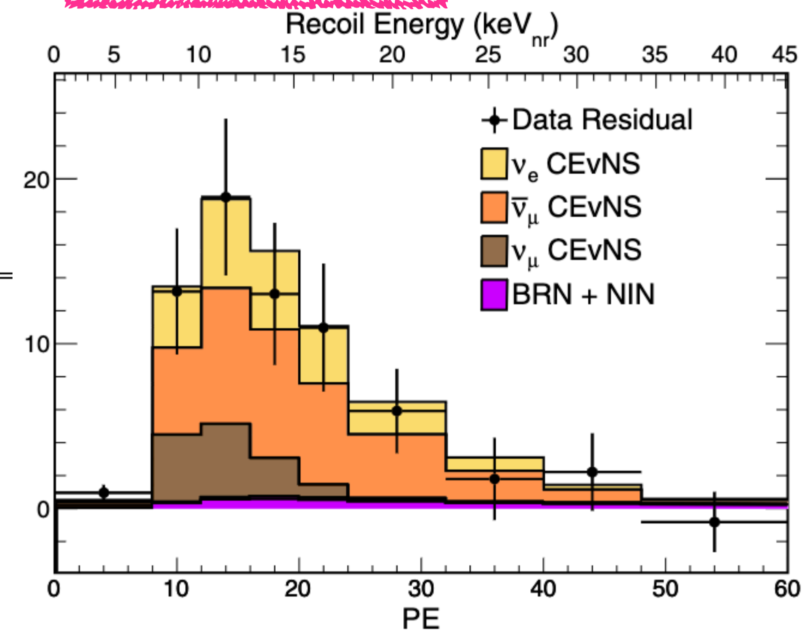
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

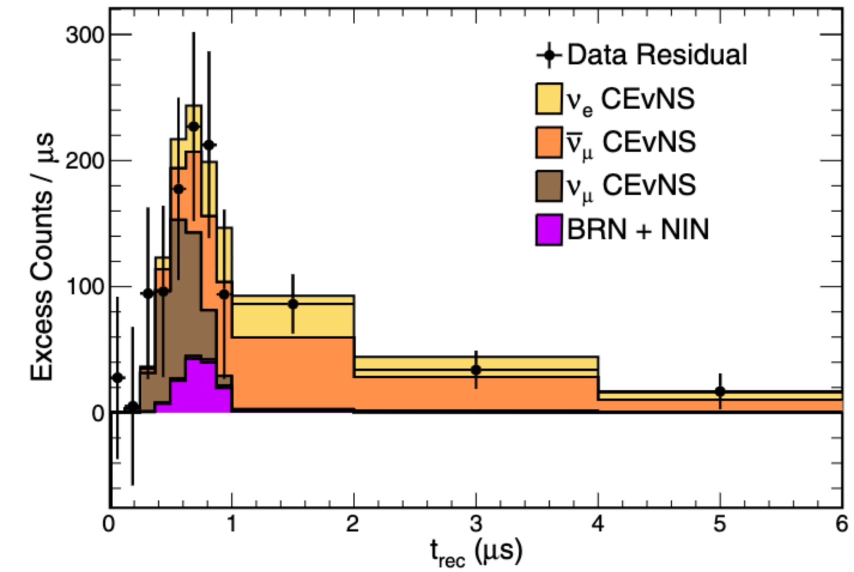


CsI (2021)

Akimov et al, PRL 129 (2022) 081801

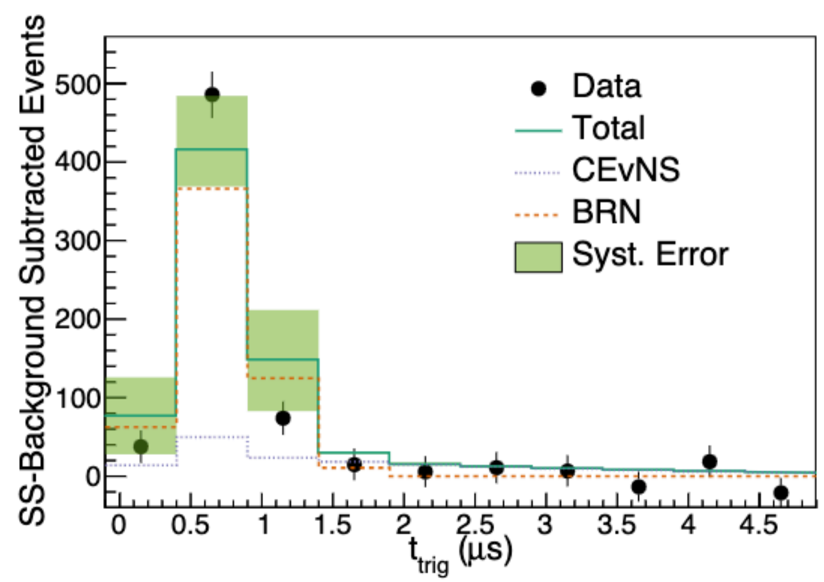
ES bg + time distributions

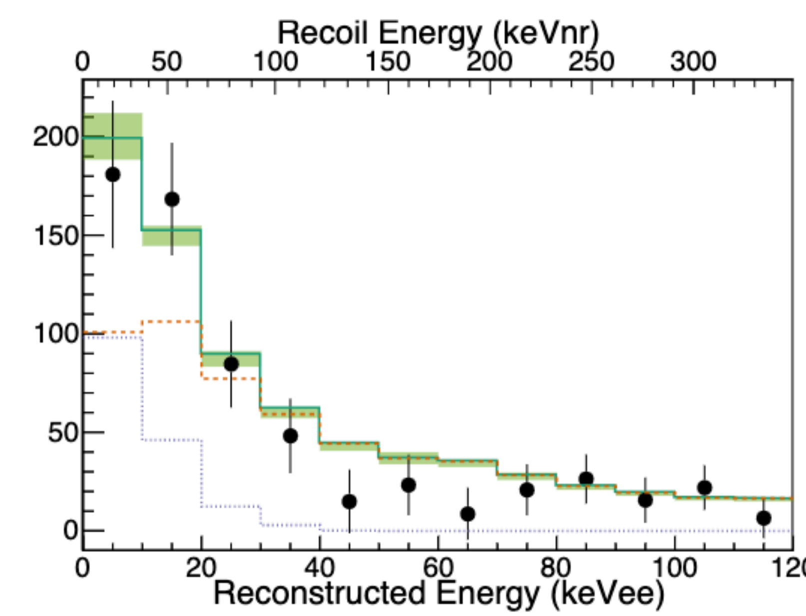




LAr (2020)

Akimov et al, PRL 126 (2021) 012002

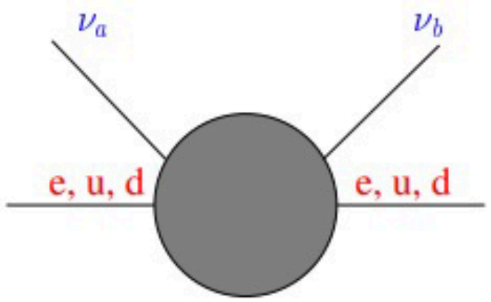




Results

Nonstandard interactions (NSI)

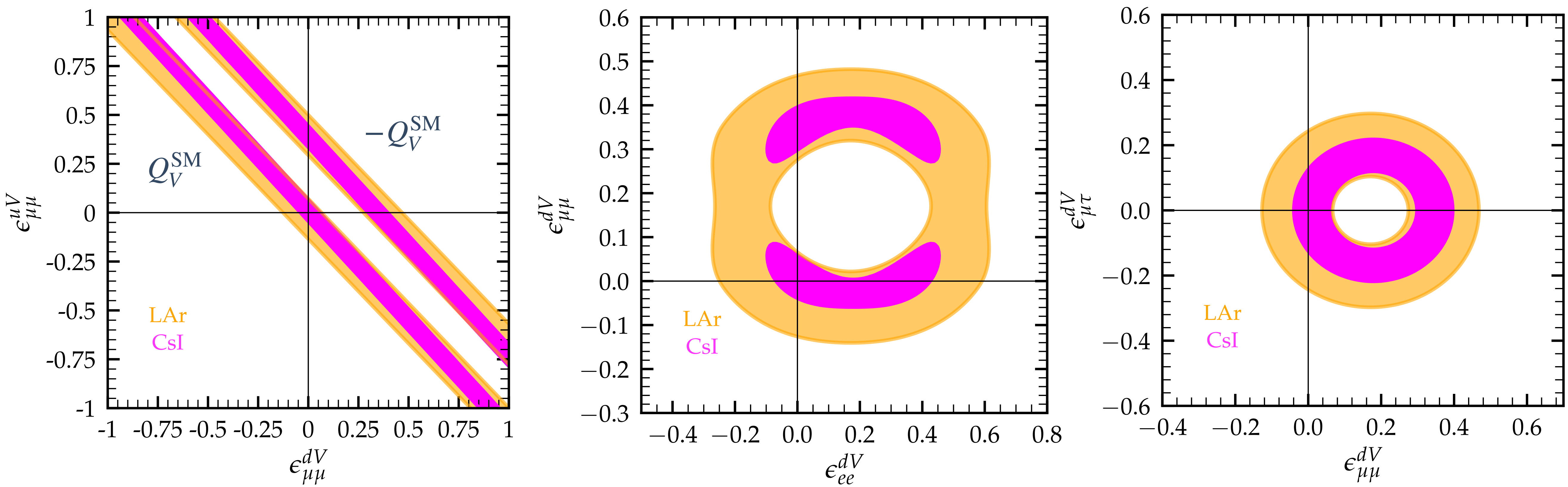
$$\mathcal{L}_{\rm NC}^{\rm NSI} = -2\sqrt{2}G_F \sum_{q,l,l'} \varepsilon_{ll'}^{qX} \left(\bar{\nu}_l \gamma^\mu P_L \nu_{l'}\right)\left(\bar{f}\gamma_\mu P_X f\right), X = L, R$$



ε_{ll}^{qV} : non universal $\qquad$ $\varepsilon_{ll'}^{qV}$: flavor changing

$$\left(Q_V^{\rm SM}\right)^2 \to \left(Q_V^{\rm NSI}\right)^2 = \left[\left(g_V^p + 2\varepsilon_{ll}^{uV} + \varepsilon_{ll}^{dV}\right) Z + \left(g_V^n + \varepsilon_{ll}^{uV} + 2\varepsilon_{ll}^{dV}\right) N\right]^2 + \sum_{l \neq l'} \left[\left(2\varepsilon_{ll'}^{uV} + \varepsilon_{ll'}^{dV}\right) Z + \left(\varepsilon_{ll'}^{uV} + 2\varepsilon_{ll'}^{dV}\right) N\right]^2$$

Barranco, Miranda, Rashba, JHEP 2005, 021 (2005)



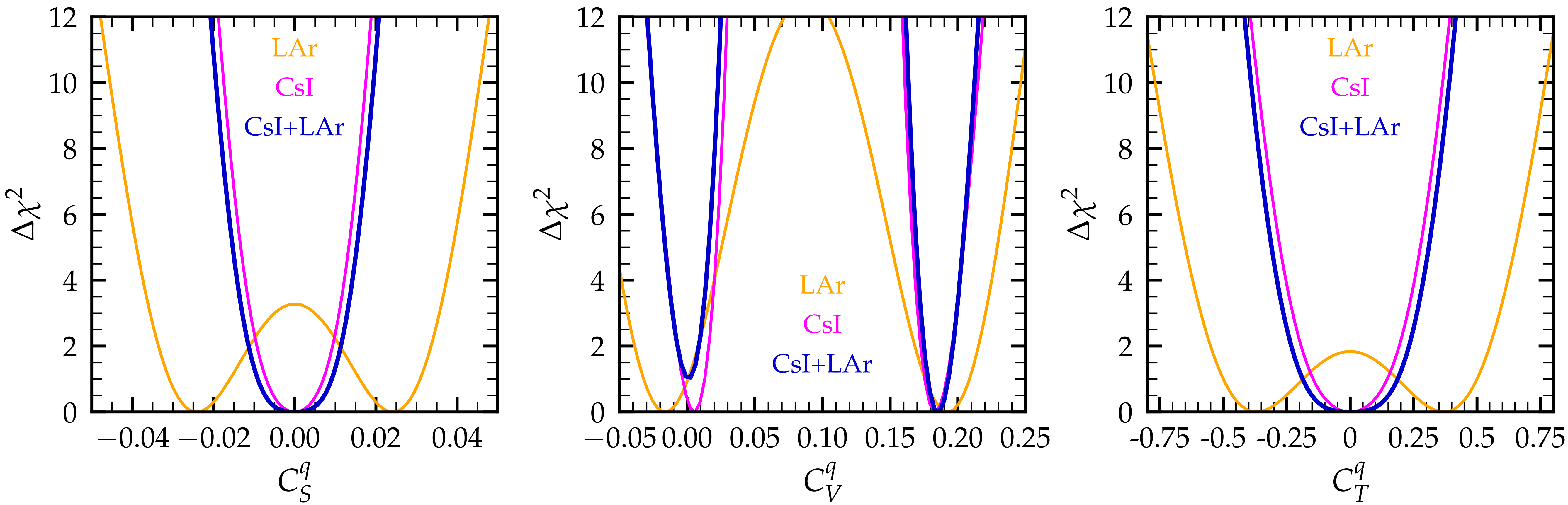
Neutrino generalized interactions (NGI)

$$\mathcal{L}_{\rm NC}^{\rm NGI} = \frac{G_F}{\sqrt{2}} \sum_{S,P,V,A,T} \left[\overline{\nu}\Gamma^X \nu\right] \left[\overline{q}\Gamma_X \left(C_X^q + i\gamma_5 D_X^q\right) q\right]$$

$$\text{with } \Gamma = \{\mathbb{I}, i\gamma_5, \gamma^\mu, \gamma^\mu\gamma_5, \sigma^{\mu\nu}\}$$

Lindner et al, 2017
Aristizábal Sierra et al, 2018

⇒ new contributions due to the scalar, vector (interference with SM) and tensor weak charges: C_S^q, C_V^q, C_T^q



New light mediators

Light vector mediator

$$\left.\frac{d\sigma_{\nu_l N}}{dE_{\rm nr}}\right|_{\rm CE\nu NS}^{\rm LV} = \left(1 + \frac{C_{\rm V}}{\sqrt{2}G_F Q_{\rm V}^{\rm SM}\left(2m_N E_{\rm nr} + m_{\rm V}^2\right)}\right)\left.\frac{d\sigma_{\nu_l N}}{dE_{\rm nr}}\right|_{\rm CE\nu NS}^{\rm SM}$$

$$C_V = C_V(g_{\nu V}, g_{qV})$$

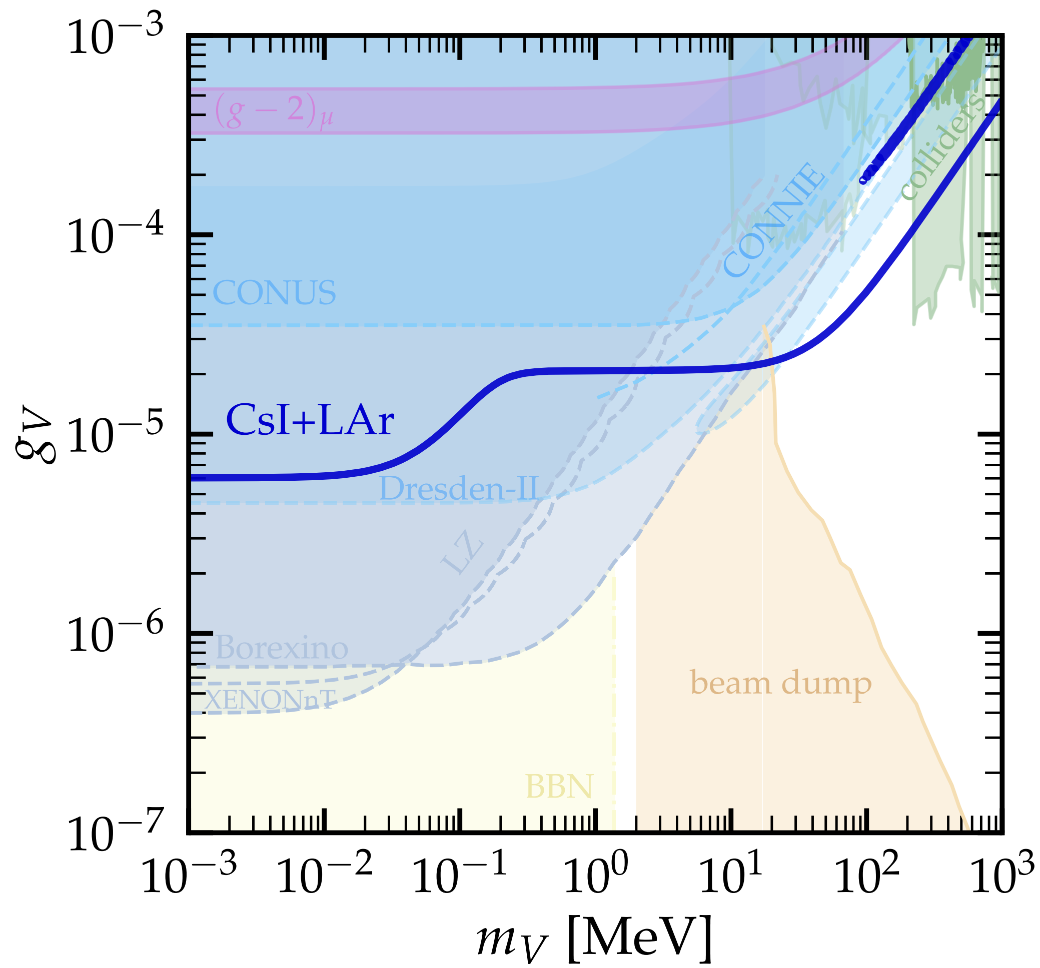
Light scalar mediator

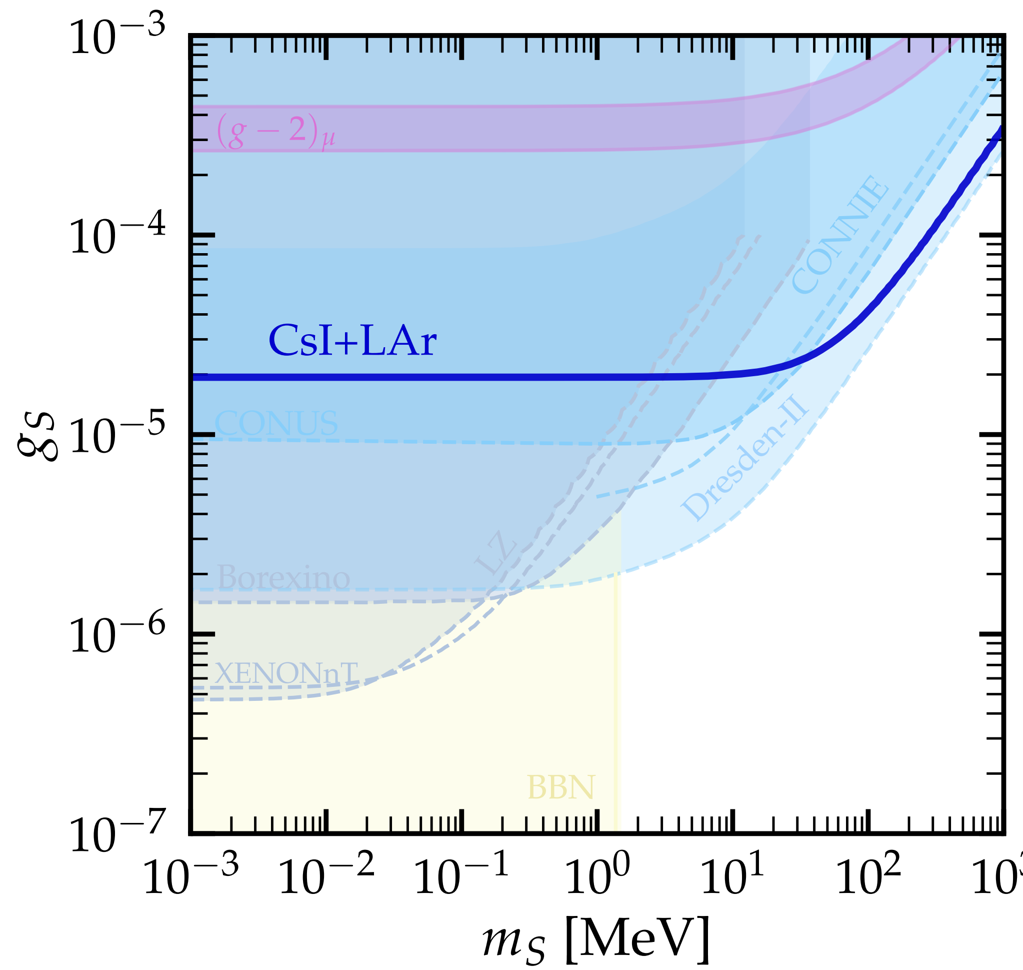
$$\left.\frac{d\sigma_{\nu_l N}}{dE_{\rm nr}}\right|_{\rm CE\nu NS}^{\rm LS} = \frac{m_N^2 E_{\rm nr} C_{\rm S}^2}{4\pi E_\nu^2 \left(2m_N E_{\rm nr} + m_{\rm S}^2\right)^2} F_W^2(|\vec{q}|^2)$$

$$C_S = C_S(g_{\nu S}, g_{qS})$$

$$g_X = \sqrt{g_{\nu X} g_{fX}}$$

$$(f = u, d, e)$$





See also: Coloma et al. 2202.10829, Atzori-Corona et al. 2205.09484

Neutrino (effective) magnetic moment

- Minimal SM extension (with m_ν) predicts $\mu_\nu \simeq 3 \times 10^{-19} \left(\frac{m_\nu}{\text{eV}}\right) \mu_B$ ➡ larger in BSM

- The (effective) neutrino magnetic moment gives extra contribution to CEvNS and ES cross section:

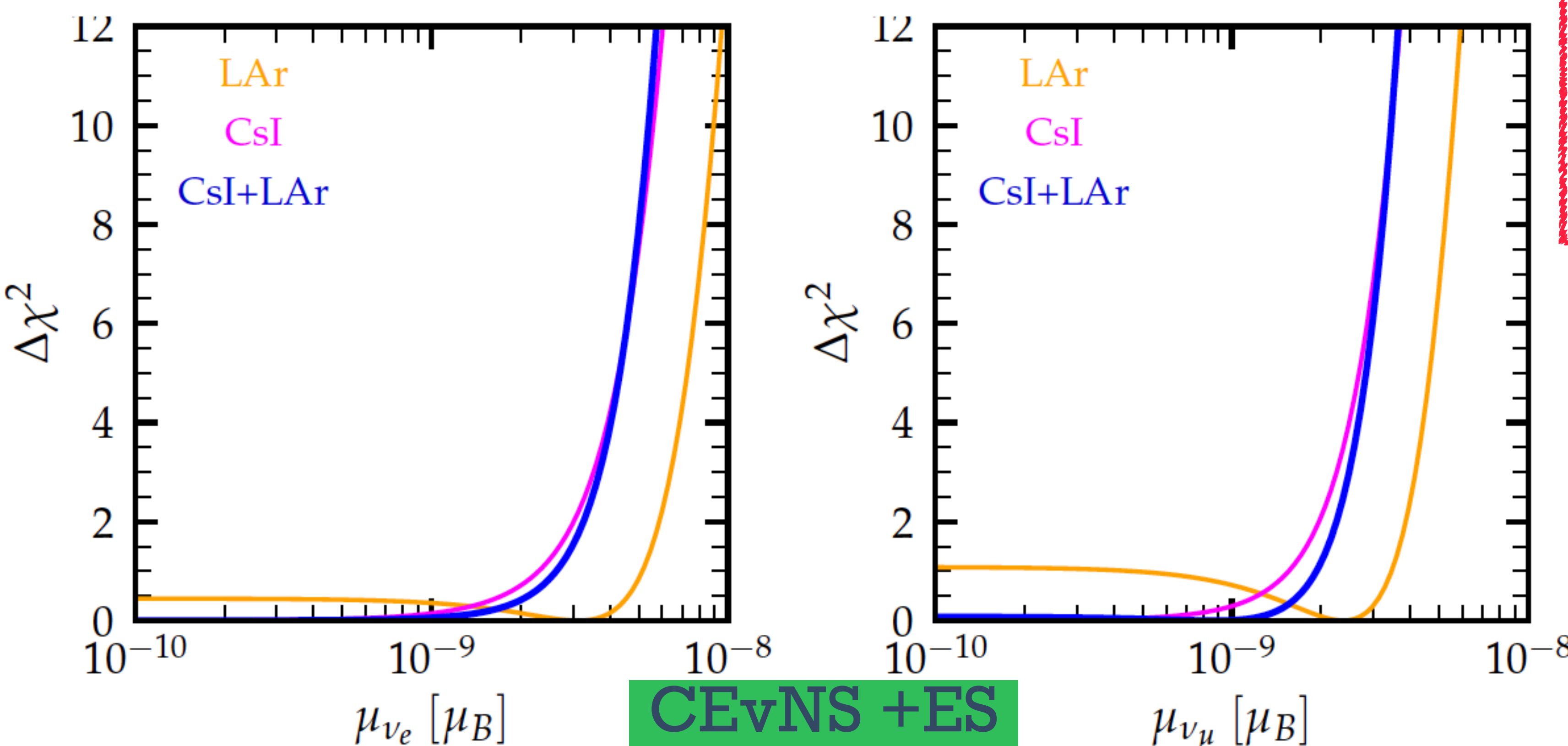
$$\left.\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\rm nr}}\right|^{\rm MM}_{\rm CE\nu NS} = \frac{\pi \alpha^2_{\rm EM}}{m_e^2}\left(\frac{1}{E_{\rm nr}} - \frac{1}{E_\nu}\right) Z^2 F_W^2(|\vec{q}|^2) \left|\frac{\mu_{\nu_\ell}}{\mu_{\rm B}}\right|^2$$

$$\left.\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\rm er}}\right|^{\rm MM}_{\rm ES} = \frac{\pi \alpha^2_{\rm EM}}{m_e^2}\left(\frac{1}{E_{\rm er}} - \frac{1}{E_\nu}\right) Z^{\mathcal{A}}_{\rm eff}(E_{\rm er}) \left|\frac{\mu_{\nu_\ell}}{\mu_{\rm B}}\right|^2$$

⚠ Effective MM are process-dependent quantities:

$$\mu^{\rm eff}_{\nu_\ell} = \sum_k \left| \sum_j U^*_{\ell k} \lambda_{jk} \right|^2$$

For full Transition Magnetic Moment parameterization see **Grimus et al, NPB2003** **Miranda et al, JHEP 2019**



90% C.L. limits with (without) ES

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

Neutrino charge radius

- In the SM, it arises from radiactive corrections to the vectorial coupling:

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

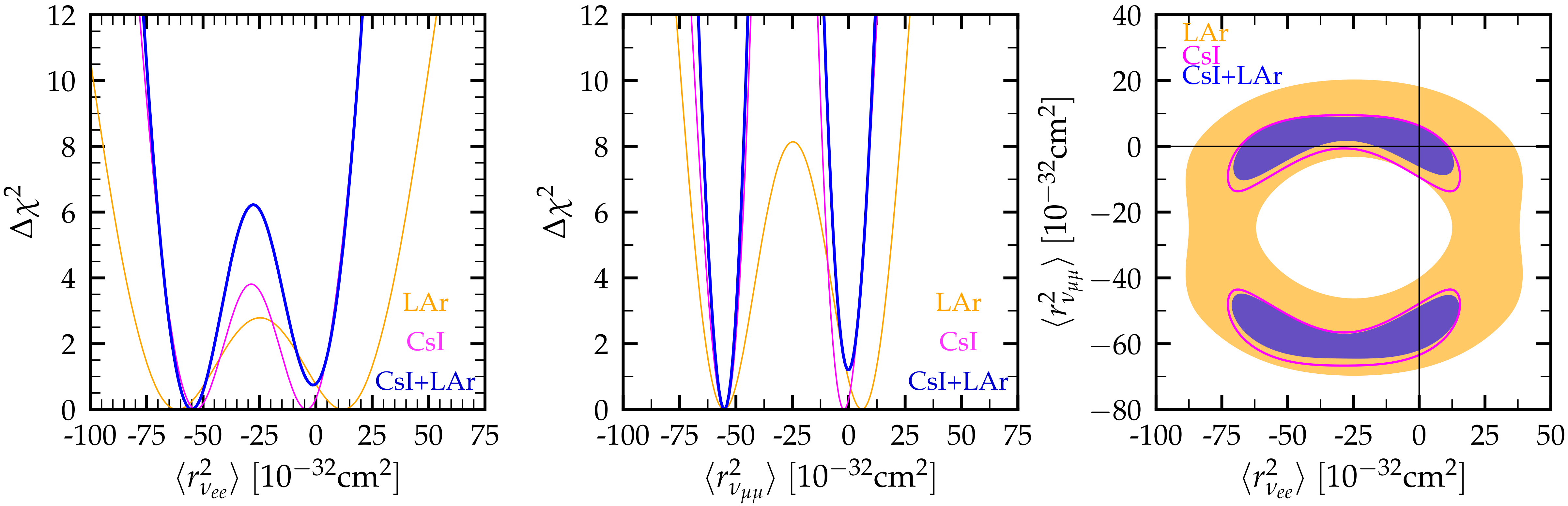
Bernabeu et al NPB 2004

- New contribution to the CEvNS and ES cross section, proportional to_

$$Q^{\rm CR}_{ll} = \frac{\sqrt{2}\pi\alpha_{\rm EM}}{3G_F}\left\langle r^2_{\nu_{ll}}\right\rangle$$

$$g_V^p \rightarrow g_V^p - Q^{\rm CR}_{ll}$$ CEvNS

$$g_V^{\nu_l} \rightarrow g_V^{\nu_l} + Q^{\rm CR}_{ll}$$ ES



$$\langle r^2_{\nu_{ee}}\rangle \in [-61.2, -48.2] \cup [-4.7, 2.2] \times 10^{-32}\ \text{cm}^2$$

$$\langle r^2_{\nu_{\mu\mu}}\rangle \in [-58.2, -52.1] \times 10^{-32}\ \text{cm}^2 \qquad (1\sigma)$$

CEvNS only

ES contribution negligible

Neutrino electric (milli) charge

- In BSM models, neutrinos can acquire small electric charges: **millicharges**

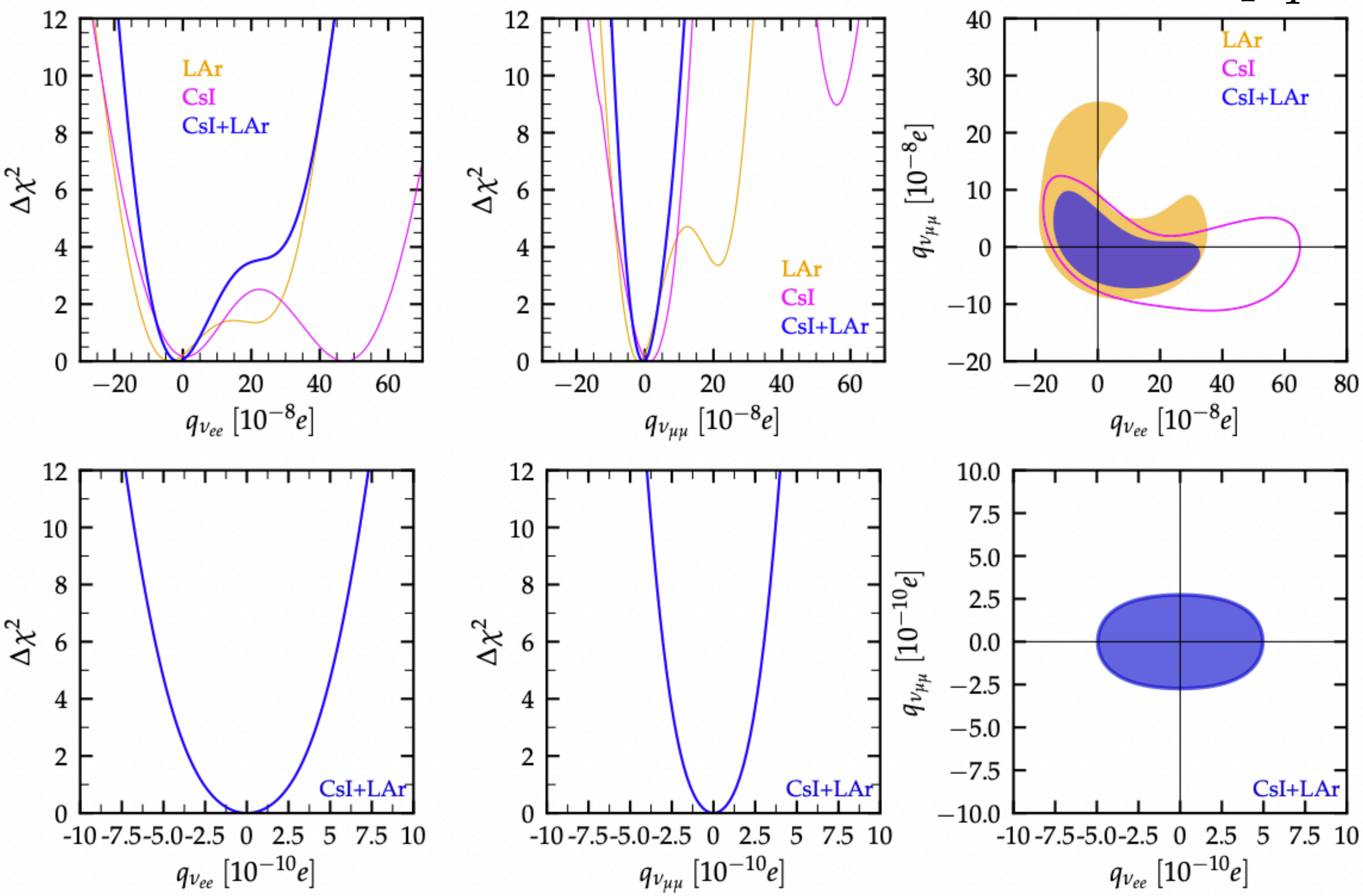
Giunti and Studenikin, Rev. Mod. Phys 2015

- This electric charge would generate a new contribution to the CEvNS and ES cross section, proportional to

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

neutrino millicharge

momentum transfered



CEvNS only (1σ)

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

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

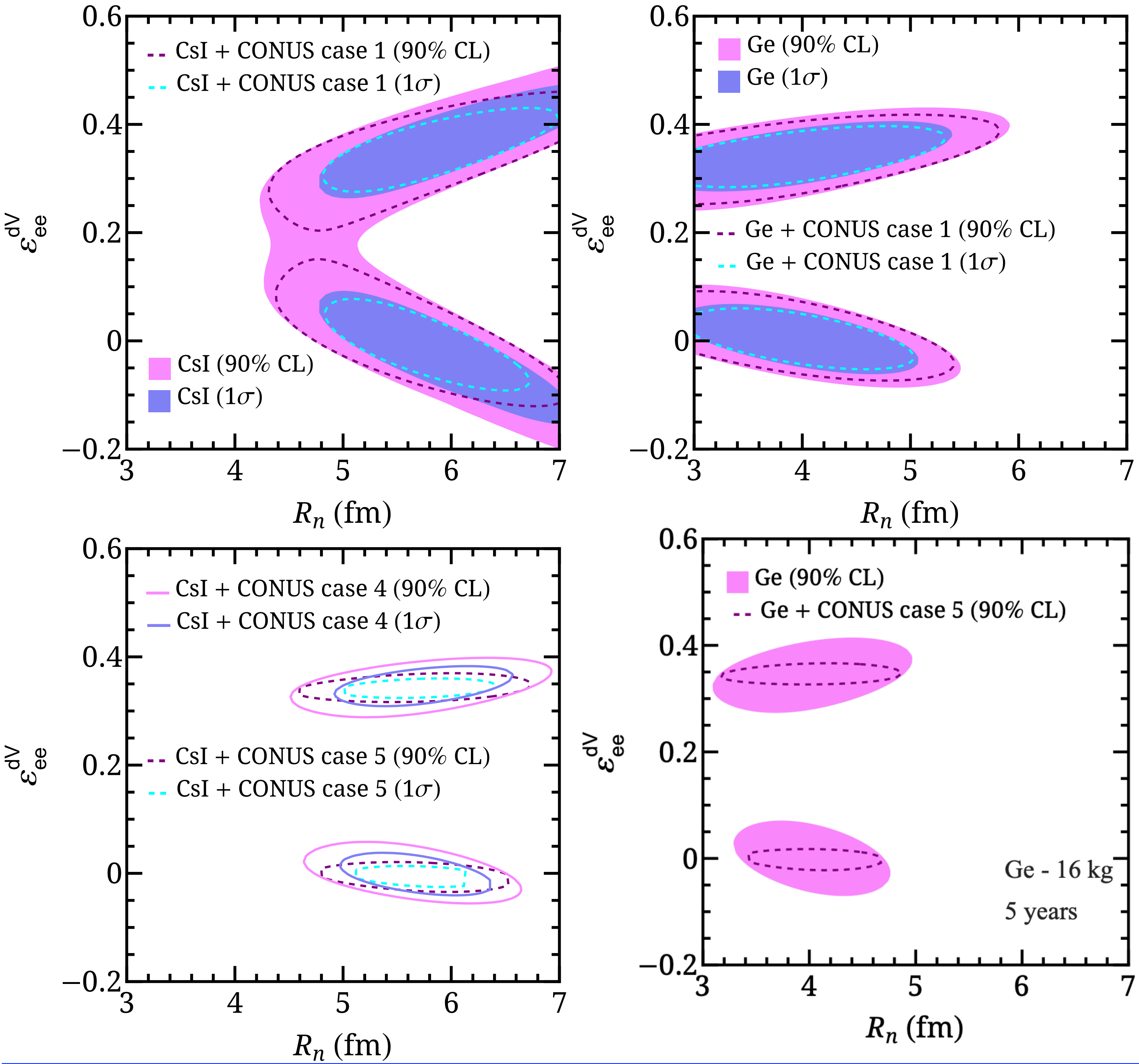
CEvNS +ES (1σ)

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

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

Probing nuclear physics & NSI

- Uncertainties in the determination of nuclear parameters relevant for CEvNS (e.g. R_n) can hide new physics effects (e.g. NSI)



- π-DAR sources sensitive to R_n and NSI
- Reactor sources blind to R_n

⇒ Combined analysis can lift degeneracies

⇒ π-DAR exp: CsI (COHERENT), Ge (SNS), Xe(ESS)

⇒ reactor exp: CONUS-like and νGeN-like

Rossi, Sánchez-Garcia, MT, 2311.17168

Summary

- **CEvNS** provide a powerful tool to search for new physics BSM.
- From the global analysis of **COHERENT** **CsI + LAr** data we have derived constraints on different **BSM neutrino scenarios:**
  - ✓ New neutrino interactions
  - ✓ Exotic neutrino electromagnetic properties

  ➡ The last CsI data (2021) dominate the sensitivity of the combined CsI + LAr analysis.

  ➡ Analysis with ES bg improves the constraints for light vector mediator, neutrino magnetic moment and neutrino millicharge.

  ➡ Although some of the limits derived are not competitive with existing searches, they provide complementary and relevant information.

Backup

CEvNS and ES cross sections

CEvNS cross section (SM)

$$\left.\frac{d\sigma_{\nu N}}{dE_{nr}}\right|_{\rm SM}^{\rm CEvNS} = \frac{G_F^2 m_N}{\pi} F_W^2\left(|\vec{q}|^2\right)\left(1-\frac{m_N E_{nr}}{2E_\nu^2}\right)\left(Q_V^{\rm SM}\right)^2$$

SM weak charge:

$$Q_V^{SM} = g_V^p Z + g_V^n N$$

$$g_V^p = \left(1-4\sin^2\theta_W\right)/2$$

$$g_V^n = -1/2$$

ES cross section (SM)

$$\left.\frac{d\sigma_{\nu_l A}}{dE_{er}}\right|_{\rm SM}^{\rm ES} = Z_{\rm eff}^A(E_{\rm er})\frac{G_F^2 m_e}{2\pi}\left(\left(g_V^{\nu_l}+g_A^{\nu_l}\right)^2+\left(g_V^{\nu_l}-g_A^{\nu_l}\right)^2\left(1-\frac{E_{\rm er}}{E_\nu}\right)-\left(\left(g_V^{\nu_l}\right)^2-\left(g_A^{\nu_l}\right)^2\right)\frac{m_e E_{\rm er}}{E_\nu^2}\right)$$

$\nu_e - e$ scattering $\quad g_V^{\nu_e} = \left(4\sin^2\theta_W+1\right)/2 \quad g_A^{\nu_e} = 1/2$

$\nu_{\mu,\tau} - e$ scattering $\quad g_V^{\nu_x} = \left(4\sin^2\theta_W-1\right)/2 \quad g_A^{\nu_x} = -1/2$

Statistical analysis

CsI (2021)

$$\chi^2_{\rm CsI}\Big|_{\rm CE\nu NS+ES} = 2\sum_{i=1}^{9}\sum_{j=1}^{11}\left[N_{\rm th}^{\rm CsI} - N_{ij}^{\rm exp} + N_{ij}^{\rm exp}\ln\left(\frac{N_{ij}^{\rm exp}}{N_{\rm th}^{\rm CsI}}\right)\right] + \sum_{k=0}^{4(5)}\left(\frac{\alpha_k}{\sigma_k}\right)^2$$

with:

$$N_{\rm th}^{\rm CsI,CE\nu NS+ES} = (1+\alpha_0+\alpha_5)N_{ij}^{\rm CE\nu NS}(\alpha_4,\alpha_6,\alpha_7) + (1+\alpha_0)N_{ij}^{\rm ES}(\alpha_6,\alpha_7)$$
$$+ (1+\alpha_1)N_{ij}^{\rm BRN}(\alpha_6) + (1+\alpha_2)N_{ij}^{\rm NIN}(\alpha_6) + (1+\alpha_3)N_{ij}^{\rm SSB}$$

We include ES background which could mimic a CEvNS signal.

Akimov et al, PRL 129 (2022) 081801

LAr (2020)

$$\chi^2_{\rm LAr} = \sum_{i=1}^{12}\sum_{j=1}^{10}\frac{1}{\sigma_{ij}^2}\Big[(1+\beta_0+\beta_1\Delta_{\rm CE\nu NS}^{F_{90+}}+\beta_1\Delta_{\rm CE\nu NS}^{F_{90-}}+\beta_2\Delta_{\rm CE\nu NS}^{t_{\rm trig}})N_{ij}^{\rm CE\nu NS}$$
$$+ (1+\beta_3)N_{ij}^{\rm SSB}$$
$$+ (1+\beta_4+\beta_5\Delta_{\rm pBRN}^{E_+}+\beta_5\Delta_{\rm pBRN}^{E_-}+\beta_6\Delta_{\rm pBRN}^{t_{\rm trig}^+}+\beta_6\Delta_{\rm pBRN}^{t_{\rm trig}^-}+\beta_7\Delta_{\rm pBRN}^{t_{\rm trig}^{\rm w}})N_{ij}^{\rm pBRN}$$
$$+ (1+\beta_8)N_{ij}^{\rm dBRN} - N_{ij}^{\rm exp}\Big]^2$$
$$+ \sum_{k=0,3,4,8}\left(\frac{\beta_k}{\sigma_k}\right)^2 + \sum_{k=1,2,5,6,7}(\beta_k)^2$$

Akimov et al, PRL 126 (2021) 012002

Atzori-Corona et al, JHEP05 (2022) 109

Comparison with other results

D. Papoulias, Magnificent CEvNS workshop 2023

Flavor	$\vert\mu_\nu\vert$ $[10^{-11}\mu_B]$	q_ν $[10^{-12}e]$	$\langle r^2_\nu \rangle$ $[10^{-32}\mathrm{cm}^2]$
ν_e	≤ 1.4 (LZ)	$[-0.3, 0.6]$ (LZ)	$[-121, 37.5]$ (LZ)
	≤ 0.9 (XENONnT)	$[-0.1, 0.6]$ (XENONnT)	$[-93.4, 9.5]$ (XENONnT)
	≤ 3.7 (Borexino)	≤ 1 (Reactor)	$[-4.2, 6.6]$ (TEXONO)
	≤ 2.9 (GEMMA)	$[-9.3, 9.5]$ (Dresden-II)	$[-5.94, 8.28]$ (LSND)
	$\leq$ 360 (COHERENT)	**$[-260, 260]$ (COHERENT)**	[-61.2, -48.2] ∪ [-4.7, 2.2] **(COHERENT)**
ν_μ	≤ 2.3 (LZ)	$[-0.7, 0.7]$ (LZ)	$[-109, 112.3]$ (LZ)
	≤ 1.5 (XENONnT)	$[-0.6, 0.6]$ (XENONnT)	$[-50.2, 54]$ (XENONnT)
	≤ 5 (Borexino)	≤ 11 (XMASS-I)	$[-1.2, 1.2]$ (CHARM-II)
	$\leq$ 240 (COHERENT)	**$[-140, 140]$ (COHERENT)**	**$[-58.2, -52.1]$ (COHERENT)**
ν_τ	≤ 2 (LZ)	$[-0.6, 0.6]$ (LZ)	$[-93.7, 97]$ (LZ)
	≤ 1.3 (XENONnT)	$[-0.5, 0.5]$ (XENONnT)	$[-43, 46.8]$ (XENONnT)
	≤ 5.9 (Borexino)	≤ 11 (XMASS-I)	

DM exp: very low E-threshold!

Different effective parameters!!
Better use TMM parameterization for comparisons!

In general not very competitive but they complement other searches