BSM searches using the first CEvNS detection in LAr

[Based on Miranda et al, JHEP 05 (2020) 130, arXiv:2003.12050]

Mariam Tórtola
IFIC, CSIC/Universitat de València

Magnificent CEvNS 2020
16-20 November 2020

Outline

- Our current knowledge of the neutrino sector:
  - Neutrino oscillation parameters: rather well known from global fits
  - Neutrino masses: below eV
  - Neutrino BSM properties beyond masses: not observed so far
    - ➡ upper limits on their size
- CEvNS provide a powerful tool to search for new physics BSM:
  - Non-standard neutrino interactions with matter (NSI)
  - Exotic neutrino electromagnetic properties
  - Light and heavy sterile neutrinos
  - Light mediators
  - …
- Constraints on BSM neutrino physics using first results of CENNS-10.

The three-flavour ν picture

neutrino mixing

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

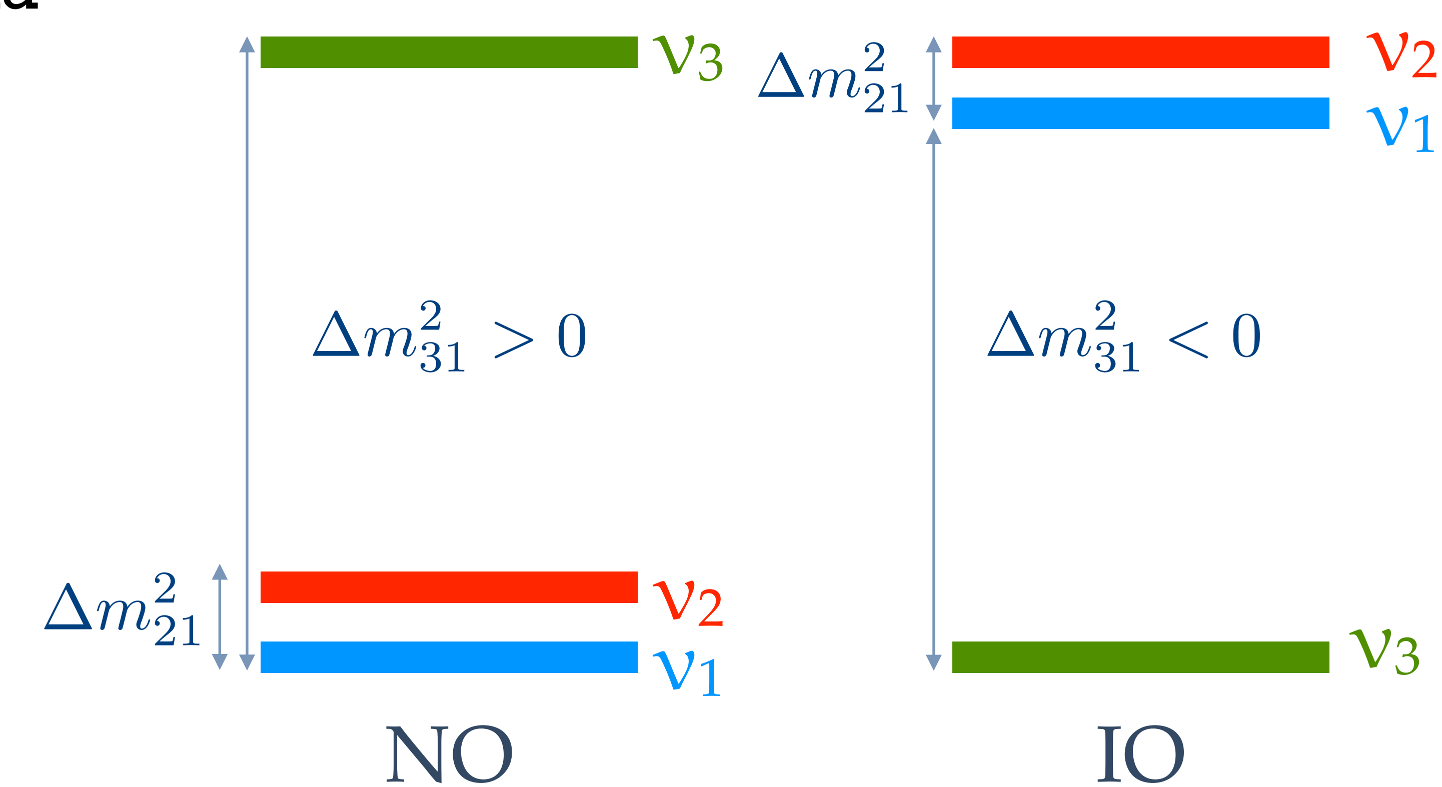
- ✓ 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- ✓ 3 CP phases: 1 Dirac + 2 Majorana
- ✓ 3 masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

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

neutrino mass spectrum



Experimental data

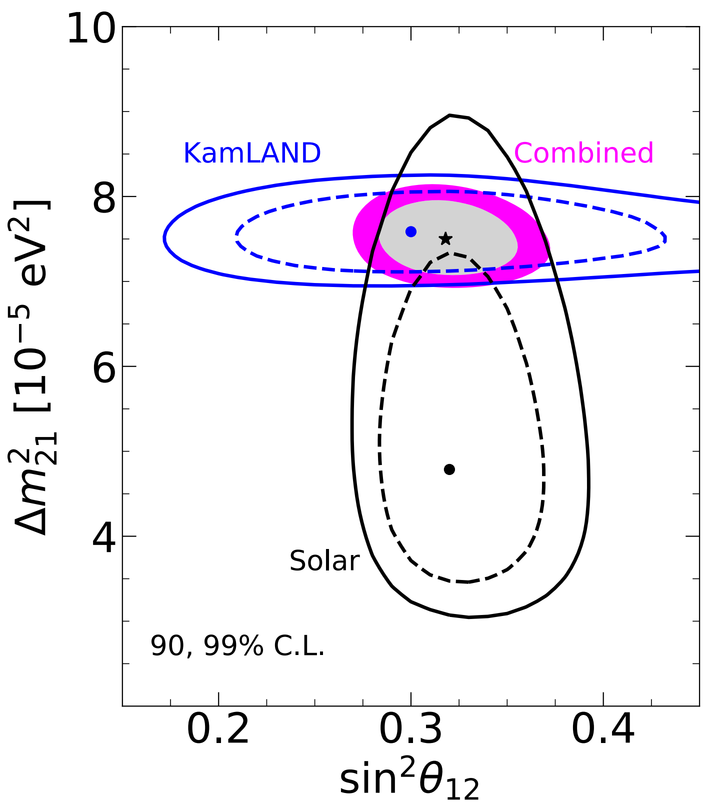
de Salas et al, arXiv:2006.11237 [Updated with Nu-2020 data]

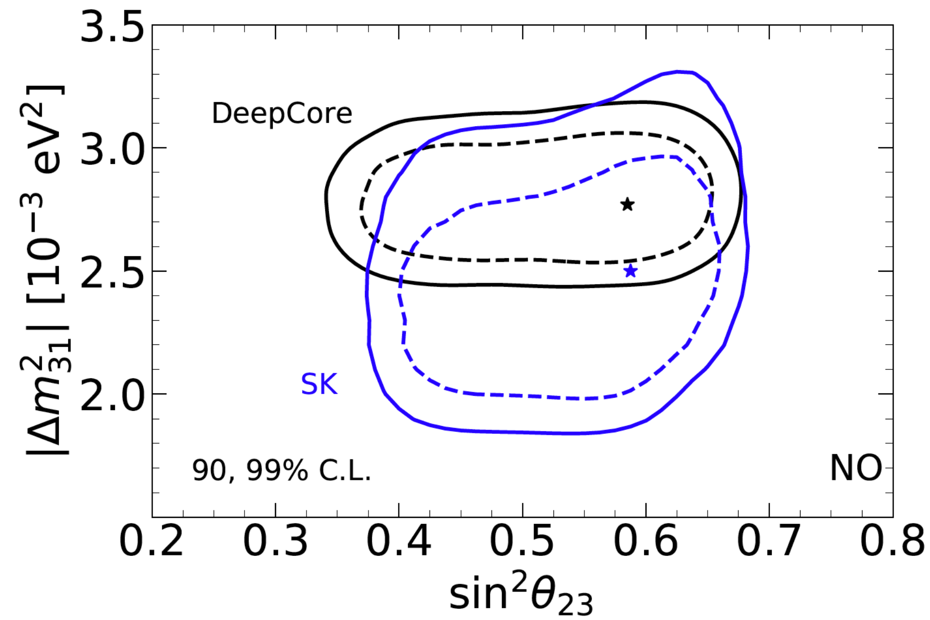
solar sector

Cl, Ga, SK

SNO, Borexino

KamLAND





atmospheric results

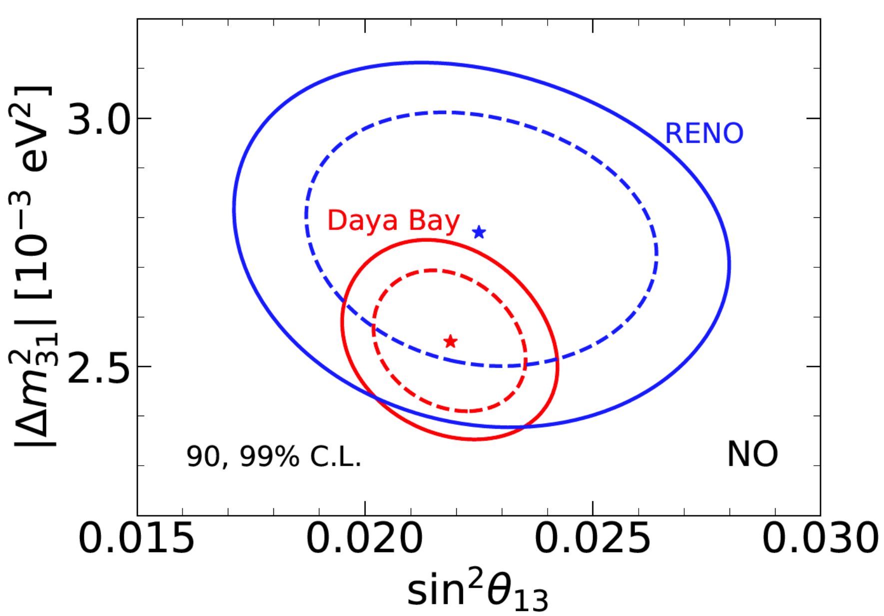
Super-K

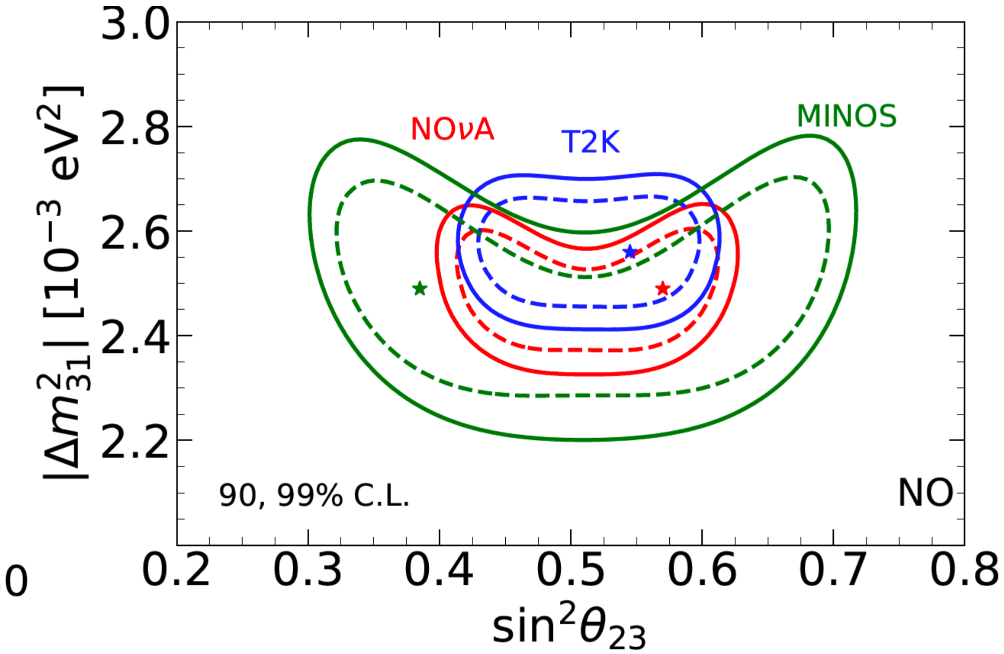
IC-DeepCore

SBL reactors

Daya Bay

RENO





LBL experiments

MINOS

T2K

NOvA

Neutrino oscillation parameters

de Salas et al, arXiv:2006.11237 [Updated with Nu-2020 data]

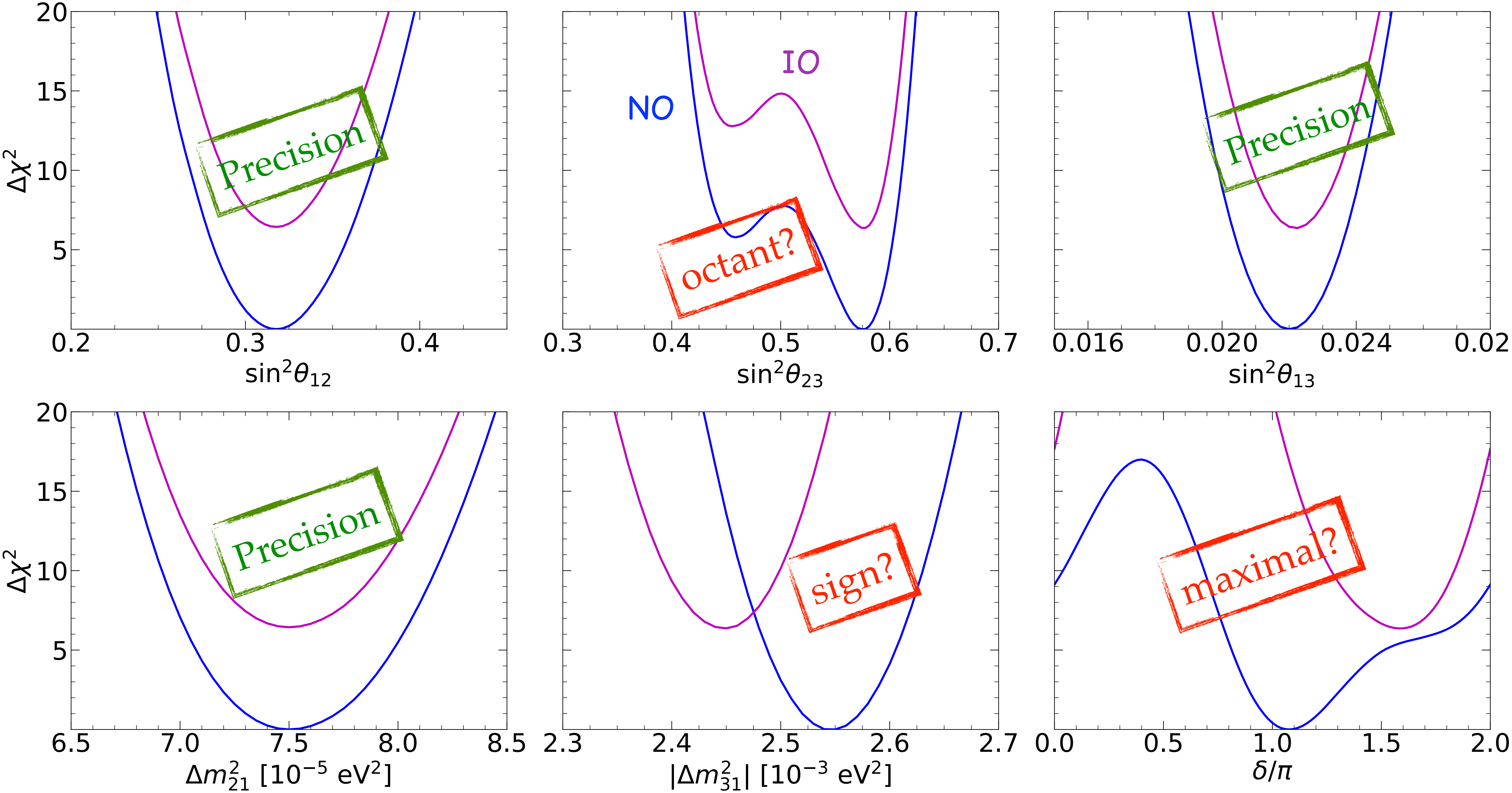
See also NuFIT and Bari group analysis

https://globalfit.astroparticles.es/

parameter	best fit $\pm 1\sigma$	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	6.94–8.14	2.7%
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.47–2.63	1.1%
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.37–2.53	
$\sin^2\theta_{12}$ $/10^{-1}$	3.18 ± 0.16	2.71–3.69	5.2%
$\sin^2\theta_{23}$ $/10^{-1}$ (NO)	5.74 ± 0.14	4.34–6.10	5.1%
$\sin^2\theta_{23}$ $/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	4.33–6.08	
$\sin^2\theta_{13}$ $/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.000–2.405	3.0%
$\sin^2\theta_{13}$ $/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.018–2.424	
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.71–1.99	20%
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.11–1.96	9.0%

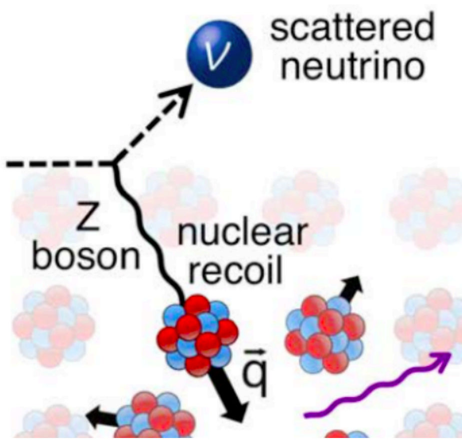
Global fit to ν oscillation parameters

de Salas et al, arXiv:2006.11237 [Updated with Nu-2020 data]

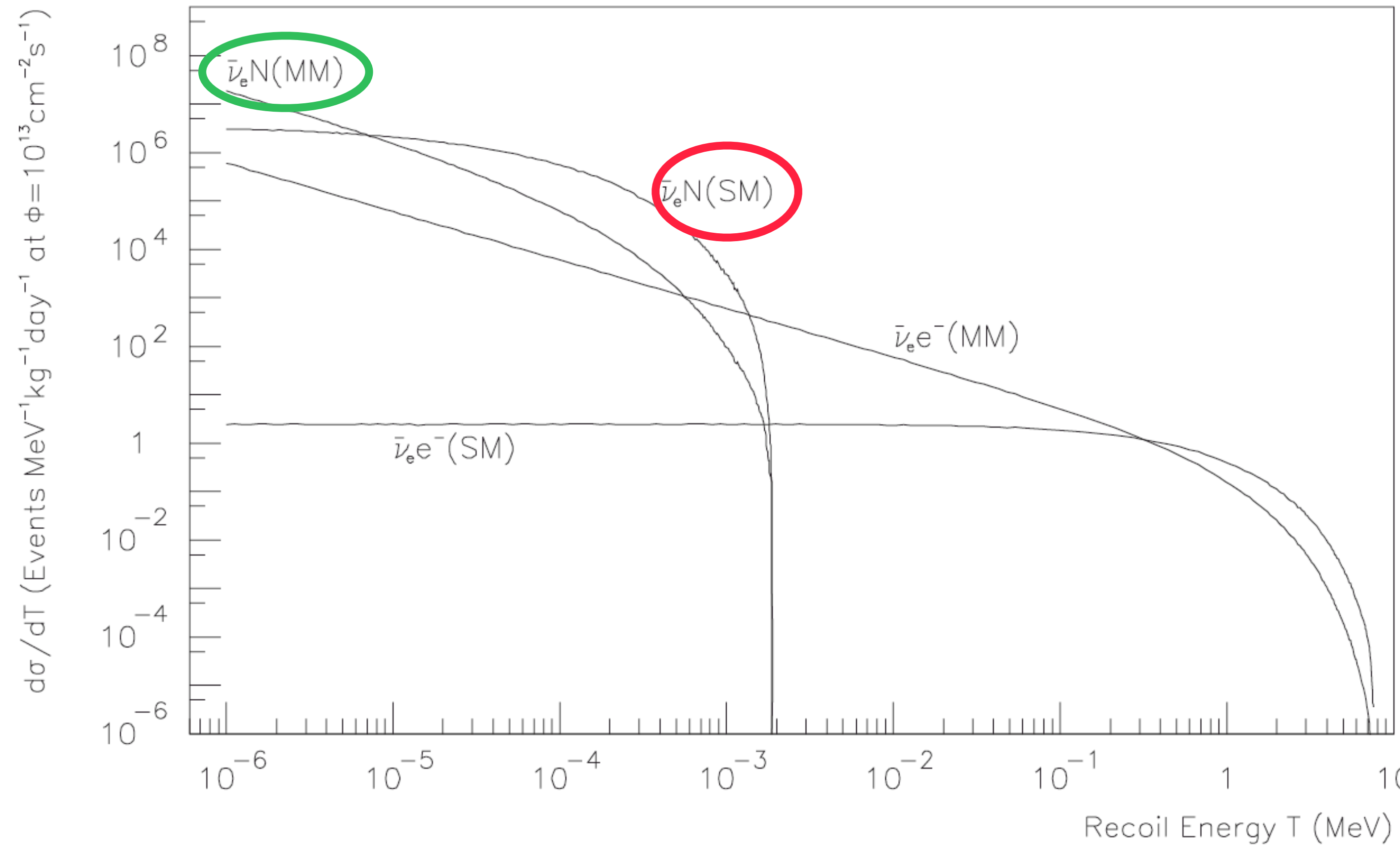


BSM searches with CEvNS experiments

Coherent Elastic ν Nucleus Scattering (CEνNS)



D. Freedman PRD9 (1974) 1389



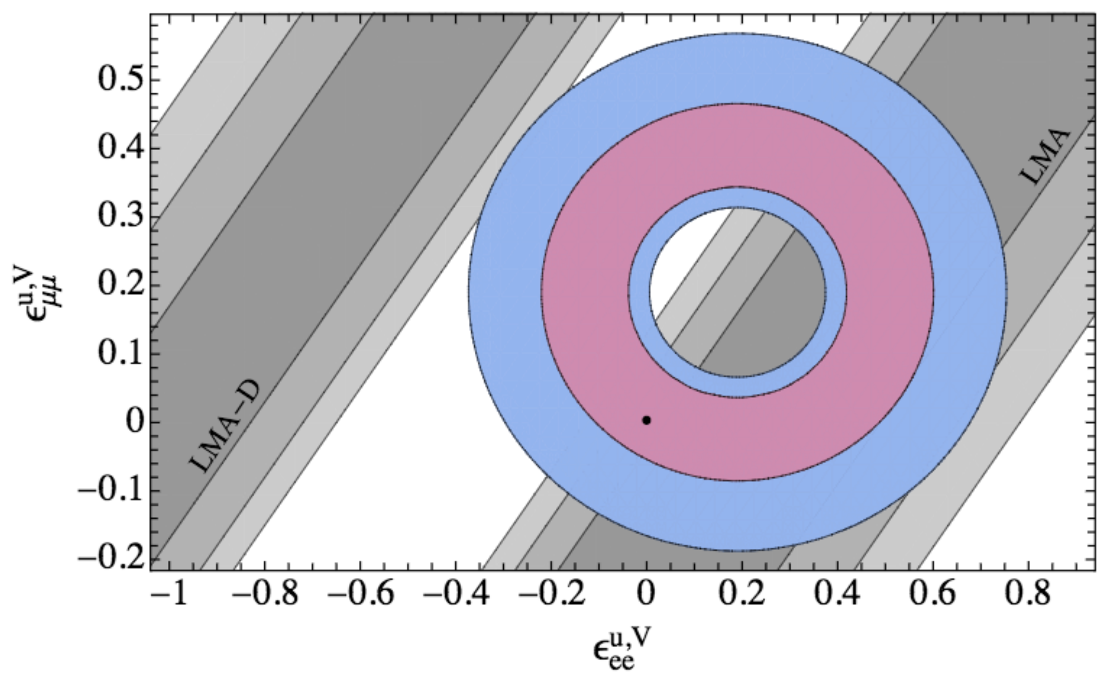
Results for a reactor neutrino flux of 10^{13} cm^{-2}s^{-1}, for the SM and for neutrino magnetic moment of 10^{-10} μ_B.

First observed at the Spallation Neutron Source (Oak Ridge National Laboratory) in 2017

COHERENT Coll. Science 357 (2017) 1123

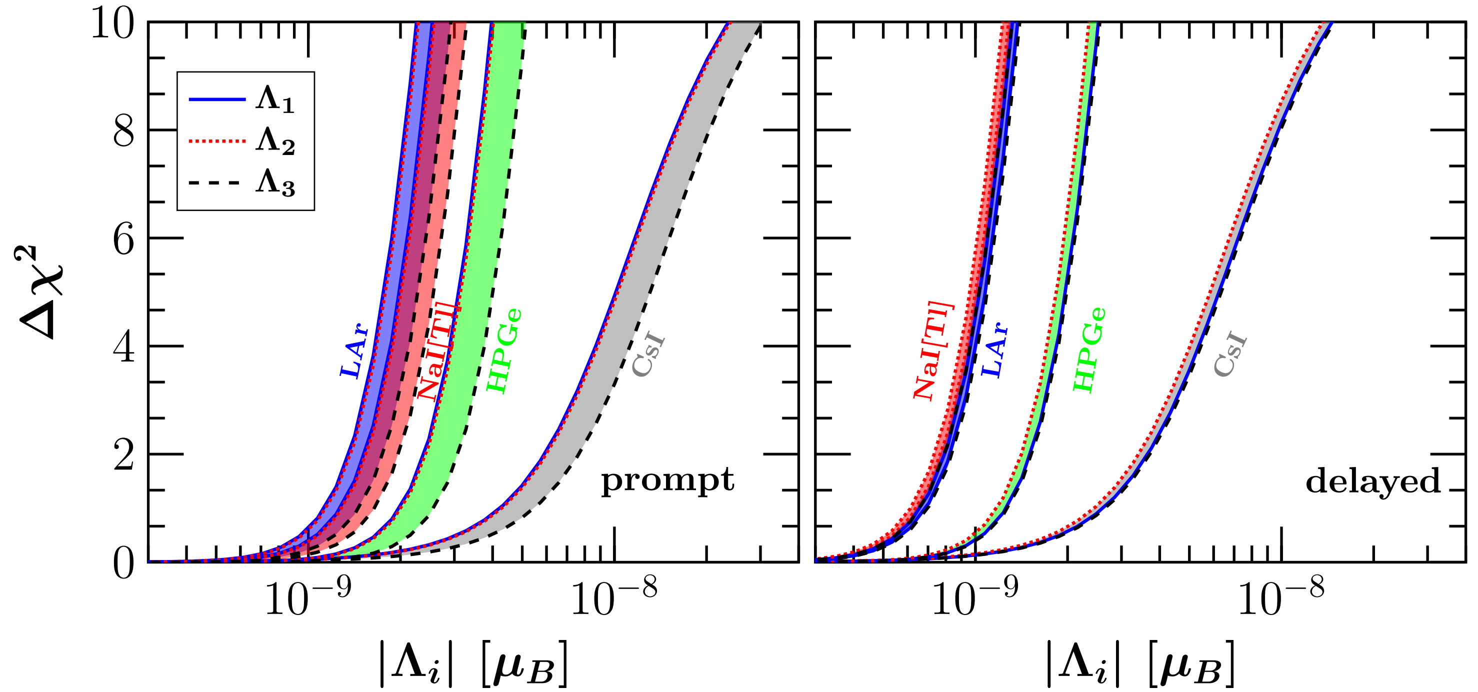
Probing BSM physics with CEvNS experiments (CsI data)

Non-standard interactions (NSI)



Coloma et al, PRD 2017

Neutrino electromagnetic properties



Miranda et al, JHEP 2019

See also:

Liao & Marfatia, PLB 2017

Aristizabal-Sierra et al, PRD 2018

Esteban et al, JHEP 2018

Giunti, PRD 2019 …

See also:

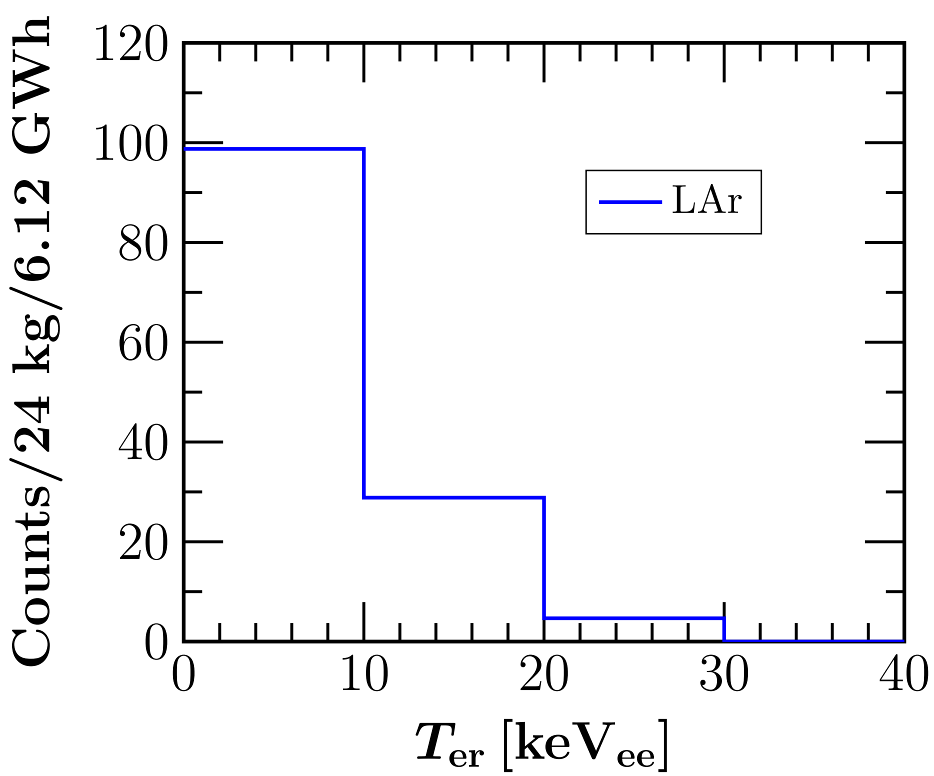
Papoulias, arXiv:1907.11644

Cadeddu et al, PRD 2020

Analysis of CENNS-10 LAr data

For details on CENNS-10 LAr data: Poster by Benjamin Suh

Simulated number of events at CENNS-10 LAr detector (Analysis A)



χ^2 analysis:

$$\chi^2(X) = \min_{\alpha} \left[\frac{(N_{\rm meas} - N_{\rm theor}(X)[1+\alpha])^2}{\sigma^2_{\rm stat}} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 \right]$$

- $N_{\rm meas} = 159$
- $N_{\rm theor}$ (X) theoretical prediction for BSM scenario X
- $\sigma_{stat} = \sqrt{N_{meas} + N_{BRN}}$ with $N_{\rm BRN} = 563$
- $\alpha \equiv$ normalization pull with $\sigma_\alpha = 8.5\%$

See Cadeddu et al, PRD 2020 for a binned analysis

Non-standard neutrino interactions

- Effective NC-NSI Lagrangian:

$$\mathcal{L}_{NC}^{NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_X f)$$

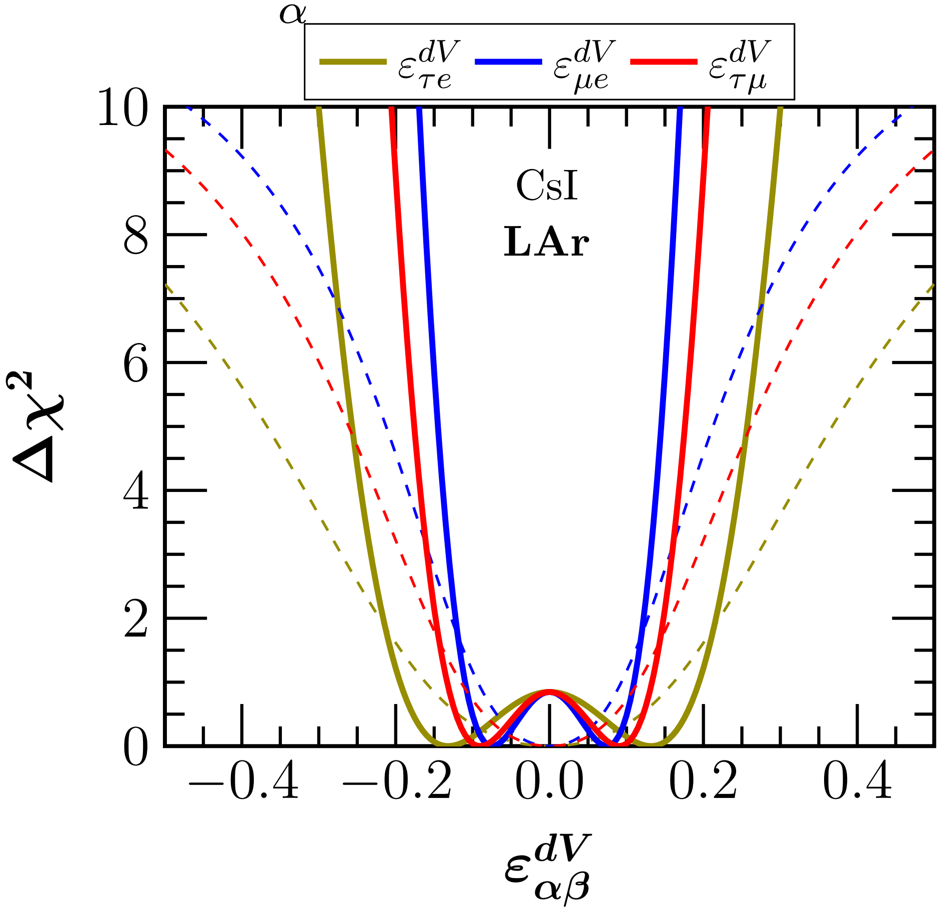
P=L,R

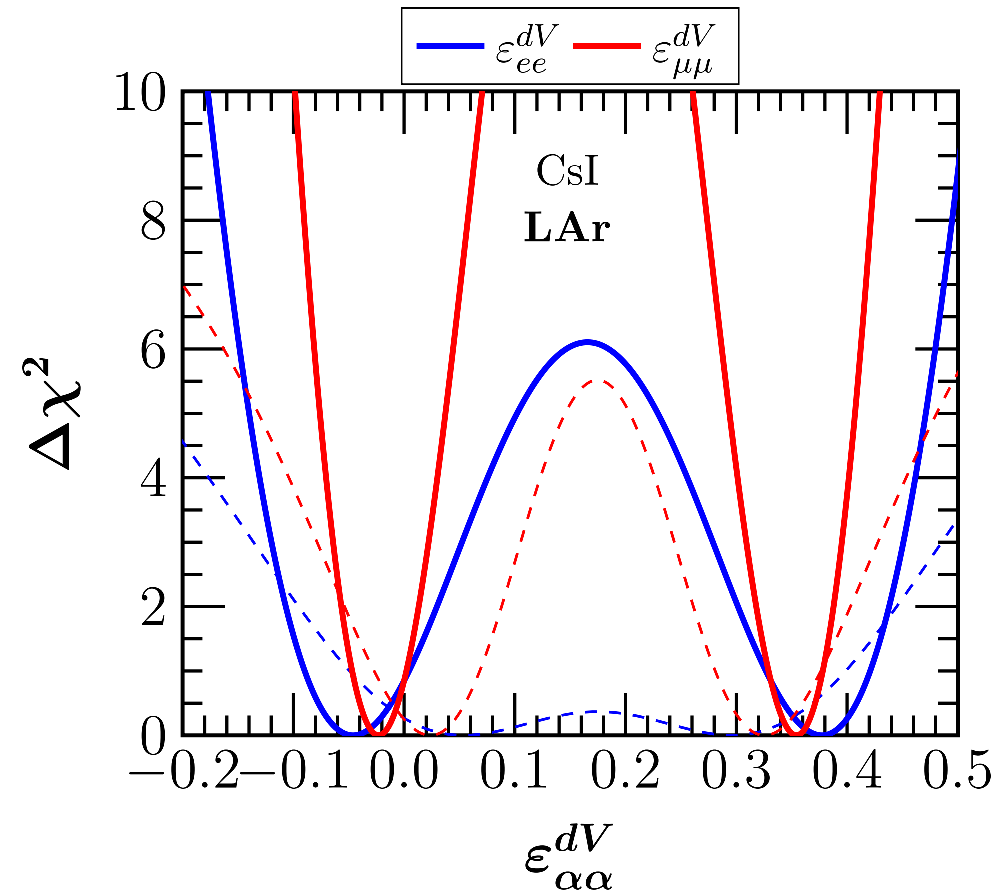
- Weak charge of the CEvNS reaction modified to:

$$\epsilon_{\alpha\beta}^{qV} = \epsilon_{\alpha\beta}^{qL} + \epsilon_{\alpha\beta}^{qR}$$

$$\begin{aligned}\mathcal{Q}_{\rm NSI}^{V} = & \left[\left(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}\right) Z F_p(Q^2) + \left(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV}\right) N F_n(Q^2)\right] \\ + & \sum_{\alpha} \left[\left(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}\right) Z F_p(Q^2) + \left(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV}\right) N F_n(Q^2)\right].\end{aligned}$$

Constraints on NSI couplings (1 at a time)

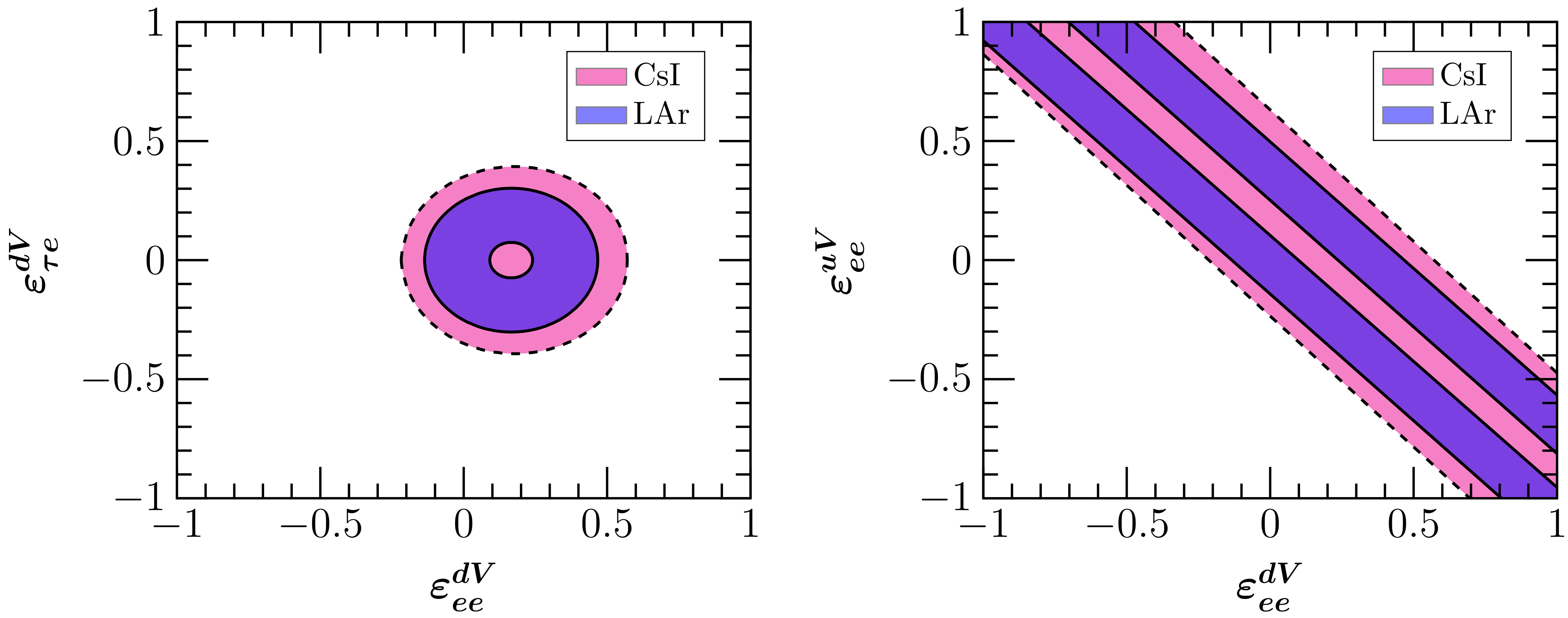




Non-standard neutrino interactions

- ✦ Constraints on two NSI parameters at a time:

Miranda et al, JHEP 05 (2020) 130, arXiv:2003.12050



➡ LAr results improve the bounds on NSI parameters compared to CsI

➡ Some results not competitive with other searches, but correlations very relevant!

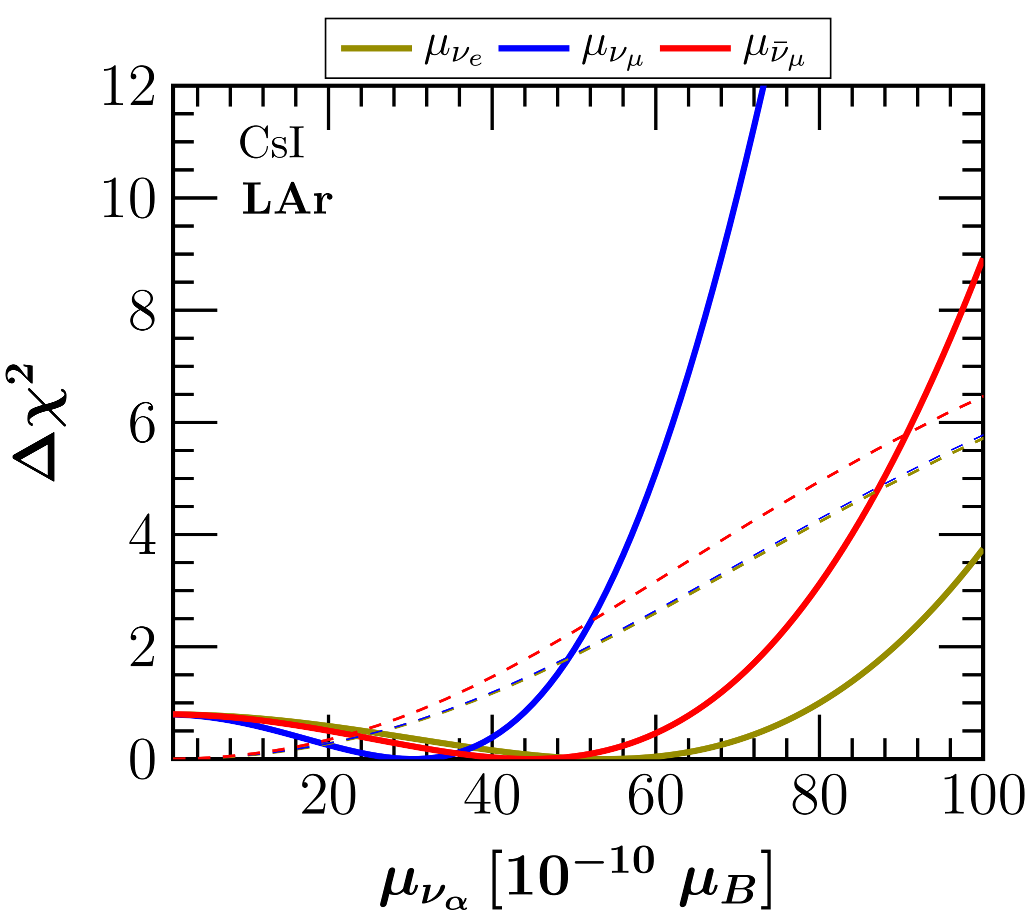
See Farzan and Tórtola, Front. in Phys. 2018

Neutrino electromagnetic properties

- Effective neutrino magnetic moment gives extra contribution to CEvNS cross section:

$$\left(\frac{d\sigma}{dT_A}\right)_{\rm EM} = \frac{\pi \alpha_{EM}^2 \mu_\nu^2 Z^2}{m_e^2} \left(\frac{1 - T_A/E_\nu}{T_A}\right) F_p^2(Q^2)$$

[Here we will consider flavor-dependent effective MM μ_ν. For full Transition Magnetic Moment parameterization see Miranda et al, JHEP 2019]



- Constraints on effective μ_ν (90% C.L.):

$$\mu_{\nu_e} < 94 \times 10^{-10} \mu_B$$

$$\mu_{\nu_\mu} < 54 \times 10^{-10} \mu_B$$

$$\mu_{\bar{\nu}_\mu} < 78 \times 10^{-10} \mu_B$$

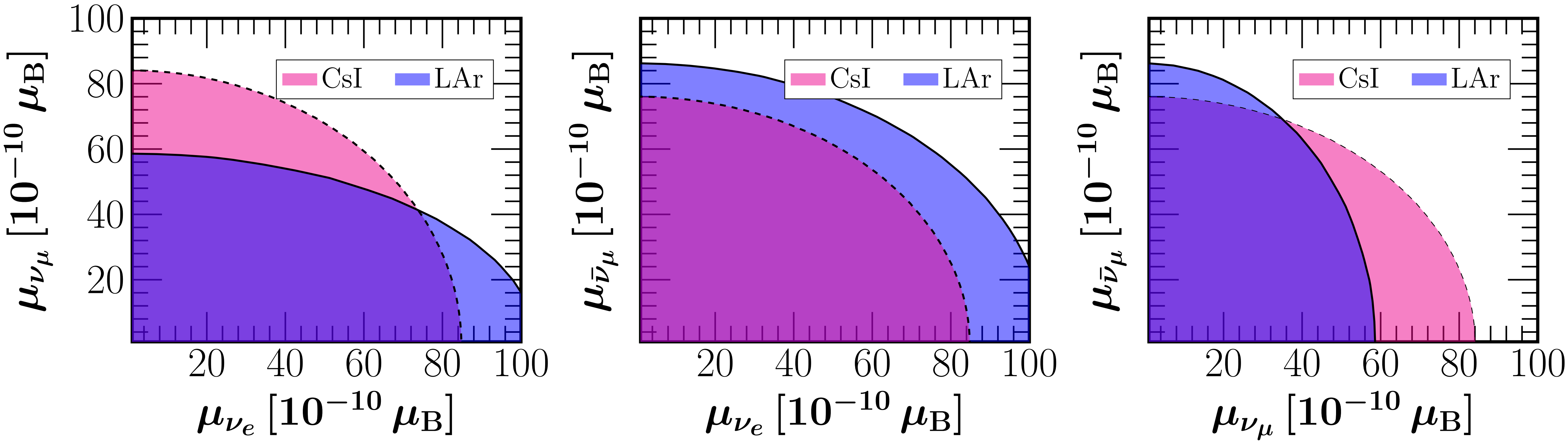
- Current constraints from solar Borexino data:

$$\mu_{eff} < 2.8 \times 10^{-11} \mu_B$$

different parameters!! better use TMM parameterization for comparisons!

Neutrino electromagnetic properties

✦ Constraints on two effective magnetic moments at a time (LAr vs CsI):



➡ LAr results only improve slightly CsI since they fit better to $\mu_\nu \neq 0$ (see previous plot)

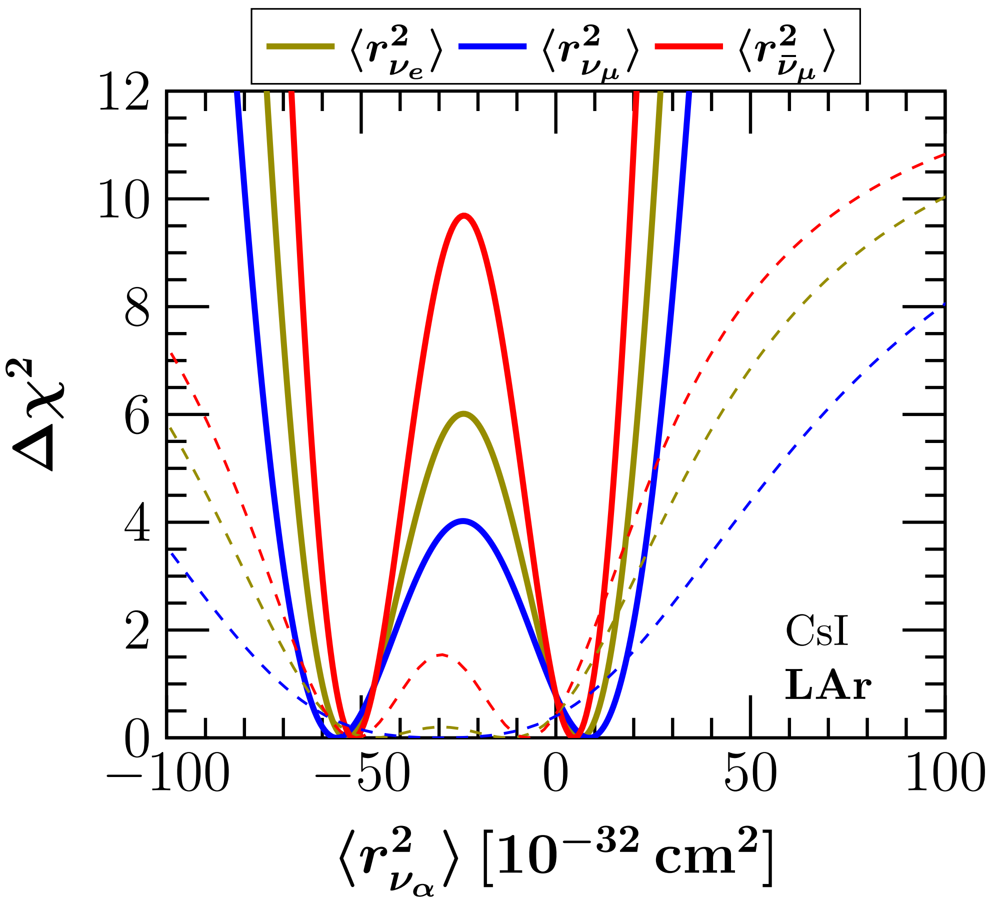
Miranda et al, JHEP 05 (2020) 130, arXiv:2003.12050

Neutrino electromagnetic properties

- The effect of the neutrino charge radius $\langle r^2_{\nu_\alpha} \rangle$ ($\alpha = e, \mu, \tau$) on the SM cross section can be seen as a shift on the weak mixing angle:

$$\sin^2\theta_W \to \sin^2\theta_W + \frac{\sqrt{2}\pi\alpha_{\rm EM}}{3G_F}\langle r^2_{\nu_\alpha} \rangle$$

- Sensitivity on the neutrino charge radii $\langle r^2_{\nu_\alpha} \rangle$ ($\alpha = e, \mu, \tau$)



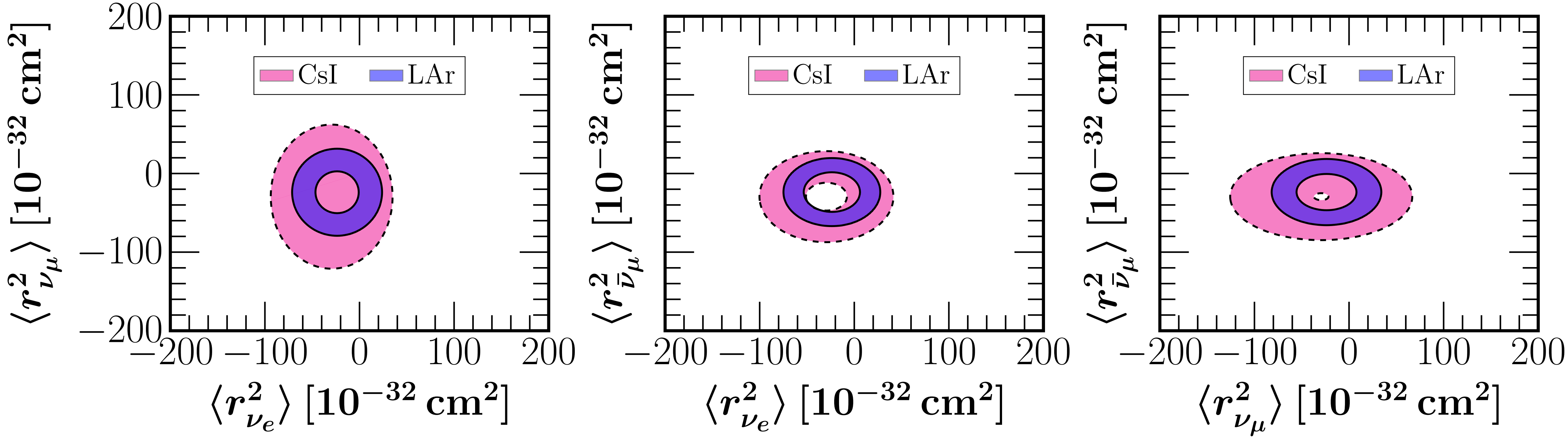
➡ 90% C.L. (units 10^{-32} cm^2):

$$\langle r^2_{\nu_e} \rangle = (-64, -41) \ \& \ (-7, 16)$$
$$\langle r^2_{\nu_\mu} \rangle = (-69, -37) \ \& \ (-10, 21)$$
$$\langle r^2_{\bar{\nu}_\mu} \rangle = (-60, -43) \ \& \ (-5, 12)$$

Neutrino electromagnetic properties

✦ Constraints on two neutrino charge radii $\langle r^2_{\nu_\alpha} \rangle$ taken simultaneously:

Miranda et al, JHEP 05 (2020) 130, arXiv:2003.12050



➡ Improvement with respect to CsI results

➡ One order of magnitude weaker with respect to other searches

See limits from other experiments in Cadeddu et al, PRD 2018

Light mediators

- We consider on simplified U(1)' scenarios with an additional vector Z' or a scalar ϕ arising from the generic Lagrangians:

$$\mathcal{L}_{\text{vector}} = Z'_\mu \left(g_{Z'}^{qV} \bar{q}\gamma^\mu q + g_{Z'}^{\nu V} \bar{\nu}_L \gamma^\mu \nu_L \right)$$
$$\mathcal{L}_{\text{scalar}} = \phi \left(g_\phi^{qS} \bar{q} q + g_\phi^{\nu S} \bar{\nu}_R \nu_L + \text{h.c.} \right)$$

- For a Z' mediator, the weak charge of the CEvNS reaction modified to:

$$\mathcal{Q}_V^{Z'} = \mathcal{Q}_W^V + \frac{g_{Z'}^{\nu V}}{\sqrt{2} G_F} \frac{\left(2g_{Z'}^{uV} + g_{Z'}^{dV}\right) Z F_p(Q^2) + \left(g_{Z'}^{uV} + 2g_{Z'}^{dV}\right) N F_n(Q^2)}{2 m_A T_A + M_{Z'}^2} \,.$$

- The scalar mediator contribution to the total cross section:

$$\left(\frac{d\sigma}{dT_A}\right)_{\text{scalar}} = \frac{G_F^2 m_A^2}{4\pi} \frac{g_\phi^{\nu S} \mathcal{Q}_\phi^2 T_A}{E_\nu^2 \left(2 m_A T_A + M_\phi^2\right)^2}$$

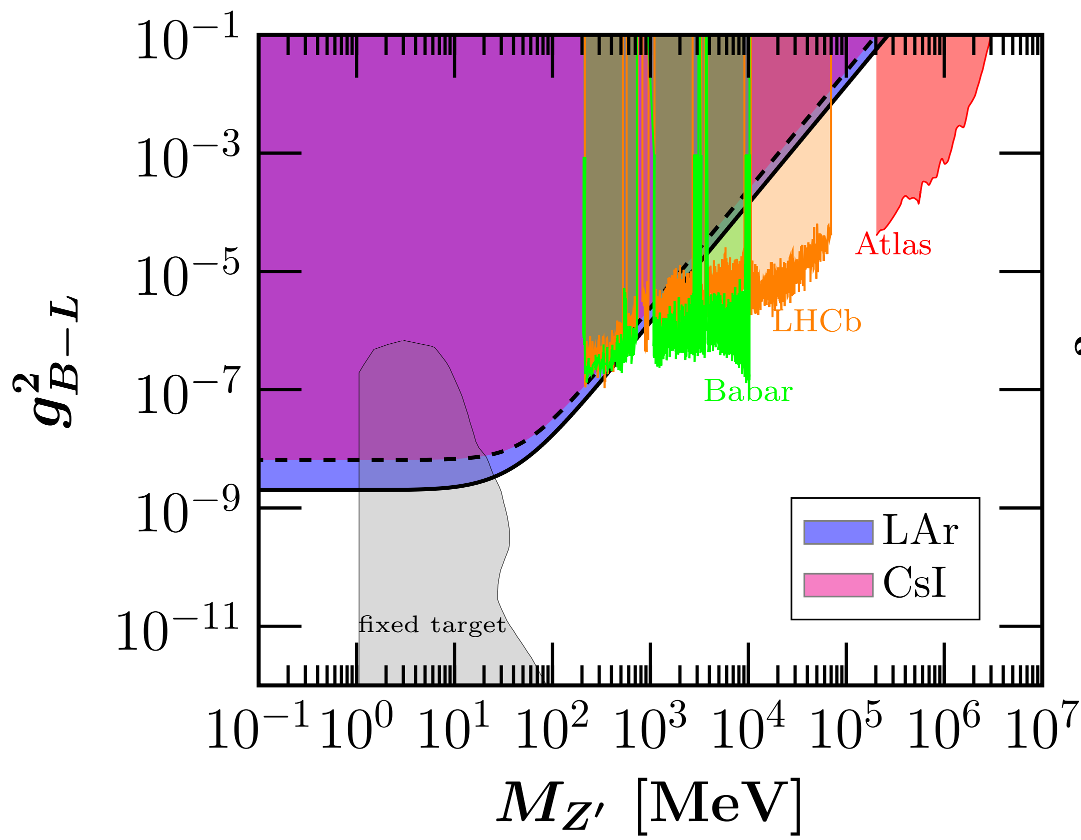
with:

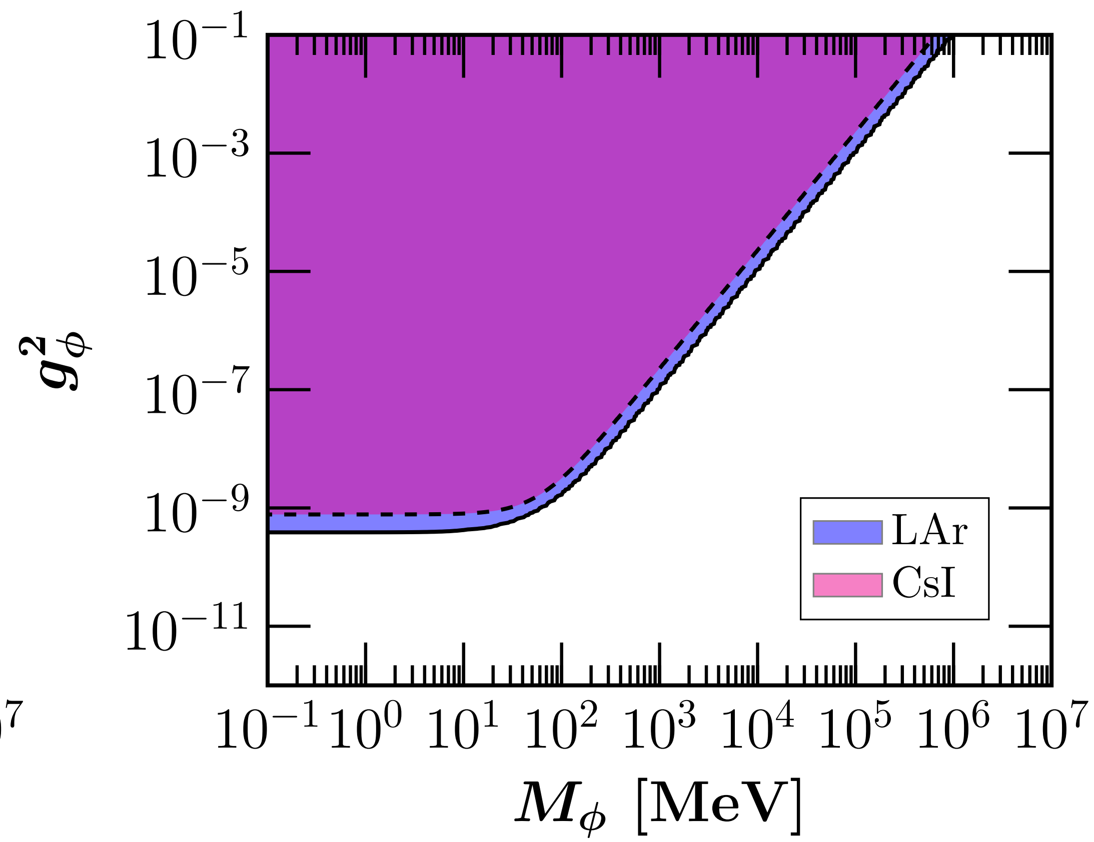
$$\mathcal{Q}_\phi = Z F_p(Q^2) \sum_{q=u,d} g_\phi^{qS} \frac{m_p}{m_q} f_{T_q}^p + N F_n(Q^2) \sum_{q=u,d} g_\phi^{qS} \frac{m_n}{m_q} f_{T_q}^n \,.$$

Light mediators

✦ 90% C.L. excluded regions for Z' and scalar light mediators from CEvNS data

Miranda et al, JHEP 05 (2020) 130, arXiv:2003.12050





$U(1)_{B-L}$ extension of SM with

$$g_{Z'}^{qV} = -\,g_{Z'}^{\nu V}/3$$

➡ One can also appreciate some improvement with respect to CsI results

➡ Z': CEvNs provides complementary constraints to light mediator parameters.

Summary

- CEvNS provide a powerful tool to search for new physics BSM (already shown for CsI data)

- We have derived constraints on BSM neutrino physics using the first detection of CEvNS in argon, in CENNS-10 experiment:

  - ☑ Non-standard neutrino interactions with matter (NSI)
  - ☑ Exotic neutrino electromagnetic properties
  - ☑ Light mediators

➡ We have shown the improvement of results with with respect previous CsI data

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