

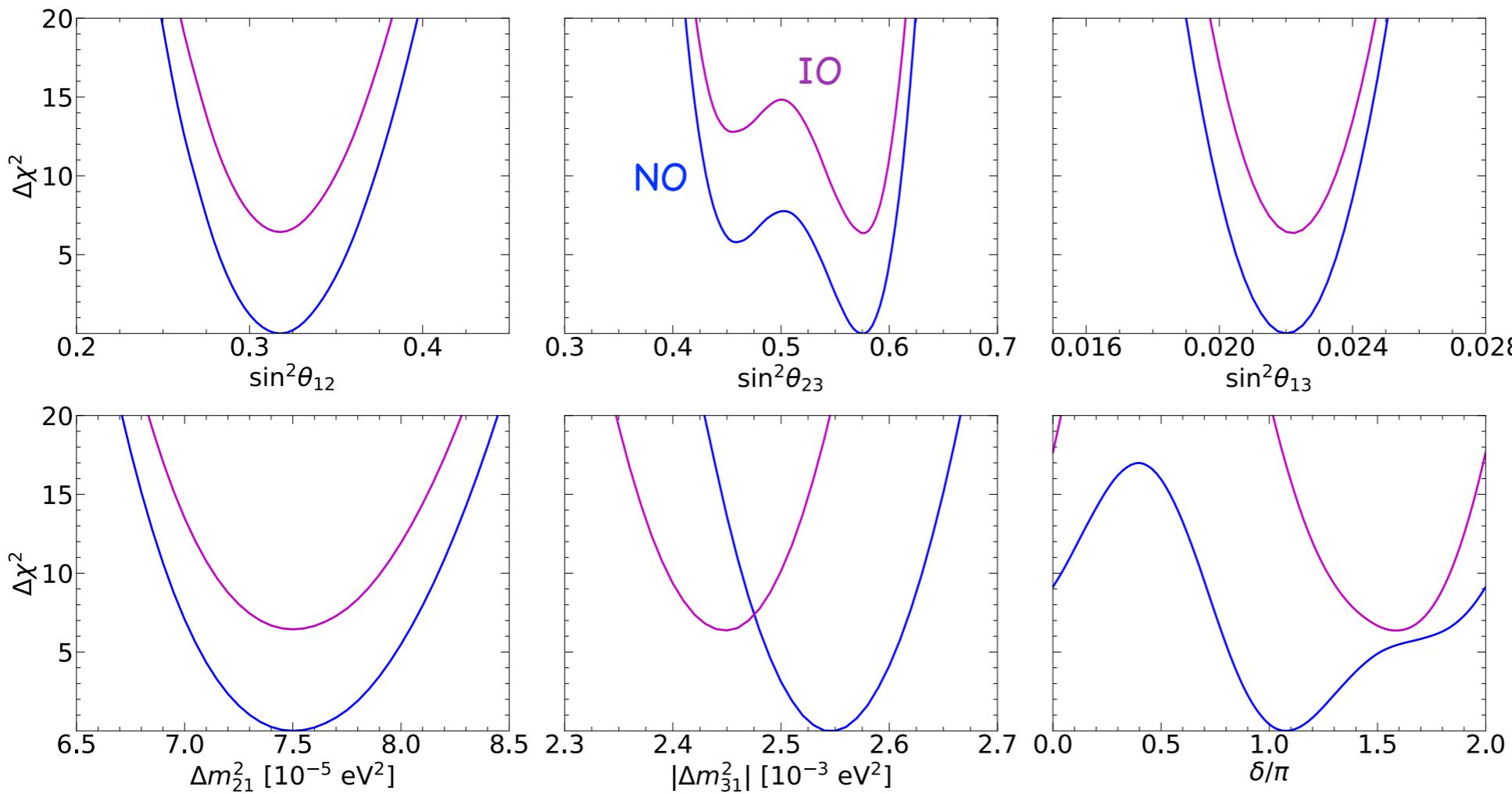
Exploring neutrino electromagnetic properties with CEvNS

Mariam Tórtola
IFIC, CSIC/Universitat de València



Motivation: why CEvNS?

- ◆ Our current knowledge of the **neutrino sector**:
- ✓ Neutrino oscillation parameters: rather well known from **global fits**



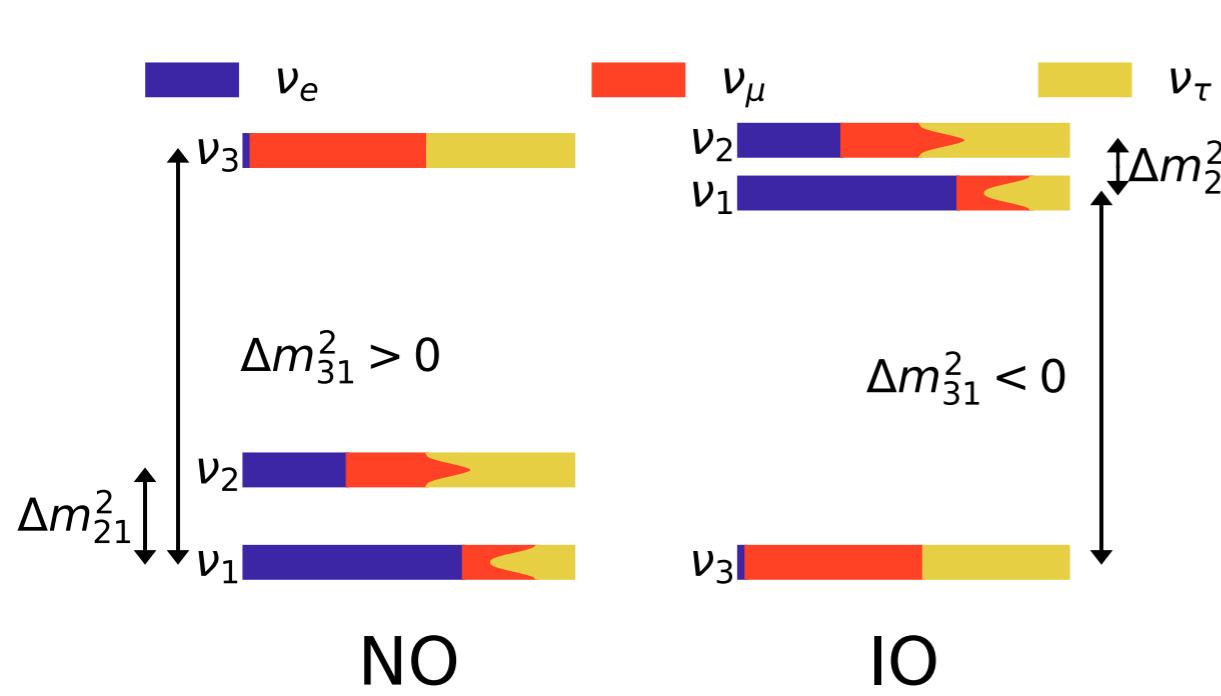
Mass ordering:
NO or IO?

Octant of
 θ_{23} ?

CP violation:
maximal?

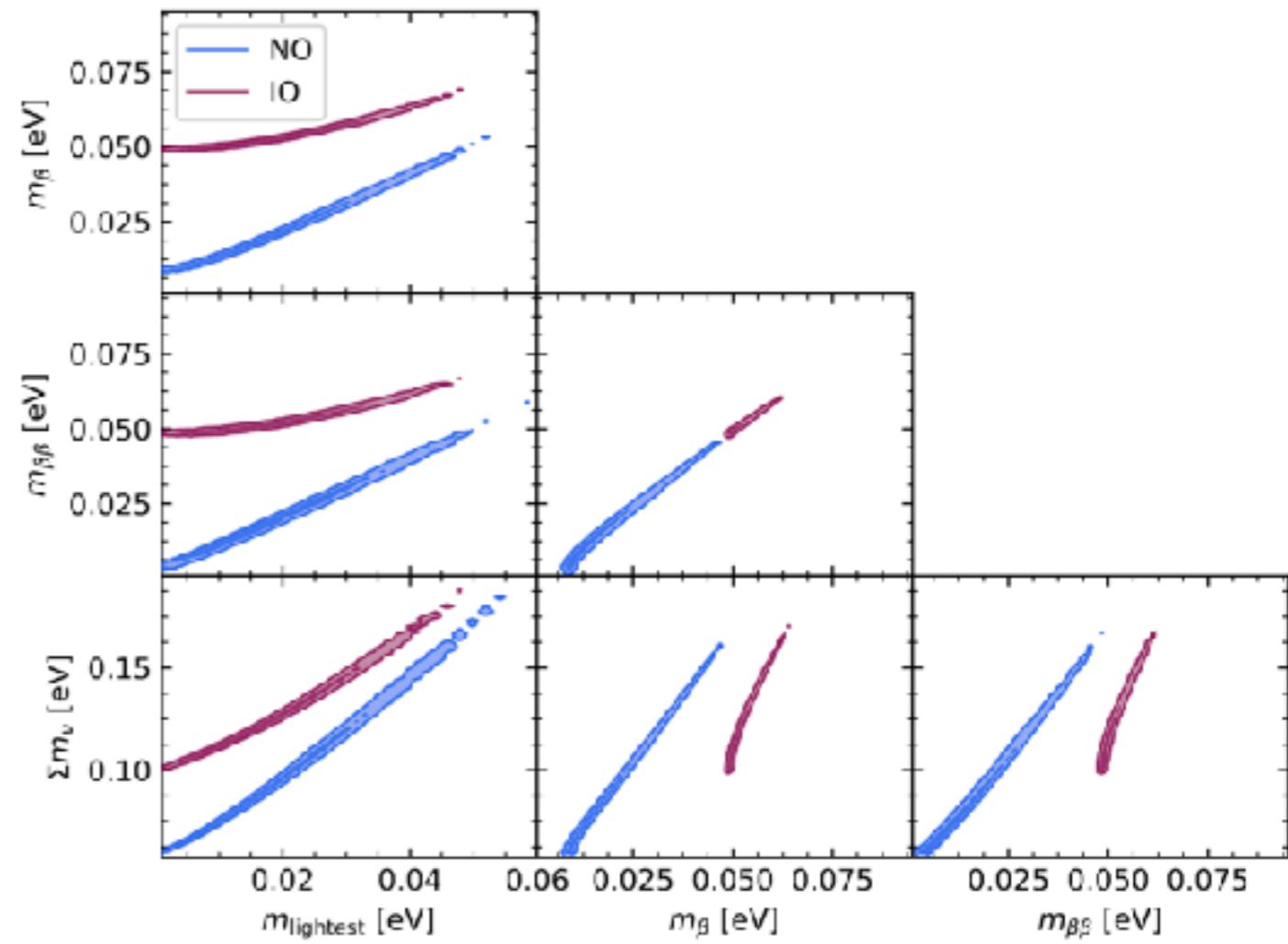
Motivation: why CEvNS?

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



From oscillations:

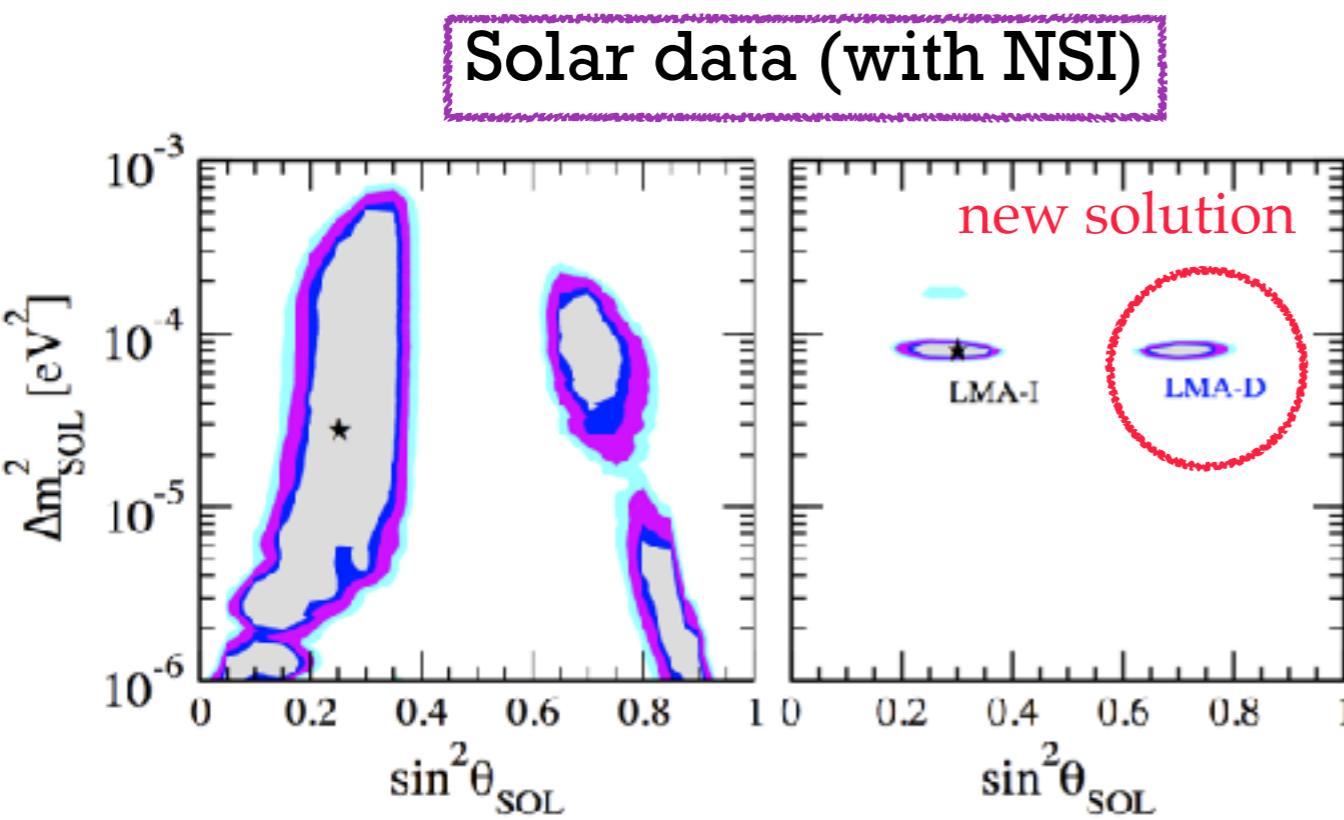
$$m_\nu \geq \sqrt{\Delta m_{31}^2(\text{NO})} \gtrsim 0.05 \text{ eV}$$



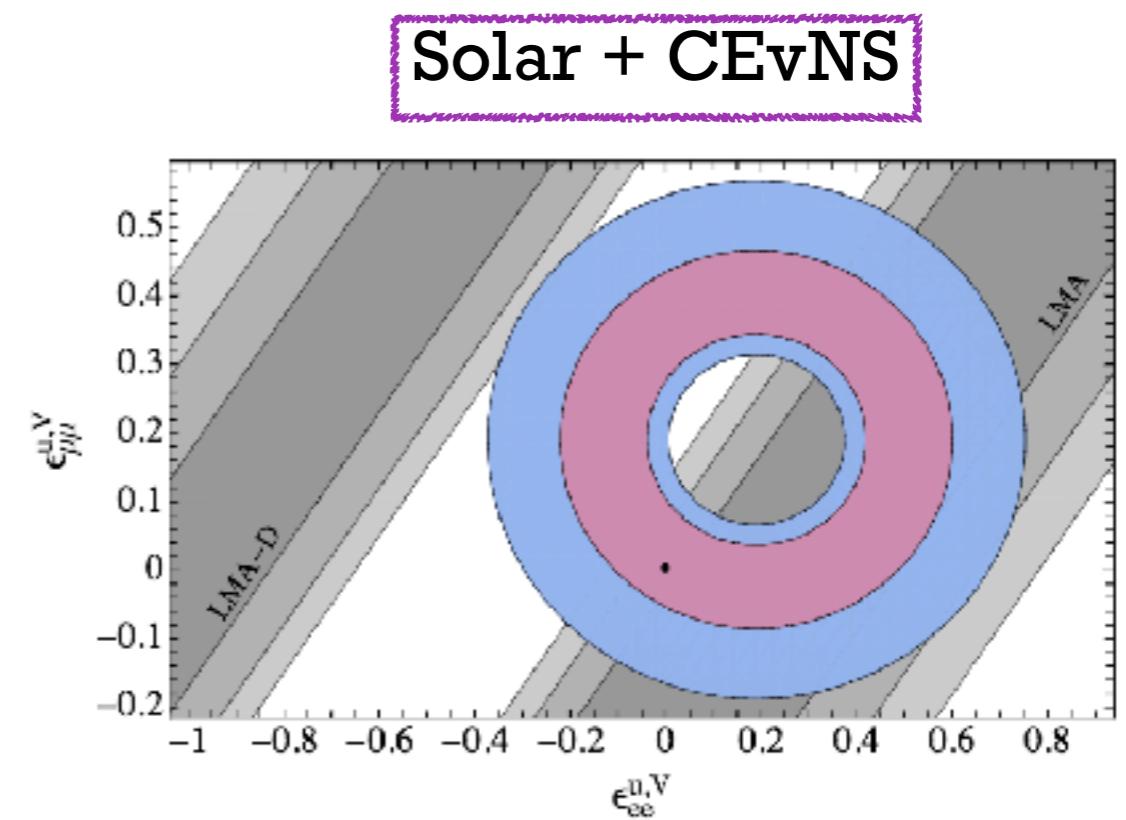
de Salas et al, JHEP 02 (2021) 071

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 + $0\nu\beta\beta$ decay)
 - ✓ **Neutrino BSM properties** (not observed so far): can affect current picture



Miranda et al, JHEP 2006



Coloma et al, PRD 2017

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 + $0\nu\beta\beta$ decay)
 - ✓ **Neutrino BSM properties** (not observed so far): can affect current picture
- ◆ **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
 - ✓ Dark matter
 - ✓ Solar neutrinos
 - ✓ Supernova neutrinos



No introduction on CEvNS:
see plenary talk by M. Vignati
and other talks in the session

Based on

JHEP

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: December 1, 2022
REVISED: February 27, 2023
ACCEPTED: March 26, 2023
PUBLISHED: April 6, 2023

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

V. De Romeri,^a O.G. Miranda,^b D.K. Papoulias,^c G. Sanchez Garcia,^{a,b} M. Tórtola^a and J.W.F. Valle^a

^aAHEP Group, Institut de Física Corpuscular — CSIC/Universitat de València, and Departament de Física Teòrica, Universitat de València, Parc Científic de Paterna, C/ Catedrático José Beltrán, 2 E-46980 Paterna (Valencia), Spain

^bDepartamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, Apariato Postal 14-740, 07000 Ciudad de Mexico, Mexico

^cDepartment of Physics, National and Kapodistrian University of Athens, Zografou Campus GR-15772 Athens, Greece

E-mail: deromeri@ific.uv.es, omar.miranda@cinvestav.mx, dkpapoulias@phys.uoa.gr, gsanchez@fis.cinvestav.mx, mariam@ific.uv.es, valle@ific.uv.es

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](https://arxiv.org/abs/2211.11905)

JHEP 04 (2023) 035 [arXiv:2211.11905]

In collaboration with V. De Romeri,
O. G. Miranda, D. K. Papoulias,
G. Sanchez Garcia and J. W. F. Valle

This talk :

Neutrino electromagnetic properties

- ◆ Neutrino magnetic moment
- ◆ Neutrino millicharge
- ◆ Neutrino charge radius

Based on



PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: December 1, 2022
REVISED: February 27, 2023
ACCEPTED: March 26, 2023
PUBLISHED: April 6, 2023

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

V. De Romeri,^a O.G. Miranda,^b D.K. Papoulias,^c G. Sanchez Garcia,^{a,b} M. Tórtola^a and J.W.F. Valle^a

^aAHEP Group, Institut de Física Corpuscular — CSIC/Universitat de València and Departament de Física Teòrica, Universitat de València, Parc Científic de Paterna, C/ Catedrático José Beltrán, 2 E-46980 Paterna (Valencia), Spain

^bDepartamento de Física, Centro de Investigación y de Estudios Avanzados del IPN, Apariato Postal 14-740, 07000 Ciudad de Mexico, Mexico

^cDepartment of Physics, National and Kapodistrian University of Athens, Zografou Campus GR-15772 Athens, Greece

E-mail: deromeri@ific.uv.es, omar.miranda@cinvestav.mx, dkpapoulias@phys.uoa.gr, gsanchez@fis.cinvestav.mx, mariam@ific.uv.es, valle@ific.uv.es

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](https://arxiv.org/abs/2211.11905)

JHEP 04 (2023) 035 [arXiv:2211.11905]

In collaboration with V. De Romeri,
O. G. Miranda, D. K. Papoulias,
G. Sanchez Garcia and J. W. F. Valle

This talk :

Neutrino electromagnetic properties

Other results presented in TAUP-2023:

NGI, light mediators

New physics implications of COHERENT data

The observation of coherent elastic neutrino nucleus scattering (CEvNS) has opened the window to many physics opportunities. In this talk I will discuss the implication of the observation of CEvNS by the COHERENT Collaboration using two dif

👤 Valentina De Romeri (IFIC CSIC/UV (Valencia, Spain))

🕒 29 August 2023 16:00

Sensitivity of Coherent Elastic Neutrino-Nucleus Scattering experiments to Non-Standard Interactions

The process of Coherent Elastic Neutrino-Nucleus Scattering (CEvNS), first observed in 2017 by the COHERENT collaboration, has provided a powerful tool to study new physics scenarios within the neutrino sector. In this talk, we focus on the

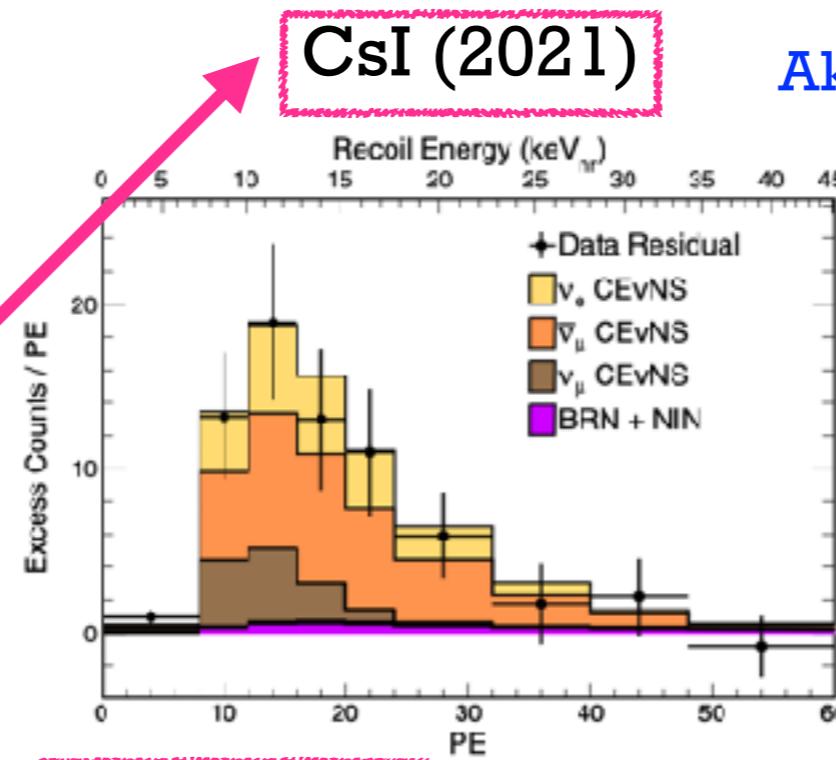
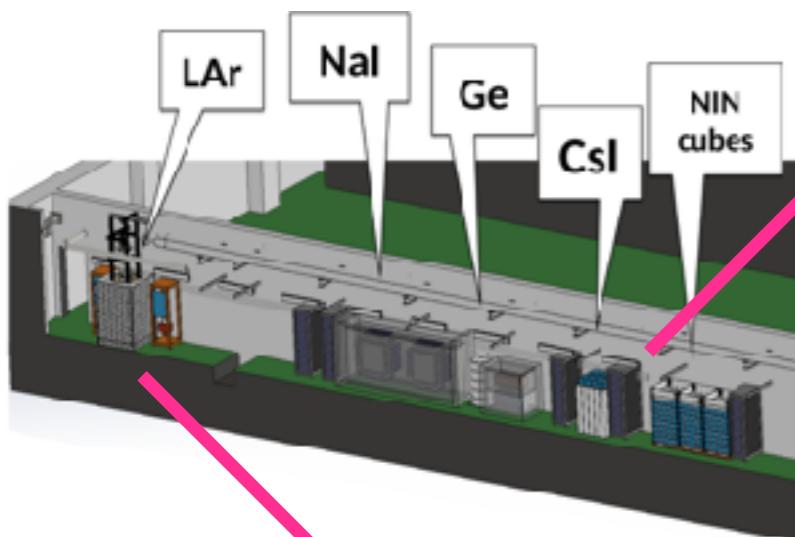
👤 Gonzalo Sanchez Garcia (Instituto de Física Corpuscular CSIC/UV (Valencia, Spain))

🕒 30 August 2023 17:30

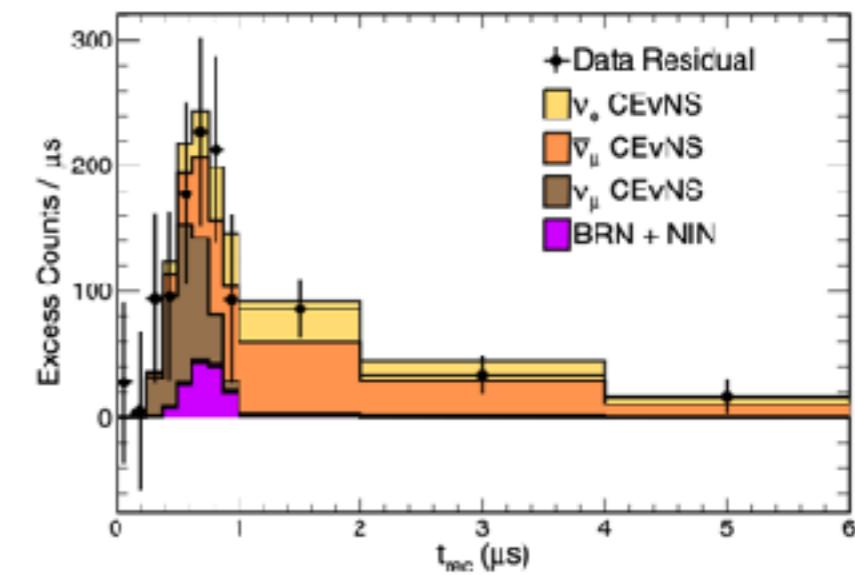
NSI

See also talk by T. Rink (light VB & θ_w with CONUS)

CEvNS data from COHERENT

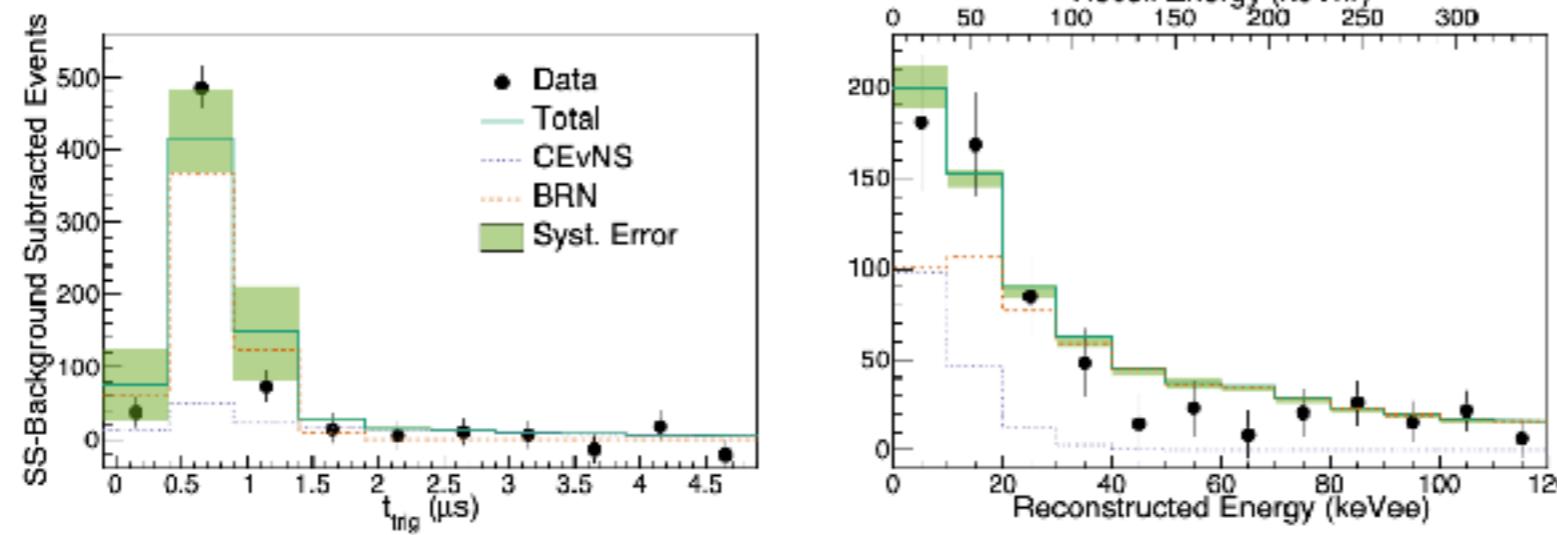


Akimov et al, PRL 129 (2022) 081801



Akimov et al, PRL 126 (2021) 012002

LAr (2020)



Statistical analysis

CsI (2021)

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

with:

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

We include ES background which could mimic a CEvNS signal.

Akimov et al, PRL 129 (2022) 081801

LAr (2020)

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

Akimov et al, PRL 126 (2021) 012002

Atzori-Corona et al, JHEP05 (2022) 109

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:

$$\frac{d\sigma_{\nu_e N}}{dE_{\text{nr}}} \Big|_{\text{CE}\nu\text{NS}}^{\text{MM}} = \frac{\pi \alpha_{\text{EM}}^2}{m_e^2} \left(\frac{1}{E_{\text{nr}}} - \frac{1}{E_\nu} \right) Z^2 F_W^2(|\vec{q}|^2)$$

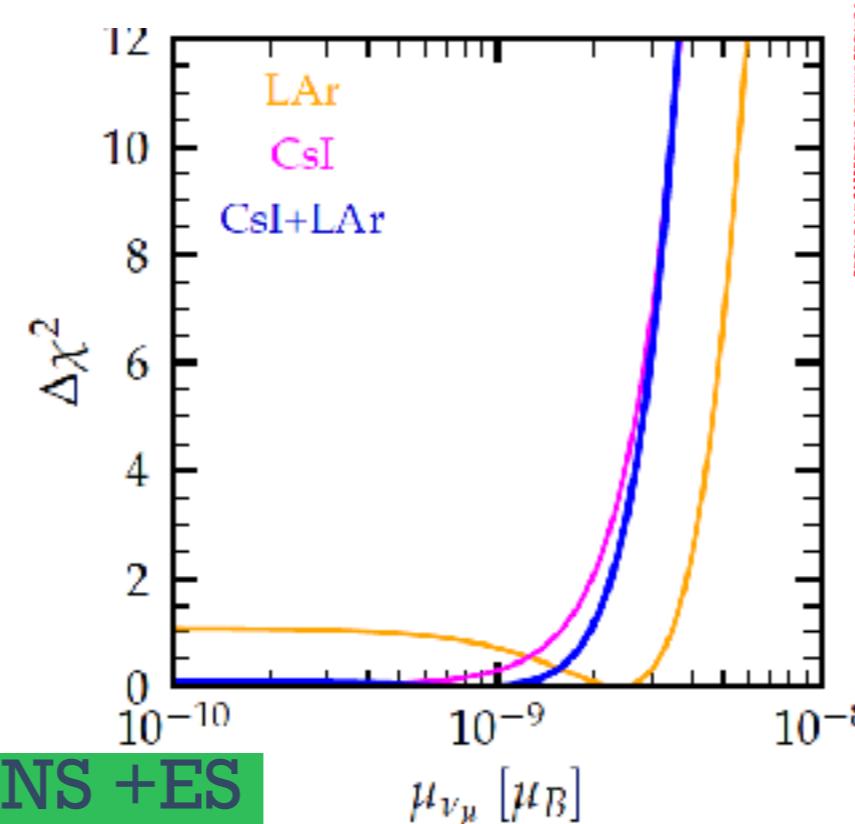
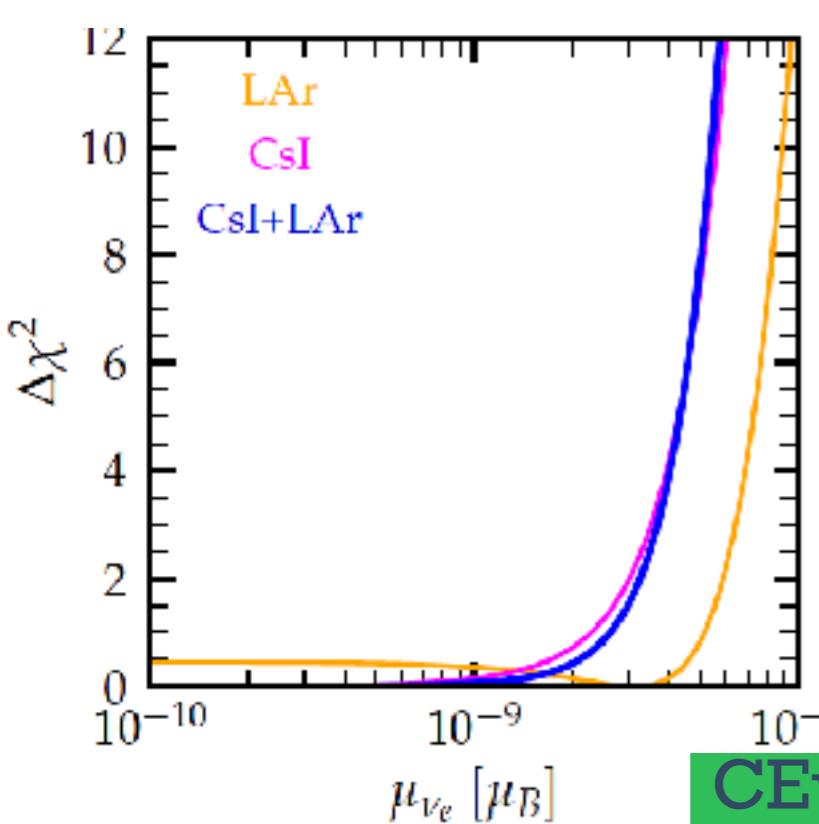
$$\frac{d\sigma_{\nu_e N}}{dE_{\text{er}}} \Big|_{\text{ES}}^{\text{MM}} = \frac{\pi \alpha_{\text{EM}}^2}{m_e^2} \left(\frac{1}{E_{\text{er}}} - \frac{1}{E_\nu} \right) Z_{\text{eff}}^A(E_{\text{er}})$$

$$\left| \frac{\mu_{\nu_e}}{\mu_B} \right|^2$$



Effective MM are process-dependent quantities:

$$\mu_{\nu_\ell}^{\text{eff}} = \sum_k \left| \sum_j U_{\ell k}^* \lambda_{jk} \right|^2$$



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

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

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

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

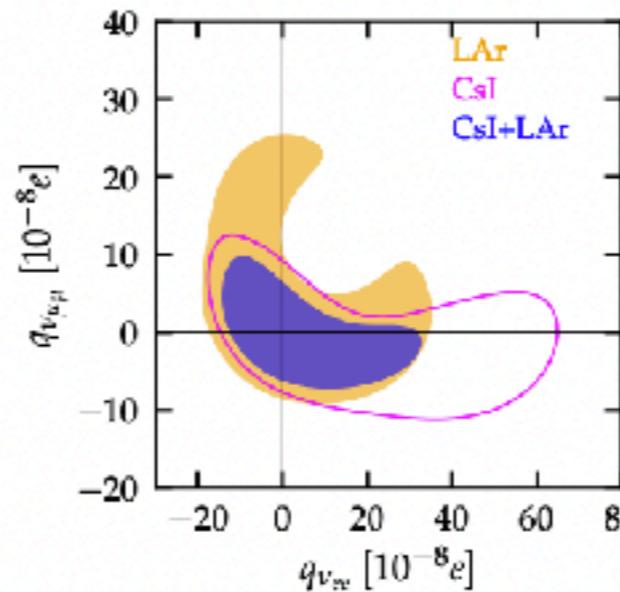
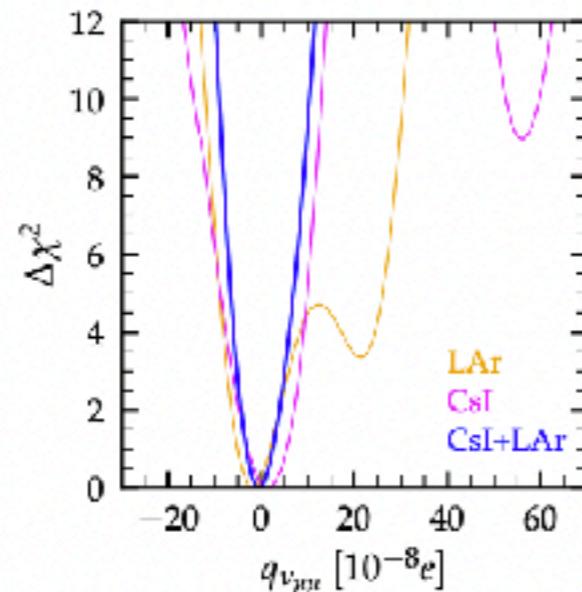
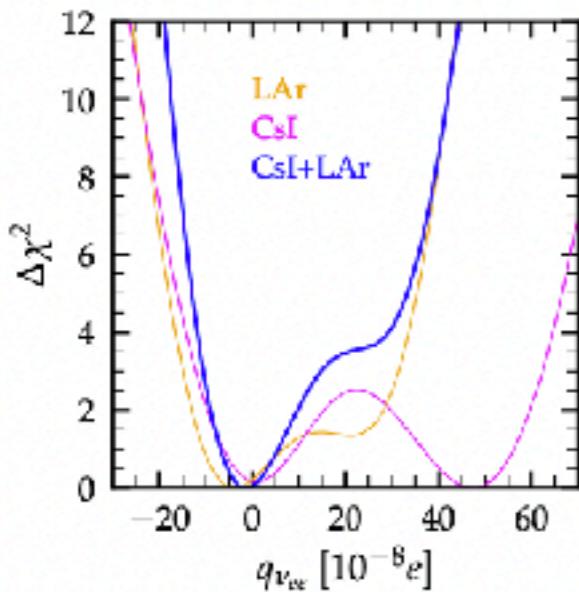
Neutrino electric (milli) charge

- ◆ 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

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

neutrino
 millicharge

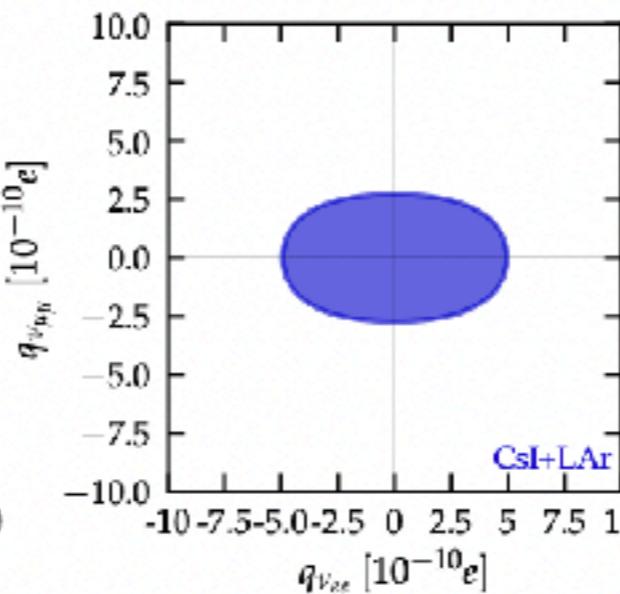
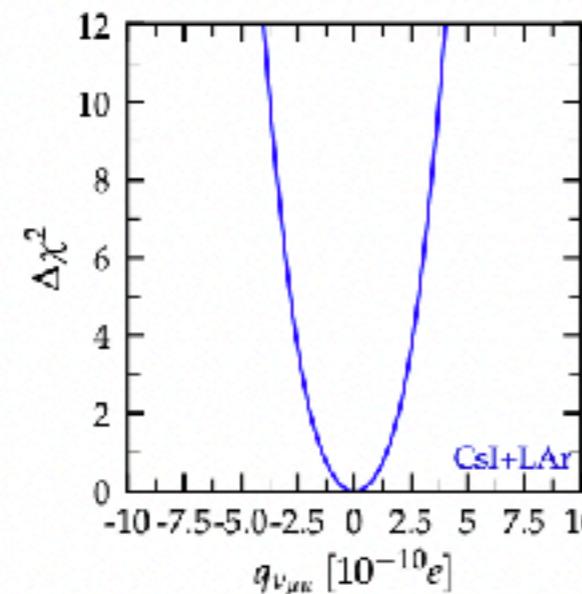
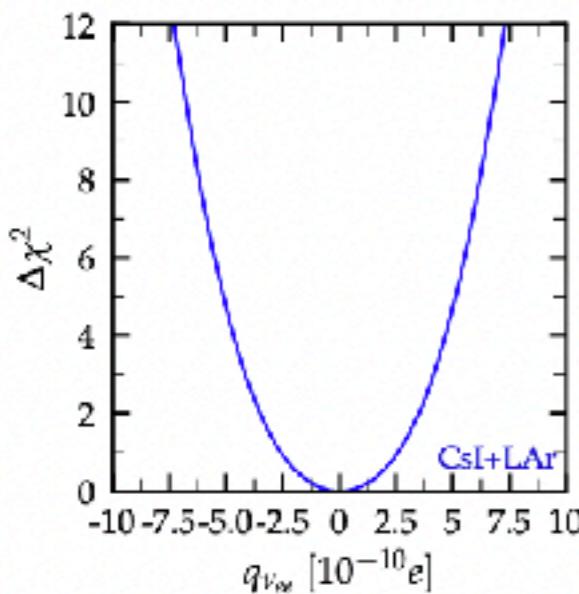
momentum transferred



CEvNS only (1σ)

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

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



CEvNS + ES (1σ)

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

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

Neutrino charge radius

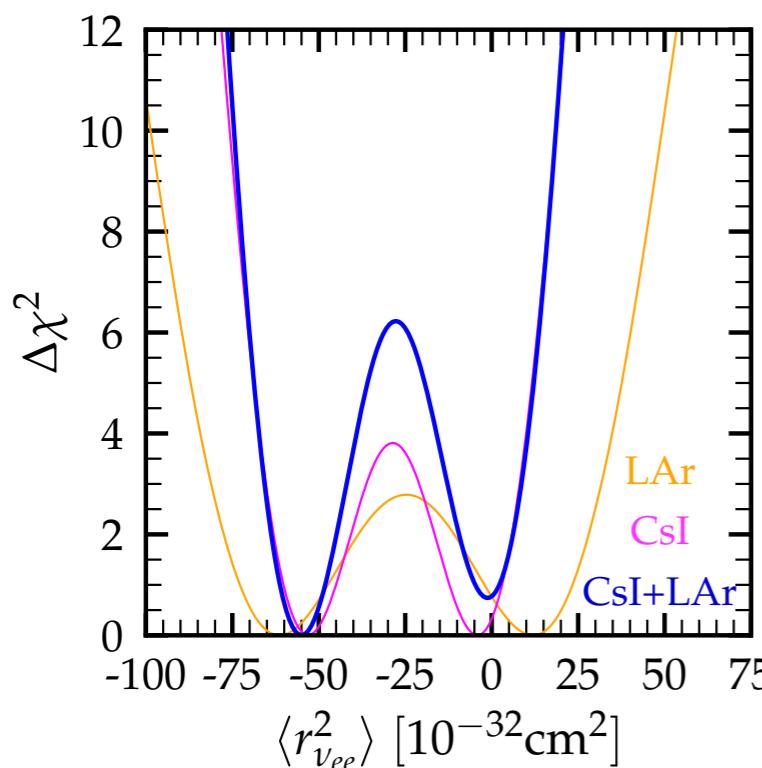
- ♦ It is the only EM neutrino parameter that is different from zero in the SM:

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

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

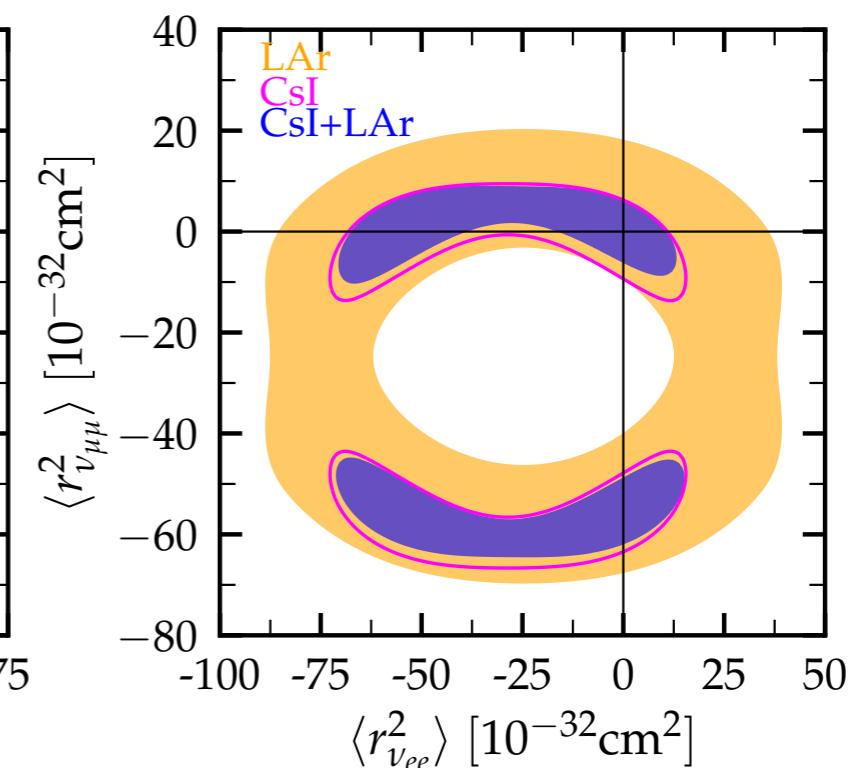
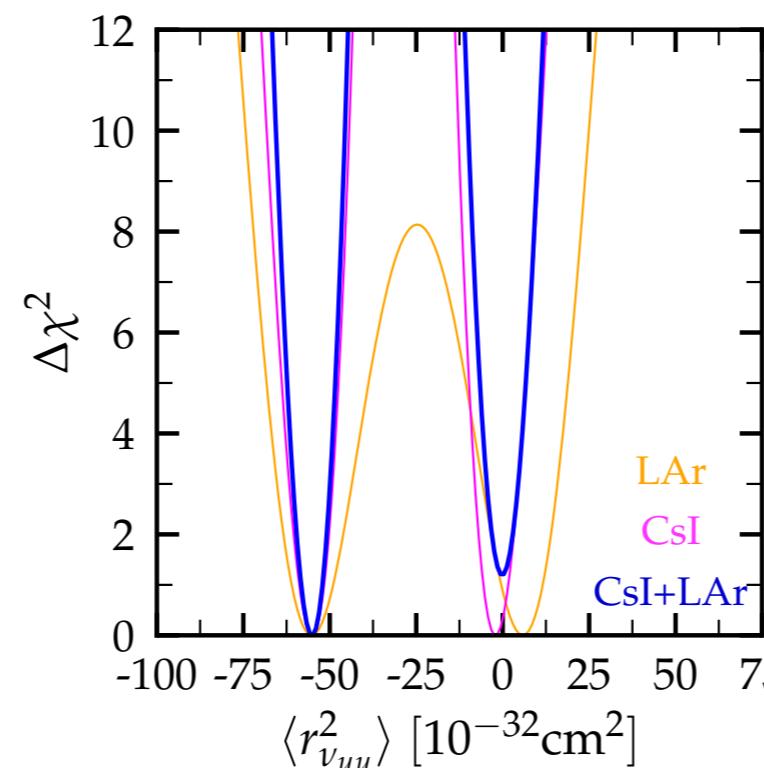
$$Q_{\ell\ell}^{\text{CR}} = \frac{\sqrt{2}\pi\alpha_{\text{EM}}}{3G_F} \langle r_{\nu_{\ell\ell}}^2 \rangle$$

Here: only **diagonal CR**, but transition CR ($\ell \neq \ell'$) can be generated via mixing and/or physics BSM



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

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



CEvNS only

ES contribution negligible

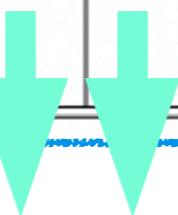
Comparison with previous results

D. Papoulias, Magnificent CEvNS workshop 2023

Flavor	$ \mu_\nu [10^{-11} \mu_B]$	$q_\nu [10^{-12} e]$	$\langle r_\nu^2 \rangle [10^{-32} \text{cm}^2]$
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)
	≤ 360 (COHERENT)	[-260, 260] (COHERENT)	$[-61.2, -48.2] \cup [-4.7, 2.2]$ (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)
	≤ 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

Summary

- ◆ CEvNS provide a powerful tool to search for new physics BSM.
- ◆ From the global analysis of COHERENT data we have derived constraints on neutrino electromagnetic properties:
 - ✓ Neutrino magnetic moment
 - ✓ Neutrino charge radius
 - ✓ Neutrino millicharge
- The last CsI data (2021) dominate the sensitivity of the combined CsI + LAr analysis.
- Analysis with ES events improves the constraints obtained for neutrino magnetic moment and neutrino millicharge.
- Although some of the limits derived are not competitive with existing searches, they provide complementary and relevant information.