

Probing electroweak physics with COHERENT data

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Research & Innovation

Outline

Electroweak physics

- Nuclear physics
- Weak mixing angle

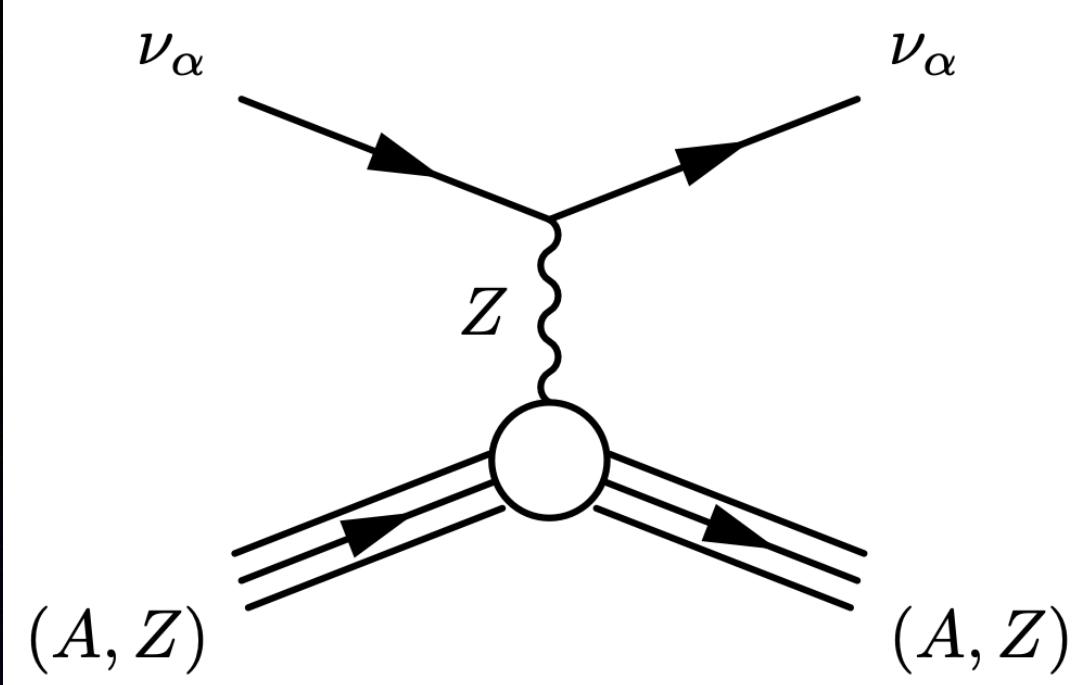
Electromagnetic neutrino properties

- Neutrino magnetic moment
- Neutrino millicharge
- Neutrino charge radius

SM CEvNS cross section

Nuclear physics

Particle physics



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

Red arrows point from the terms $(Q_V^{\text{SM}})^2$ and $m_N E_{\text{nr}} / 2 E_\nu^2$ in the equation above to the equations below.

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

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

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

- Observable: nuclear rms radius
- Largest theoretical uncertainty
- Affects the shape of CEvNS spectra

- Observable: $\sin^2 \theta_W$
- poorly measured at low energies
- Affects the normalization of CEvNS spectra

Probing the nuclear rms radius

Klein-Nystrand form factor

$$F_W(|\vec{q}|^2) = 3 \frac{j_1(|\vec{q}|R_A)}{|\vec{q}|R_A} \left(\frac{1}{1 + |\vec{q}|^2 a_k^2} \right)$$

Proton rms radii are fixed

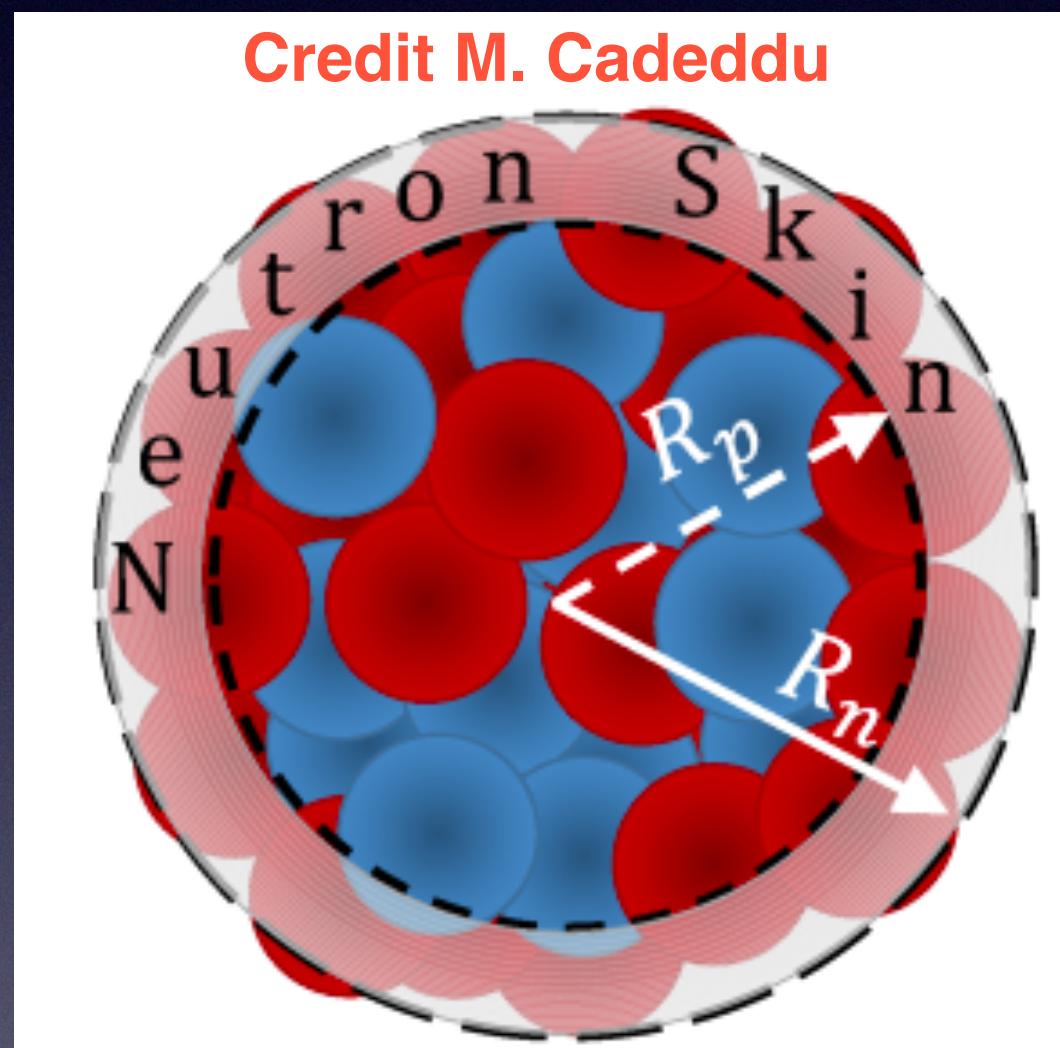
$$R_p(\text{l}) = 4.766 \text{ fm}$$

$$R_p(\text{Cs}) = 4.824 \text{ fm}$$

$$R_p(\text{Ar}) = 3.448 \text{ fm}$$

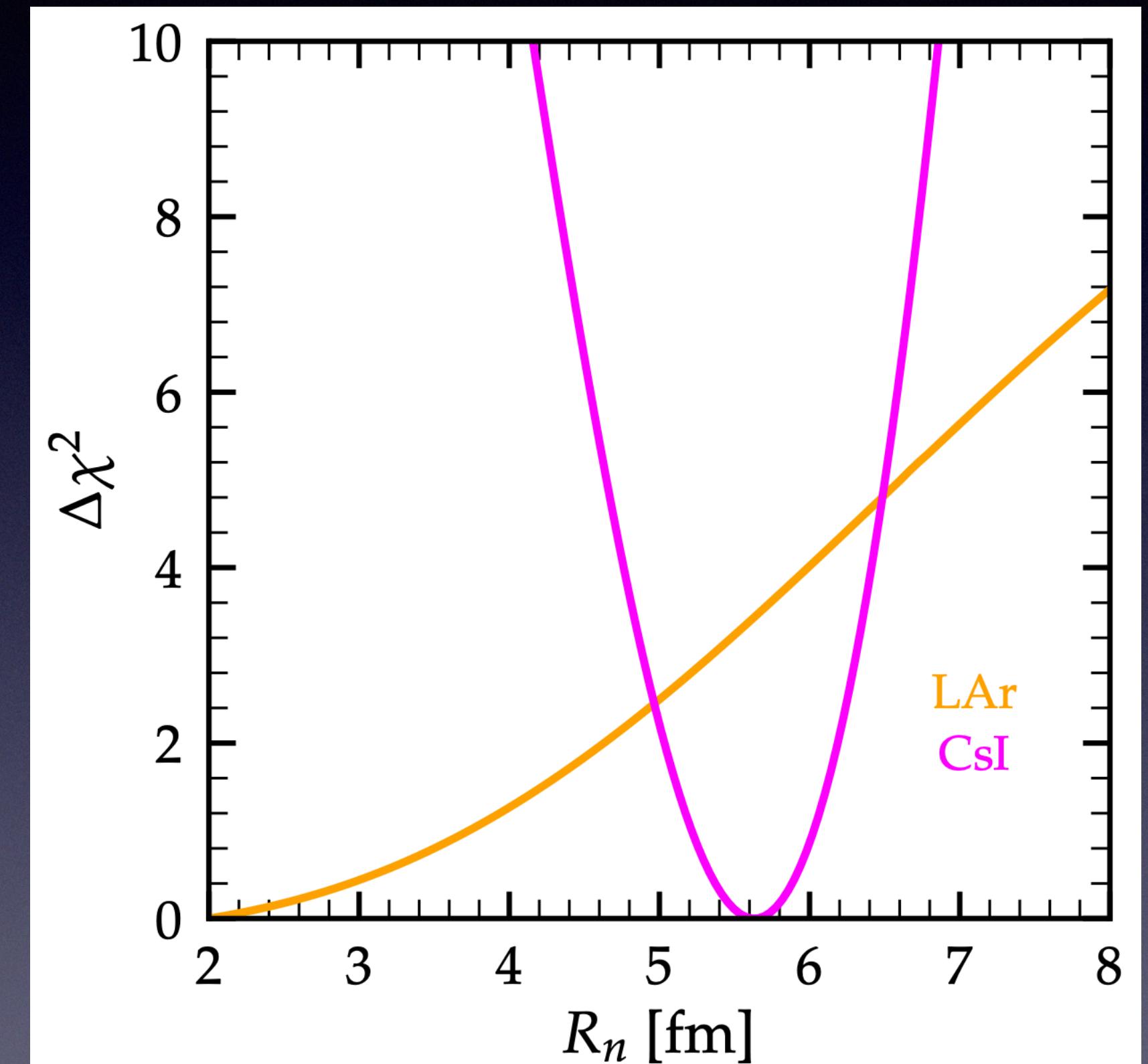
Neutron rms radii float freely

$$R_n = 1.23 A^{1/3} (1 + a_4)$$



$$R_n(\text{Ar}) \in [0.00, 3.72] \text{ fm},$$

$$R_n(\text{CsI}) \in [5.22, 6.03] \text{ fm}.$$



Probing the nuclear rms radius

CsI (2021) analysis

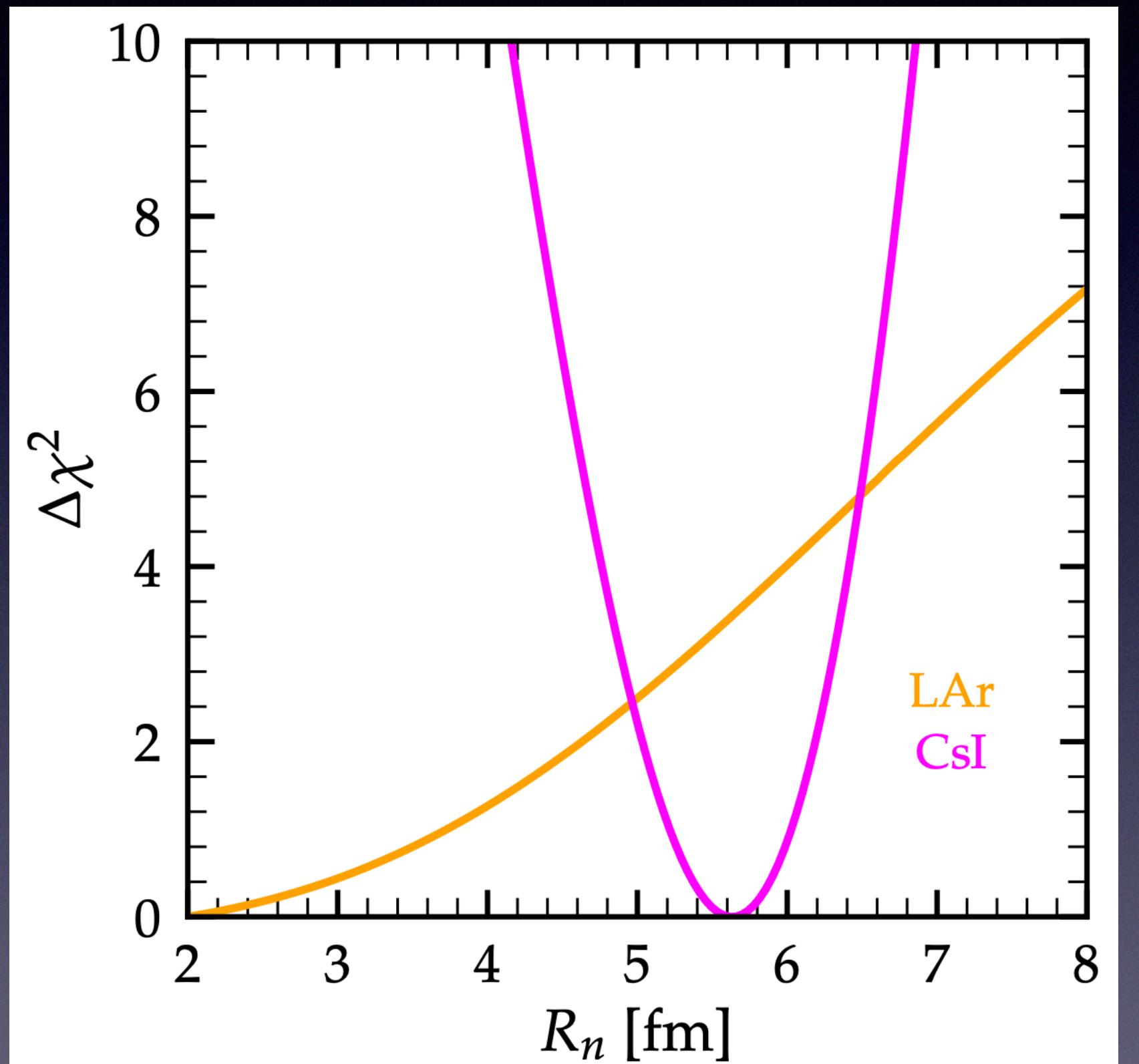
$$R_n(\text{CsI}) = 5.62^{+0.41}_{-0.40} \text{ fm}$$

De Romeri, Miranda, DKP, Sanchez, Tortola, Valle: arXiv: 2211.11905

CsI (2017) analysis

$$R_n(\text{CsI}) = 5.80^{+0.89}_{-0.93} \text{ fm}$$

P. Coloma, I. Esteban, M. C. Gonzalez-Garcia, and J. Menendez, JHEP 08, (2020) 030

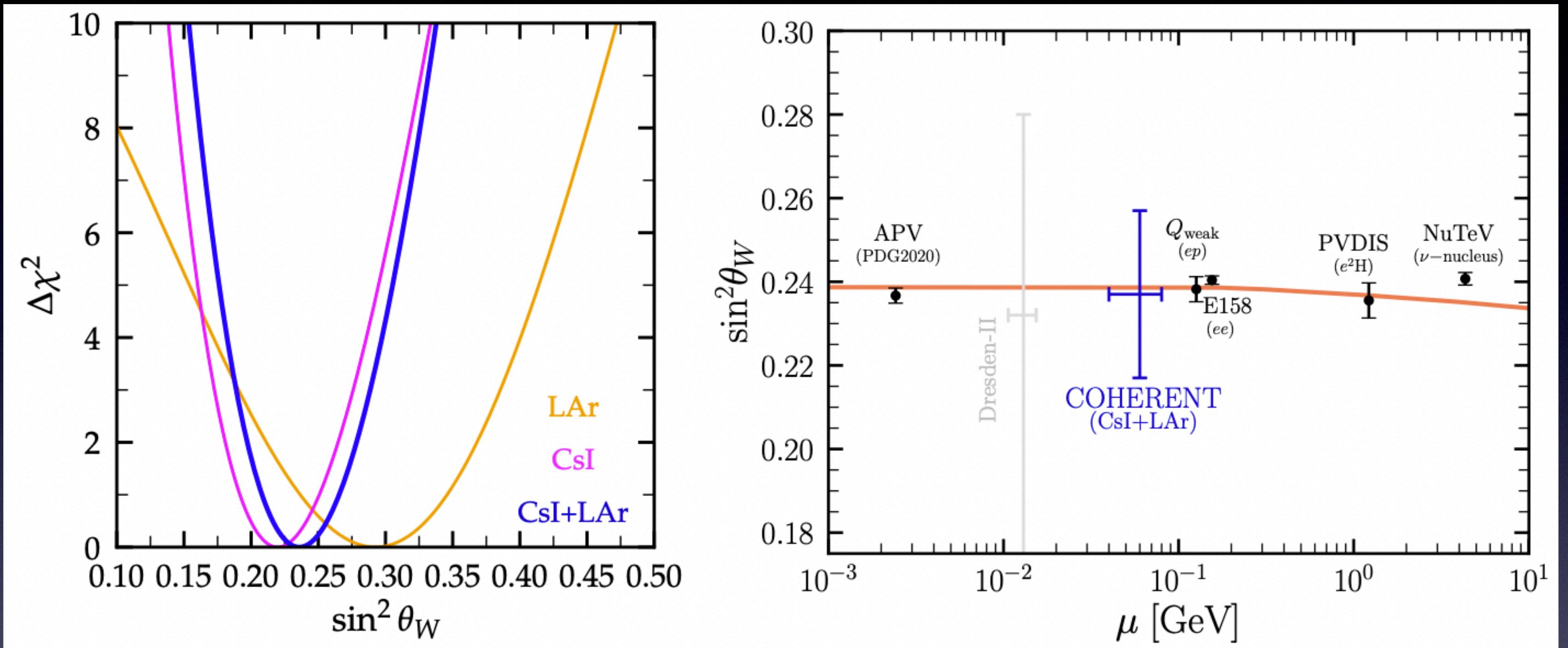


The full-CsI data with $2 \times$ statistics
and an improved understanding of the error budget
lead to a by factor 2 reduction of R_n uncertainty

Tomorrow's talk by
M. Cadeddu

Probing the weak mixing angle

$$Q_V^{\text{SM}} = \frac{1}{2} (1 - 4 \sin^2 \theta_W) Z - \frac{1}{2} N$$



The combined fit yields:

CsI (2021) + LAr (2020) $\sin^2 \theta_W = 0.237^{+0.029}_{-0.029} (1\sigma)$

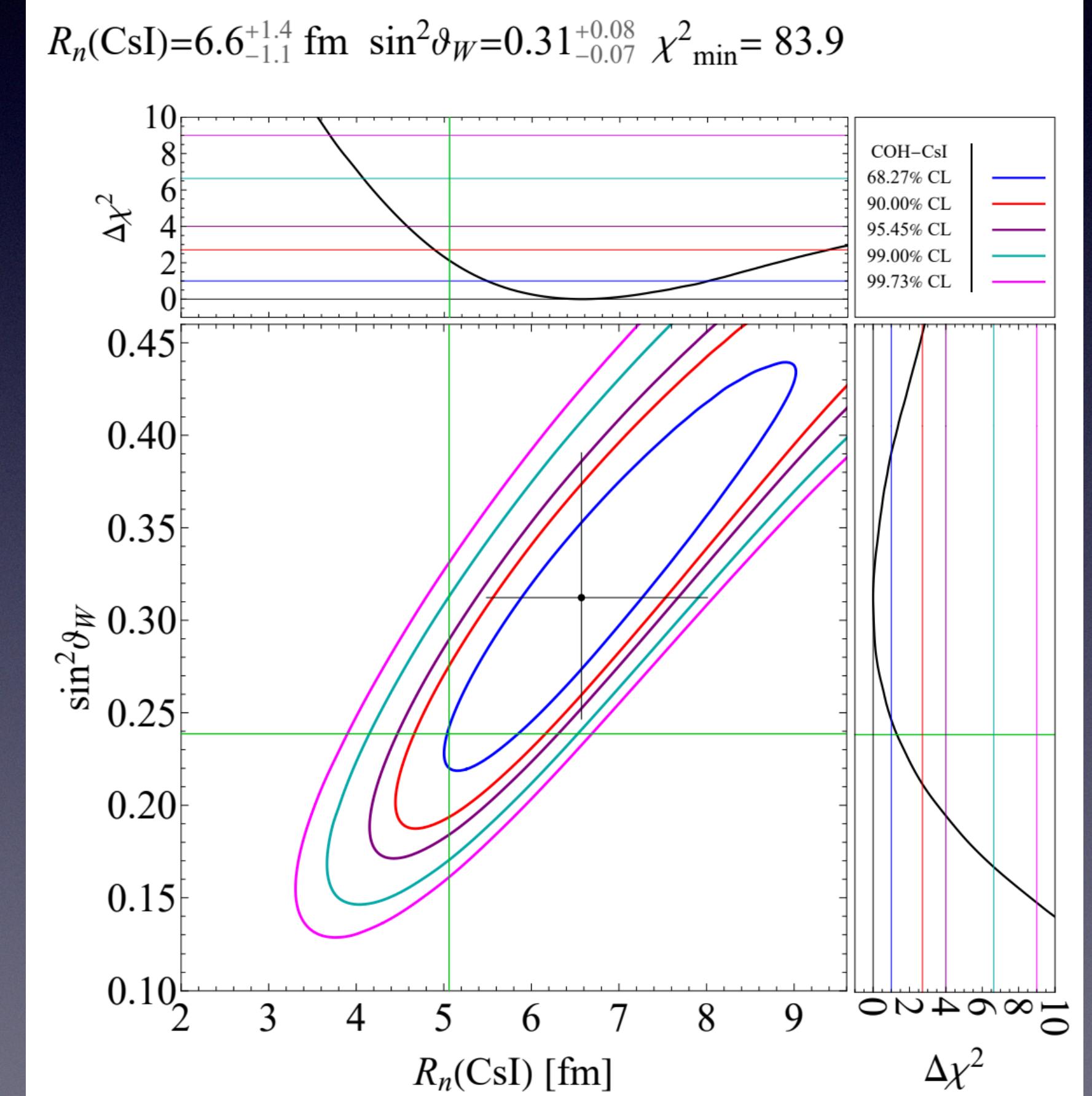
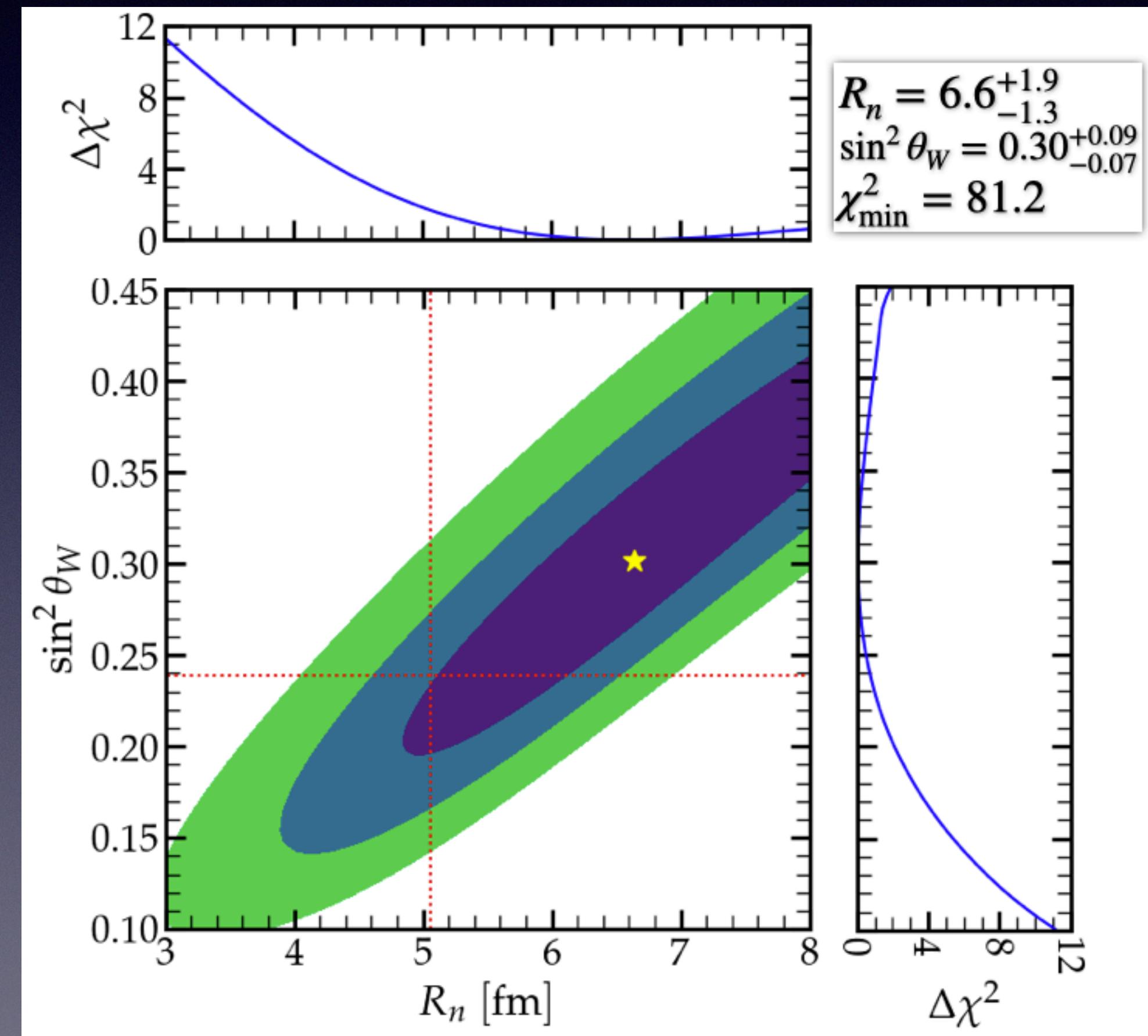
De Romeri, Miranda, DKP, Sanchez, Tortola, Valle: arXiv: 2211.11905

CsI (2017) + LAr (2020) $\sin^2 \theta_W = 0.26^{+0.04}_{-0.03} (1\sigma)$

M. Cadeddu, Dordei, Giunti, Li, Picciano, Zhang: PRD 102, 015030 (2020)

Tomorrow's talk by
A. Majumdar for the
Dresden-II analysis

Combining $\sin^2 \theta_W$ and R_n



Electromagnetic neutrino properties

For neutrinos the electric charge is zero and there are **no electromagnetic interactions at tree level**. However, such interactions can arise at the quantum level from loop diagrams at higher order of the perturbative expansion of the interaction.

➤ **Effective Hamiltonian** $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_\mu^{(\nu)}(x) A^\mu(x) = \sum_{k,j=1} \bar{\nu}_k(x) \Lambda_\mu^{kj} \nu_j(x) A^\mu(x)$

➤ We are interested in the neutrino part of the amplitude which is given by the following matrix element $\langle \nu_f(p_f) | j_\mu^{(\nu)}(0) | \nu_i(p_i) \rangle = \bar{u}_f(p_f) \Lambda_\mu^{fi}(q) u_i(p_i)$

➤ The electromagnetic properties of neutrinos are embedded by the **vertex function**

$$\Lambda_\mu(q) = (\gamma_\mu - q_\mu \not{q}/q^2) [F_Q(q^2) + F_A(q^2)q^2\gamma_5] - i\sigma_{\mu\nu}q^\nu [F_M(q^2) + iF_E(q^2)\gamma_5]$$

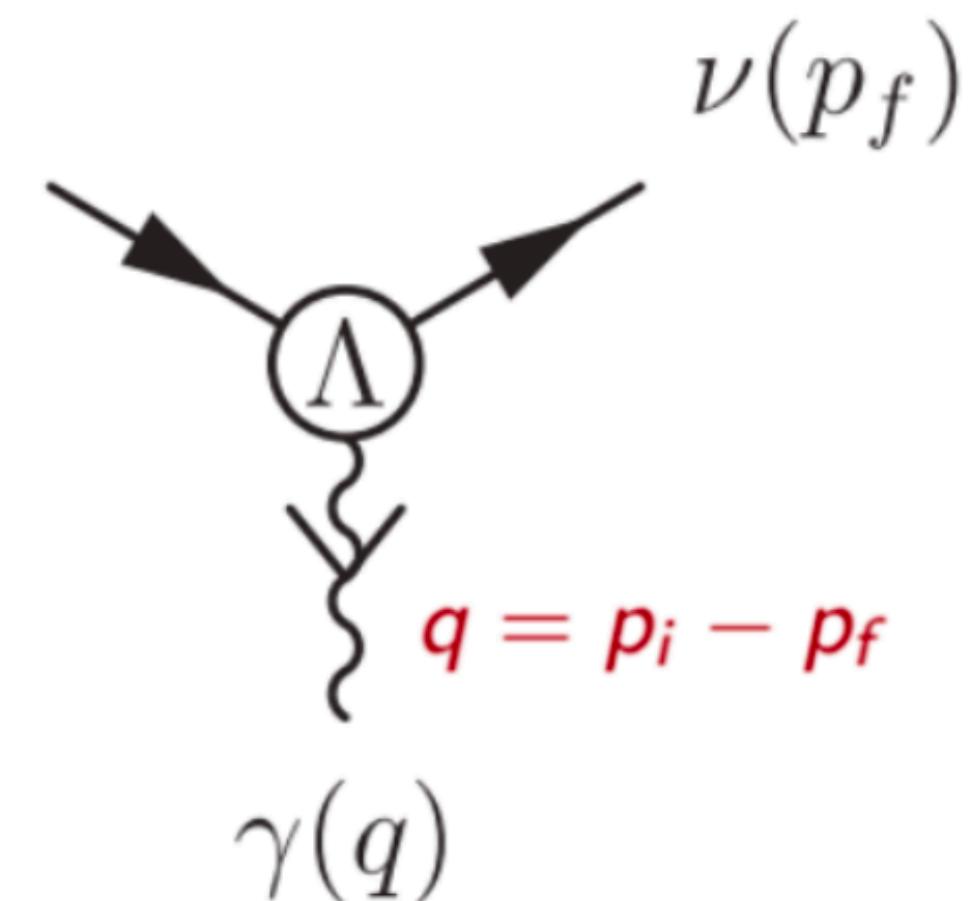
Lorentz-invariant
form factors:

$$q^2 = 0 \implies \begin{array}{cc} \text{charge} & \text{anapole} \\ \downarrow & \downarrow \\ Q & a \end{array}$$

Charge and anapole moment

$$\begin{array}{cc} \text{magnetic} & \text{electric} \\ \downarrow & \downarrow \\ \mu & \varepsilon \end{array}$$

Magnetic and electric dipole moments



[C. Giunti, A. Studenikin, Neutrino electromagnetic interactions: A window to new physics, Rev Mod Phys, 87, 531 (2015), Arxiv:1403.6344]

Neutrino (effective) magnetic moment

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

$$\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\text{er}}} \Big|_{\text{ES}}^{\text{MM}} = \frac{\pi\alpha_{\text{EM}}^2}{m_e^2} \left(\frac{1}{E_{\text{er}}} - \frac{1}{E_\nu} \right) Z_{\text{eff}}^{\mathcal{A}}(E_{\text{er}}) \left| \frac{\mu_{\nu_\ell}}{\mu_B} \right|^2 \quad \text{EvES} \\ \text{(for CsI only)}$$

Neutrino (effective) magnetic moment



The effective neutrino magnetic moment is a process-dependent quantity which is expressed in terms of the fundamental transition magnetic moments

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

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

CEvNS

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

EvES
(for CsI only)

Dirac neutrinos: $H_{\text{EM}}^D = \frac{1}{2} \bar{\nu}_R \lambda \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} + \text{h.c.}$

- $\lambda = \mu - i\epsilon$ is an arbitrary complex matrix
- $\mu = \mu^\dagger$ and $\epsilon = \epsilon^\dagger$.

Majorana neutrinos: $H_{\text{EM}}^M = -\frac{1}{4} \nu_L^T C^{-1} \lambda \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} + \text{h.c.}$

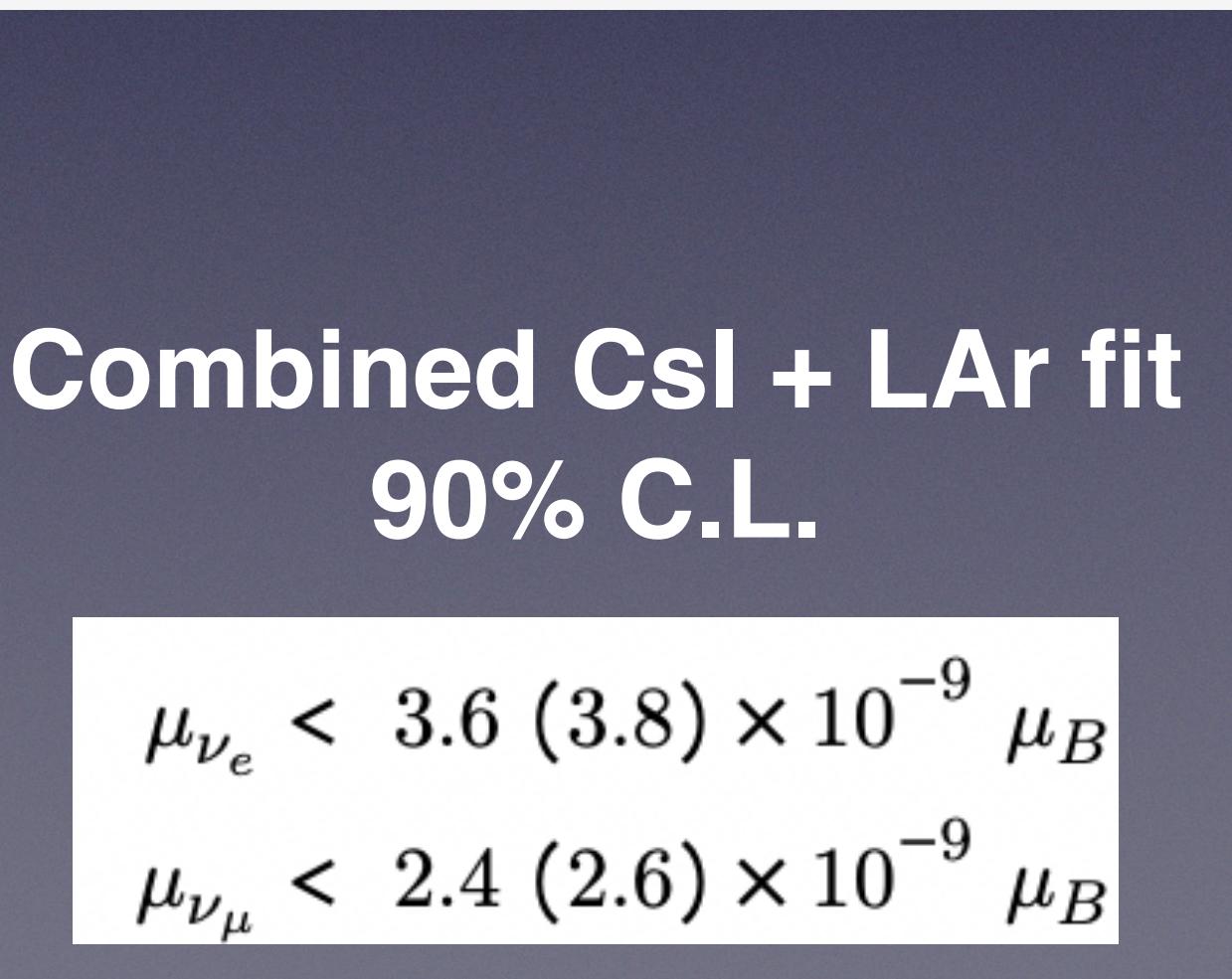
- $\lambda = \mu - i\epsilon$: antisymmetric complex matrix ($\lambda_{\alpha\beta} = -\lambda_{\beta\alpha}$)
- $\mu^T = -\mu$ and $\epsilon^T = -\epsilon$ are two imaginary matrices.
- three complex or six real parameters are required

Neutrino (effective) magnetic moment



The effective neutrino magnetic moment is a process-dependent quantity which is expressed in terms of the fundamental transition magnetic moments

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



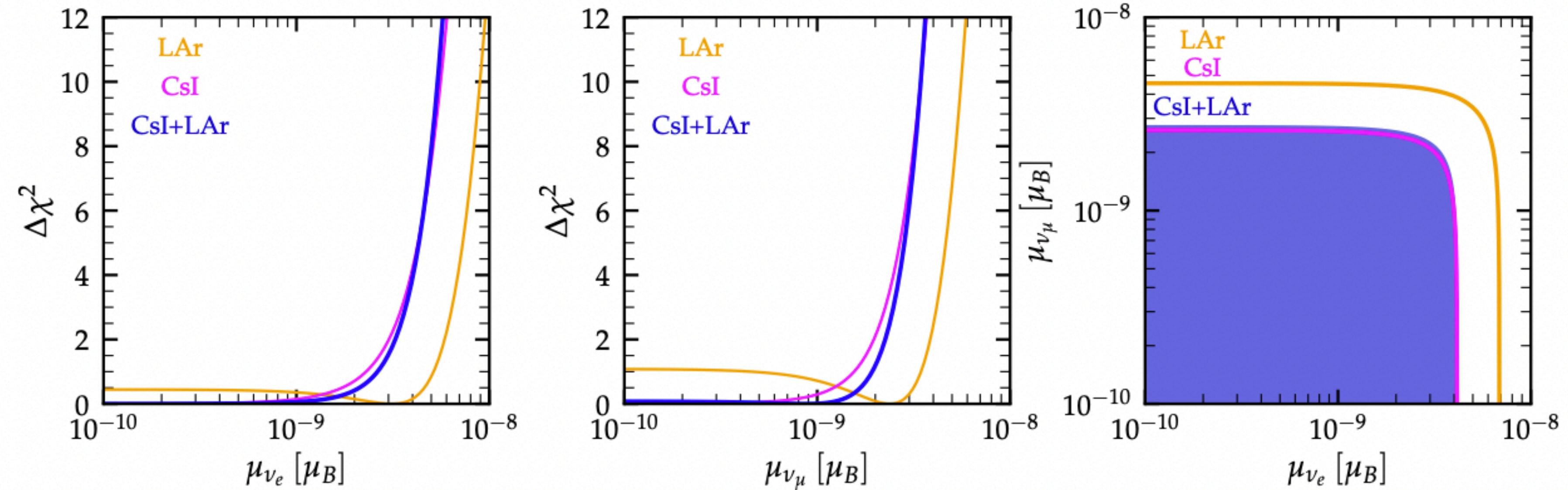
$$\frac{d\sigma_{\nu_\ell N}}{dE_{\text{nr}}} \Big|_{\text{CE}\nu\text{NS}}^{\text{MM}} = \frac{\pi\alpha_{\text{EM}}^2}{m_e^2} \left(\frac{1}{E_{\text{nr}}} - \frac{1}{E_\nu} \right) Z^2 F_W^2(|\vec{q}|^2) \left| \frac{\mu_{\nu_\ell}}{\mu_B} \right|^2$$

CEvNS

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

**EvES
(for CsI only)**

De Romeri, Miranda, DKP, Sanchez, Tortola, Valle: arXiv: 2211.11905



Neutrino (milli)charge

New contribution to SM cross section

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

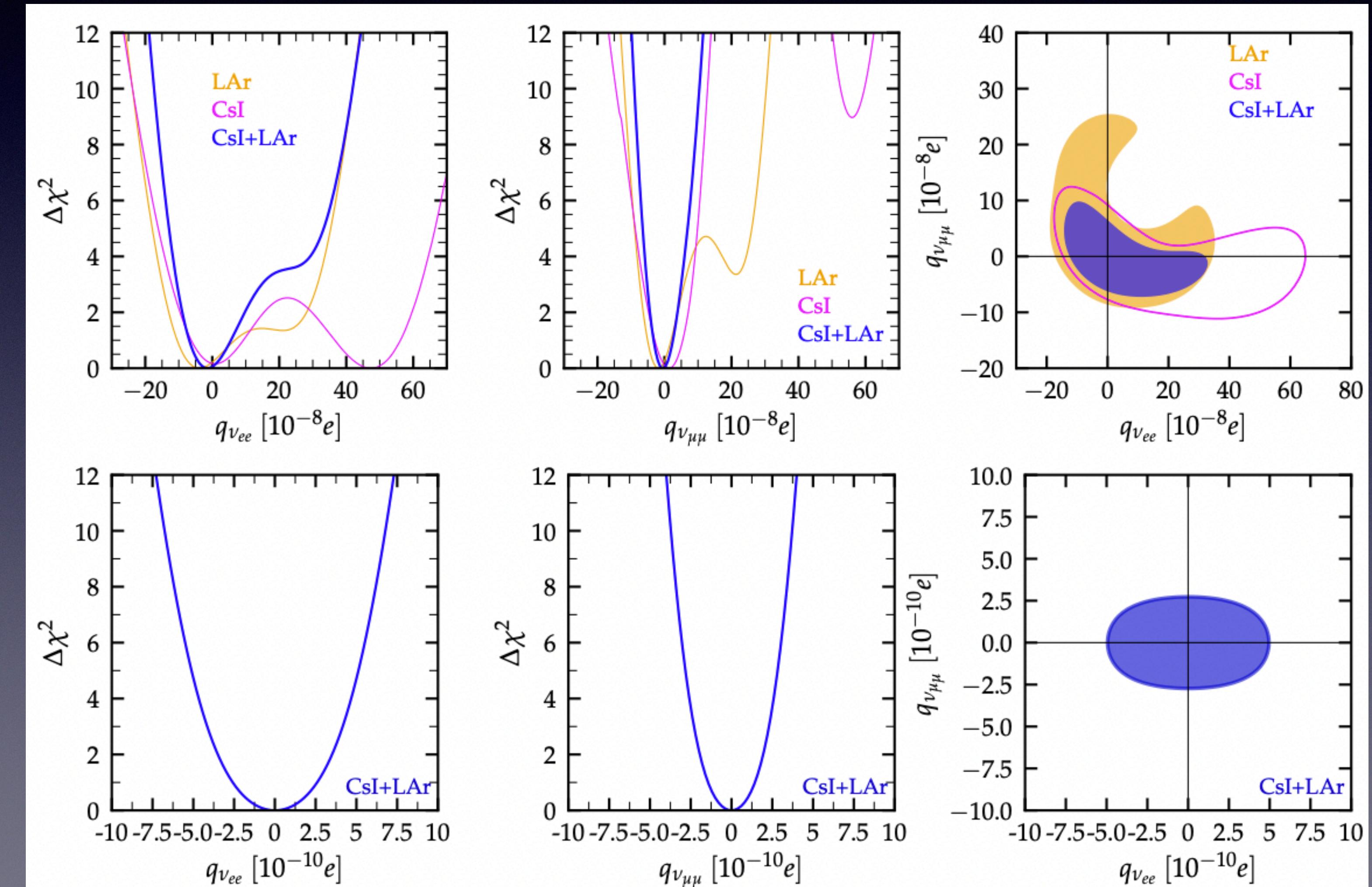
CEvNS

$$g_V^p \rightarrow g_V^p - Q_{\ell\ell}^{\text{EC}}$$

ES
(for CsI only)

$$g_V^{\nu_\ell} \rightarrow g_V^{\nu_\ell} + Q_{\ell\ell}^{\text{EC}}$$

De Romeri, Miranda, DKP, Sanchez, Tortola, Valle: arXiv: 2211.11905



Neutrino (milli)charge

De Romeri, Miranda, DKP, Sanchez, Tortola, Valle: arXiv: 2211.11905

Combined CsI + LAr fit (1σ)

CEvNS only

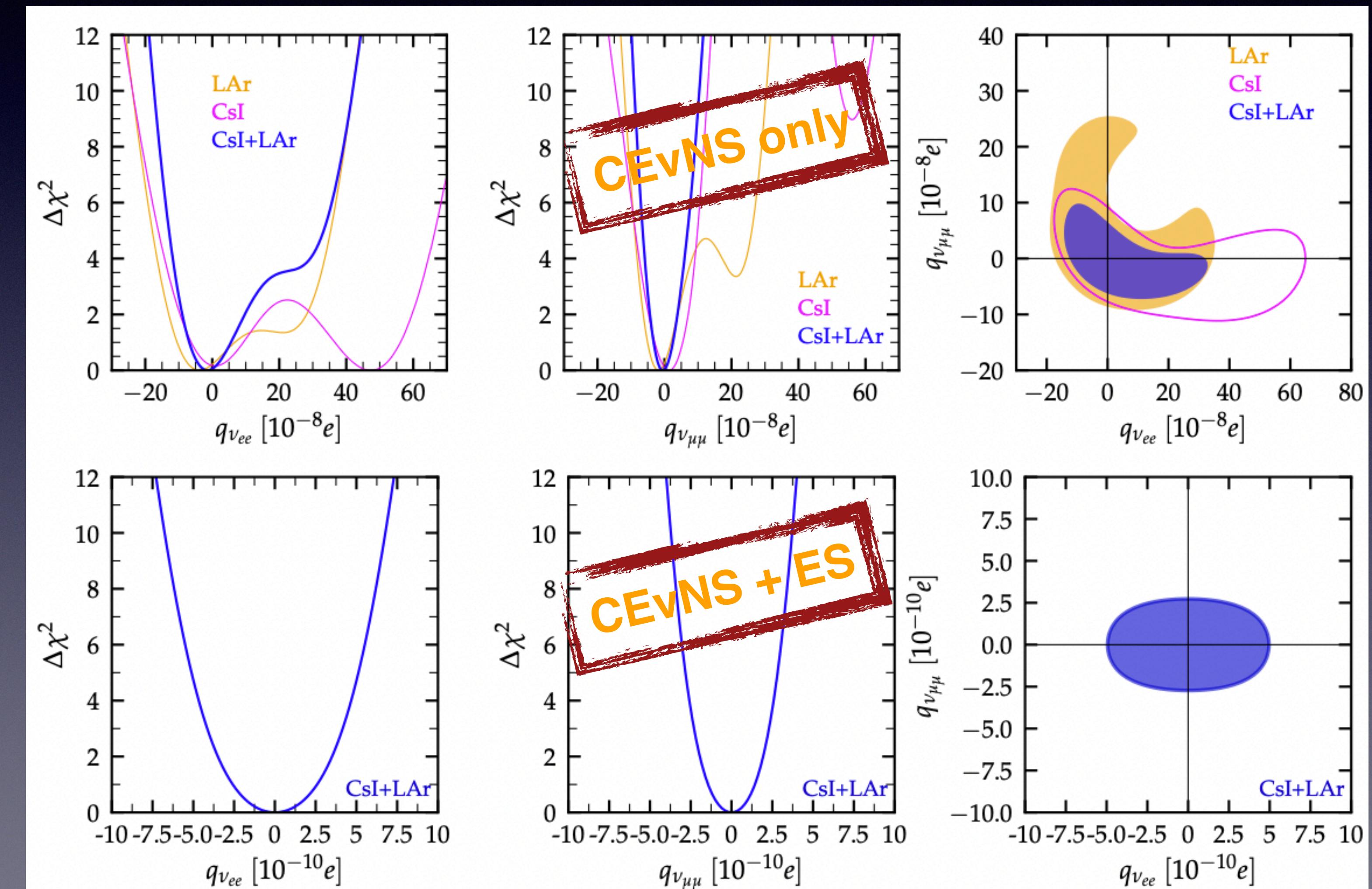
$$q_{\nu_{ee}} \in [-6.9, 5.6] \times 10^{-8} e,$$

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

CEvNS + ES

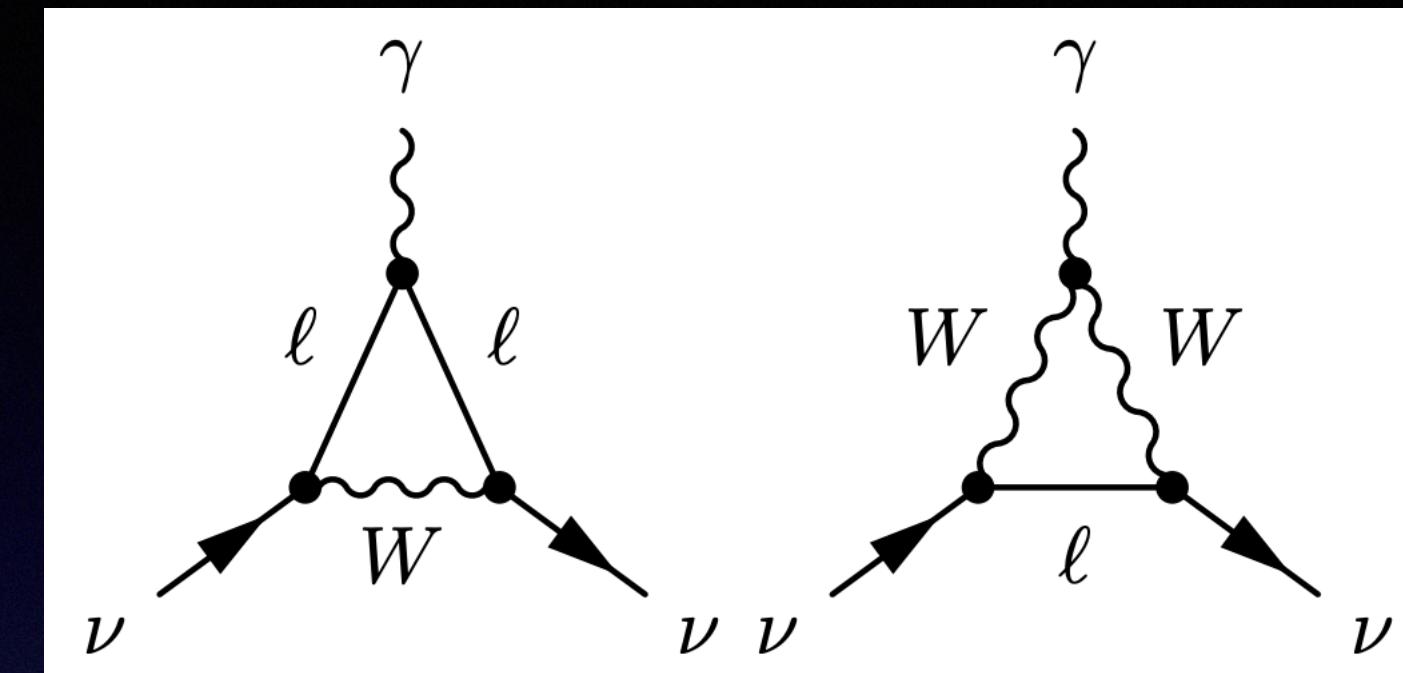
$$q_{\nu_{ee}} \in [-2.6, 2.6] \times 10^{-10} e,$$

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



Neutrino charge radius

- Neutrino charge radius (CR) is the only EM neutrino parameter that is different from zero within the SM framework
- Radiative corrections generate an effective electromagnetic interaction vertex



$$\mathbb{f}_Q(q^2) = \mathbb{f}_Q(0) + q^2 \left. \frac{d\mathbb{f}_Q(q^2)}{dq^2} \right|_{q^2=0} + \dots \Rightarrow \text{Charge radius}$$

$$\langle r^2 \rangle = 6 \left. \frac{d\mathbb{f}_Q(q^2)}{dq^2} \right|_{q^2=0}$$

SM: only flavor diagonal CR are possible due to lepton number conservation

$$\langle r_{\nu_{\ell\ell}}^2 \rangle_{\text{SM}} = -\frac{G_F}{2\sqrt{2}\pi^2} \left[3 - 2 \ln \frac{m_\ell^2}{M_W^2} \right]$$

The SM values are

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

Bernabeu, Papavassiliou, Vidal, Nucl. Phys. B 680 (2004) 450–478

Neutrino charge radius

New contribution to SM cross section

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

CEvNS

$$g_V^p \rightarrow g_V^p - Q_{\ell\ell}^{\text{CR}}$$

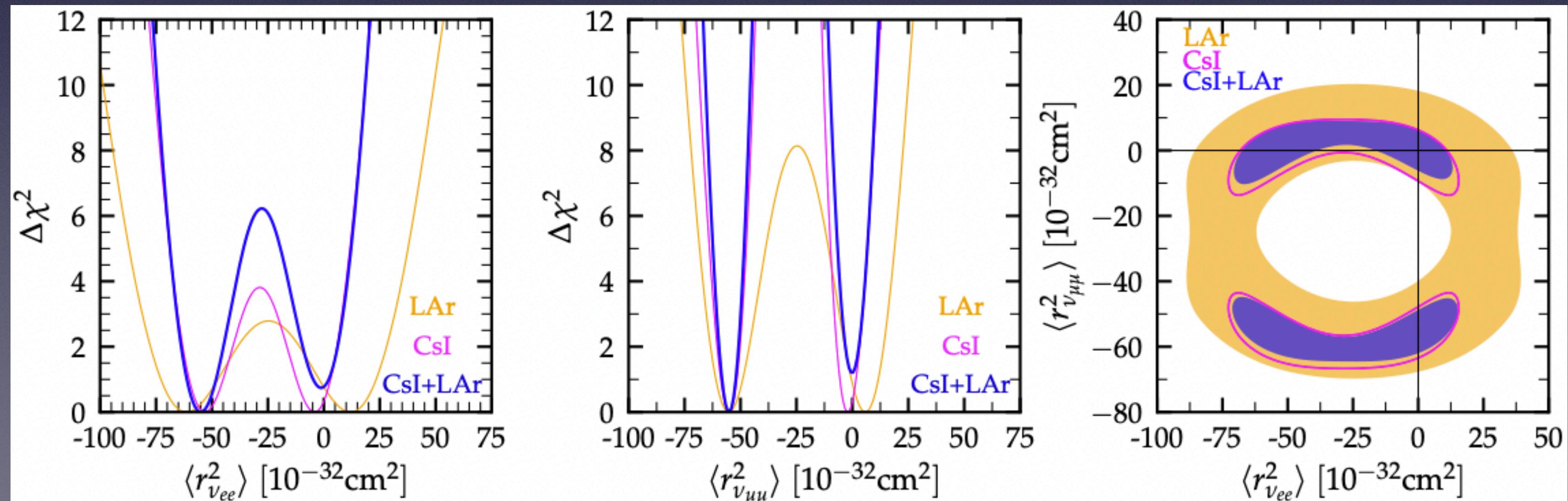
ES

$$g_V^{\nu_\ell} \rightarrow g_V^{\nu_\ell} + Q_{\ell\ell}^{\text{CR}}$$

Combined CsI + LAr fit (1σ)

$$\begin{aligned} \langle r_{\nu_{ee}}^2 \rangle &\in [-61.2, -48.2] \cup [-4.7, 2.2] \times 10^{-32} \text{ cm}^2, \\ \langle r_{\nu_{\mu\mu}}^2 \rangle &\in [-58.2, -52.1] \times 10^{-32} \text{ cm}^2. \end{aligned}$$

De Romeri, Miranda, DKP, Sanchez, Tortola, Valle: arXiv: 2211.11905



Neutrino charge radius

New contribution to SM cross section

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

CEvNS

$$g_V^p \rightarrow g_V^p - Q_{\ell\ell}^{\text{CR}}$$

ES

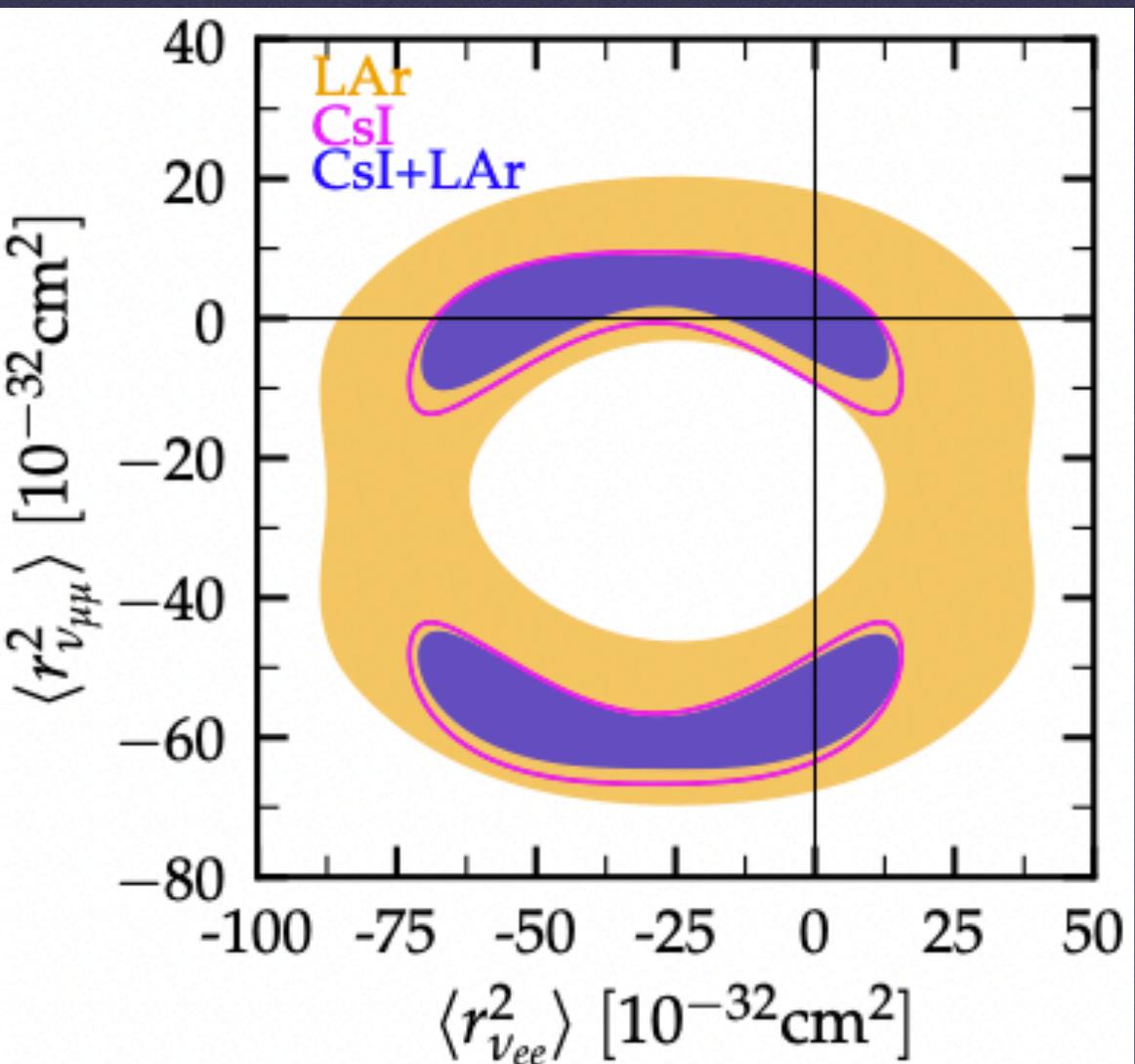
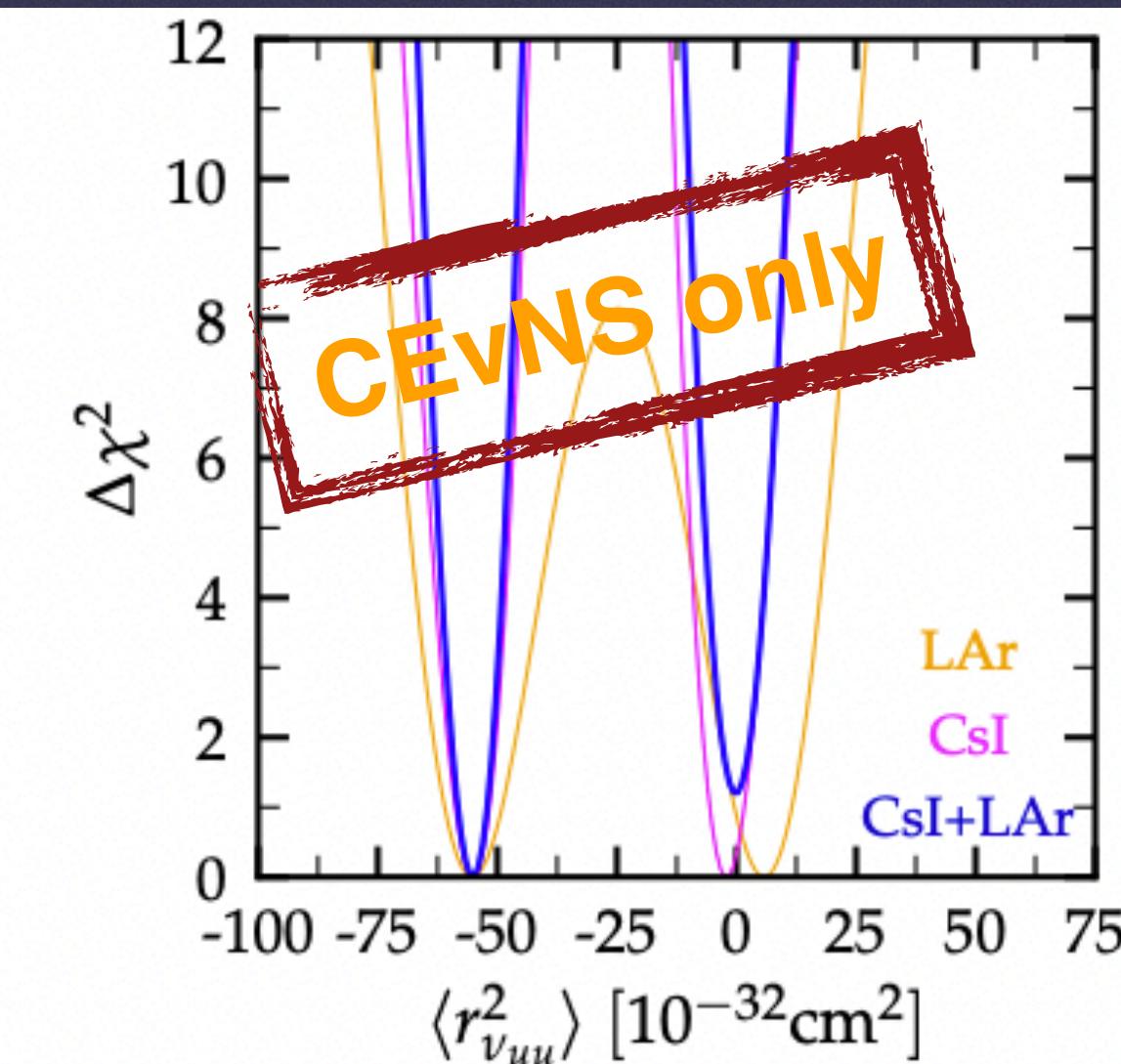
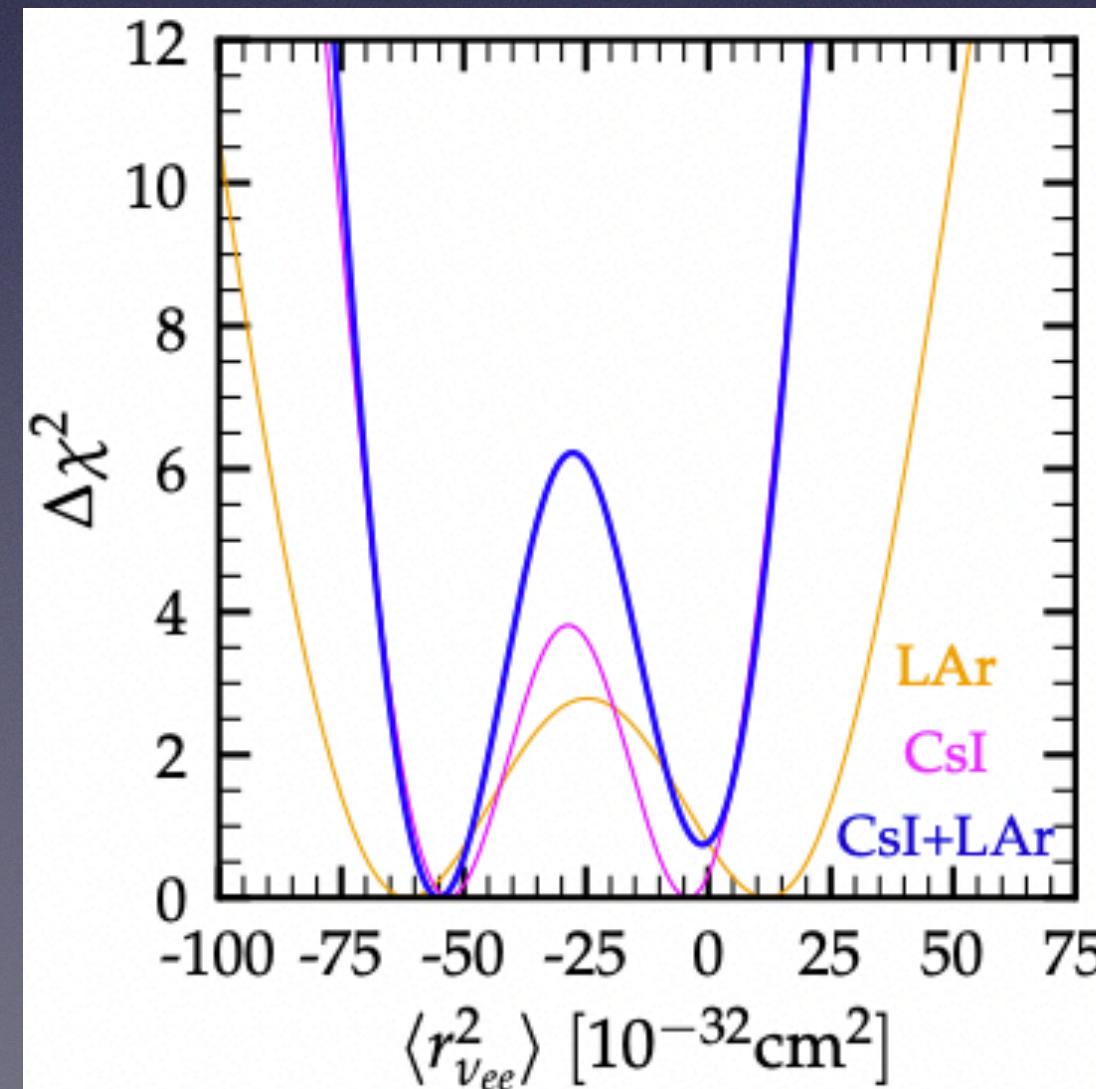
$$g_V^{\nu_\ell} \rightarrow g_V^{\nu_\ell} + Q_{\ell\ell}^{\text{CR}}$$

ES contribution is negligible

Combined CsI + LAr fit (1σ)

$$\begin{aligned} \langle r_{\nu_{ee}}^2 \rangle &\in [-61.2, -48.2] \cup [-4.7, 2.2] \times 10^{-32} \text{ cm}^2, \\ \langle r_{\nu_{\mu\mu}}^2 \rangle &\in [-58.2, -52.1] \times 10^{-32} \text{ cm}^2. \end{aligned}$$

De Romeri, Miranda, DKP, Sanchez, Tortola, Valle: arXiv: 2211.11905



Comparison with existing results

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)	

Summary

Electroweak physics

Scenario	SM	weak mixing angle ($\sin^2 \theta_W$)	nuclear neutron radius (R_n)
CsI	83.2 (0.849)	82.8 (0.854)	81.9 (0.845)
LAr	106.5 (0.887)	105.5 (0.887)	105.5 (0.887)
CsI+LAr	189.7 (0.870)	189.7 (0.874)	—

Electromagnetic Neutrino properties

Scenario	millicharge ($q_{\nu_{ee}}, q_{\nu_{\mu\mu}}$)	charge radius ($\langle r_{\nu_{ee}}^2 \rangle, \langle r_{\nu_{\mu\mu}}^2 \rangle$)	MM _{active} ($\mu_{\nu_e}, \mu_{\nu_\mu}$)
CsI	83.2 (0.867)	82.8 (0.863)	83.2 (0.867)
LAr	106.4 (0.902)	105.5 (0.894)	105.4 (0.893)
CsI+LAr	189.7 (0.878)	188.4 (0.872)	189.6 (0.877)

- Efficiency and timing uncertainty play key role in the analysis of CsI data
- CsI data dominate the combined CsI+LAr fit
- A factor 2 improvement is obtained regarding the uncertainty on R_n
- The new CsI data improve the agreement between the RGE extrapolation and extracted constraint on $\sin^2 \theta_W$
- ES events become relevant for the analysis of CsI, especially for the extraction of millicharge constraints

Thank you for your attention



Moritz Neuberger

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