Elucidating the Electromagnetic Properties of Neutrinos with CEνNS

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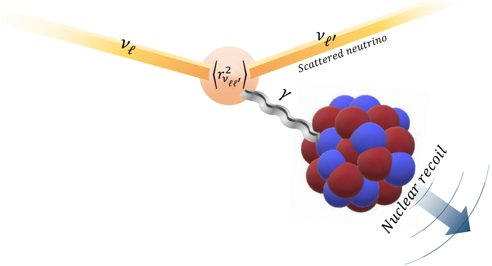
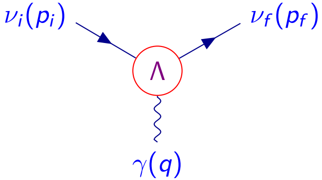


Neutrino Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_\mu^{(\nu)}(x) A^\mu(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda_\mu^{kj} \nu_j(x) A^\mu(x)$

- Effective electromagnetic vertex:



$$\langle \nu_f(p_f) | j_\mu^{(\nu)}(0) | \nu_i(p_i) \rangle = \overline{u_f}(p_f) \Lambda_\mu^{fi}(q) u_i(p_i)$$

$$q = p_i - p_f$$

- Vertex function:

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

Lorentz-invariant form factors: charge, anapole, magnetic, electric

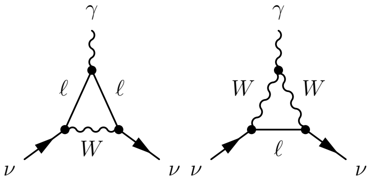
$q^2 = 0 \quad \Longrightarrow \quad$ q, a, μ, ε

helicity-conserving: q, a — helicity-flipping: μ, ε

Neutrino Charge Radius

- In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level.
- Radiative corrections generate an effective electromagnetic interaction vertex

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) F(q^2)$$



- $F(q^2) = \cancel{F(0)} + q^2 \left.\dfrac{dF(q^2)}{dq^2}\right|_{q^2=0} + \ldots = q^2 \dfrac{\langle r^2 \rangle}{6} + \ldots$
- In the Standard Model: [Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_\ell} \rangle_{\text{SM}} = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3 - 2\log\left(\frac{m_\ell^2}{m_W^2}\right)\right]$$

$$\langle r^2_{\nu_e} \rangle_{\text{SM}} = -8.2 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\mu} \rangle_{\text{SM}} = -4.8 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\tau} \rangle_{\text{SM}} = -3.0 \times 10^{-33}\,\text{cm}^2$$

Experimental Bounds

Method	Experiment	Limit [cm^2]	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3 \times 10^{-32}$	90%	1992
	TEXONO	$-4.2 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 6.6 \times 10^{-32}$	90%	2009
Accelerator $\nu_e\, e^-$	LAMPF	$-7.12 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 10.88 \times 10^{-32}$	90%	1992
	LSND	$-5.94 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 8.28 \times 10^{-32}$	90%	2001
Accelerator $\nu_\mu\, e^-$	BNL-E734	$-5.7 \times 10^{-32} < \langle r^2_{\nu_\mu}\rangle < 1.1 \times 10^{-32}$	90%	1990
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2 \times 10^{-32}$	90%	1994

[see the review Giunti, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344

and the update in Cadeddu, Giunti, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, PRD 98 (2018) 113010, arXiv:1810.05606]

- Neutrino charge radii contributions to ν_ℓ–$\mathcal{N}$ CEνNS:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\Bigg\{\Bigg[\underbrace{-\frac{1}{2}}_{g_V^n} N F_N(|\vec{q}|^2)$$
$$+\left(\underbrace{\frac{1}{2} - 2\sin^2\vartheta_W}_{g_V^p \simeq 0.023} - \frac{2}{3}\, m_W^2 \sin^2\vartheta_W \langle r^2_{\nu_{\ell\ell}}\rangle\right) Z F_Z(|\vec{q}|^2)\Bigg]^2$$
$$+\frac{4}{9}\, m_W^4 \sin^4\vartheta_W Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell'\neq\ell} |\langle r^2_{\nu_{\ell'\ell}}\rangle|^2\Bigg\}$$

- In the Standard Model there are only diagonal charge radii $\langle r^2_{\nu_\ell}\rangle \equiv \langle r^2_{\nu_{\ell\ell}}\rangle$ because lepton numbers are conserved.

- Diagonal charge radii generate the coherent shifts

$$\sin^2\vartheta_W \to \sin^2\vartheta_W\left(1 + \frac{1}{3} m_W^2 \langle r^2_{\nu_\ell}\rangle\right) \quad \Longleftrightarrow \quad \nu_\ell + \mathcal{N} \to \nu_\ell + \mathcal{N}$$

- Transition charge radii generate the incoherent contribution

$$\frac{4}{9}\, m_W^4 \sin^4\vartheta_W Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell'\neq\ell} |\langle r^2_{\nu_{\ell'\ell}}\rangle|^2 \quad \Longleftrightarrow \quad \nu_\ell + \mathcal{N} \to \sum_{\ell'\neq\ell} \nu_{\ell'\neq\ell} + \mathcal{N}$$

[Kouzakov, Studenikin, PRD 95 (2017) 055013, arXiv:1703.00401]

COHERENT Neutrino Spectrum and Time

- Neutrinos at the Oak Ridge Spallation Neutron Source are produced by a pulsed proton beam striking a mercury target.

- Prompt monochromatic ν_μ from stopped pion decays:

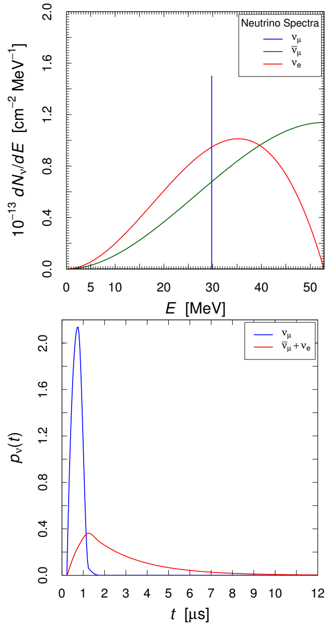
$$\pi^+ \to \mu^+ + \nu_\mu$$

- Delayed $\bar{\nu}_\mu$ and ν_e from the subsequent muon decays:

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

- The COHERENT energy and time information allow us to distinguish the interactions of ν_e, ν_μ, and $\bar{\nu}_\mu$.

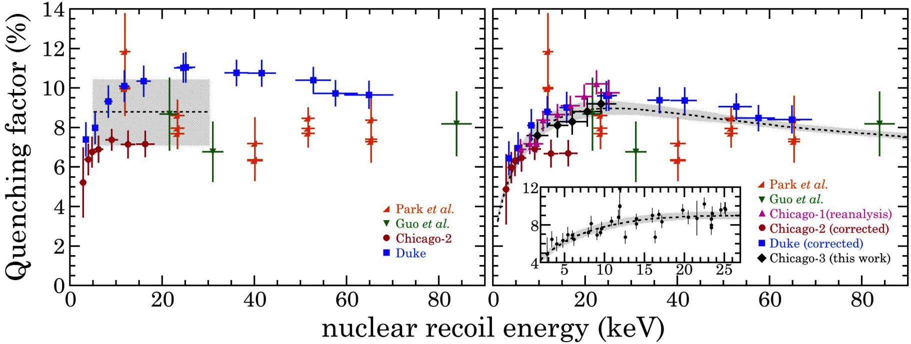
- Note that $\langle r^2_{\bar{\nu}_{\ell\ell'}} \rangle = -\langle r^2_{\nu_{\ell\ell'}} \rangle$, but also $g_V^{p,n}(\bar{\nu}) = -g_V^{p,n}(\nu)$.



Fits with the old and new quenching factors

[Cadeddu, Dordei, Giunti, Y.F. Li, Y.Y. Zhang, arXiv:1908.06045]

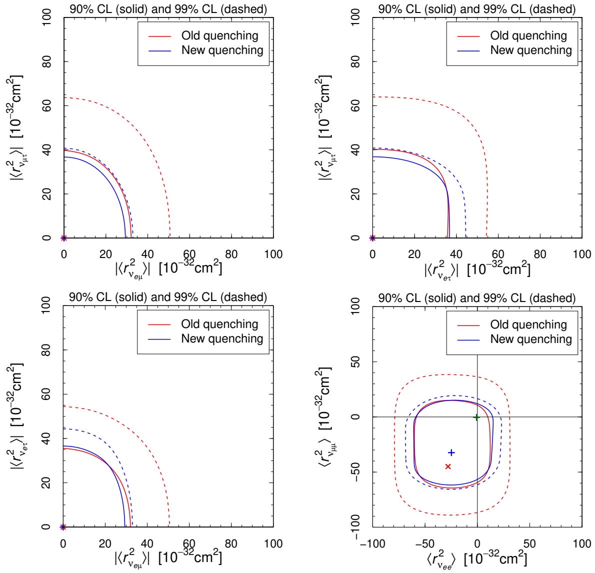
- Old quenching factor: COHERENT Collaboration, arXiv:1708.01294
- New quenching factor: Collar, Kavner, Lewis, arXiv:1907.04828



See also: D. Papoulias, arXiv:1907.11644
A. Khan, W. Rodejohann, arXiv:1907.12444

Fits with the old and new quenching factors

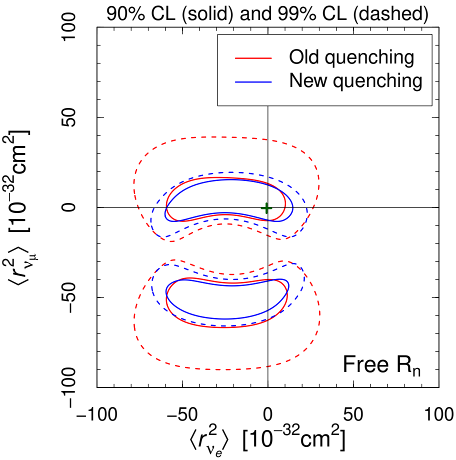
[Cadeddu, Dordei, Giunti, Y.F. Li, Y.Y. Zhang, arXiv:1908.06045]



- Free neutron distribution radii $R_n(^{133}\mathrm{Cs})$, $R_n(^{127}\mathrm{I})$.
- Slight improvement of 90% CL bounds with the new quenching factor.
- Significant improvement of 99% CL bounds strengthen the statistical reliability.
- The bounds on the diagonal charge radii are still not competitive with other measurements.
- Note the unique bounds on the transition charge radii that were not considered before Cadeddu et al, arXiv:1810.05606.

Fits without transition charge radii

[Cadeddu, Dordei, Giunti, Y.F. Li, Y.Y. Zhang, arXiv:1908.06045]



- Motivated by the Standard Model, where there are only diagonal charge radii.
- Explanation of the excluded area in the middle:
  - The cross section contribution of a diagonal charge radius $\langle r^2_{\nu_\ell} \rangle$ approximately cancel the weak neutral current contributions for

$$\langle r^2_{\nu_\ell} \rangle \simeq -\frac{3\,N}{4\,Z\,m_W^2 \sin^2\vartheta_W}$$

$$\simeq -26 \times 10^{-32}\,\text{cm}^2$$

  - Around this value the cross section is strongly suppressed and cannot fit the COHERENT data.

Neutrino Electric Charges

- Neutrinos can be millicharged particles in theories beyond the Standard Model.

- Neutrino charge contributions to ν_ℓ–$\mathcal{N}$ CEνNS:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\Bigg\{\Bigg[\underbrace{-\frac{1}{2}}_{g_V^n} NF_N(|\vec{q}|^2)$$

$$+\Bigg(\underbrace{\frac{1}{2} - 2\sin^2\vartheta_W}_{g_V^p \simeq 0.023} + \frac{2m_W^2 \sin^2\vartheta_W}{MT}\, q_{\nu_{\ell\ell}}\Bigg) ZF_Z(|\vec{q}|^2)\Bigg]^2$$

$$+\frac{4m_W^4 \sin^4\vartheta_W}{M^2 T^2}\, Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell' \neq \ell} |q_{\nu_{\ell\ell'}}|^2\Bigg\}$$

- $q_{\bar{\nu}_{\ell\ell'}} = -q_{\nu_{\ell\ell'}}$, but also $g_V^{p,n}(\bar{\nu}) = -g_V^{p,n}(\nu)$.

Approximate limits on neutrino millicharges

Limit	Method	Reference
$\|q_{\nu_e}\| \lesssim 3 \times 10^{-21}\, e$	Neutrality of matter	Raffelt (1999)
$\|q_{\nu_e}\| \lesssim 3.7 \times 10^{-12}\, e$	Nuclear reactor	Gninenko et al, (2006)
$\|q_{\nu_e}\| \lesssim 1.5 \times 10^{-12}\, e$	Nuclear reactor	Studenikin (2013)
$\|q_{\nu_\tau}\| \lesssim 3 \times 10^{-4}\, e$	SLAC e^- beam dump	Davidson et al, (1991)
$\|q_{\nu_\tau}\| \lesssim 4 \times 10^{-4}\, e$	BEBC beam dump	Babu et al, (1993)
$\|q_{\nu}\| \lesssim 6 \times 10^{-14}\, e$	Solar cooling (plasmon decay)	Raffelt (1999)
$\|q_{\nu}\| \lesssim 2 \times 10^{-14}\, e$	Red giant cooling (plasmon decay)	Raffelt (1999)

Neutrality of matter

- From electric charge conservation in neutron beta decay $(n \to p + e^- + \bar{\nu}_e)$

$$q_{\nu_e} = q_n - (q_p + q_e) = \frac{A}{Z}(q_n - q_{\text{mat}}) \quad \text{with} \quad q_{\text{mat}} = \frac{Z(q_p + q_e) + N q_n}{A}$$

- $q_{\text{mat}} = (-0.1 \pm 1.1) \times 10^{-21}\, e$ with SF_6, which has $A = 146.06$ and $Z = 70$

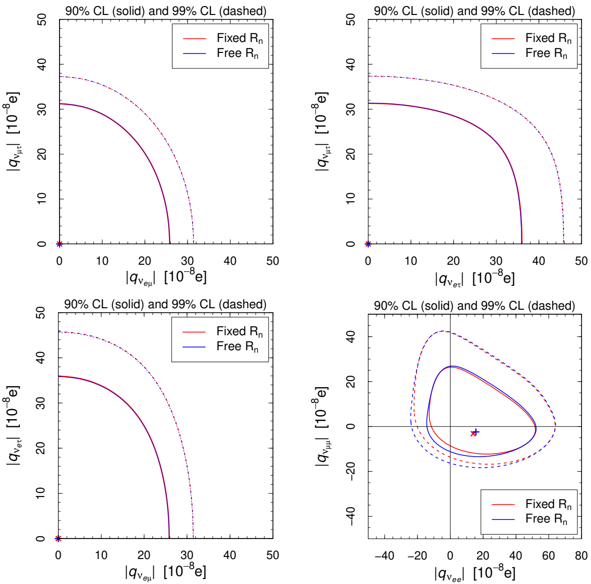
[Bressi, et al., PRA 83 (2011) 052101, arXiv:1102.2766]

- $q_n = (-0.4 \pm 1.1) \times 10^{-21}\, e$ [Baumann, Kalus, Gahler, Mampe, PRD 37 (1988) 3107]

- $q_{\nu_e} = (-0.6 \pm 3.2) \times 10^{-21}\, e$ [Giunti, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]

COHERENT constraints on neutrino millicharges

[Cadeddu, Dordei, Giunti, Y.F. Li, Y.Y. Zhang, arXiv:1908.06045]



- The bounds on the charges involving the electron neutrino flavor

  $q_{\nu_{ee}}$ $q_{\nu_{e\mu}}$ $q_{\nu_{e\tau}}$

  are not competitive with respect to those obtained in reactor neutrino experiments, that are at the level of $10^{-12}\,e$ in neutrino-electron elastic scattering experiments.

- The bounds on

  $q_{\nu_{\mu\mu}}$ $q_{\nu_{\mu\tau}}$

  are the first ones obtained from laboratory data.

Neutrino Magnetic and Electric Moments

- Extended Standard Model with right-handed neutrinos and $\Delta L = 0$:

$$\mu^{\mathrm{D}}_{kk} \simeq 3.2 \times 10^{-19} \mu_{\mathrm{B}} \left(\frac{m_k}{\mathrm{eV}} \right) \qquad \varepsilon^{\mathrm{D}}_{kk} = 0$$

$$\left. \begin{array}{c} \mu^{\mathrm{D}}_{kj} \\ i\varepsilon^{\mathrm{D}}_{kj} \end{array} \right\} \simeq -3.9 \times 10^{-23} \mu_{\mathrm{B}} \left(\frac{m_k \pm m_j}{\mathrm{eV}} \right) \sum_{\ell=e,\mu,\tau} U^*_{\ell k} U_{\ell j} \left(\frac{m_\ell}{m_\tau} \right)^2$$

off-diagonal moments are GIM-suppressed

[Fujikawa, Shrock, PRL 45 (1980) 963; Pal, Wolfenstein, PRD 25 (1982) 766; Shrock, NPB 206 (1982) 359; Dvornikov, Studenikin, PRD 69 (2004) 073001, JETP 99 (2004) 254]

- Extended Standard Model with Majorana neutrinos ($|\Delta L| = 2$):

$$\mu^{\mathrm{M}}_{kj} \simeq -7.8 \times 10^{-23} \mu_{\mathrm{B}}\, i \left(m_k + m_j \right) \sum_{\ell=e,\mu,\tau} \mathrm{Im} \left[U^*_{\ell k} U_{\ell j} \right] \frac{m^2_\ell}{m^2_W}$$

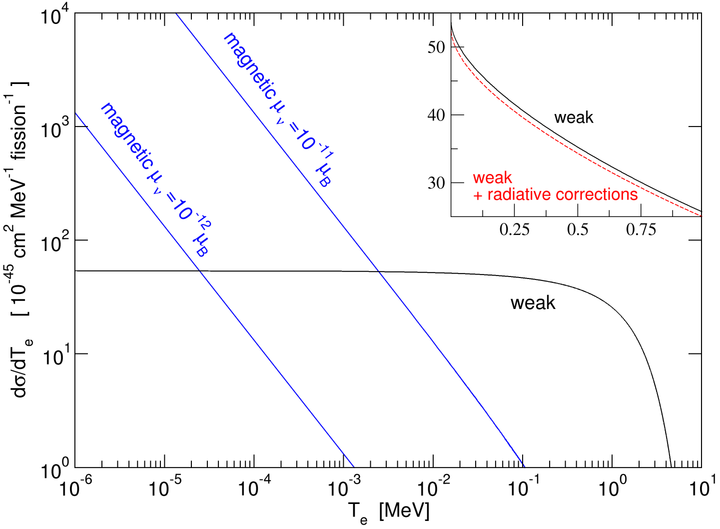
$$\varepsilon^{\mathrm{M}}_{kj} \simeq 7.8 \times 10^{-23} \mu_{\mathrm{B}}\, i \left(m_k - m_j \right) \sum_{\ell=e,\mu,\tau} \mathrm{Re} \left[U^*_{\ell k} U_{\ell j} \right] \frac{m^2_\ell}{m^2_W}$$

[Shrock, NPB 206 (1982) 359]

GIM-suppressed, but additional model-dependent contributions of the scalar sector can enhance the Majorana transition dipole moments

[Pal, Wolfenstein, PRD 25 (1982) 766; Barr, Freire, Zee, PRL 65 (1990) 2626; Pal, PRD 44 (1991) 2261]

$$\left(\frac{d\sigma_{\nu e^-}}{dT_e}\right)_{\text{mag}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e}-\frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_B}\right)^2$$



Method	Experiment	Limit $[\mu_B]$	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}$	90%	2012
Accelerator $\nu_e\, e^-$	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}$	90%	1992
Accelerator $(\nu_\mu, \bar{\nu}_\mu)\, e^-$	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}$	90%	1990
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}$	90%	1992
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}$	90%	2001
Accelerator $(\nu_\tau, \bar{\nu}_\tau)\, e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}$	90%	2001
Solar $\nu_e\, e^-$	Super-Kamiokande	$\mu_S(E_\nu \gtrsim 5\,\text{MeV}) < 1.1 \times 10^{-10}$	90%	2004
	Borexino	$\mu_S(E_\nu \lesssim 1\,\text{MeV}) < 2.8 \times 10^{-11}$	90%	2017

[see the review Giunti, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]

- Gap of about 8 orders of magnitude between the experimental limits and the $\lesssim 10^{-19}\,\mu_B$ prediction of the minimal Standard Model extensions.
- $\mu_\nu \gg 10^{-19}\,\mu_B$ discovery $\Rightarrow$ non-minimal new physics beyond the SM.
- Neutrino spin-flavor precession in a magnetic field

[Lim, Marciano, PRD 37 (1988) 1368; Akhmedov, PLB 213 (1988) 64]

- Neutrino magnetic (and electric) moment contributions to CEνNS $\nu_\ell + \mathcal{N} \to \sum_{\ell'} \nu_{\ell'} + \mathcal{N}$:

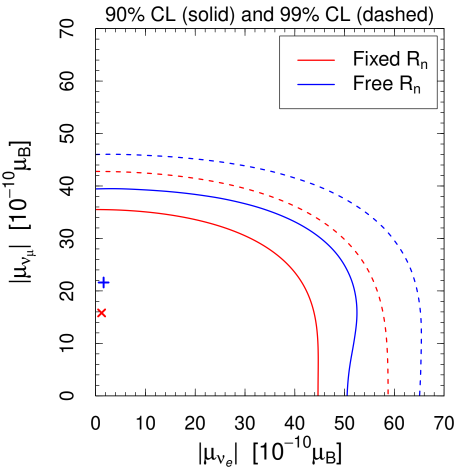
$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_{\text{F}}^2 M}{\pi} \left(1 - \frac{MT}{2E_\nu^2}\right) \left[g_V^n N F_N(|\vec{q}|^2) + g_V^p Z F_Z(|\vec{q}|^2)\right]^2 + \frac{\pi\alpha^2}{m_e^2} \left(\frac{1}{T} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell' \neq \ell} \frac{|\mu_{\ell\ell'}|^2}{\mu_{\text{B}}^2}$$

- The magnetic moment interaction adds incoherently to the weak interaction because it flips helicity.

- The m_e is due to the definition of the Bohr magneton: $\mu_{\text{B}} = e/2m_e$.

COHERENT constraints on ν magnetic moments

[Cadeddu, Dordei, Giunti, Y.F. Li, Y.Y. Zhang, arXiv:1908.06045]



- The sensitivity to $|\mu_{\nu_e}|$ is not competitive with that of reactor experiments:

$$|\mu_{\nu_e}| < 2.9 \times 10^{-11}\,\mu_B \quad (90\%\ \mathrm{CL})$$

[GEMMA, AHEP 2012 (2012) 350150]

- The constraint on $|\mu_{\nu_\mu}|$ is not too far from the best current laboratory limit:

$$|\mu_{\nu_\mu}| < 6.8 \times 10^{-10}\,\mu_B \quad (90\%\ \mathrm{CL})$$

[LSND, PRD 63 (2001) 112001]

Conclusions

- The observation of CEνNS in the COHERENT experiment opened the way for new powerful measurements of the properties of nuclei and neutrinos.
- CEνNS measurements probe the electromagnetic properties of neutrinos:
  - Neutrino charge radii (predicted by the Standard Model).
  - Neutrino millicharges (possible in theories beyond Standard Model).
  - Neutrino magnetic moments (possible in theories beyond Standard Model).
- COHERENT data constrain this properties, but are still not competitive with other measurements, except for the constraint on q_{ν_μ} that is the first one obtained from laboratory data.
- The new CEνNS experiments will allow to improve the current constraints and maybe observe the neutrino charge radii predicted by the Standard Model.
- It is important to continue and improve CEνNS observation not only with $\bar{\nu}_e$ from reactors, but also with ν_μ beams in order to explore the properties of ν_μ, that are typically less constrained than the properties of ν_e in other experiments.