Constraints on neutrino electromagnetic properties from COHERENT elastic neutrino-nucleus scattering

Speaker:

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M. Cadeddu et al. *Phys.Rev.D* 102 (2020) 1, 015030

Based on a work in collaboration with M. Cadeddu, N. Cargioli, F. Dordei, C. Giunti, E. Picciau, Y. F. Li, Y. Y. Zhang.

Coherent Elastic Neutrino-Nucleus Scattering

- Predicted in 1974 for $|\vec{q}|R \ll 1$ [Freedman, Physical Review D, 1974, 9(5): 1389]
- Taking into account interactions with both neutrons and protons

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[g_V^n N F_N(q^2) + g_V^p Z F_Z(q^2)\right]^2$$

Tree Level $g_V^n = -\frac{1}{2} \quad g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W$

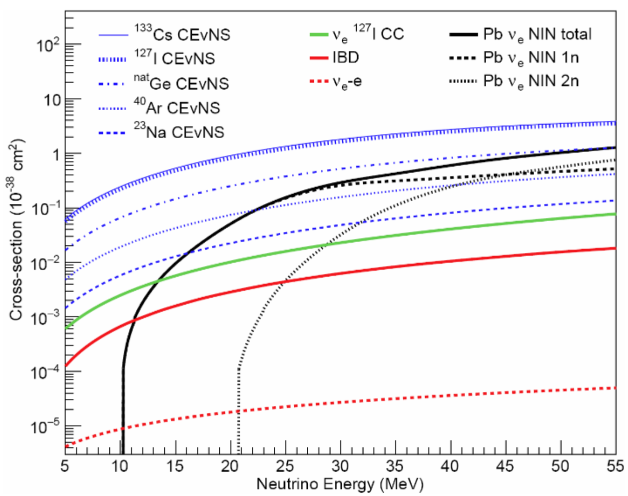
The neutron contribution is dominant! $\Rightarrow$ $\frac{d\sigma}{dT} \sim N^2 F_N^2(q^2)$

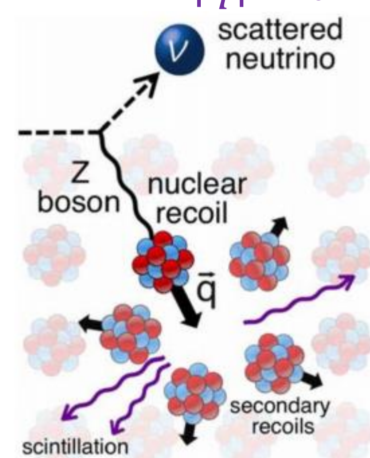
- The form factors $F_N(|\vec{q}|^2)$ and $F_Z(|\vec{q}|^2)$ describe the loss of coherence for $|\vec{q}|R \gtrsim 1$.

$T \simeq |\vec{q}|^2/2M$

$M \sim 100$ GeV, $R \sim 5$ fm

$\rightarrow T \lesssim 10$ keV

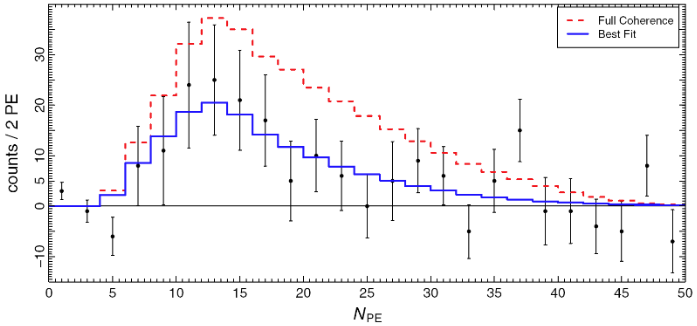




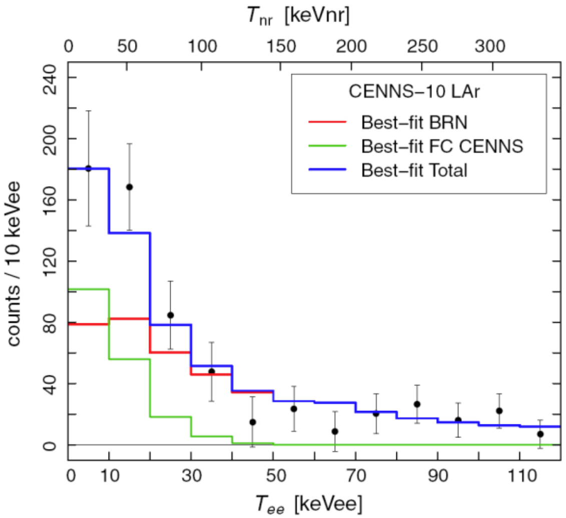
The COHERENT experiment

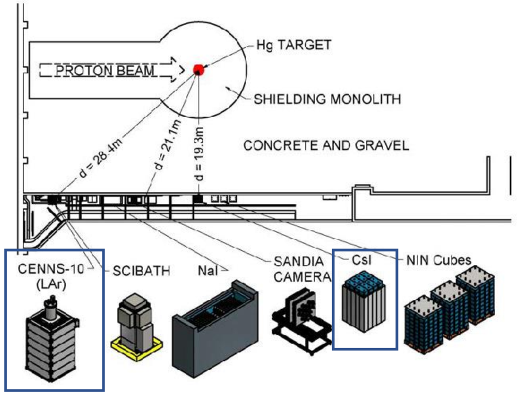
[Akimov et al. *Science* Vol 357, Issue 6356 15 September 2017]

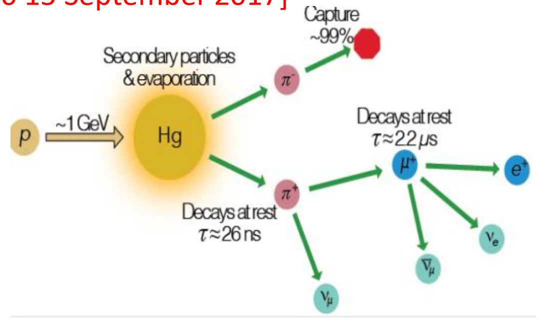
14.6 kg CsI(2017)



24 kg LAr(2020)







[COHERENT, arXiv:1803.09183, arXiv:2003.10630]

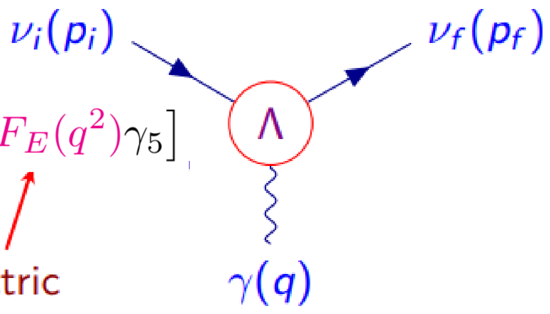
- Prompt monochromatic ν_μ:
  $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- Delayed $\bar{\nu}_\mu$ and ν_e :
  $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- The COHERENT energy and time information allow us to distinguish the interactions of ν_e, ν_μ and $\bar{\nu}_\mu$

Neutrino electromagnetic properties

- Effective electromagnetic Hamiltonian: [Giunti, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]

$$\mathcal{H}_{\rm em}^{(\nu)} = j_\mu^{(\nu)}(x) A^\mu(x) = \sum_{k,j=1}^{N} \bar{\nu}_k(x) \Lambda_\mu^{kj} \nu_j(x) A^\mu(x)$$

- Vertex function:



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

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

$q^2 = 0 \Longrightarrow$ $\mathfrak{q}$, a, μ, ε

$$F_Q(q^2) = F_Q(0) + q^2 \frac{dF_Q(q^2)}{dq^2}\bigg|_{q^2=0} + \cdots = q_\nu + \frac{q^2}{6}\langle r_\nu^2 \rangle \ldots$$

In the Standard Model: $F_Q(q^2) \approx \frac{q^2}{6}\langle r_\nu^2 \rangle$

Beyond the Standard Model: $F_Q(q^2) \approx q_\nu$

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

$$\langle r_{\nu_e}^2 \rangle_{\rm SM} = -0.83 \times 10^{-32}\,{\rm cm}^2,$$
$$\langle r_{\nu_\mu}^2 \rangle_{\rm SM} = -0.48 \times 10^{-32}\,{\rm cm}^2,$$
$$\langle r_{\nu_\tau}^2 \rangle_{\rm SM} = -0.30 \times 10^{-32}\,{\rm cm}^2.$$

[Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

Neutrino Charge Radii in CEνNS

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) F_Q(q^2) \longrightarrow r^2_{\nu_{\ell\ell'}}$$

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E,T) = \frac{G_F^2 M}{\pi}\left(1-\frac{MT}{2E^2}\right)\left\{\left[\left(g_V^p - \tilde{Q}_{\ell\ell}\right) Z F_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2)\right]^2 + Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell'\neq\ell} |\tilde{Q}_{\ell'\ell}|^2\right\}$$

$$\tilde{Q}_{\ell\ell'} = \frac{\sqrt{2}\pi\alpha}{3G_F}\langle r^2_{\nu_{\ell\ell'}}\rangle$$

- Diagonal charge radii: $\nu_\ell + \mathcal{N} \to \nu_\ell + \mathcal{N}$
- Transition charge radii: $\nu_\ell + \mathcal{N} \to \sum_{\ell'\neq\ell} \nu_{\ell'\neq\ell} + \mathcal{N}$
- Only depends on the fine-structure constant.

Process	Collaboration	Limit [10^{-32} cm^2]	CL
Reactor $\bar{\nu}_e - e$	Krasnoyarsk	$|\langle r^2_{\bar{\nu}_e}\rangle| < 7.3$	90%
	TEXONO	$-4.2 < \langle r^2_{\bar{\nu}_e}\rangle < 6.6$	90%
Accelerator $\nu_e - e$	LAMPF	$-7.12 < \langle r^2_{\nu_e}\rangle < 10.88$	90%
	LSND	$-5.94 < \langle r^2_{\nu_e}\rangle < 8.28$	90%
Accelerator $\nu_\mu - e$ and $\bar{\nu}_\mu - e$	BNL-E734	$-5.7 < \langle r^2_{\nu_\mu}\rangle < 1.1$	90%
	CHARM-II	$|\langle r^2_{\nu_\mu}\rangle| < 1.2$	90%

[M. CADEDDU et al. PHYS. REV. D 98, 113010 (2018)]

Neutrino millicharge in CEνNS

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) F_Q(q^2) \longrightarrow q_{\nu_{\ell\ell'}}$$

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E,T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E^2}\right)\left\{\left[\left(g_V^p - \tilde{Q}_{\ell\ell}\right) Z F_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2)\right]^2 + Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell' \neq \ell} |\tilde{Q}_{\ell'\ell}|^2\right\}$$

$$Q_{\ell\ell'} = \frac{2\sqrt{2}\pi\alpha}{G_F q^2} q_{\nu_{\ell\ell'}}$$

- The strongest constraint: Neutrality of matter:
  From electric charge conservation in neutron beta decay ($n \to p + e^- + \bar{\nu}_e$)

$$q_{\nu_e} = (-0.6 \pm 3.2) \times 10^{-21} e$$

- SN 1987A:

$$|q_{\nu_e}| \lesssim 2 \times 10^{-17}\, e$$

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

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

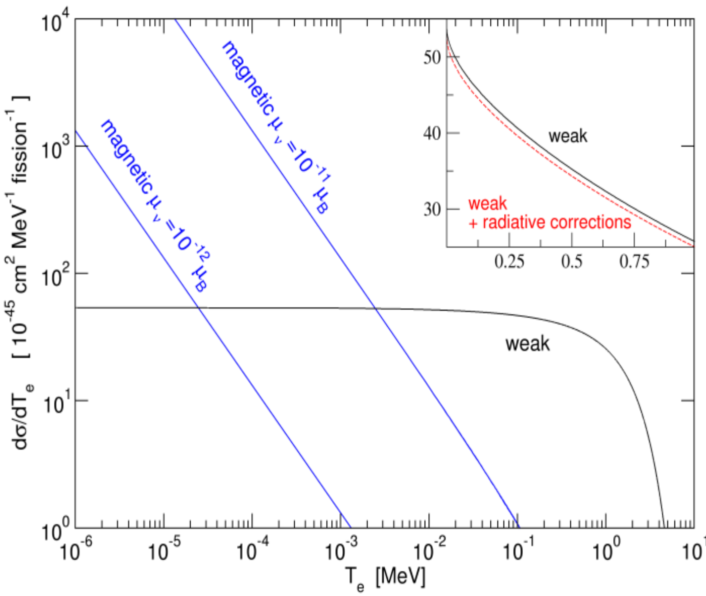
Neutrino Magnetic and Electric Moments

$$-i\sigma_{\mu\nu}q^{\nu}\left[F_M(q^2)+iF_E(q^2)\gamma_5\right] \longrightarrow \mu_{\nu_\ell}$$

$$\frac{d\sigma^{\text{mag}}_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\text{nr}}}(E,T_{\text{nr}}) = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_{\text{nr}}}-\frac{1}{E}\right)Z^2F_Z^2(|\vec{q}|^2)\left|\frac{\mu_{\nu_\ell}}{\mu_{\text{B}}}\right|^2$$

[Konstantin A. Kouzakov, Phys.Rev.D 95 (2017) 5, 055013]

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\text{nr}}}(E,T_{\text{nr}}) = \frac{d\sigma^{\text{SM}}_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\text{nr}}}(E,T_{\text{nr}}) + \frac{d\sigma^{\text{mag}}_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\text{nr}}}(E,T_{\text{nr}})$$



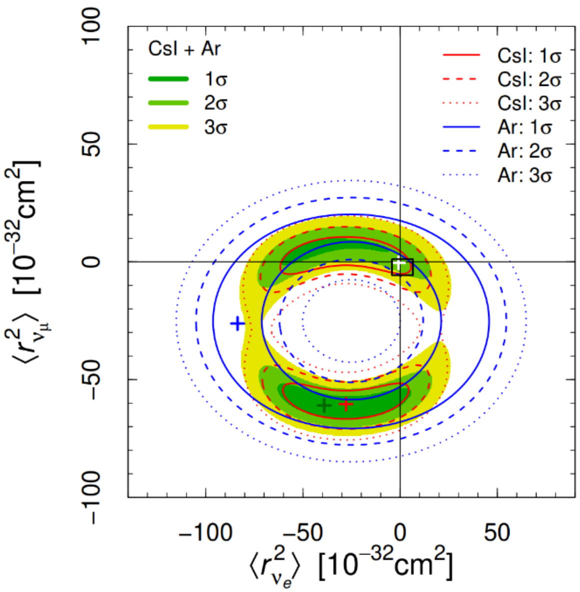
Method	Experiment	Limit	CL
Reactor $\bar{\nu}_e$–e^-	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}\,\mu_{\text{B}}$	90%
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}\,\mu_{\text{B}}$	95%
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}\,\mu_{\text{B}}$	90%
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}\,\mu_{\text{B}}$	90%
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}\,\mu_{\text{B}}$	90%
Accelerator ν_e–e^-	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}\,\mu_{\text{B}}$	90%
Accelerator $(\nu_\mu,\bar{\nu}_\mu)$–e^-	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}\,\mu_{\text{B}}$	90%
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}\,\mu_{\text{B}}$	90%
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}\,\mu_{\text{B}}$	90%
Accelerator $(\nu_\tau,\bar{\nu}_\tau)$–$e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}\,\mu_{\text{B}}$	90%

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

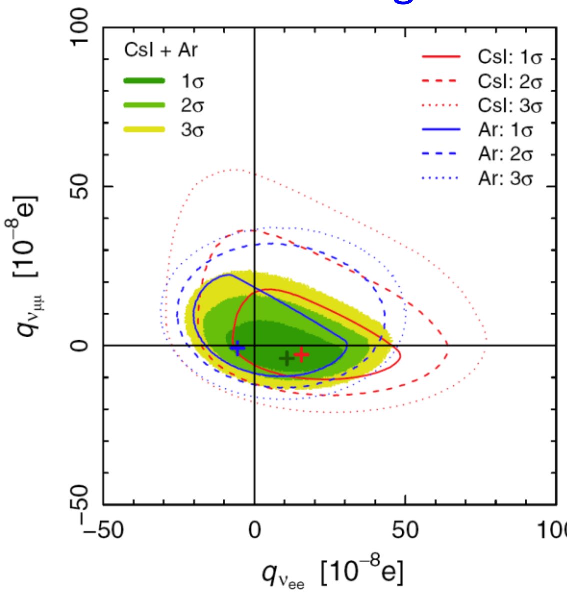
Fit of COHERENT data: neutrino electromagnetic properties

[M. Cadeddu et al. *Phys.Rev.D* 102 (2020) 1, 015030)]

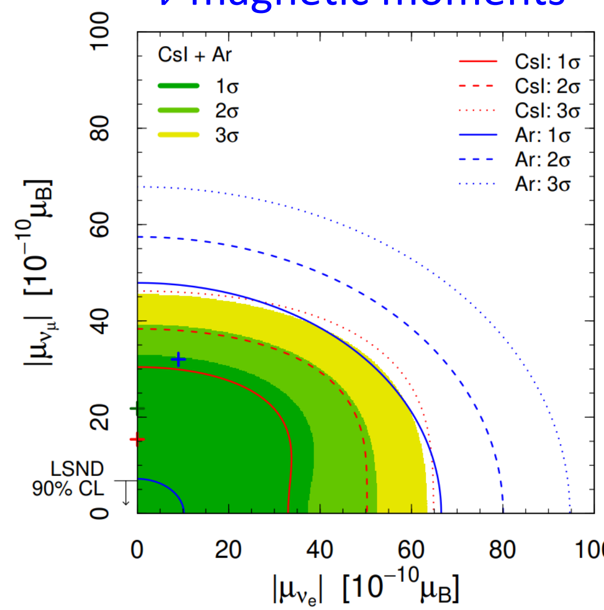
ν charge radii



ν millicharge



ν magnetic moments



- constraints on the neutrino charge radii:

$$-78 < \langle r^2_{\nu_e} \rangle < 22, -71 < \left\langle r^2_{\nu_\mu} \right\rangle < 17 \quad [10^{-32}\mathrm{cm}^2].$$

- constraints on the neutrino millicharge:

$$-20 < q_{\nu_e} < 42, -12 < q_{\nu_\mu} < 20 \quad [10^{-8}e].$$

- constraints on the effective neutrino magnetic moment:

$$|\mu_{\nu_e}| < 56, \left|\mu_{\nu_\mu}\right| < 41 \quad [10^{-10}\mu_B].$$

- neutrino charge radii, 100 higher than SM
- Improvement of the only existing laboratory bound of $q_{\nu_{\mu\mu}}$.
- Muon neutrino magnetic moment only about five times larger than the best current laboratory limit.

Summary

- CEνNS: unique process to explore the neutrino electromagnetic properties.
- The combined fit of the COHERENT CsI and Ar: improvement of constraints on neutrino electromagnetic properties.
- CEνNS: a new way to explore the nuclear and neutrino physics
  - Electroweak precision tests:
    - M. Cadeddu et al. *Phys.Rev.D* 101 (2020) 3, 033004
    - O. Tomalak et al. *JHEP* 02 (2021) 097
  - NSI:
    - B. Dutta et al. *JHEP* 09 (2020) 106
    - C. Giunti, *Phys.Rev.D* 101 (2020) 3, 035039
  - light vector mediators
    - O.G. Miranda et al. *JHEP* 05 (2020) 130
    - M. Cadeddu et al. *JHEP* 01 (2021) 116
  - Nuclear structure:
    - M. Cadeddu et al. Phys.Rev.Lett.120.072501
    - M. Cadeddu et al. arXiv: 2102.06153
    - D. K. Papoulias, *Phys.Rev.D* 102 (2020) 113004
    - P. Coloma et al. *JHEP* 08 (2020) 08, 030
  - …

Thanks