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

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中国物理学会高能物理分会
第十三届全国粒子物理学术会议

Outline

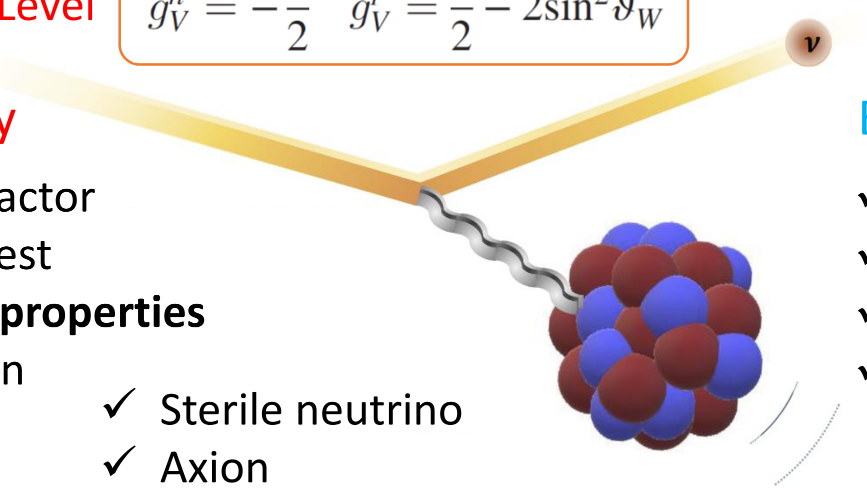
- 1. Coherent elastic neutrino-nucleus scattering(CEνNS)
- 2. Neutrino electromagnetic properties
  - Neutrino charge radii and millicharge
  - Neutrino magnetic moment and electric moment
- 3. Analysis of neutrino electromagnetic properties using COHERENT data
  - Neutrino charge radii
  - Neutrino millicharge
  - Neutrino effective magnetic moment
- Summary

Coherent Elastic Neutrino-Nucleus Scattering

- Predicted in 1974 for $|\vec{q}|R \ll 1$
- Frist observed in 2017
- 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 $g_V^n = -\frac{1}{2} \quad g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W$



Phenomenology

- ✓ Nuclear form factor
- ✓ EW precision test
- ✓ **New neutrino properties**
- ✓ New interaction
  - ✓ Sterile neutrino
  - ✓ Axion
  - ✓ Dark matter
  - ✓ Supernova

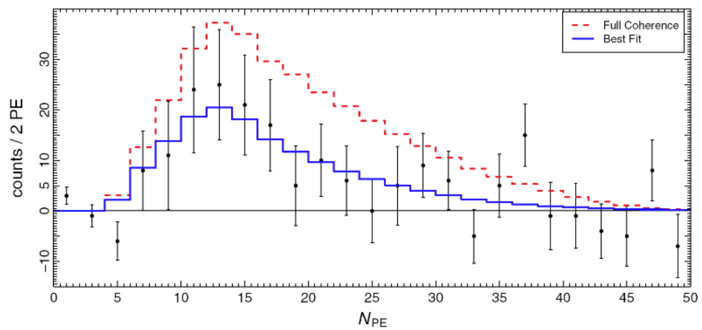
Experiment

- ✓ Stopped-pion neutrino
- ✓ Reactor neutrino
- ✓ DM observatories
- ✓ Solar neutrino

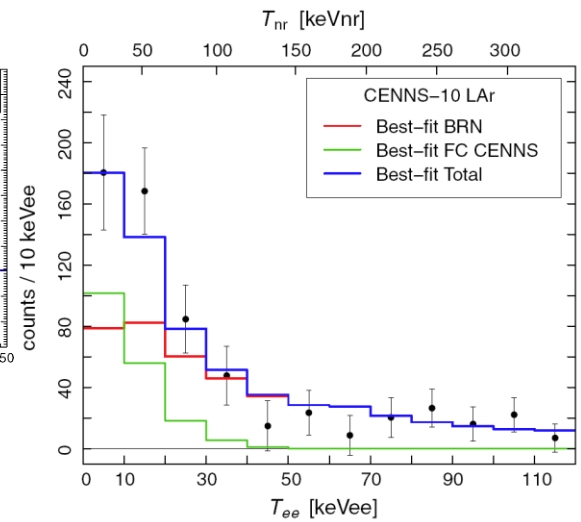
The COHERENT experiment

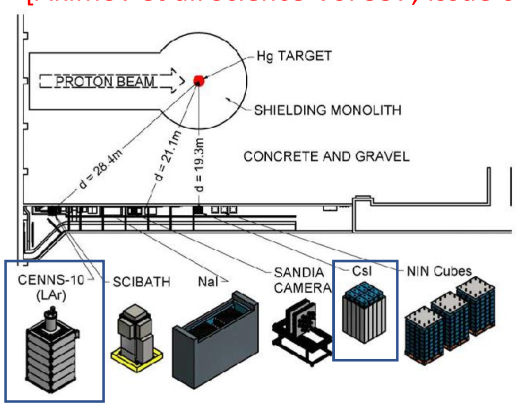
[Akimov et al. *Science* Vol 357, Issue 6356 15 September 2017]

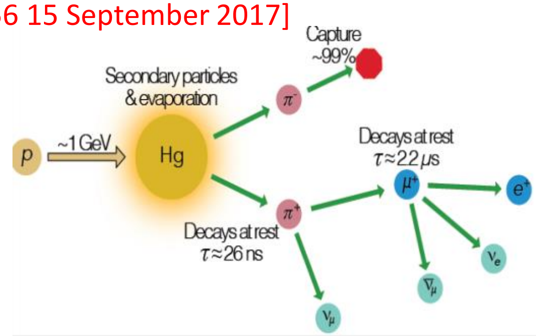
14.6 kg CsI(2017)



24 kg LAr(2020)







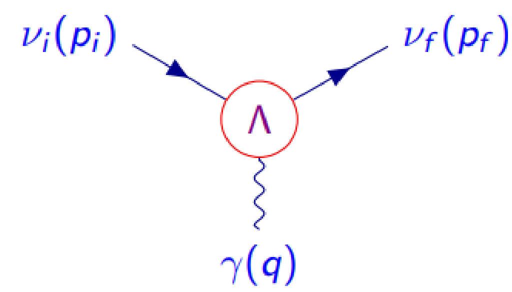
[COHERENT, arXiv:1803.09183, arXiv:2003.10630]

- 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 Hamiltonian:

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



- Effective electromagnetic vertex:

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

- 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

$q^2 = 0 \implies$ q, a, μ, ε

- CP invariance $\Rightarrow F_E = 0$

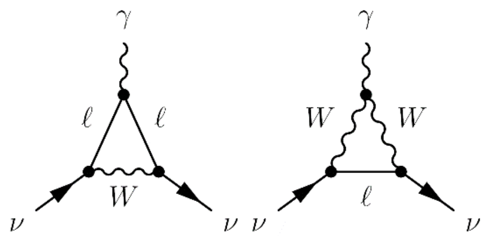
Neutrino charge radii and millicharge

- In the Standard Model of electroweak interactions neutrinos are exactly neutral particles, but they have the charge radii induced by radiative corrections.

- In the Standard Model there are only diagonal charge radii $\langle r^2_{\nu_l} \rangle \equiv \langle r^2_{\nu_{ll}} \rangle$ because lepton numbers are conserved. [Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_\ell} \rangle_{\rm SM} = -\frac{G_{\rm F}}{2\sqrt{2}\pi^2}\left[3 - 2\log\left(\frac{m^2_\ell}{m^2_W}\right)\right]$$

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



- $\left(\gamma_\mu - q_\mu \not{q}/q^2\right)\left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right]$

$$F_Q(q^2) = F\cancel{(0)} + q^2 \frac{dF(q^2)}{dq^2}\bigg|_{q^2=0} + \cdots = q^2 \frac{\langle r^2 \rangle}{6} + \cdots$$

- For ultrarelativistic neutrino $\gamma^5 \to \pm 1 \Rightarrow$ The phenomenology of the charge radius and anapole moments is similar.
- Beyond the Standard Model, neutrinos may be not exactly neutral

$$F_Q(q^2) = F(0) + q^2 \frac{dF(q^2)}{dq^2}\bigg|_{q^2=0} + \cdots \approx q_\nu + \cdots$$

Neutrino Charge Radii in CEνNS

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

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

$$\tilde{Q}_{\ell\ell'} = \frac{2}{3} m_W^2 \sin^2\vartheta_W \langle r^2_{\nu_{\ell\ell'}}\rangle \overset{\text{or}}{=} \frac{\sqrt{2}\pi\alpha}{3G_F}\langle r^2_{\nu_{\ell\ell'}}\rangle$$

- Diagonal charge radii: $\nu_\ell + \mathcal{N} \to \nu_\ell + \mathcal{N}$
- Transition charge radii: $\nu_\ell + \mathcal{N} \to \sum_{\ell'\neq\ell} \nu_{\ell'\neq\ell} + \mathcal{N}$
- Consider radiative corrections, 10% difference between these definitions.
- Only depends on the fine-structure constant.

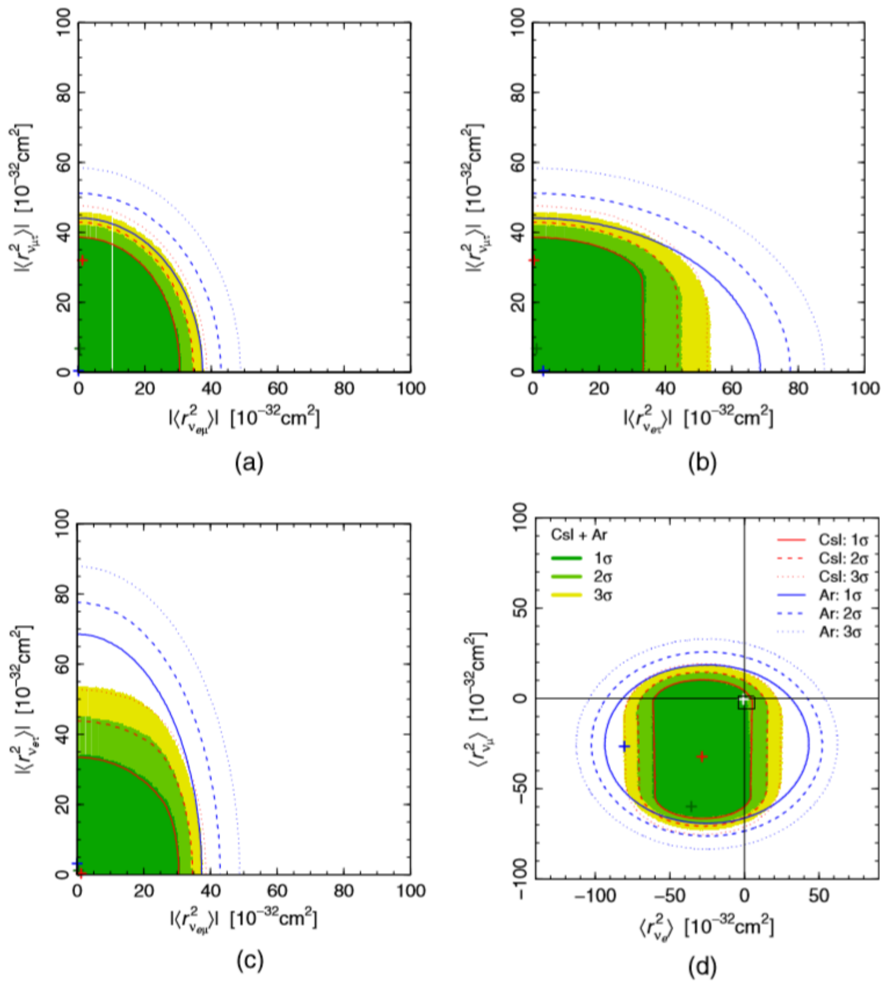
Process	Collaboration	Limit [10^{-32} cm^2]	CL
Reactor $\bar{\nu}_e - e$	Krasnoyarsk	$\lvert\langle r^2_{\bar{\nu}_e}\rangle\rvert < 7.3$	90%
	TEXONO	$-4.2 < \langle r^2_{\bar{\nu}_e}\rangle < 6.6$	90%
Accelerator $\nu_e - e$	LAMPF	$-7.12 < \langle r^2_{\nu_e}\rangle < 10.88$	90%
	LSND	$-5.94 < \langle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

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

Fit of COHERENT data: neutrino charge radii

PhysRevD.102.015030

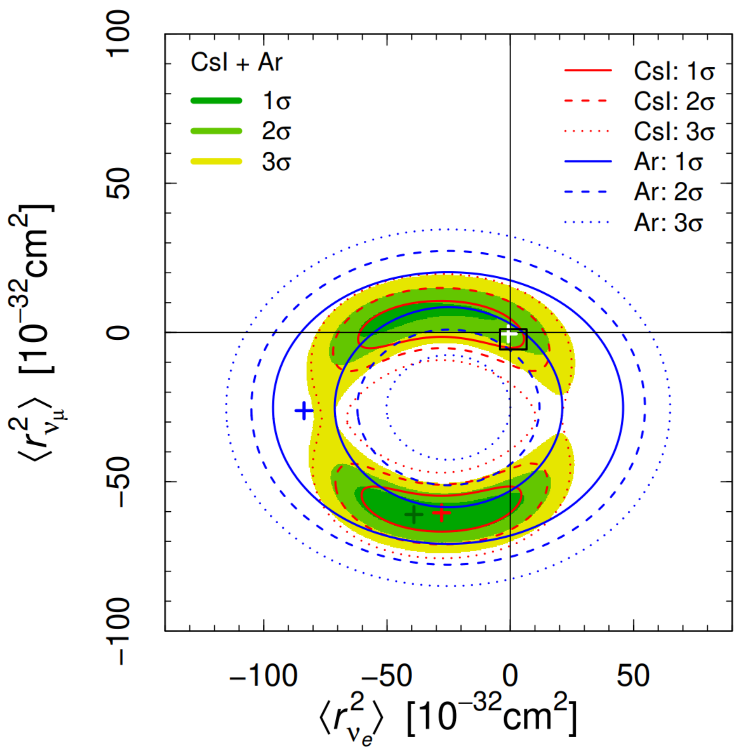
With transition charge radii



- The bounds of the combined fit are similar to those obtained with the CsI data only.
- The limits on the diagonal neutrino charge radii $\sim 10^{-31}\ \mathrm{cm}^2$.
- The limits on transition charge radii, first obtained.
- interesting on physics beyond the Standard Model.

Fit of COHERENT data: neutrino charge radii

Without transition charge radii



- Motivated by the Standard Model, only diagonal charge radii.
- The contribution of the Ar data leads to a restriction of the allowed regions.
- Limit: $\sim 10^{-31}\ \mathrm{cm}^2$
- The combined fit tends to favor the allowed island at large negative values
- compatible with the bounds of TEXONO and BNL-E734 experiments.

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 ($n \rightarrow p + e^- + \bar{\nu}_e$)
  $$q_{\nu_e} = (-0.6 \pm 3.2) \times 10^{-21} e$$
- SN 1987A:
  $$|q_{\nu_e}| \lesssim 2 \times 10^{-17}\, e$$

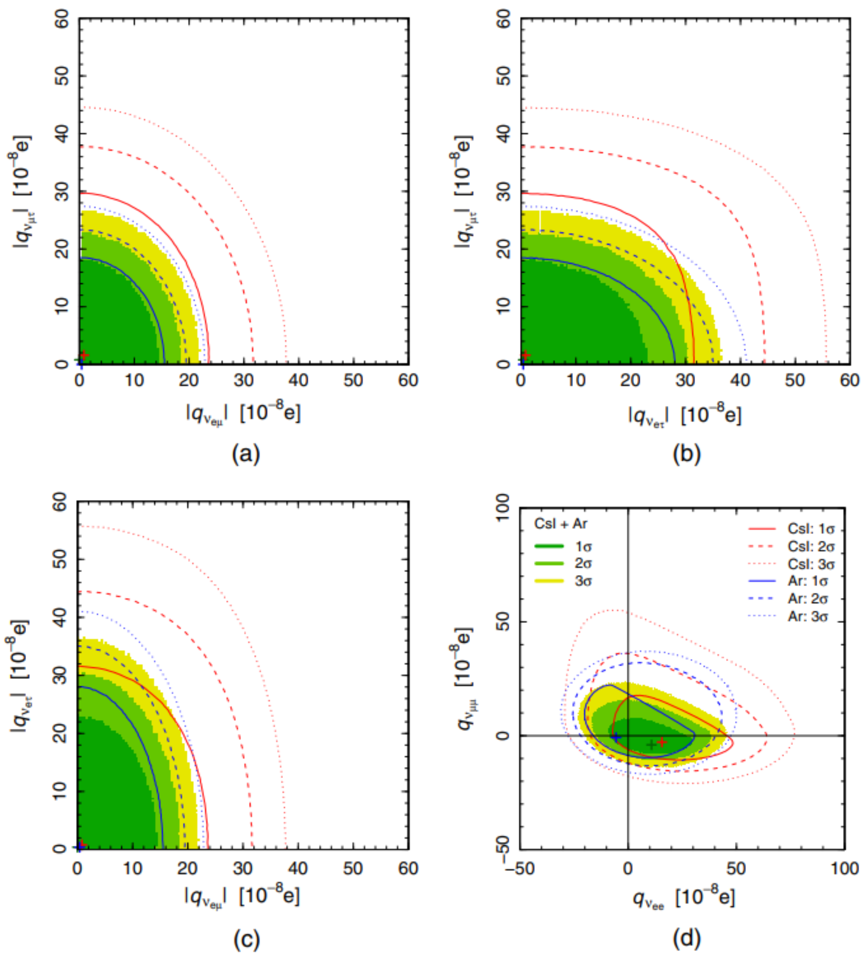
Limit	Method	Reference
$\|q_{\nu_\tau}\| \lesssim 3 \times 10^{-4} e$	SLAC e^- beam dump	Davidson et al, (1991)
$\|q_{\nu_\tau}\| \lesssim 4 \times 10^{-4} e$	BEBC beam dump	Babu et al, (1993)
$\|q_\nu\| \lesssim 6 \times 10^{-14} e$	Solar cooling (plasmon decay)	Raffelt (1999)
$\|q_\nu\| \lesssim 2 \times 10^{-14} e$	Red giant cooling (plasmon decay)	Raffelt (1999)
$\|q_{\nu_e}\| \lesssim 3 \times 10^{-21} e$	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)

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

Fit of COHERENT data: neutrino millicharge

PhysRevD.102.015030

With transition charge



- The combined fit of CsI and Ar data leads to a significant restriction of the allowed values of the neutrino electric charges.
- The effect of neutrino charge will be significantly enhanced when q^2 is small.
- Limit: $\sim 10^{-7}\ e$
- The bounds on $q_{\nu_{\mu\mu}}$, $q_{\nu_{\mu\tau}}$ are the first ones obtained from laboratory data.

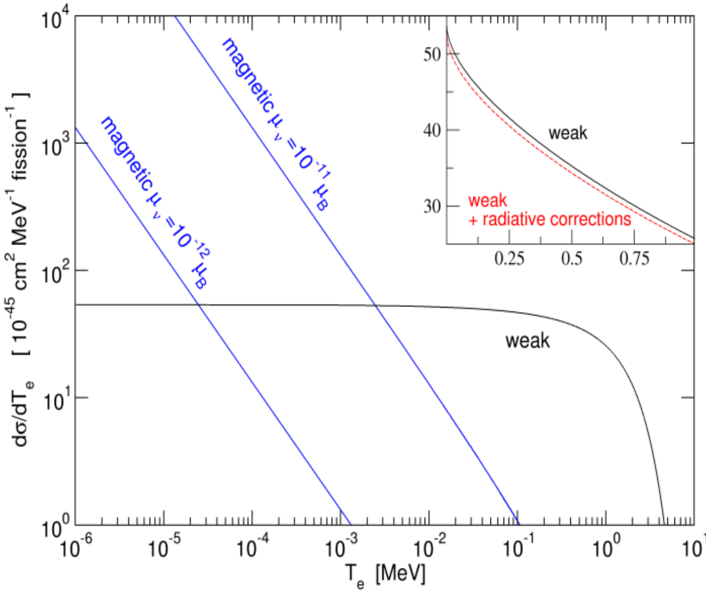
Neutrino Magnetic and Electric Moments

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

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

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

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

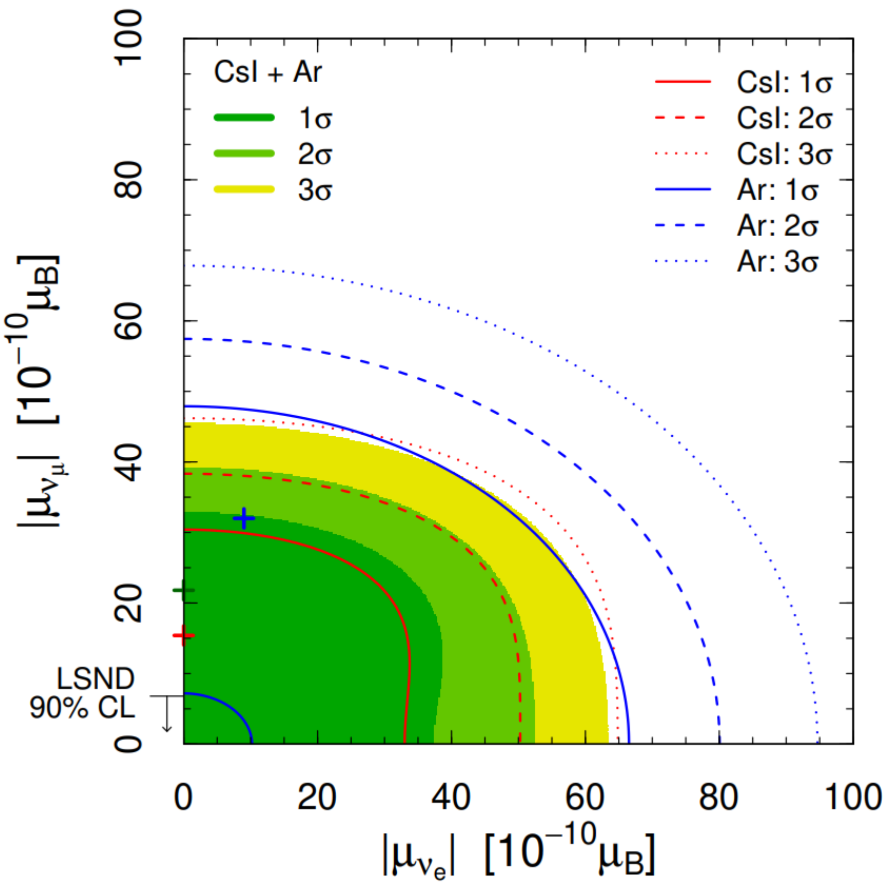


Method	Experiment	Limit	CL
Reactor $\bar{\nu}_e$–e^-	Krasnoyarsk	$\mu_{\nu_e} < 2.4\times10^{-10}\,\mu_{\rm B}$	90%
	Rovno	$\mu_{\nu_e} < 1.9\times10^{-10}\,\mu_{\rm B}$	95%
	MUNU	$\mu_{\nu_e} < 9\times10^{-11}\,\mu_{\rm B}$	90%
	TEXONO	$\mu_{\nu_e} < 7.4\times10^{-11}\,\mu_{\rm B}$	90%
	GEMMA	$\mu_{\nu_e} < 2.9\times10^{-11}\,\mu_{\rm B}$	90%
Accelerator ν_e–e^-	LAMPF	$\mu_{\nu_e} < 1.1\times10^{-9}\,\mu_{\rm B}$	90%
Accelerator $(\nu_\mu,\bar{\nu}_\mu)$–e^-	BNL-E734	$\mu_{\nu_\mu} < 8.5\times10^{-10}\,\mu_{\rm B}$	90%
	LAMPF	$\mu_{\nu_\mu} < 7.4\times10^{-10}\,\mu_{\rm B}$	90%
	LSND	$\mu_{\nu_\mu} < 6.8\times10^{-10}\,\mu_{\rm B}$	90%
Accelerator $(\nu_\tau,\bar{\nu}_\tau)$–$e^-$	DONUT	$\mu_{\nu_\tau} < 3.9\times10^{-7}\,\mu_{\rm B}$	90%

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

Fit of COHERENT data: Neutrino Magnetic Moments

PhysRevD.102.015030



- Effective neutrino magnetic moment.
- $\mu_{\nu_e}, \mu_{\nu_\mu} \sim 10^{-9}\mu_B$

- Electron neutrino magnetic moment is not competitive with the current reactor limits.

- Muon neutrino magnetic moment is only about 5 times larger than the best current laboratory limits.
- Have potential to match the current limit.

Summary

- CEνNS: unique process to explore the neutrino electromagnetic properties.
  - obtain constraints on the neutrino charge radii:
    $$-78 < \langle r_{\nu_e}^2 \rangle < 22 \times 10^{-32}\ \mathrm{cm}^2, -71 < \langle r_{\nu_\mu}^2 \rangle < 17 \times 10^{-32}\ \mathrm{cm}^2.$$
  - obtain constraints on the neutrino millicharge :
    $$-20 < q_{\nu_e} < 42 \times 10^{-8}\ e, -12 < q_{\nu_\mu} < 20 \times 10^{-8}\ e.$$
  - obtain the constraints on the effective neutrino magnetic moment:
    $$|\mu_{\nu_e}| < 56 \times 10^{-10} \mu_B, |\mu_{\nu_\mu}| < 41 \times 10^{-10} \mu_B$$
- The combined fit of the COHERENT CsI and Ar data leads to a significant restriction of the allowed values.
- The constraints on transition charge radii, q_{ν_μ} are the first one obtained from laboratory data.
- COHERENT Spallation Neutron Source experiment:
  - SNS:NaI, HPGe, CCM, LAr, European Spallation Source
- Reactor neutrino experiment:
  - CONUS, CONNIE, Taishan

Thanks