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

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Outline

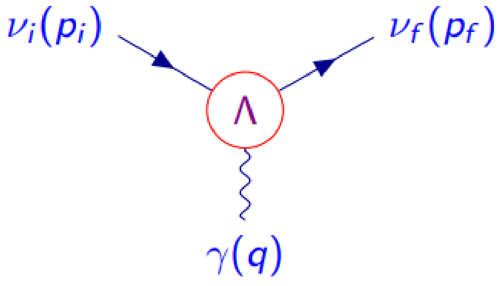
- 1. Neutrino electromagnetic properties
  - Neutrino charge radii and millicharge
  - Neutrino magnetic moment and electric moment
- 2. Coherent elastic neutrino-nucleus scattering(CEνNS)
- 3. COHERENT experiment
- 4. Analysis of neutrino electromagnetic properties using COHERENT data
  - Neutrino charge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

- Summary

Neutrino electromagnetic properties

- Effective Hamiltonian:

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



- Effective electromagnetic vertex:

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

- Vertex function:

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

Lorentz-invariant form factors:	charge	anapole	magnetic	electric
$q^2 = 0 \Longrightarrow$	$\mathfrak{q}$	a	μ	ε

- CP invariance ⇒ $F_E = 0$

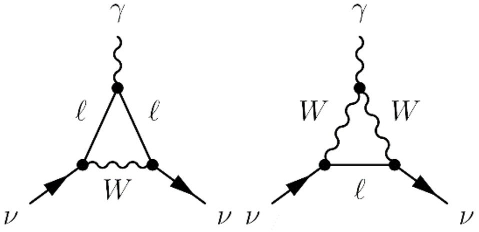
Neutrino charge radii and millicharge

- 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 $\langle r_{\nu_l}^2 \rangle \equiv \langle r_{\nu_{ll}}^2 \rangle$ because lepton numbers are conserved. [Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

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

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



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

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

- 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

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

Neutrino Magnetic and Electric Moments

- Extended Standard Model with right-handed neutrinos:

$$\left.\begin{matrix}\mu^{\mathrm{D}}_{kj}\\ i\epsilon^{\mathrm{D}}_{kj}\end{matrix}\right\} \simeq \frac{3eG_{\mathrm{F}}}{16\sqrt{2}\pi^2}(m_k \pm m_j) \times \left(\delta_{kj} - \frac{1}{2}\sum_{l=e,\mu,\tau} U^*_{lk}U_{lj}\frac{m_l^2}{m_W^2}\right)$$

$$\mu^{\mathrm{D}}_{kk} \simeq \frac{3eG_{\mathrm{F}}m_k}{8\sqrt{2}\pi^2} \simeq 3.2 \times \boxed{10^{-19}}\left(\frac{m_k}{\mathrm{eV}}\right)\mu_{\mathrm{B}}$$

- Extended Standard Model with Majorana neutrinos:

$$\mu^{\mathrm{M}}_{kj} \simeq -\frac{3ieG_{\mathrm{F}}}{16\sqrt{2}\pi^2}(m_k + m_j)\sum_{l=e,\mu,\tau} \mathrm{Im}\left[U^*_{lk}U_{lj}\right]\frac{m_l^2}{m_W^2}$$

$$\epsilon^{\mathrm{M}}_{kj} \simeq \frac{3ieG_{\mathrm{F}}}{16\sqrt{2}\pi^2}(m_k - m_j)\sum_{l=e,\mu,\tau} \mathrm{Re}\left[U^*_{lk}U_{lj}\right]\frac{m_l^2}{m_W^2}$$

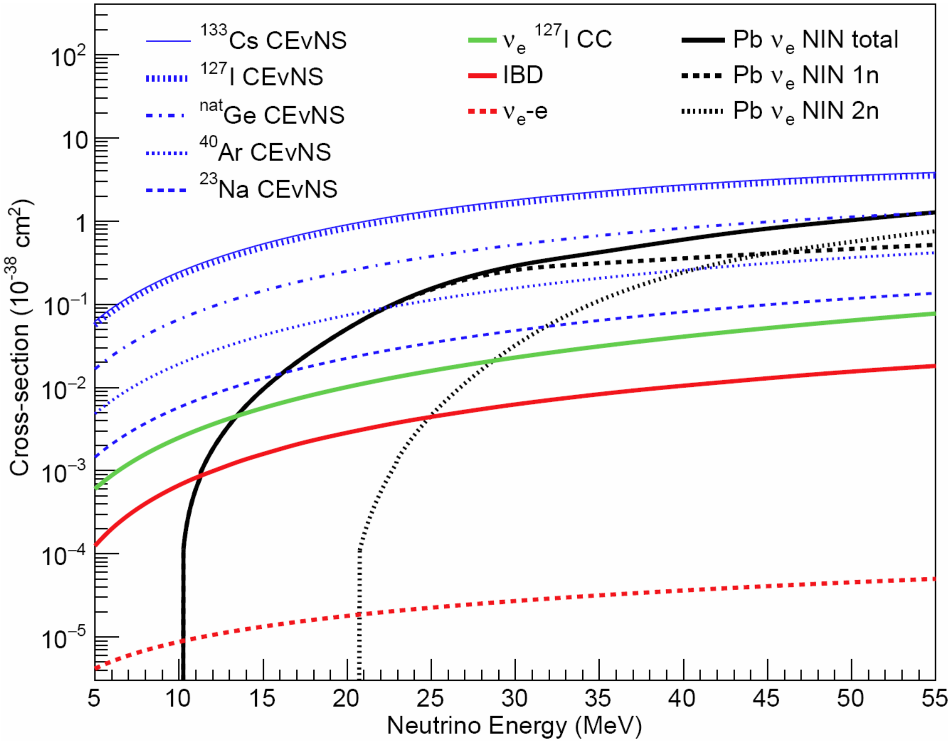
- $-i\sigma_{\mu\nu}q^\nu\left[F_M(q^2) + iF_E(q^2)\gamma_5\right]$
- For ultrarelativistic neutrino $\gamma^5 \to \pm 1 \Rightarrow$ The phenomenology of the magnetic and electric moments is similar.
- Experimental observation: effective neutrino magnetic moments

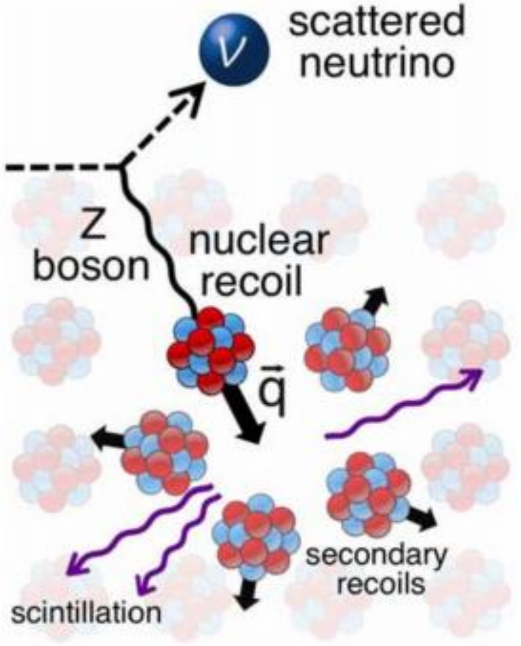
$$\mu^2_{\nu_\ell} \simeq \mu^2_{\bar{\nu}_\ell} \approx \sum_j \left|\sum_k U^*_{\ell k} \times (\mu_{jk} - i\epsilon_{jk})\right|^2 \xleftarrow{\text{SBL}} \mu^2_{\nu_\ell}(L, E_\nu) = \sum_j \left|\sum_k U^*_{\ell k} e^{-i\Delta m^2_{kj}L/2E_\nu} \times (\mu_{jk} - i\epsilon_{jk})\right|^2$$

Coherent Elastic Neutrino-Nucleus Scattering

- Predicted in 1974, first observed at 2017, for $|\vec{q}|R \ll 1$

[Freedman, Physical Review D, 1974, 9(5): 1389]





[COHERENT Collaboration,Science 357 (2017) 1123]

Coherent Elastic Neutrino-Nucleus Scattering

- Taking into account interactions with both neutrons and protons

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

Tree Level

$$g_V^n=-\frac{1}{2}\qquad g_V^p=\frac{1}{2}-2\sin^2\vartheta_W$$

With radiative corrections

$$g_V^p(\nu_\ell)=\rho\left(\frac{1}{2}-2\sin^2\vartheta_W\right)-\frac{\hat{\alpha}_Z}{4\pi\hat{s}_Z^2}\left(1-2\frac{\hat{\alpha}_s(m_W)}{\pi}\right)+\frac{\alpha}{6\pi}\left(3-2\ln\frac{m_\ell^2}{m_W^2}\right)$$

$$g_V^n=-\frac{\rho}{2}-\frac{\hat{\alpha}_Z}{8\pi\hat{s}_Z^2}\left(7-5\frac{\hat{\alpha}_s(m_W)}{\pi}\right)$$

SM neutrino charge radius

[J. Erler and S. Su, Prog. Part. Nucl. Phys. 71, 119 (2013).]

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

[Bednyakov, Naumov, arXiv:1806.08768]

- The form factors $F_N(|\vec{q}|^2)$ and $F_Z(|\vec{q}|^2)$ describe the loss of coherence for $|\vec{q}|R\gtrsim 1$.
- Coherence requires very small values of the nuclear kinetic recoil energy:

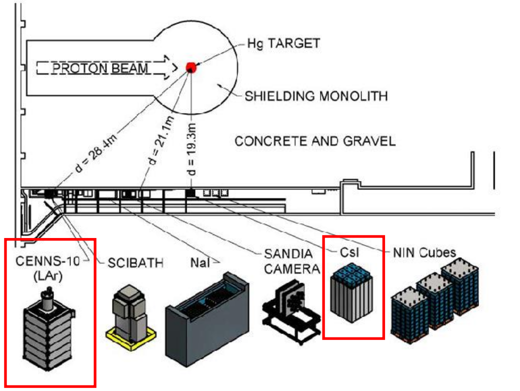
$$T\simeq|\vec{q}|^2/2M$$

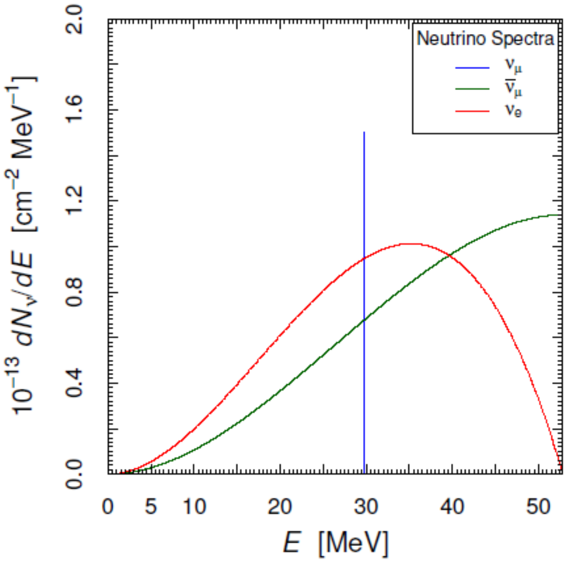
$$M\sim 100\text{ GeV},\ R\sim 5\text{ fm}\ \rightarrow T\lesssim 10\text{ keV}$$

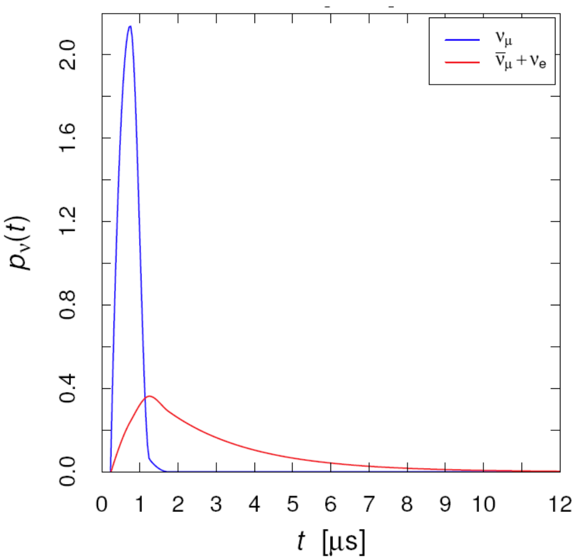
The COHERENT experiment

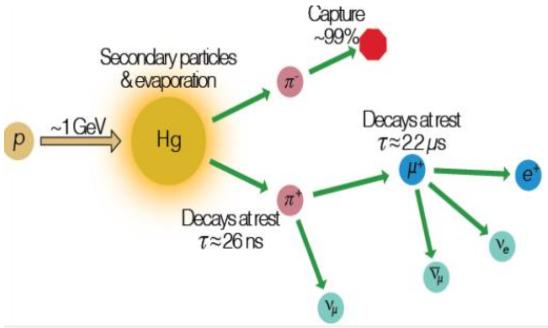
- 14.6 kg CsI scintillating crystal and 24 kg LAr detector.
- Prompt monochromatic ν_μ from stopped pion decays:
  $$\pi^+ \to \mu^+ + \nu_\mu$$
- Delayed $\bar{\nu}_\mu$ and ν_e from the subsequent muon decays:
  $$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$
- The COHERENT energy and time information allow us to distinguish the interactions of ν_e, ν_μ and $\bar{\nu}_\mu$

[COHERENT, arXiv:1803.09183]







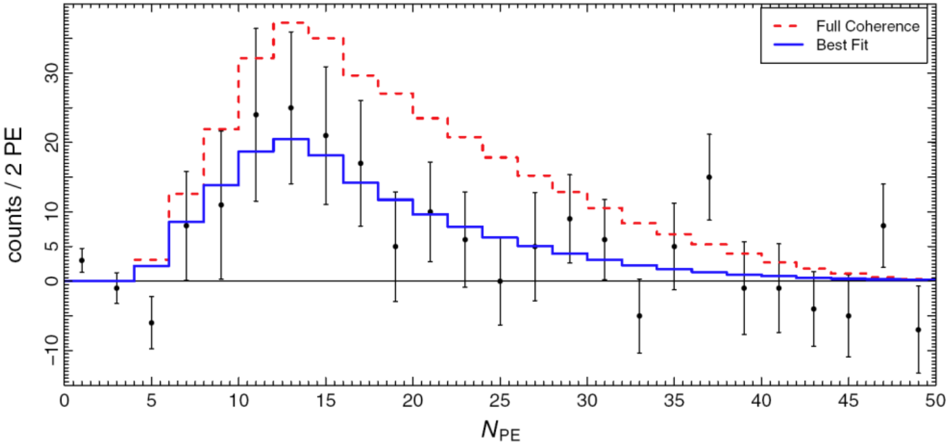


COHERENT expected event

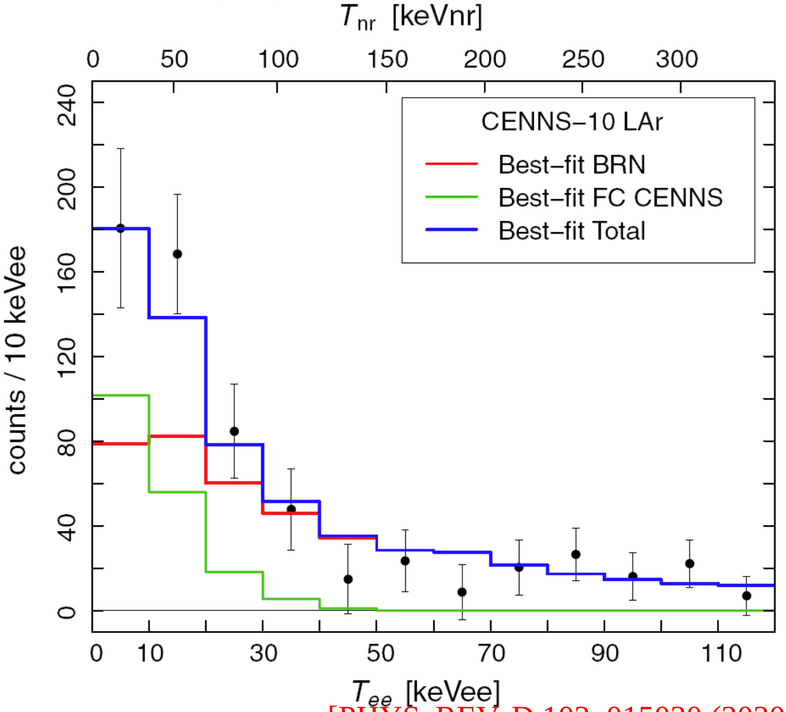
- The expected CEνNS signal is given by:

$$N_i^{\mathrm{CE}\nu\mathrm{NS}} = N(X) \int_{T_{\mathrm{nr}}^{i}}^{T_{\mathrm{nr}}^{i+1}} dT_{\mathrm{nr}} A(T_{\mathrm{nr}}) \int_{E_{\min}}^{E_{\max}} dE \sum_{\nu=\nu_e,\nu_\mu,\bar{\nu}_\mu} \frac{dN_\nu}{dE} \frac{d\sigma_{\nu-\mathcal{N}}}{dT_{\mathrm{nr}}}(E, T_{\mathrm{nr}})$$

$N(X)$: Number of nuclei in the detector
A: Acceptance of the detector
dN_ν/dE: Neutrino fluxes at SNS
$d\sigma/dT_{\mathrm{nr}}$: CEνNS cross section



[PHYS. REV. D 101, 033004 (2020)]



[PHYS. REV. D 102, 015030 (2020)]

We use both energy and time information.

I: Neutrino charge radii in CEνNS

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

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

- Diagonal charge radii: $\nu_\ell + \mathcal{N} \to \nu_\ell + \mathcal{N}$
- Transition charge radii: $\nu_\ell + \mathcal{N} \to \sum_{\ell'\neq\ell} \nu_{\ell'\neq\ell} + \mathcal{N}$

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

- Consider radiative corrections, 10% difference between these definitions.
- Only depends on the fine-structure constant.

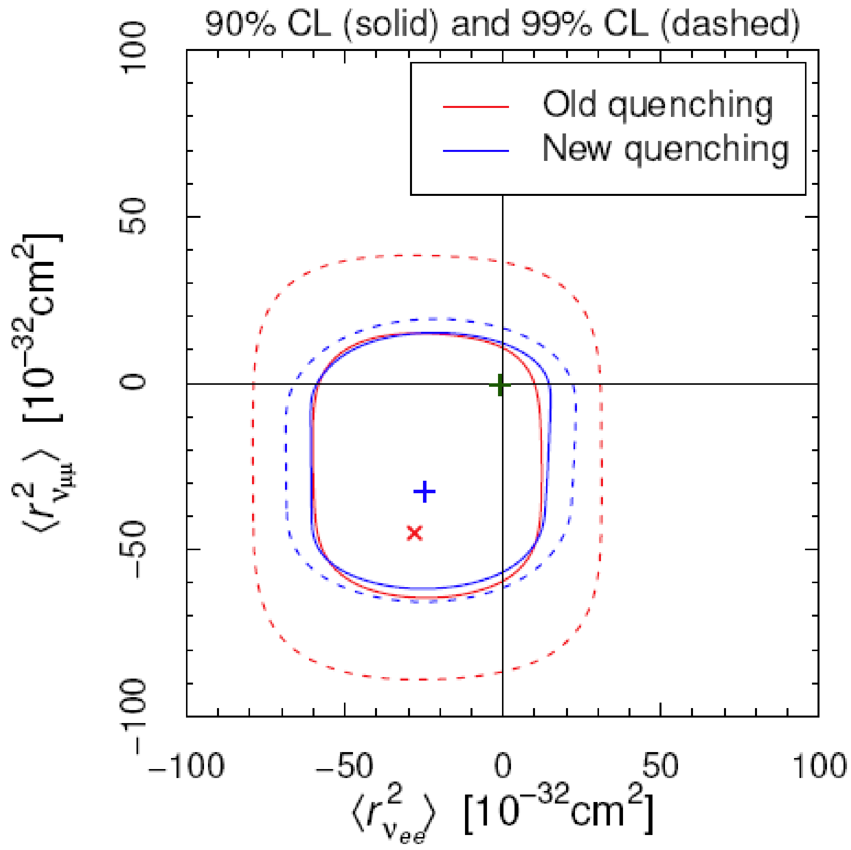
Process	Collaboration	Limit [$\boxed{10^{-32}}$ cm^2]	CL
Reactor $\bar{\nu}_e - e$	Krasnoyarsk	$\lvert\langle r^2_{\bar{\nu}_e}\rangle\rvert < 7.3$	90%
	TEXONO	$-4.2 < \langle r^2_{\bar{\nu}_e}\rangle < 6.6$	90%
Accelerator $\nu_e - e$	LAMPF	$-7.12 < \langle r^2_{\nu_e}\rangle < 10.88$	90%
	LSND	$-5.94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

I: Fit of COHERENT CsI data: neutrino charge radii

Physical Review D. 2020, 101 (3): 033004.

with the old and new quenching factors



- New quenching factor: uncertainty 18.9%→5.1% [Collar et al. arXiv:1907.04828]
- Test the effect of uncertainty of QF.

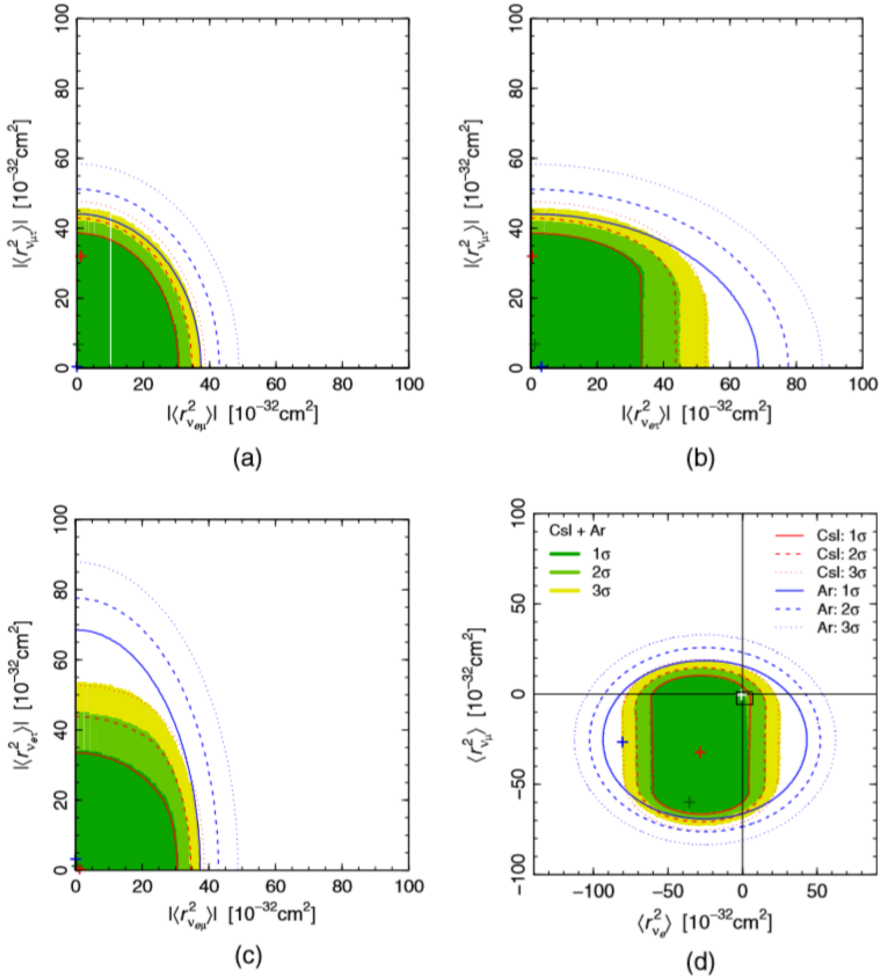
- 90% C.L. allowed regions: Slight improved.
- 99% C.L. allowed regions: Strongly reduced.
- New quenching factor strengthens the statistical reliability.

- The bounds on the diagonal charge radii $\sim 10^{-31}$ cm^2.

I: Fit of COHERENT data: neutrino charge radii

PhysRevD.102.015030

With transition charge radii



(a)

(b)

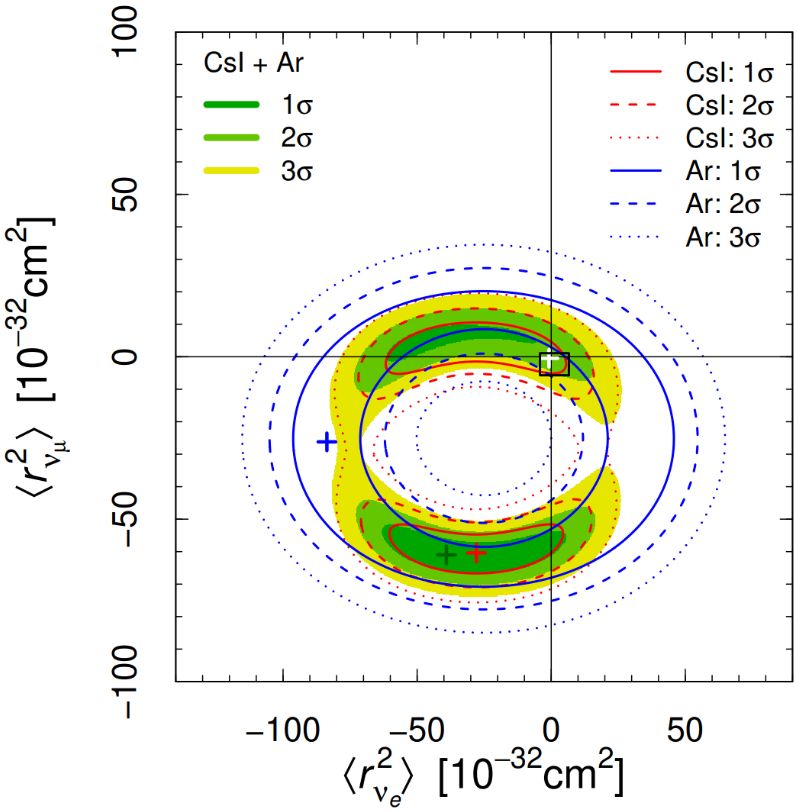
(c)

(d)

- The bounds of the combined fit: 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.

I: 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.
- The limits: $\sim 10^{-31}\ \mathrm{cm}^2$
- The combined fit tends to favor the allowed island at large negative values
- compatible with the bounds of TEXONO and BNL-E734 experiments.

II: Neutrino millicharge in CEνNS

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

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

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

- The strongest constraint: Neutrality of matter:

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

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

- 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]

II: Fit of COHERENT data: neutrino millicharge

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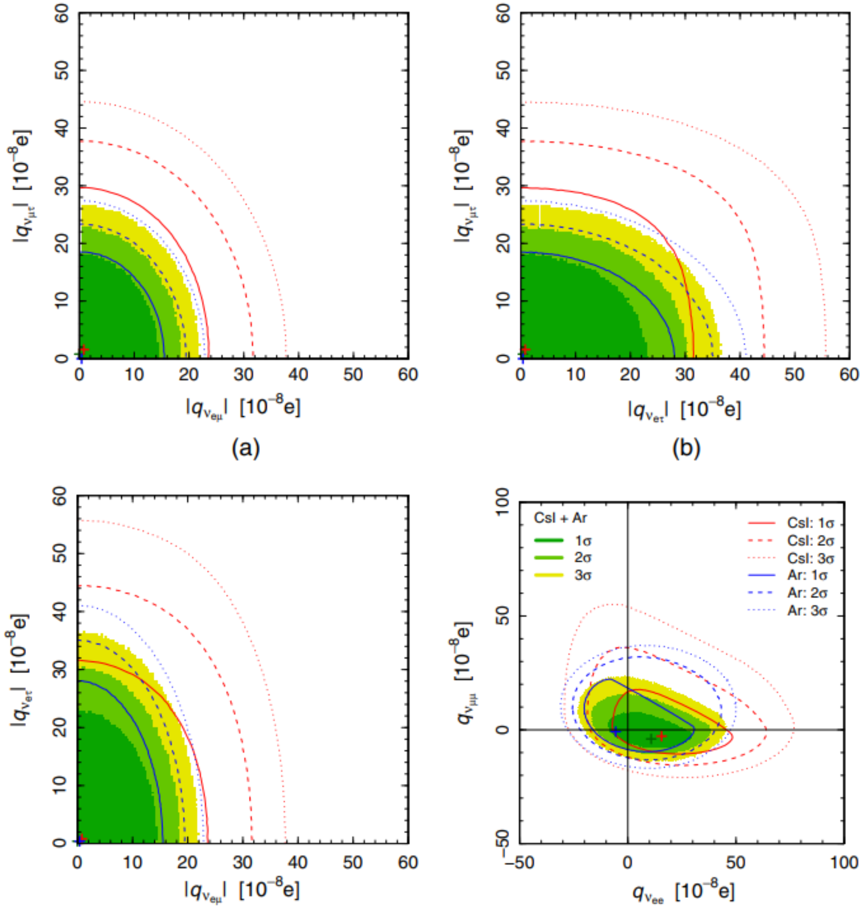
With transition charge



(a) (b)

(c) (d)

- 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.
- The limits: $\sim 10^{-7}\, e$
- The bounds on $q_{\nu_{\mu\mu}}$, $q_{\nu_{\mu\tau}}$: the first ones obtained from laboratory data.

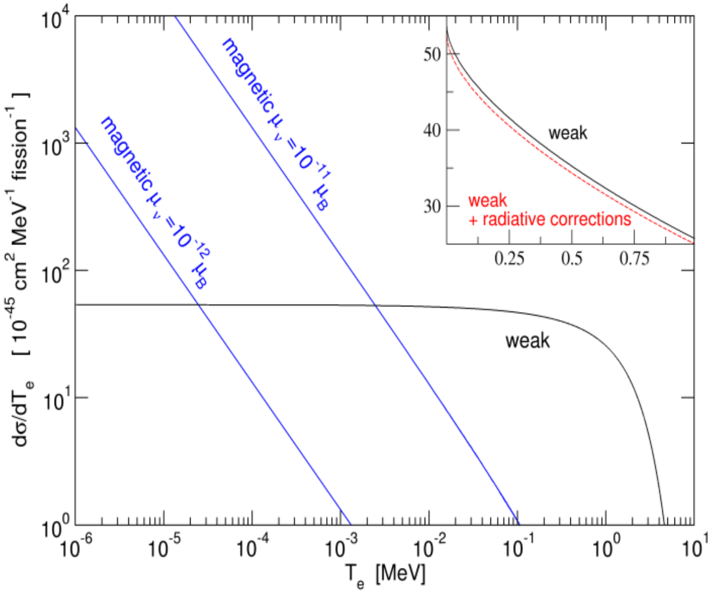
III: Neutrino Magnetic and Electric Moments

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

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

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

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



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

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

III: Fit of COHERENT data: Neutrino Magnetic Moments

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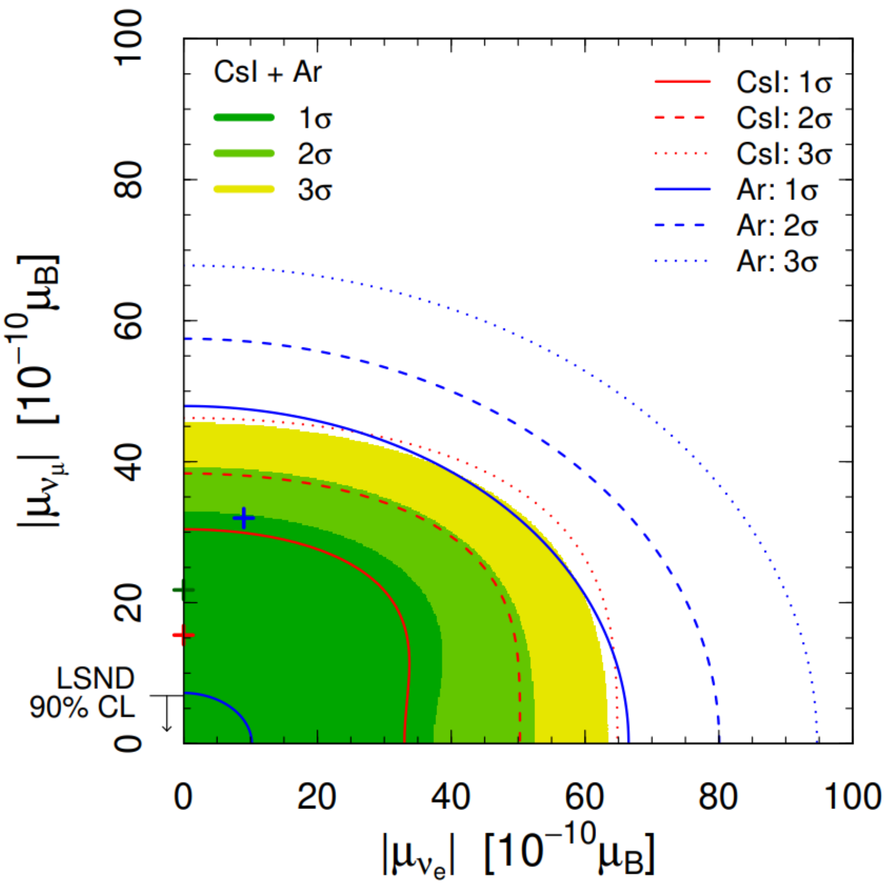

- Effective neutrino magnetic moment.
- $\mu_{\nu_e}, \mu_{\nu_\mu} \sim 10^{-9}\mu_B$

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

- Muon neutrino magnetic moment: 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:

$$-78 < \left\langle r_{\nu_e}^2 \right\rangle < 22, -71 < \left\langle r_{\nu_\mu}^2 \right\rangle < 17 \times 10^{-32}\ \mathrm{cm}^2.$$

  - obtain constraints on the neutrino millicharge:

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

  - obtain the constraints on the effective neutrino magnetic moment:

$$\left|\mu_{\nu_e}\right| < 56, \left|\mu_{\nu_\mu}\right| < 41 \times 10^{-10} \mu_B$$

- The combined fit of the COHERENT CsI and Ar : restriction of the allowed values.
- The constraints on transition charge radii, millicharge: first one obtained from laboratory data.
- CsI detector improvement: statistic and quenching.
- COHERENT Spallation Neutron Source experiment:
  - SNS:NaI, HPGe, European Spallation Source
- Reactor neutrino experiment:
  - CONUS, CONNIE, NU-CLEUS, MINER, Ricochet, TEXONO, vGEN

Thanks