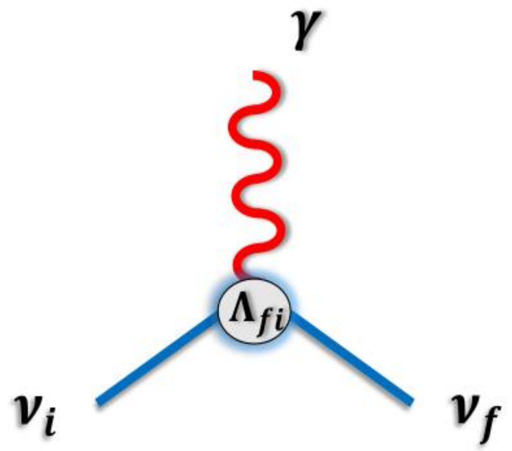
Neutrino Electromagnetic Properties:
a Window to New Physics



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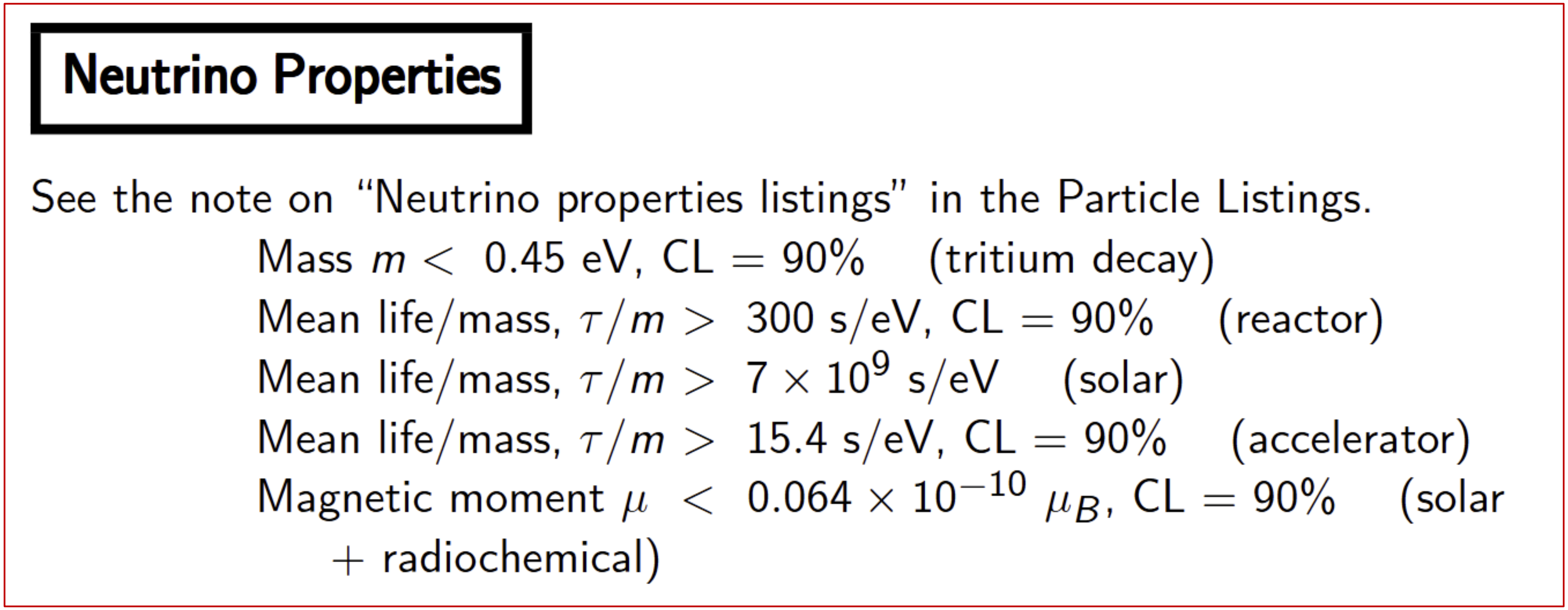
NEUTRINO '26
International Conference on Neutrino Physics and Astrophysics
June 22nd - 26th, 2026
UCI Department of Physics & Astronomy

Fundamental Properties of Neutrinos

- **Neutrino properties include mass, lifetime, electric and magnetic moment or electromagnetic properties in general**



Neutrino Properties

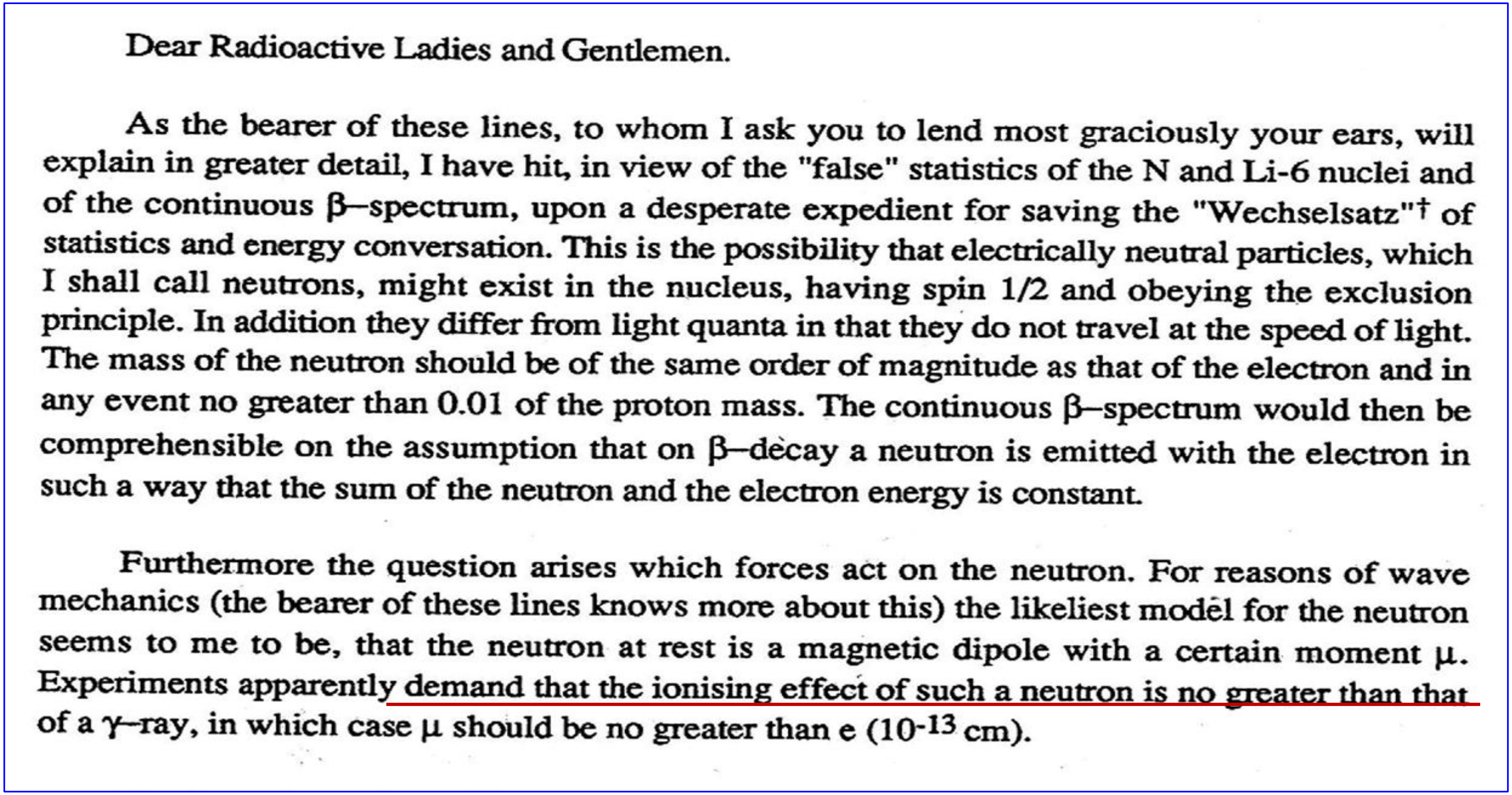
See the note on "Neutrino properties listings" in the Particle Listings.

Mass $m < 0.45$ eV, CL = 90% (tritium decay)
Mean life/mass, $\tau/m > 300$ s/eV, CL = 90% (reactor)
Mean life/mass, $\tau/m > 7 \times 10^9$ s/eV (solar)
Mean life/mass, $\tau/m > 15.4$ s/eV, CL = 90% (accelerator)
Magnetic moment $\mu < 0.064 \times 10^{-10}\ \mu_B$, CL = 90% (solar + radiochemical)

- **From the PDG quotation, this number is for the effective electron flavor neutrinos at the long-baseline limit.**

Neutrino Magnetic Moment: History

- **The neutrino magnetic moment** (MM) was introduced by Pauli in his famous letter (1930)



Dear Radioactive Ladies and Gentlemen.

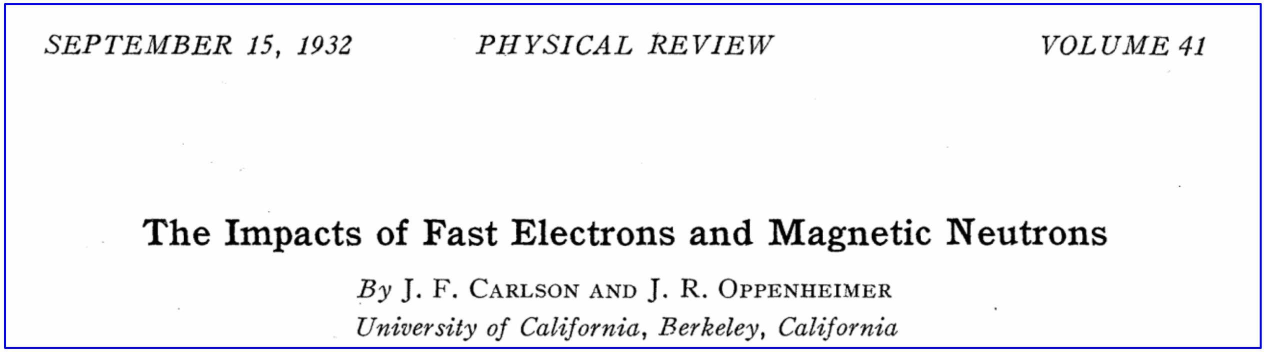
As the bearer of these lines, to whom I ask you to lend most graciously your ears, will explain in greater detail, I have hit, in view of the "false" statistics of the N and Li-6 nuclei and of the continuous β–spectrum, upon a desperate expedient for saving the "Wechselsatz"† of statistics and energy conversation. This is the possibility that electrically neutral particles, which I shall call neutrons, might exist in the nucleus, having spin 1/2 and obeying the exclusion principle. In addition they differ from light quanta in that they do not travel at the speed of light. The mass of the neutron should be of the same order of magnitude as that of the electron and in any event no greater than 0.01 of the proton mass. The continuous β–spectrum would then be comprehensible on the assumption that on β–decay a neutron is emitted with the electron in such a way that the sum of the neutron and the electron energy is constant.

Furthermore the question arises which forces act on the neutron. For reasons of wave mechanics (the bearer of these lines knows more about this) the likeliest model for the neutron seems to me to be, that the neutron at rest is a magnetic dipole with a certain moment μ. Experiments apparently demand that the ionising effect of such a neutron is no greater than that of a γ–ray, in which case μ should be no greater than e (10^{-13} cm).

Neutrino Magnetic Moment: History

- **The neutrino magnetic moment (MM) was introduced by Pauli in his famous letter (1930)**

- **Carlson and Oppenheimer (1932):**
  Neutrino propagation in matter with nonzero magnetic moment



SEPTEMBER 15, 1932 *PHYSICAL REVIEW* *VOLUME 41*

The Impacts of Fast Electrons and Magnetic Neutrons

By J. F. Carlson and J. R. Oppenheimer
University of California, Berkeley, California

- **Bethe (1935): The neutrino-electron cross section with MM could be larger than that of IBD (Bethe & Peierls, Nature 1934)**

- **First limit by Nahmias (1935):** $\mu_\nu < 2 \times 10^{-4}\,\mu_B$

- **Limits by Cowan and Reines (neutrino detection with IBD in 1956)**
  $\mu_\nu < 10^{-7}\mu_B$ **(1954);** $\mu_\nu < 10^{-9}\mu_B$ **(1957)**

A: Fundamental Theory
of Magnetic and Electric Moments of Neutrinos

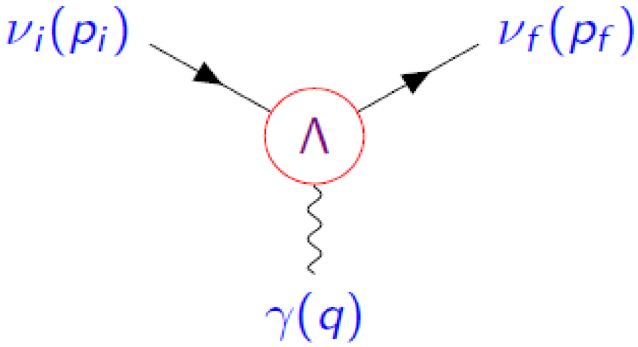
Based on the Review Article:

Ann. Rev. Nucl. Part. Sci. 75 (2025) 1-33 and updates

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:

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

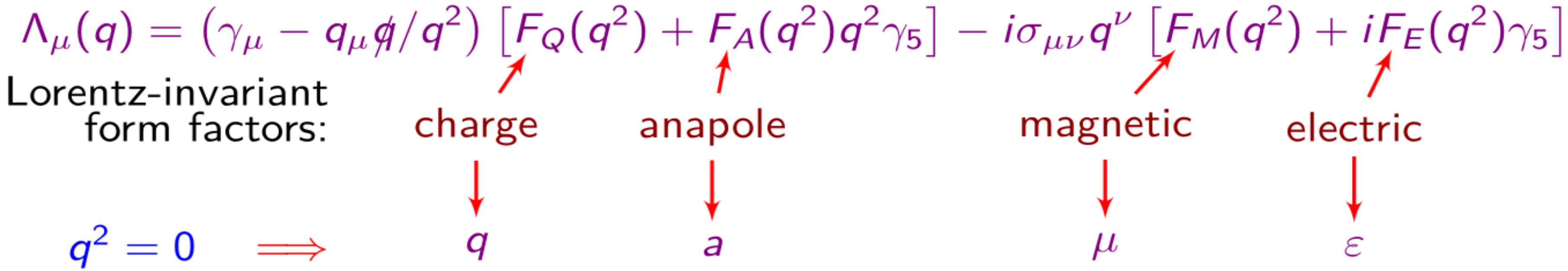
Lorentz-invariant form factors: charge ↑ F_Q, anapole ↑ F_A, magnetic ↑ F_M, electric ↑ F_E

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

helicity-conserving: q, a

helicity-flipping: μ, ε

Electromagnetic 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:

$q^2 = 0 \quad \Longrightarrow \quad q \quad a \quad \mu \quad \varepsilon$

- Hermitian form factors: $F_Q = F_Q^\dagger,\ F_A = F_A^\dagger,\ F_M = F_M^\dagger,\ F_E = F_E^\dagger$
- Majorana neutrinos: $F_Q = -F_Q^T,\ F_A = F_A^T,\ F_M = -F_M^T,\ F_E = -F_E^T$

no diagonal charges and electric and magnetic moments in the mass basis!

- Left-handed ultrarelativistic neutrinos: $\gamma_5 \to -1$:
  - charge and anapole have similar phenomenology
  - magnetic and electric moments have similar phenomenology:

dipole moments $d = \mu - i\varepsilon$

- Ultrarelativistic neutrinos: chirality $\simeq$ helicity:
  - the charge and anapole terms conserve helicity
  - the magnetic and electric terms invert helicity

Neutrino Magnetic and Electric Moment

- Effective dimension-5 Lagrangian:

$$\mathcal{L}_{\text{mag}} = \frac{1}{2} \sum_{k,j=1}^{\mathcal{N}} \overline{\nu_{Lk}}\, \sigma^{\alpha\beta} \left(\mu_{kj} + \varepsilon_{kj}\, \gamma_5 \right) N_{Rj}\, F_{\alpha\beta} + \text{H.c.}$$

- Note that the magnetic and electric moments (as the charge and anapole) are well-defined in the mass basis.

- $\mathcal{N} = 3$, $N_{Rj} = \nu_{Rj}$, and $\Delta L = 0$ $\Longrightarrow$ Dirac neutrinos with diagonal and off-diagonal (transition) magnetic and electric moments

- $\mathcal{N} = 3$ and $N_{Rj} = \nu_{Lj}^{c}$ $\Longrightarrow$ Majorana neutrinos with transition magnetic and electric moments only

- $\mathcal{N} > 3$ $\Longrightarrow$ active + sterile Dirac ($\Delta L = 0$) or Majorana neutrinos

  "neutrino dipole portal" or "neutrino magnetic moment portal"

Dirac Neutrinos

[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]

Simplest extension of the Standard Model with
three right-handed neutrinos and $\Delta L = 0$

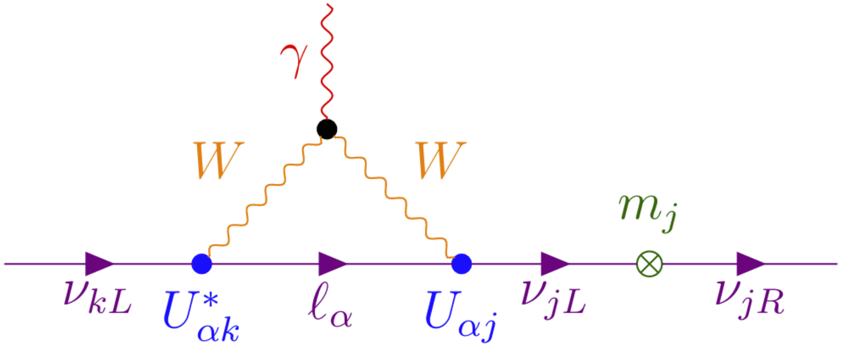
$$\mathcal{L}_{\text{mag}} = \frac{1}{2} \sum_{k,j=1}^{3} \overline{\nu_{Lk}} \, \sigma^{\alpha\beta} \left(\mu_{kj} + \varepsilon_{kj} \, \gamma_5 \right) \nu_{Rj} \, F_{\alpha\beta} + \text{H.c.}$$

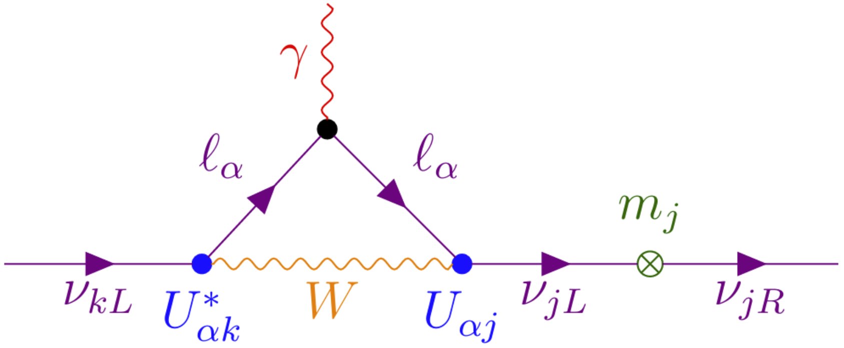
$$\left. \begin{array}{c} \mu^{\text{D}}_{kj} \\ i\varepsilon^{\text{D}}_{kj} \end{array} \right\} \simeq \frac{3eG_{\text{F}}}{16\sqrt{2}\pi^2} \left(m_k \pm m_j \right) \left(\delta_{kj} - \frac{1}{2} \sum_{\ell=e,\mu,\tau} U^{*}_{\ell k} U_{\ell j} \frac{m_\ell^2}{m_W^2} \right)$$

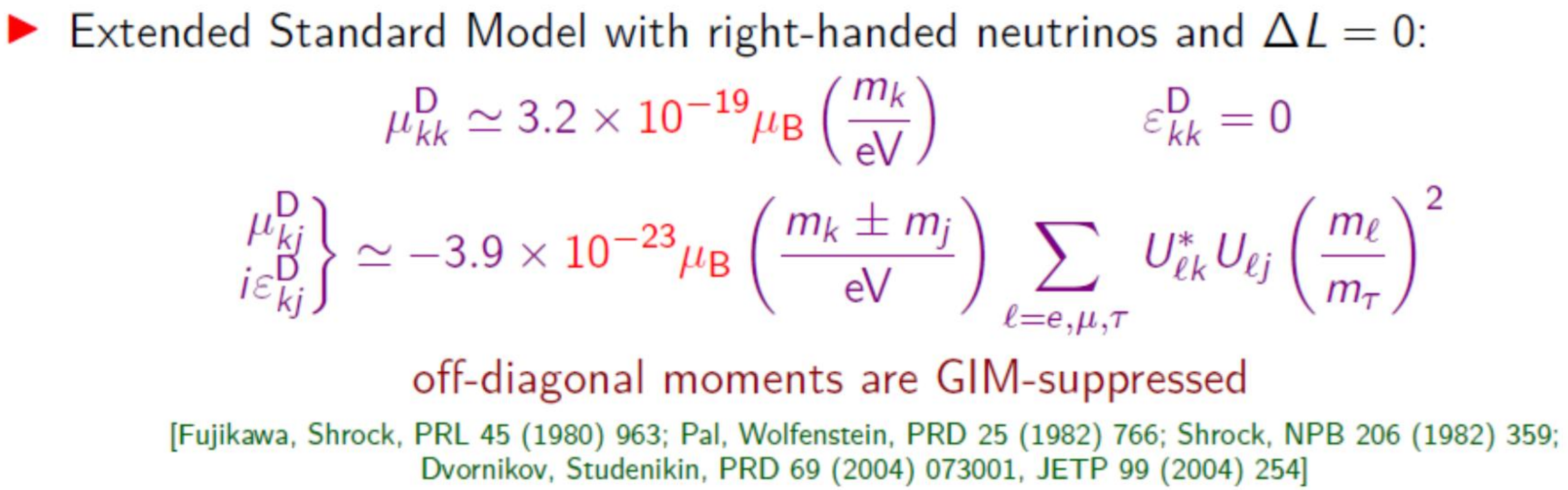
- The constraint $\Delta L = 0$ is necessary to forbid a Majorana mass term for the three right-handed neutrinos ν_{1R}, ν_{2R}, ν_{3R}.
- The magnetic and electric moments are proportional to the neutrino masses!
- This is because Standard Model interactions involve only ν_{1L}, ν_{2L}, ν_{3L}.

Dirac Neutrinos

- **After the discovery of neutrino oscillation (and thus neutrino mass), neutrino can have nonzero magnetic moment !**







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

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

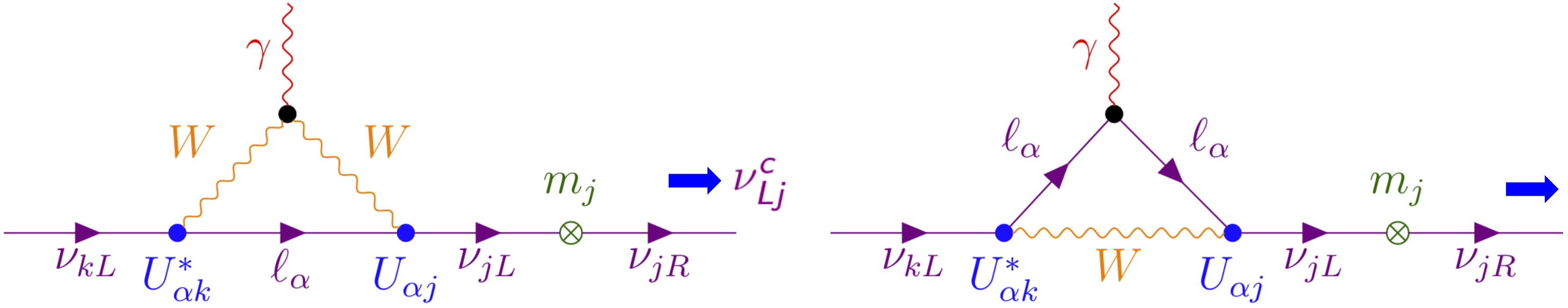
$$\left. \begin{matrix} \mu^{\mathrm{D}}_{kj} \\ i\varepsilon^{\mathrm{D}}_{kj} \end{matrix} \right\} \simeq -3.9 \times 10^{-23} \mu_{\mathrm{B}} \left(\frac{m_k \pm m_j}{\mathrm{eV}} \right) \sum_{\ell=e,\mu,\tau} U^*_{\ell k} U_{\ell j} \left(\frac{m_\ell}{m_\tau} \right)^2$$

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]

Majorana Neutrinos

- **After the discovery of neutrino oscillation (and thus neutrino mass), neutrino can have nonzero magnetic moment !**



- Only GIM-suppressed transition magnetic and electric moments $(k \neq j)$:

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

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

[Shrock, NPB 206 (1982) 359]

However, additional model-dependent contributions of the scalar sector can enhance the Majorana transition magnetic and electric moments

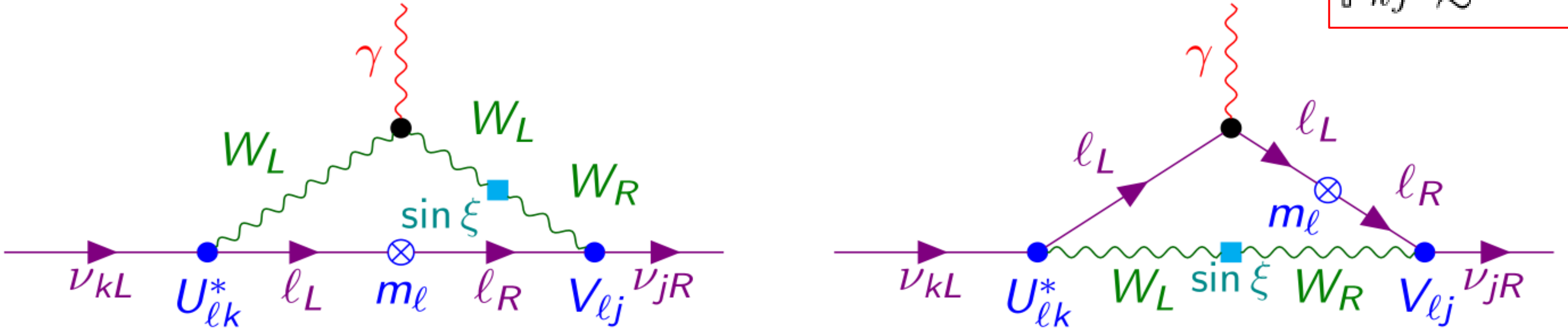
[Pal, Wolfenstein, PRD 25 (1982) 766; Barr, Freire, Zee, PRL 65 (1990) 2626; Pal, PRD 44 (1991) 2261]

How large the MMs could be ?

- Right-handed interactions mediated by W_R avoid the necessity of the mass insertion to flip chirality:

Shrock, 1982

$$\boxed{\mu_{kj} \lesssim 10^{-16} \mu_{\mathrm{B}}.}$$



- **Problem: The same diagrams without the photon line contribute to the neutrino masses → ad hoc symmetry (Voloshin 1988), vector leptons, etc.**

- **General EFT Approach to Neutrino Magnetic Moments:**

$$\mu_\nu^{\mathrm{D}} \lesssim 3 \times 10^{-15} \mu_{\mathrm{B}} \left(\frac{m_\nu}{\mathrm{eV}}\right) \left(\frac{\Lambda}{\mathrm{TeV}}\right)^{-2}$$

[Bell et al, hep-ph/0504134]

$$\mu_{\ell\ell'}^{\mathrm{M}} \lesssim 4 \times 10^{-9} \mu_{\mathrm{B}} \left(\frac{M^{\mathrm{M}}_{\ell\ell'}}{\mathrm{eV}}\right) \left(\frac{\Lambda}{\mathrm{TeV}}\right)^{-2} \left|\frac{m_\tau^2}{m_\ell^2 - m_{\ell'}^2}\right|$$

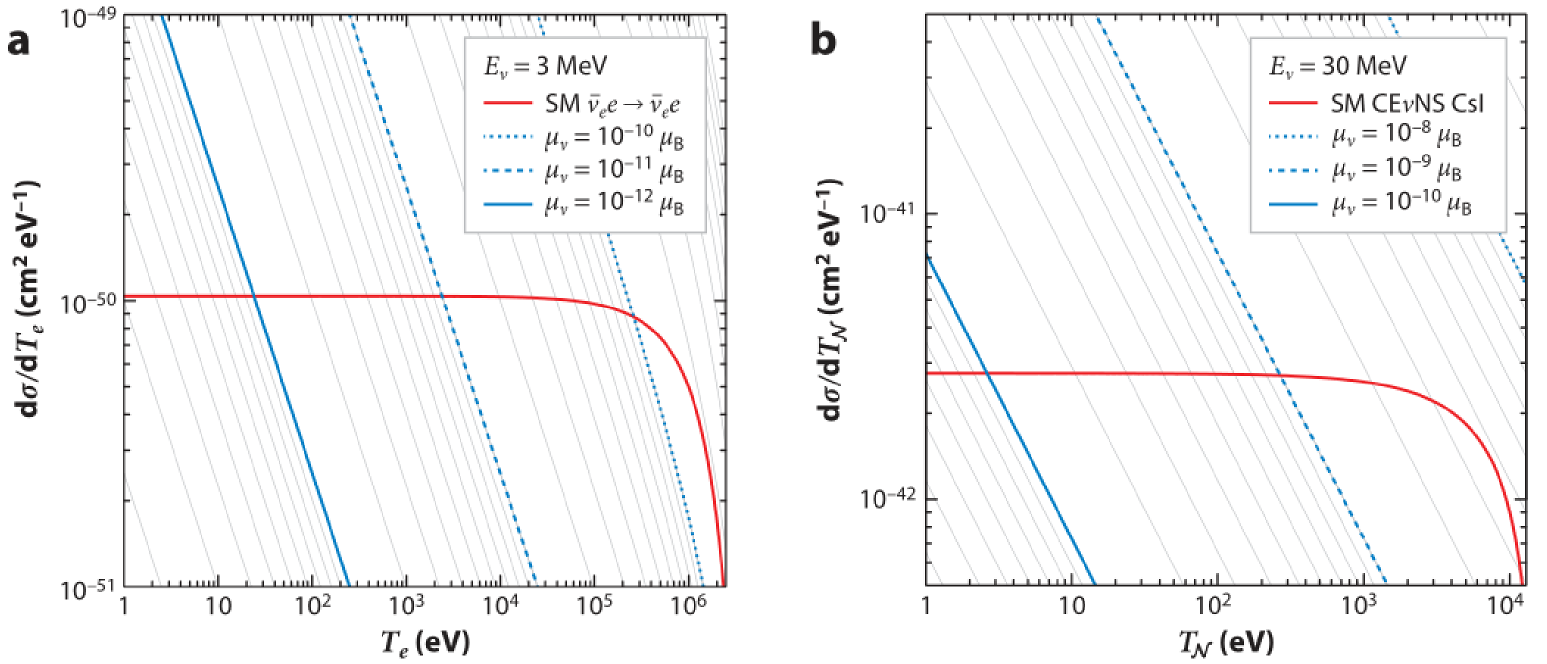
[Bell et al, hep-ph/0606248]

B: Constraints of the Magnetic Dipole Moment

Based on the Review Article:

Ann. Rev. Nucl. Part. Sci. 75 (2025) 1-33 and updates

Laboratory tests-I



- **Magnetic moment contribution could be much enhanced at lower recoils.**

→Going to smaller values of recoiled energies.

- **EνES of low energy neutrinos is among the best choices!**

Laboratory tests-II

- **Short baseline test:** **intensive beam + low threshold sensitive detectors by the electron or nucleus scattering process**

$$\nu_\ell + e^- \to \nu_{\ell'} + e^- \qquad \nu_\ell + {}^A_Z\mathcal{N} \to \nu_{\ell'} + {}^A_Z\mathcal{N}$$

$$\boxed{\frac{d\sigma(\mu_\nu)}{dT} = C\,\frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)\frac{\mu_\nu^2}{\mu_{\rm B}^2}} \qquad \boxed{\mu_{\ell'\ell} = \sum_{j,k} U_{\ell' j}\,\mu_{jk}\,U_{\ell k}^*}$$

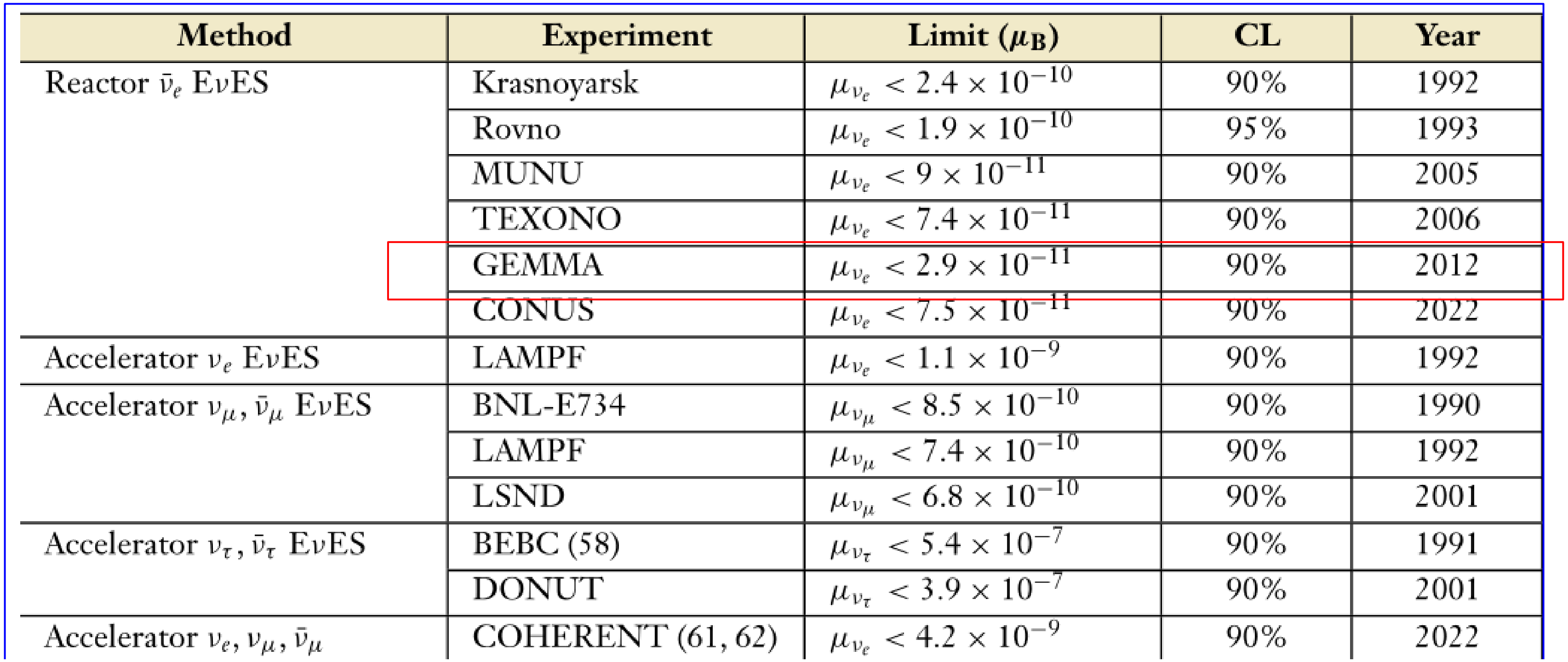
$C = Z_{\rm eff}^{\mathcal{A}}(T_e)$ and $T = T_e$ for elastic scattering with an electron bound in an atom $\mathcal{A}$; $C = Z^2[F_Z^{\mathcal{N}}(|\vec{q}|)]^2$ and $T = T_{\mathcal{N}}$ in CEνNS with a nucleus with atomic number Z.

- **Long baseline test:** **solar neutrino beam + large sensitive detectors**

$$\boxed{\mu_\nu^2 = \sum_{\ell'}\left|\sum_{\ell''}\mu_{\ell'\ell''}A_{\ell''}(E_\nu, L)\right|^2} \qquad \mu_{\rm S}^2 \simeq \sum_{\ell} P_{e\ell}^{\rm S}(E_\nu)\sum_{\ell'}|\mu_{\ell'\ell}|^2$$

- **Short and long baseline tests are probing different combinations of MMs!**

Laboratory limits at short baseline



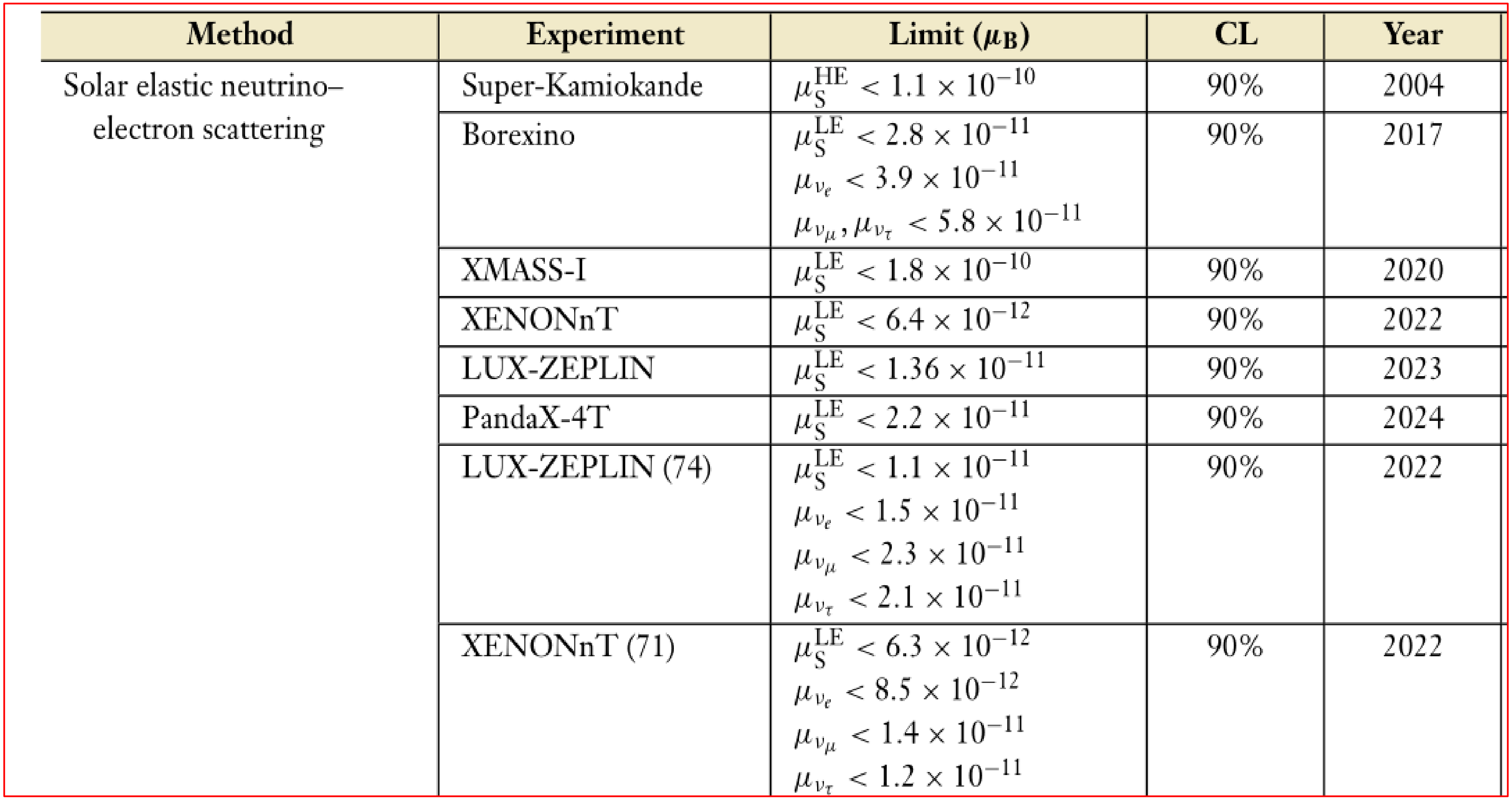
Method	Experiment	Limit (μ_B)	CL	Year
Reactor $\bar{\nu}_e$ EνES	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}$	90%	2012
	CONUS	$\mu_{\nu_e} < 7.5 \times 10^{-11}$	90%	2022
Accelerator ν_e EνES	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}$	90%	1992
Accelerator $\nu_\mu, \bar{\nu}_\mu$ EνES	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 $\nu_\tau, \bar{\nu}_\tau$ EνES	BEBC (58)	$\mu_{\nu_\tau} < 5.4 \times 10^{-7}$	90%	1991
	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}$	90%	2001
Accelerator $\nu_e, \nu_\mu, \bar{\nu}_\mu$	COHERENT (61, 62)	$\mu_{\nu_e} < 4.2 \times 10^{-9}$	90%	2022

- **Conus (2605.22815): intensive reactor antineutrinos + low-threshold Ge detectors (160 eV) by electron and nucleus scattering**

$$\mu_\nu < 5.18 \cdot 10^{-11} \mu_B \,,$$

- **The most stringent laboratory bounds come from the GEMMA:**
  → EvES with the lowest energy threshold (2.8 keV)

Laboratory tests (long baseline)



Method	Experiment	Limit (μ_B)	CL	Year
Solar elastic neutrino–electron scattering	Super-Kamiokande	$\mu_S^{HE} < 1.1 \times 10^{-10}$	90%	2004
	Borexino	$\mu_S^{LE} < 2.8 \times 10^{-11}$ $\mu_{\nu_e} < 3.9 \times 10^{-11}$ $\mu_{\nu_\mu}, \mu_{\nu_\tau} < 5.8 \times 10^{-11}$	90%	2017
	XMASS-I	$\mu_S^{LE} < 1.8 \times 10^{-10}$	90%	2020
	XENONnT	$\mu_S^{LE} < 6.4 \times 10^{-12}$	90%	2022
	LUX-ZEPLIN	$\mu_S^{LE} < 1.36 \times 10^{-11}$	90%	2023
	PandaX-4T	$\mu_S^{LE} < 2.2 \times 10^{-11}$	90%	2024
	LUX-ZEPLIN (74)	$\mu_S^{LE} < 1.1 \times 10^{-11}$ $\mu_{\nu_e} < 1.5 \times 10^{-11}$ $\mu_{\nu_\mu} < 2.3 \times 10^{-11}$ $\mu_{\nu_\tau} < 2.1 \times 10^{-11}$	90%	2022
	XENONnT (71)	$\mu_S^{LE} < 6.3 \times 10^{-12}$ $\mu_{\nu_e} < 8.5 \times 10^{-12}$ $\mu_{\nu_\mu} < 1.4 \times 10^{-11}$ $\mu_{\nu_\tau} < 1.2 \times 10^{-11}$	90%	2022

- **Low threshold DM exps. are the most sensitive probes.**
- **LS detectors with large exposure are also with great potentials.**

Astrophysical & Cosmological bounds

- **Astrophysical bounds:**
  large uncertainty, model dependence, & flavor universal

(1) Supernova bound: energy loss from MM-induced scattering from left-handed to right handed (sterile) neutrinos (escape from environment)

(2) Bounds from TRGB, Solar Cooling, Cepheid Stars, and White Dwarfs: energy loss from plasmon decay into a neutrino-antineutrino pair

$$\Gamma_{\gamma^* \to \nu\bar{\nu}}(\mu_\nu) = \frac{\mu_\nu^2}{24\pi} Z \frac{\omega_{\mathrm{P}}^2}{\omega_\gamma}$$

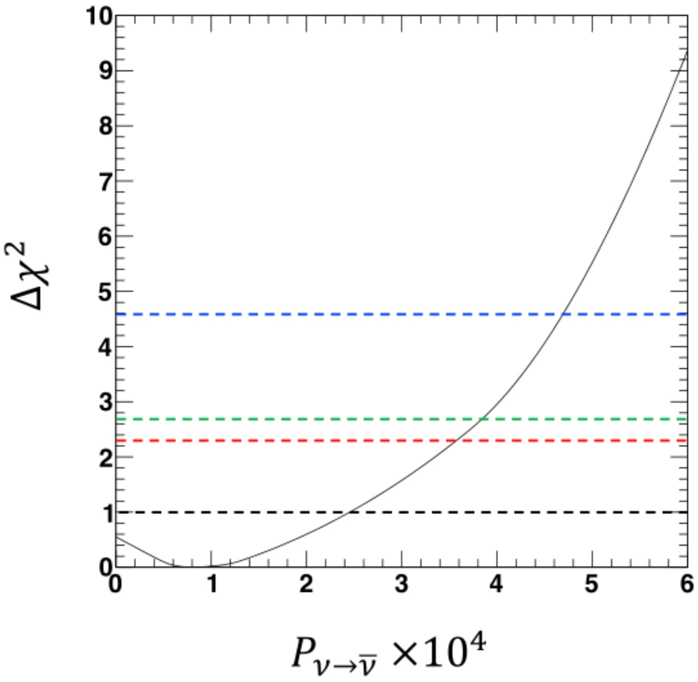
(3) Cosmological bounds: constraints on the production of right-handed neutrinos by in the primordial plasma (from the scattering of neutrinos and charged particles)

Depending on the evolution history and production time

Astrophysical & Cosmological bounds

Core-Collapse Supernovae	$\mu_\nu \lesssim (2-8)\times 10^{-12}$		1988
	$\mu_\nu \lesssim (1-4)\times 10^{-12}$		1998
	$\mu_\nu \lesssim (1.1-2.7)\times 10^{-12}$		2009
Tip of the Red Giant Branch (TRGB)	$\mu_\nu \lesssim 3\times 10^{-12}$		1989
	$\mu_\nu \lesssim 1\times 10^{-12}$		1993
	$\mu_\nu < 4.5\times 10^{-12}$	95%	2013
	$\mu_\nu \lesssim 2.6\times 10^{-12}$		2015
	$\mu_\nu < 1.2\times 10^{-12}$	95%	2020
	$\mu_\nu \lesssim (1-5)\times 10^{-12}$		2020
	$\mu_\nu \lesssim 6\times 10^{-12}$		2023
Solar Cooling	$\mu_\nu \lesssim 4\times 10^{-10}$		1999
Cepheid Stars	$\mu_\nu \lesssim 2\times 10^{-10}$		2020
White Dwarfs	$\mu_\nu \lesssim (7-9)\times 10^{-12}$		2014
	$\mu_\nu < 5\times 10^{-12}$	95%	2014
Big-Bang Nucleosynthesis (BBN)	$\mu_\nu \lesssim (1-2)\times 10^{-11}$		1981
	$\mu_\nu \lesssim 6.2\times 10^{-11}$		1997
	$\mu_\nu \lesssim 4\times 10^{-12}$		2023
Cosmological $N_{\rm eff}$	$\mu_\nu < 2.7\times 10^{-12}$	95%	2022
	$\mu_\nu < 2.6\times 10^{-12}$	95%	2022
	$\mu_\nu < 5\times 10^{-12}$	68%	2023

Spin-Flavor Precession



- Majorana neutrinos: spin-flavor precession generate active $\bar{\nu}_{eR}$:

$$\nu_{eL} \to \nu_{eR} = \bar{\nu}_{eR}$$

- $P_{\nu_{eL}\to\bar{\nu}_{eR}} < 3.6 \times 10^{-4}$ (90% CL)

[Super-Kamiokande, arXiv:2012.03807]

- 10 years 90% CL SK-Gd sensitivity:

5.5×10^{-5} (0.02% Gd loading)
2.9×10^{-5} (0.2% Gd loading)

- The interpretation of results in terms of a magnetic moment depends on the unknown magnetic field in the Sun: [Akhmedov, Pulido, hep-ph/0209192]

$$P_{\nu_{eL}\to\bar{\nu}_{eR}} \simeq 1.8 \times 10^{-10} \sin^2 2\vartheta_{12} \left(\frac{\mu_{12}}{10^{-12}\,\mu_B} \frac{B_\perp(0.05 R_\odot)}{10\,\mathrm{kG}} \right)^2$$

C: Constraints on Other Electromagnetic Properties

Based on the Review Article:

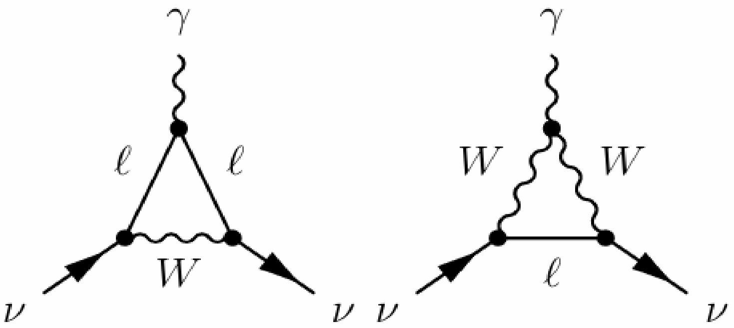
Ann. Rev. Nucl. Part. Sci. 75 (2025) 1-33 and updates

Neutrino Charge and Charge Radii

- 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

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



- $F(q^2) = \xcancel{F(0)} + q^2 \left.\frac{dF(q^2)}{dq^2}\right|_{q^2=0} + \ldots = q^2 \frac{\langle r^2 \rangle}{6} + \ldots$

- In the Standard Model:

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

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

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

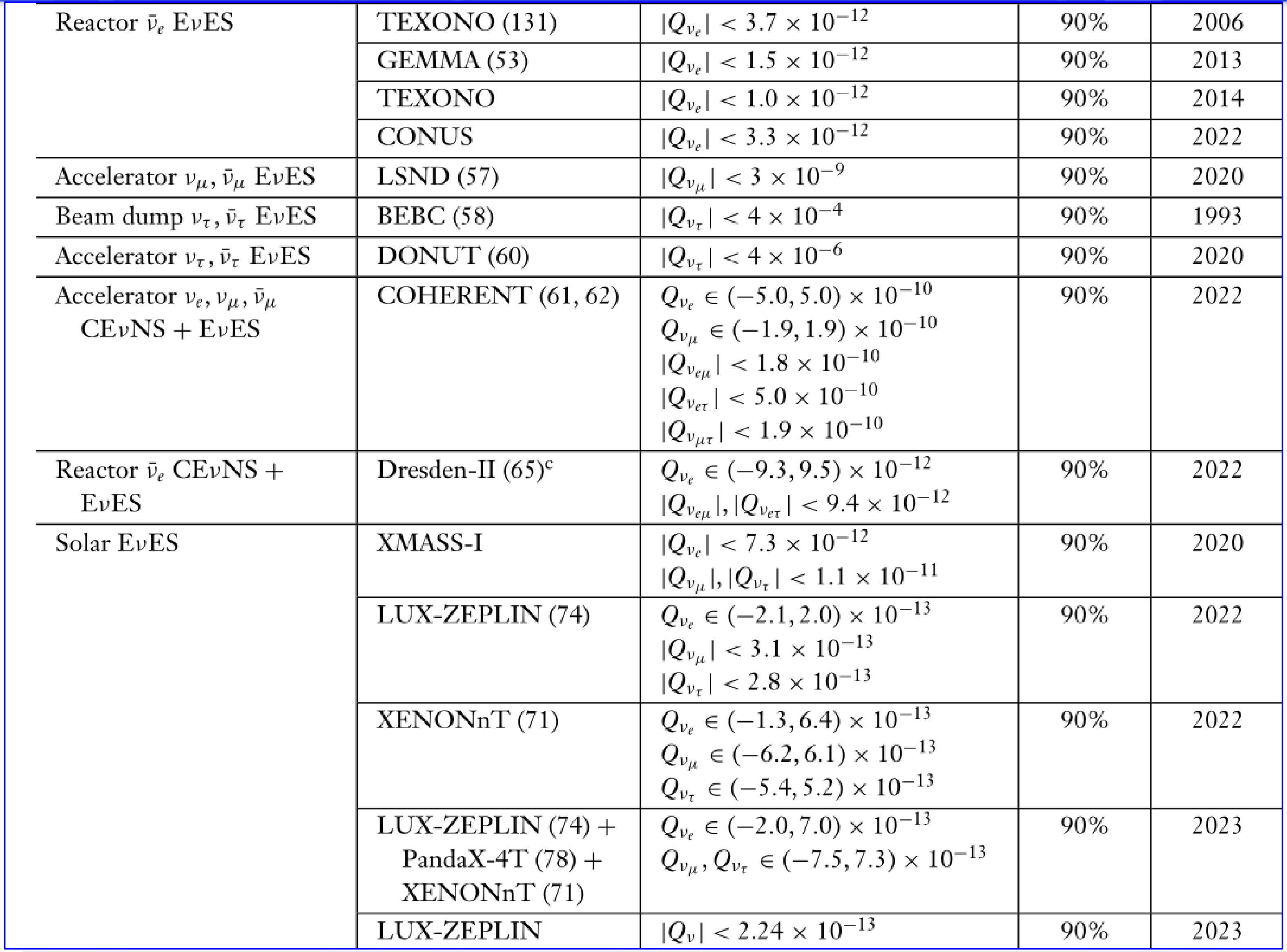
Neutrino Electron Charges

- Neutrinos can be millicharged particles in theories beyond the Standard Model. **U(1) symmetry and charge dequantization, see** **Das et al, 2005.12304 and 2504.20044**
- Neutrino charge contributions to ν_ℓ–$\mathcal{N}$ CEνNS: **→ Similar to EvES**

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

- **Enhanced at low recoiled energy with 1 / T^2**

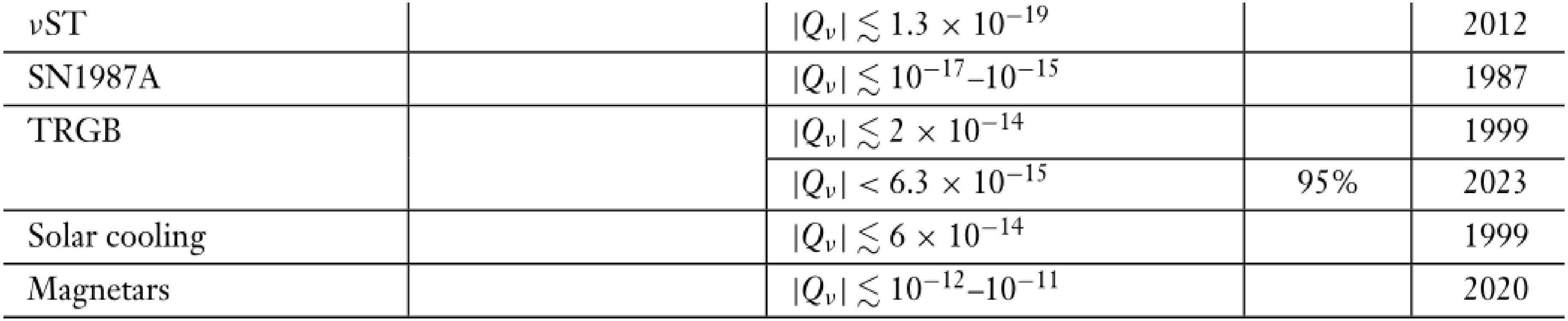
Constraints on Neutrino Electron Charges



Reactor $\bar{\nu}_e$ EνES	TEXONO (131)	$\lvert Q_{\nu_e}\rvert < 3.7 \times 10^{-12}$	90%	2006
	GEMMA (53)	$\lvert Q_{\nu_e}\rvert < 1.5 \times 10^{-12}$	90%	2013
	TEXONO	$\lvert Q_{\nu_e}\rvert < 1.0 \times 10^{-12}$	90%	2014
	CONUS	$\lvert Q_{\nu_e}\rvert < 3.3 \times 10^{-12}$	90%	2022
Accelerator $\nu_\mu, \bar{\nu}_\mu$ EνES	LSND (57)	$\lvert Q_{\nu_\mu}\rvert < 3 \times 10^{-9}$	90%	2020
Beam dump $\nu_\tau, \bar{\nu}_\tau$ EνES	BEBC (58)	$\lvert Q_{\nu_\tau}\rvert < 4 \times 10^{-4}$	90%	1993
Accelerator $\nu_\tau, \bar{\nu}_\tau$ EνES	DONUT (60)	$\lvert Q_{\nu_\tau}\rvert < 4 \times 10^{-6}$	90%	2020
Accelerator $\nu_e, \nu_\mu, \bar{\nu}_\mu$ CEνNS + EνES	COHERENT (61, 62)	$Q_{\nu_e} \in (-5.0, 5.0) \times 10^{-10}$ $Q_{\nu_\mu} \in (-1.9, 1.9) \times 10^{-10}$ $\lvert Q_{\nu_{e\mu}}\rvert < 1.8 \times 10^{-10}$ $\lvert Q_{\nu_{e\tau}}\rvert < 5.0 \times 10^{-10}$ $\lvert Q_{\nu_{\mu\tau}}\rvert < 1.9 \times 10^{-10}$	90%	2022
Reactor $\bar{\nu}_e$ CEνNS + EνES	Dresden-II (65)^c	$Q_{\nu_e} \in (-9.3, 9.5) \times 10^{-12}$ $\lvert Q_{\nu_{e\mu}}\rvert, \lvert Q_{\nu_{e\tau}}\rvert < 9.4 \times 10^{-12}$	90%	2022
Solar EνES	XMASS-I	$\lvert Q_{\nu_e}\rvert < 7.3 \times 10^{-12}$ $\lvert Q_{\nu_\mu}\rvert, \lvert Q_{\nu_\tau}\rvert < 1.1 \times 10^{-11}$	90%	2020
	LUX-ZEPLIN (74)	$Q_{\nu_e} \in (-2.1, 2.0) \times 10^{-13}$ $\lvert Q_{\nu_\mu}\rvert < 3.1 \times 10^{-13}$ $\lvert Q_{\nu_\tau}\rvert < 2.8 \times 10^{-13}$	90%	2022
	XENONnT (71)	$Q_{\nu_e} \in (-1.3, 6.4) \times 10^{-13}$ $Q_{\nu_\mu} \in (-6.2, 6.1) \times 10^{-13}$ $Q_{\nu_\tau} \in (-5.4, 5.2) \times 10^{-13}$	90%	2022
	LUX-ZEPLIN (74) + PandaX-4T (78) + XENONnT (71)	$Q_{\nu_e} \in (-2.0, 7.0) \times 10^{-13}$ $Q_{\nu_\mu}, Q_{\nu_\tau} \in (-7.5, 7.3) \times 10^{-13}$	90%	2023
	LUX-ZEPLIN	$\lvert Q_\nu\rvert < 2.24 \times 10^{-13}$	90%	2023

Constraints on Neutrino Electron Charges

➢ Astrophysical bounds



νST		$\lvert Q_\nu \rvert \lesssim 1.3 \times 10^{-19}$		2012
SN1987A		$\lvert Q_\nu \rvert \lesssim 10^{-17}$–$10^{-15}$		1987
TRGB		$\lvert Q_\nu \rvert \lesssim 2 \times 10^{-14}$		1999
		$\lvert Q_\nu \rvert < 6.3 \times 10^{-15}$	95%	2023
Solar cooling		$\lvert Q_\nu \rvert \lesssim 6 \times 10^{-14}$		1999
Magnetars		$\lvert Q_\nu \rvert \lesssim 10^{-12}$–$10^{-11}$		2020

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, arXiv:1403.6344]

Neutrino Charge Radii from CEvNS

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

→ Similar to EvES

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

- In the Standard Model there are only diagonal charge radii $\langle r_{\nu_\ell}^2\rangle \equiv \langle r_{\nu_{\ell\ell}}^2\rangle$ because lepton numbers are conserved.
- Diagonal charge radii generate the coherent shifts

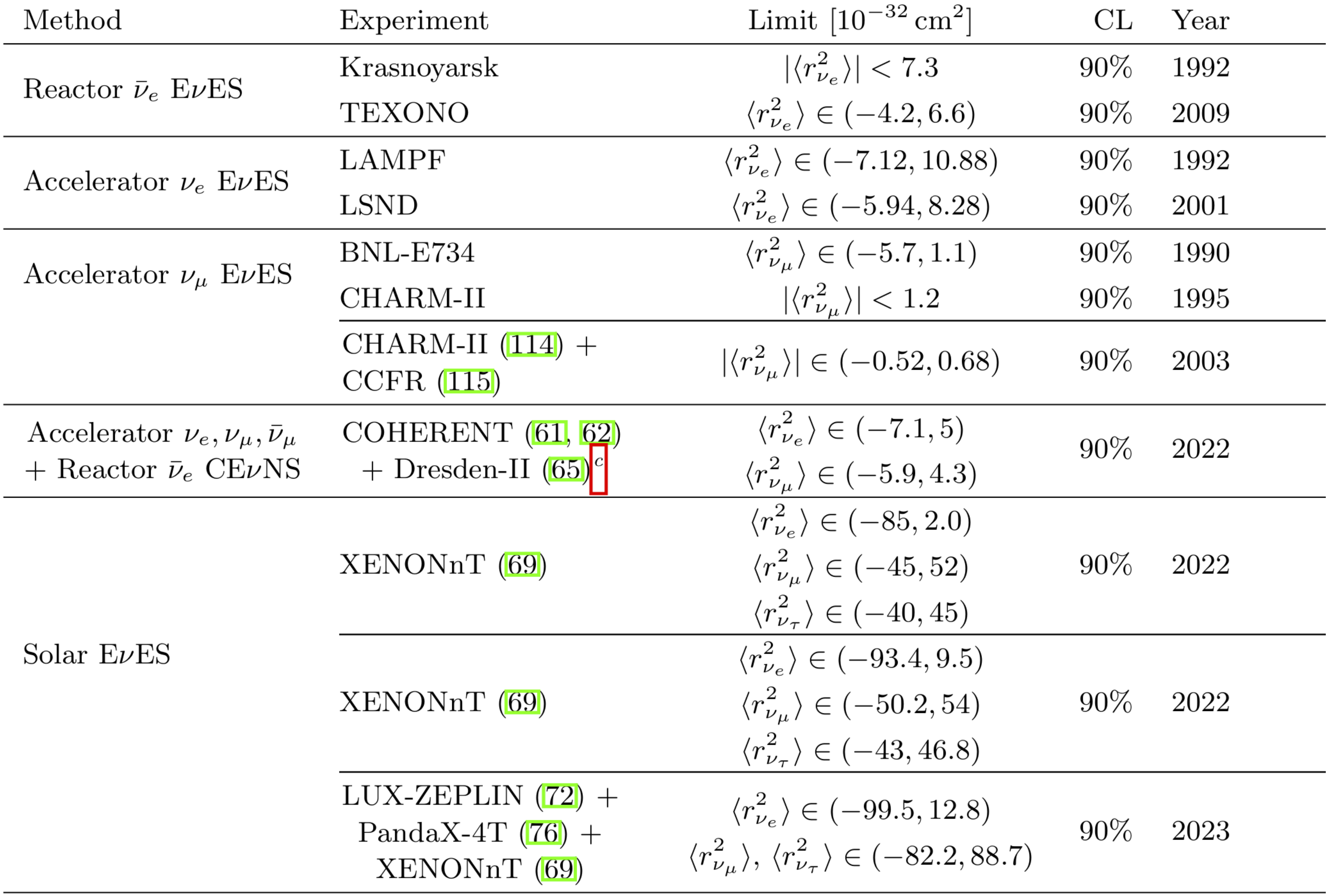
$$\sin^2\vartheta_W \to \sin^2\vartheta_W\left(1+\frac{1}{3}m_W^2\langle r_{\nu_\ell}^2\rangle\right) \quad \Longleftrightarrow \quad \nu_\ell + \mathcal{N} \to \nu_\ell + \mathcal{N}$$

- Transition charge radii generate the incoherent contribution

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

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

Constraints on the Neutrino Charge Radii

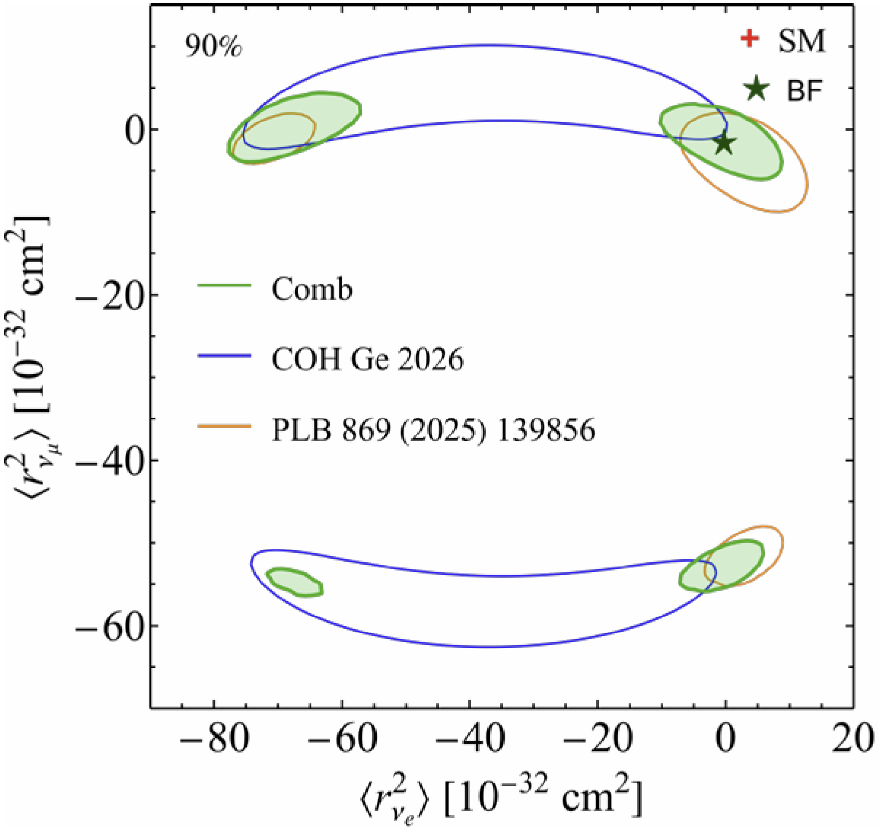


Method	Experiment	Limit $[10^{-32}\ \mathrm{cm}^2]$	CL	Year
Reactor $\bar{\nu}_e$ EνES	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3$	90%	1992
	TEXONO	$\langle r^2_{\nu_e}\rangle \in (-4.2, 6.6)$	90%	2009
Accelerator ν_e EνES	LAMPF	$\langle r^2_{\nu_e}\rangle \in (-7.12, 10.88)$	90%	1992
	LSND	$\langle r^2_{\nu_e}\rangle \in (-5.94, 8.28)$	90%	2001
Accelerator ν_μ EνES	BNL-E734	$\langle r^2_{\nu_\mu}\rangle \in (-5.7, 1.1)$	90%	1990
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2$	90%	1995
	CHARM-II (114) + CCFR (115)	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert \in (-0.52, 0.68)$	90%	2003
Accelerator $\nu_e, \nu_\mu, \bar{\nu}_\mu$ + Reactor $\bar{\nu}_e$ CEνNS	COHERENT (61, 62) + Dresden-II (65)^c	$\langle r^2_{\nu_e}\rangle \in (-7.1, 5)$ $\langle r^2_{\nu_\mu}\rangle \in (-5.9, 4.3)$	90%	2022
Solar EνES	XENONnT (69)	$\langle r^2_{\nu_e}\rangle \in (-85, 2.0)$ $\langle r^2_{\nu_\mu}\rangle \in (-45, 52)$ $\langle r^2_{\nu_\tau}\rangle \in (-40, 45)$	90%	2022
	XENONnT (69)	$\langle r^2_{\nu_e}\rangle \in (-93.4, 9.5)$ $\langle r^2_{\nu_\mu}\rangle \in (-50.2, 54)$ $\langle r^2_{\nu_\tau}\rangle \in (-43, 46.8)$	90%	2022
	LUX-ZEPLIN (72) + PandaX-4T (76) + XENONnT (69)	$\langle r^2_{\nu_e}\rangle \in (-99.5, 12.8)$ $\langle r^2_{\nu_\mu}\rangle,\ \langle r^2_{\nu_\tau}\rangle \in (-82.2, 88.7)$	90%	2023

Constraints on the Neutrino Charge Radii

- ➢ New limits on neutrino charge radii after recent measurements:

+ Reactor CEνNS data from CONUS+ [arXiv:2501.05206]
+ COHERENT Ge 2026 dataset [2603.17951]



$$\langle r^2_{\nu_e}\rangle = -0.3^{+4.4}_{-4.3}(1\sigma),{}^{+6.9}_{-7.4}\,(90\%)\times 10^{-32}\ \mathrm{cm}^2,$$
$$\langle r^2_{\nu_\mu}\rangle = -1.6^{+3.8}_{-1.9}(1\sigma),{}^{+5.0}_{-3.3}\,(90\%)\times 10^{-32}\ \mathrm{cm}^2.$$

- ➢ Most precision constraints from CEνNS data [2605.07975]
- ➢ See also 2605.27121 and 2605.22815

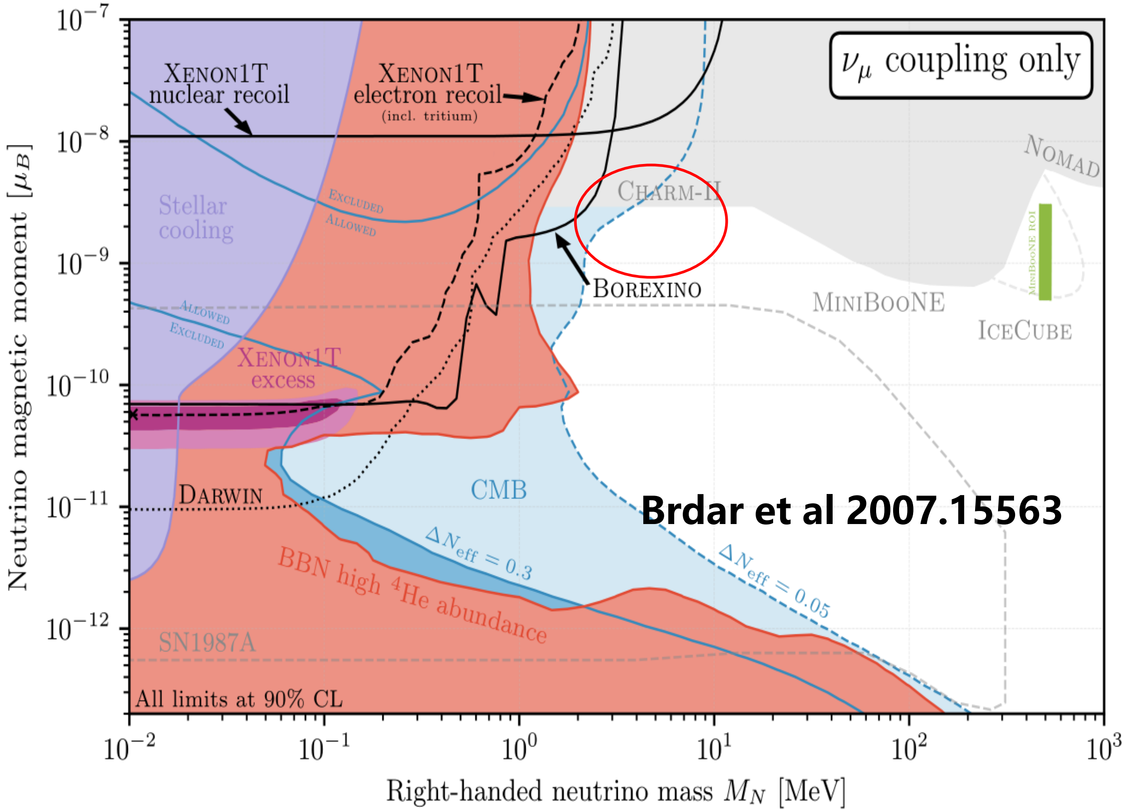
- ➢ CEνNS is one of the most powerful probes of neutrino charge radii !

Neutrino Dipole Portal

$$\mathcal{L}_{\rm NDP} = \frac{d_\alpha}{2}(\bar{N}\sigma_{\mu\nu}\nu^\alpha F^{\mu\nu}) + \text{h.c.}$$

An important portal to the dark sector

$$d_\alpha = \frac{\sqrt{\pi\alpha_{\rm EM}}}{m_e}\left|\frac{\mu_{\nu_\alpha}}{\mu_B}\right| \simeq 296\left|\frac{\mu_{\nu_\alpha}}{\mu_B}\right| \quad {\rm GeV}^{-1}$$



Brdar et al 2007.15563

- **Above GeV:**
  LEP/LHC with 10^{-3} GeV^{-1}
- **Below MeV:**
  strong BBN bound
- **Sub GeV: SN1987A**
- **MeV — GeV:**
  ν scattering plays an important role!
  Borexino, CHARM-II etc.

CEvNS: MeV to 50 MeV

Li, YFL, Xia, 2406.07477

Conclusion

- Neutrino Electromagnetic Interactions are expected in the Standard Model (charge radii) and in BSM theories: dipole magnetic and electric moments, non-standard charge radii, and millicharges
- The existence of neutrino magnetic moments is related to the existence of neutrino masses through chirality flipping BSM operators.
- Current laboratory limits are at the level of $10^{-11} - 10^{-10}\,\mu_B$
- Conjectural theoretical expectations:
  - $\mu \lesssim 10^{-14}\,\mu_B$ for Dirac neutrinos.
  - Maybe larger for Majorana neutrinos.

- Limits on the neutrino charges and charge radii.

More details see Ann.Rev.Nucl.Part.Sci. 75 (2025) 1-33 ***Thank you !***