Neutrino Properties from Coherent Elastic Neutrino-Nucleus Scattering

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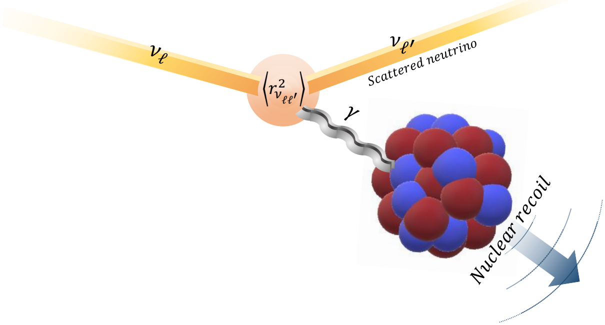
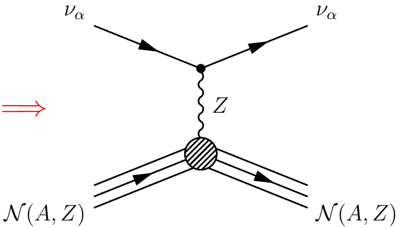


Coherent Elastic Neutrino-Nucleus Scattering

- CEνNS: pronounced "sevens"
- Neutral-Current (NC) interaction: $\boxed{\nu + \mathcal{N}(A,Z) \to \nu + \mathcal{N}(A,Z)}$

Standard Model $\Longrightarrow$



- The nucleus $\mathcal{N}(A,Z)$ recoils without any internal change of state!
- CEνNS was predicted in 1974! [Freedman, PRD 9 (1974) 1389]
- Experimental difficulty: low nuclear recoil kinetic energy $T \lesssim 10\,\text{keV}$
- CEνNS was observed for the first time 43 years later, in 2017 by the COHERENT experiment at the Oak Ridge Spallation Neutron Source with CsI ($^{133}_{55}\text{Cs}_{78}$, $^{127}_{53}\text{I}_{74}$) [COHERENT, arXiv:1708.01294]
- Second observation in 2020 by the COHERENT experiment with a LAr detector ($^{40}_{18}\text{Ar}_{22}$) [COHERENT, arXiv:2003.10630]

CEνNS Cross Section

Standard Model: $$\frac{d\sigma_{\text{CE}\nu\text{NS}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[Q_W^{SM}(Q^2)\right]^2$$

- Weak charge of the nucleus $\mathcal{N}$:

$$\boxed{|\vec{q}| = \sqrt{2\,M\,T}}$$

$$Q_W^{SM}(Q^2) = g_V^n\,N\,F_N(|\vec{q}|) + g_V^p\,Z\,F_Z(|\vec{q}|)$$

$$g_V^n = -\frac{1}{2} \qquad g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W(Q^2 \simeq 0) = 0.0227 \pm 0.0002$$

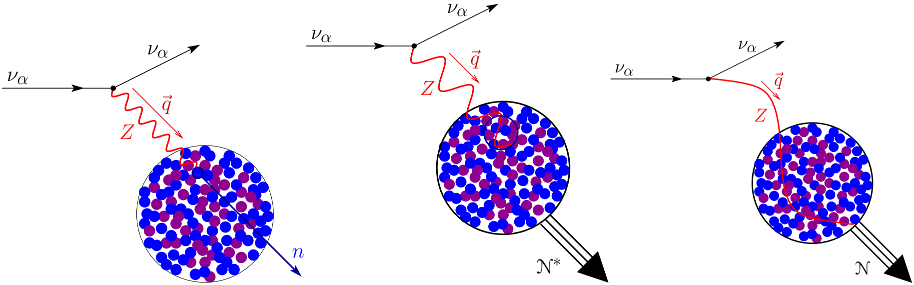
The neutron contribution is dominant! $\Longrightarrow$ $\dfrac{d\sigma_{\text{CE}\nu\text{NS}}}{dT} \propto\!\!\!\!\sim N^2$

[Freedman, PRD 9 (1974) 1389; Drukier, Stodolsky, PRD 30 (1984) 2295; Barranco, Miranda, Rashba, hep-ph/0508299]

- The coherent nuclear recoil gives a big cross section enhancement for heavy nuclei: $\sigma_{\text{NC}}^{\text{incoherent}} \propto\!\!\!\!\sim N \Longrightarrow \sigma_{\text{CE}\nu\text{NS}}/\sigma_{\text{NC}}^{\text{incoherent}} \propto\!\!\!\!\sim N$

- The nuclear form factors $F_N(|\vec{q}|)$ and $F_Z(|\vec{q}|)$ describe the loss of coherence for $|\vec{q}|R \gtrsim 1$. [Patton et al, arXiv:1207.0693; Bednyakov, Naumov, arXiv:1806.08768; Papoulias et al, arXiv:1903.03722; Ciuffoli et al, arXiv:1801.02166; Canas et al, arXiv:1911.09831; Van Dessel et al, arXiv:2007.03658]

Neutrino-Nucleus Scattering

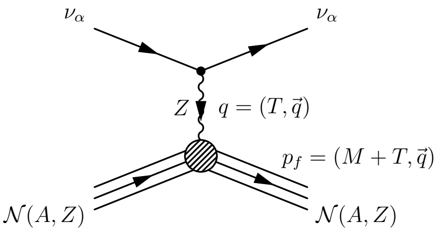


Inelastic Incoherent	Elastic Incoherent	Elastic Coherent
$\lambda_Z \ll R$	$\lambda_Z \lesssim R$	$\lambda_Z \gtrsim 2R$

$$\lambda_Z = 2\pi \frac{\hbar}{|\vec{q}|} \quad \Longrightarrow \quad \text{CE}\nu\text{NS for } |\vec{q}|\, R \lesssim \hbar$$

$$\boxed{|\vec{q}|\, R \lesssim 1} \quad \longleftarrow \quad \text{Natural Units}$$

$$\boxed{|\vec{q}|\, R \lesssim 1}$$



- Heavy target nucleus $\mathcal{N}(A, Z)$:

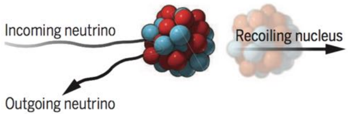
$$A \sim 100 \qquad M \sim 100\,\text{GeV}$$

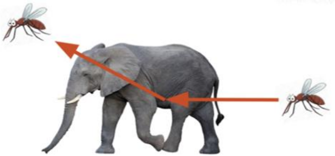
$$R \approx 1.2\, A^{1/3}\,\text{fm} \approx 5\,\text{fm}$$

- CEνNS for $|\vec{q}| \lesssim 40\,\text{MeV}$

- Non-Relativistic nuclear recoil:

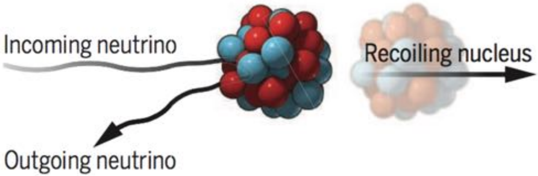
$$|\vec{q}| \simeq \sqrt{2\, M\, T} \qquad\qquad q^0 = T \quad \leftarrow \quad \text{Kinetic Energy}$$





- Observable nuclear recoil kinetic energy:

$$T \simeq \frac{|\vec{q}|^2}{2\,M} \lesssim 10\,\text{keV} \quad \leftarrow \quad \text{Very Small!}$$



Maximum momentum transfer for $\vec{p}_{\nu_f} = -\vec{p}_{\nu_i}$

$$\vec{q} = \vec{p}_{\nu_i} - \vec{p}_{\nu_f} \implies \underbrace{|\vec{q}|}_{\sqrt{2\,M\,T}} \leq 2\,|\vec{p}_{\nu_i}| = 2\,E_\nu$$

$$\boxed{T \leq \frac{2\,E_\nu^2}{M}}$$

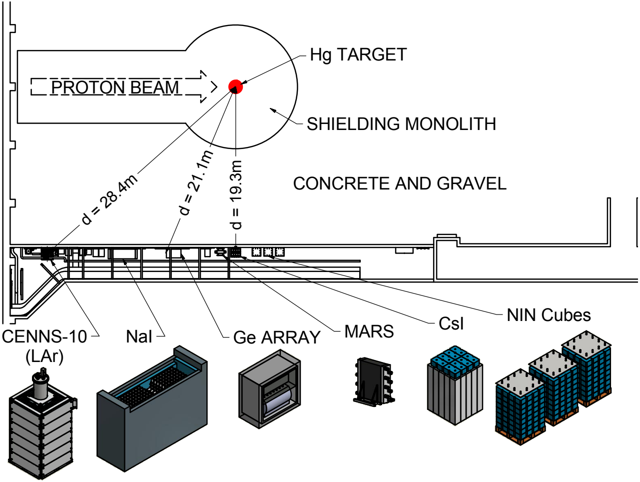
Low-energy neutrinos are needed!

$$T \lesssim 10\,\text{keV} \quad \text{and} \quad M \sim 100\,\text{GeV} \implies E_\nu \lesssim 30\,\text{MeV}$$

- Main natural sources: Sun, Supernova, Geoneutrinos.
- Main artificial sources: Reactor, Stopped pions, Radioactive nuclei.

The COHERENT Experiment

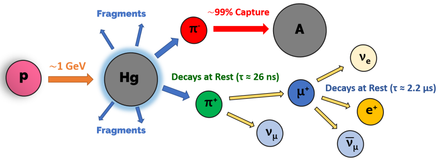
Oak Ridge Spallation Neutron Source



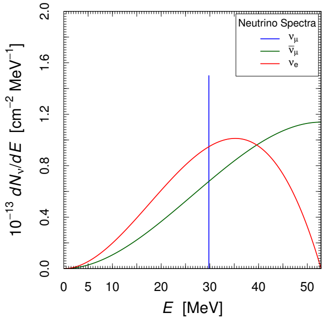
14.6 kg CsI
scintillating crystal

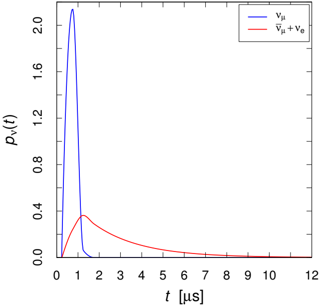
[COHERENT, arXiv:1803.09183]

COHERENT Stopped-Pion Neutrino Source



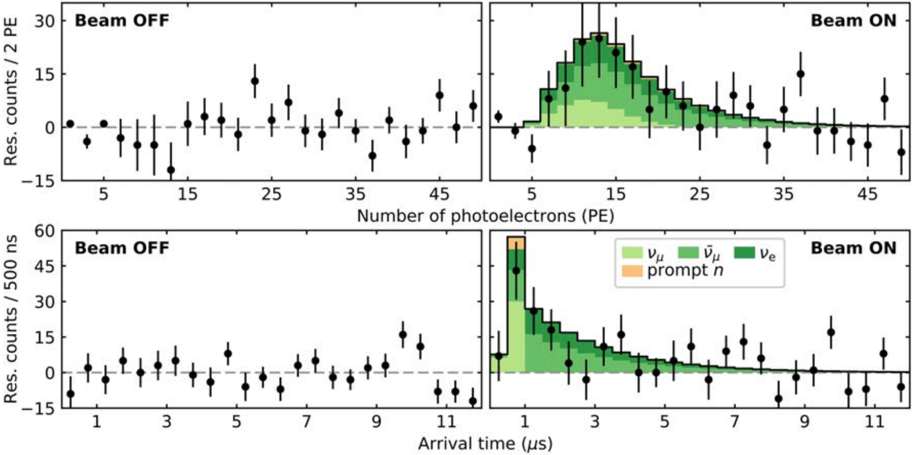
- Prompt monochromatic ν_μ from stopped pion decays:
$$\pi^+ \to \mu^+ + \nu_\mu$$
- Delayed $\bar{\nu}_\mu$ and ν_e from the subsequent muon decays:
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$
- Allows to probe SM and BSM neutral current ν_e and ν_μ interactions, that are distinguished by different energy and time distributions





COHERENT 2017: Cesium Iodide (CsI)

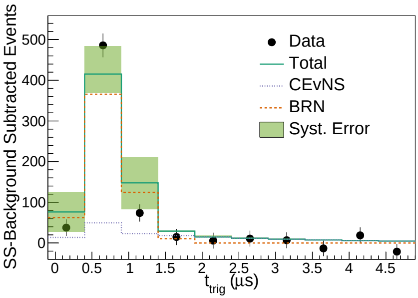
[arXiv:1708.01294]

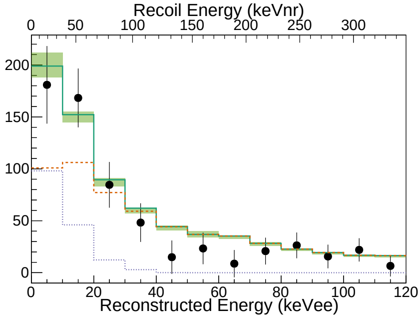


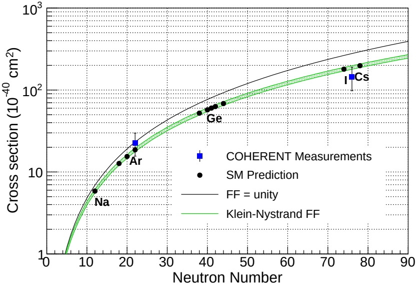
${}^{133}_{55}\mathrm{Cs}_{78}$ and ${}^{127}_{53}\mathrm{I}_{74}$ $\leftarrow$ Heavy nuclei well suited for CEνNS

COHERENT 2020: Argon (Ar)

[arXiv:2003.10630]





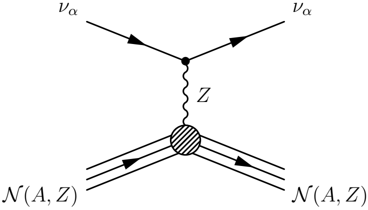


${}^{40}_{18}\mathrm{Ar}_{22}$ not so heavy

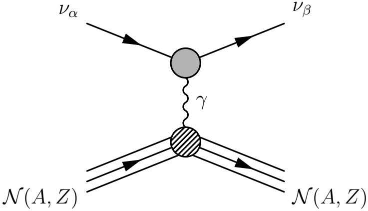
Verified theoretical $\boxed{\sigma \propto N^2}$

SM and BSM CEνNS Neutrino Interactions

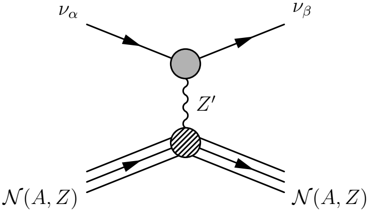
Standard Model NC



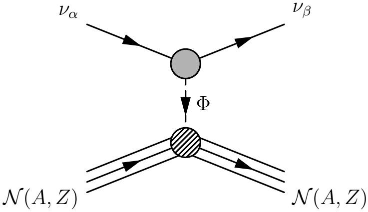
Electromagnetic Interactions



BSM Vector Mediator



BSM Scalar Mediator



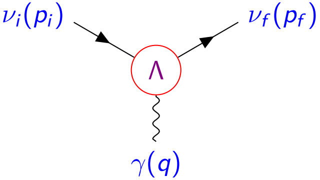
Neutrino Electromagnetic Interactions

- 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

$q^2 = 0 \implies$ q, a, μ, ε

helicity-conserving (q, a) — helicity-flipping (μ, ε)

Electromagnetic 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

$q^2 = 0 \implies$ q, a, μ, ε

- 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

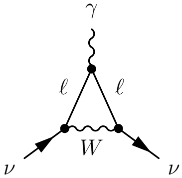
- For left-handed ultrarelativistic neutrinos $\gamma_5 \to -1 \Rightarrow$ The phenomenology of the charge and anapole are similar and the phenomenology of the magnetic and electric moments are similar.
- For ultrarelativistic neutrinos the charge and anapole terms conserve helicity, whereas the magnetic and electric terms invert helicity.

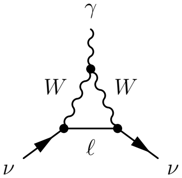
Neutrino Charge Radius

- 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 CG, Studenikin, arXiv:1403.6344
and the update in Cadeddu, CG, Kouzakov, Li, Studenikin, Zhang, arXiv:1810.05606]

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

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

- 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

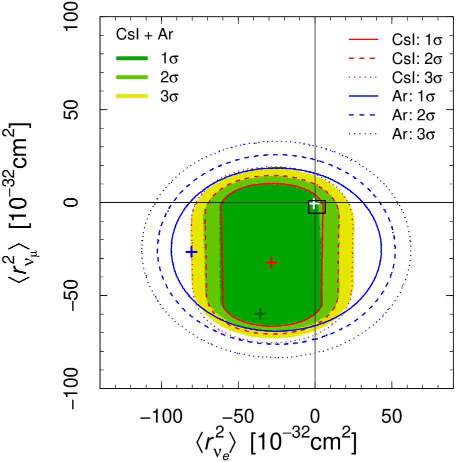
$$\sin^2\vartheta_W \to \sin^2\vartheta_W \left(1 + \frac{1}{3} m_W^2 \langle r^2_{\nu_\ell}\rangle\right) \quad \Longleftrightarrow \quad \nu_\ell + \mathcal{N} \to \nu_\ell + \mathcal{N}$$

- Transition charge radii generate the incoherent contribution

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

[Kouzakov, Studenikin, arXiv:1703.00401]

COHERENT constraints on neutrino charge radii



$$
\begin{aligned}
|\langle r^2_{\nu_{e\mu}} \rangle| &< 36 \times 10^{-32}\ \mathrm{cm}^2 \\
|\langle r^2_{\nu_{e\tau}} \rangle| &< 50 \times 10^{-32}\ \mathrm{cm}^2 \qquad (3\sigma) \\
|\langle r^2_{\nu_{\mu\tau}} \rangle| &< 44 \times 10^{-32}\ \mathrm{cm}^2
\end{aligned}
$$

[Cadeddu, Dordei, CG, Li, Picciau, Zhang, arXiv:2005.01645]

Effective charge radii
in the flavor basis:

$$\langle r^2_{\nu_{\ell\ell'}} \rangle = \sum_{j,k} U^*_{\ell j} U_{\ell' k} \langle r^2_{\nu_{jk}} \rangle$$

[see also: Papoulias, Kosmas, arXiv:1711.09773; Cadeddu, CG, Kouzakov, Li, Studenikin, Zhang, arXiv:1810.05606; Papoulias, arXiv:1907.11644; Khan, Rodejohann, arXiv:1907.12444; Cadeddu, Dordei, CG, Li, Zhang, arXiv:1908.06045; Miranda, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, arXiv:2003.12050]

Neutrino Electric Charges

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

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

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

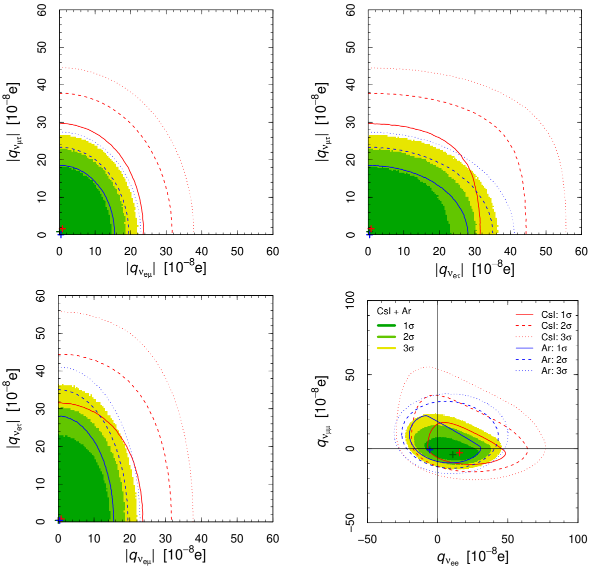
- $q_{\bar{\nu}_{\ell\ell'}} = -q_{\nu_{\ell\ell'}}$, but also $g_V^{p,n}(\bar{\nu}) = -g_V^{p,n}(\nu)$.

Limits on neutrino millicharges

Limit	Method	Reference
$\lvert q_{\nu_e}\rvert \lesssim 3 \times 10^{-21}\, e$	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)
$\lvert q_{\nu_e}\rvert \lesssim 1.0 \times 10^{-12}\, e$	Nuclear reactors	Chen et al (2014)
$\lvert q_{\nu_\mu}\rvert \lesssim 3 \times 10^{-8}\, e$	COHERENT CEνNS	Cadeddu et al (2020)
$\lvert q_{\nu_{\mu\tau}}\rvert \lesssim 2 \times 10^{-8}\, e$	COHERENT CEνNS	Cadeddu et al (2020)
$\lvert q_{\nu_\mu}\rvert \lesssim 3 \times 10^{-9}\, e$	LSND	Das et al (2020)
$\lvert q_{\nu_\tau}\rvert \lesssim 4 \times 10^{-6}\, e$	DONUT	Das et al (2020)
$\lvert q_{\nu_\tau}\rvert \lesssim 4 \times 10^{-4}\, e$	BEBC beam dump	Babu et al (1993)
$\lvert q_{\nu}\rvert \lesssim 3 \times 10^{-4}\, e$	SLAC e^- beam dump	Davidson et al (1991)
$\lvert q_{\nu}\rvert \lesssim 6 \times 10^{-14}\, e$	Solar cooling (plasmon decay)	Raffelt (1999)
$\lvert q_{\nu}\rvert \lesssim 2 \times 10^{-14}\, e$	Red giant cooling (plasmon decay)	Raffelt (1999)
$\lvert q_{\nu}\rvert \lesssim 2 \times 10^{-14}\, e$	Red giant cooling (plasmon decay)	Raffelt (1999)
$\lvert q_{\nu}\rvert \lesssim 4 \times 10^{-35}\, e$	Neutrality of Universe	Caprini, Ferreira (2003)

COHERENT constraints on neutrino millicharges

[Cadeddu, Dordei, CG, Li, Picciau, Zhang, arXiv:2005.01645]



- Effective charges in the flavor basis:

$$q_{\nu_{\ell\ell'}} = \sum_{j,k} U_{\ell j}^{*} U_{\ell' k}\, q_{\nu_{jk}}$$

- The bounds on the charges involving the electron neutrino flavor

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

  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

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

  are the first ones obtained from laboratory data.

[future prospects: Parada, arXiv:1907.04942]

Neutrino Magnetic and Electric Moments

- Extended Standard Model with Dirac massive neutrinos ($\Delta L = 0$):

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

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

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, hep-ph/0305206]

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

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

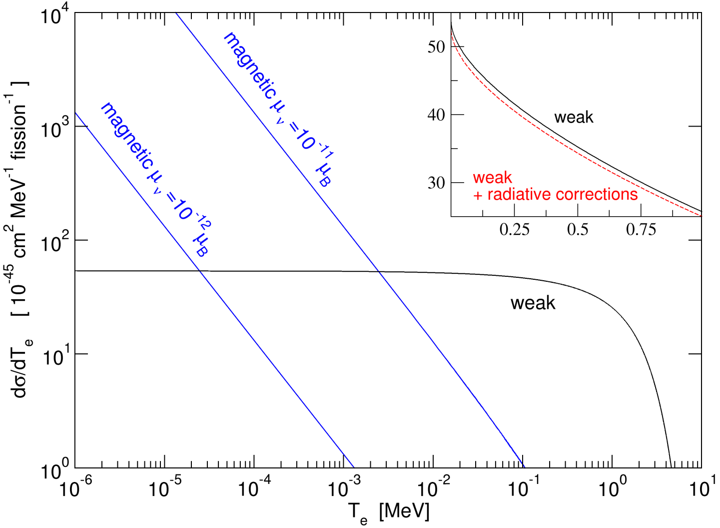
$$\varepsilon^{\mathrm{M}}_{kj} \simeq 7.8 \times 10^{-23} \mu_{\mathrm{B}} \, i \, (m_k - m_j) \sum_{\ell=e,\mu,\tau} \mathrm{Re}\left[U^*_{\ell k} U_{\ell j} \right] \frac{m^2_\ell}{m^2_W}$$

[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]

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



[Balantekin, Vassh, arXiv:1312.6858]

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 CG, Studenikin, 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:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[g_V^n N F_N(|\vec{q}|) + g_V^p Z F_Z(|\vec{q}|)\right]^2$$
$$+ \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(|\vec{q}|)\frac{\mu_{\nu_\ell}^2}{\mu_B^2}$$

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

- Effective magnetic moment of flavor neutrinos:

$$\mu_{\nu_\ell}^2 = \sum_j \left|\sum_k U_{\ell k}^* \left(\mu_{jk} - i\varepsilon_{jk}\right)\right|^2$$

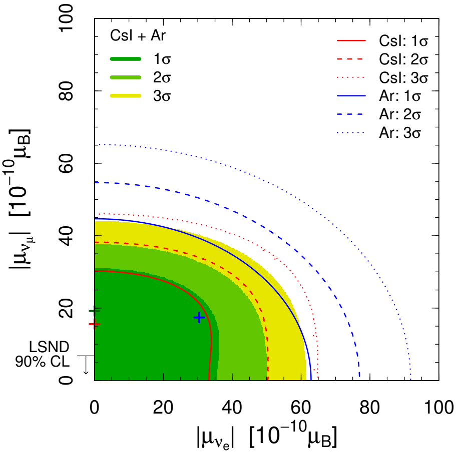
[Grimus, Stockinger, hep-ph/9708279;
Beacom, Vogel, hep-ph/9907383;
CG, Studenikin, arXiv:1403.6344]

- Neglecting the electric moments:

$$\mu_{\nu_\ell}^2 = \sum_{i,j} U_{\ell i}\,(\mu^2)_{ij}\,U_{\ell j}^* \quad \text{with} \quad (\mu^2)_{ij} = \sum_k \mu_{ik}\mu_{kj}$$

COHERENT constraints on ν magnetic moments

[Cadeddu, Dordei, CG, Li, Picciau, Zhang, arXiv:2005.01645]



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

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

[GEMMA, AHEP 2012 (2012) 350150]

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

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

[LSND, hep-ex/0101039]

[see also: Papoulias, Kosmas, arXiv:1711.09773; Papoulias, arXiv:1907.11644; Khan, Rodejohann, arXiv:1907.12444; Cadeddu, Dordei, CG, Li, Zhang, arXiv:1908.06045; Miranda, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, arXiv:2003.12050]

[future prospects: Miranda, Papoulias, Tortola, Valle, arXiv:1905.03750]

Light Vector Mediator: Universal Z'

- Cross section: $$\frac{d\sigma_{\nu\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) Q_W^2$$

- Weak charge: $$Q_W = Q_W^{SM} + \frac{3g_{Z'}^2}{\sqrt{2}G_F}\left(\frac{ZF_Z(|\vec{q}|) + NF_N(|\vec{q}|)}{|\vec{q}|^2 + M_{Z'}^2}\right)$$

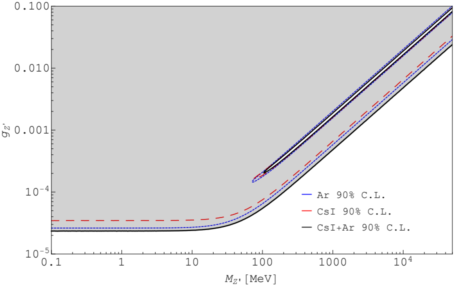
- Since $Q_W^{SM} \simeq -N/2$, for $M_{Z'} \gg |\vec{q}| \approx 30 MeV$ there is a cancellation for

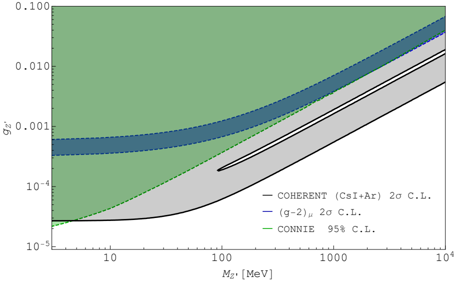
$$Q_W \approx -\frac{N}{2} + \frac{3g_{Z'}^2}{\sqrt{2}G_F}\left(\frac{Z+N}{M_{Z'}^2}\right) = 0 \quad \Leftrightarrow \quad g_{Z'} \approx 1.4 \times 10^{-6}\,\frac{M_{Z'}}{\text{MeV}}$$

- There is a degeneracy with the SM contribution for

$$Q_W \approx -\frac{N}{2} + \frac{3g_{Z'}^2}{\sqrt{2}G_F}\left(\frac{Z+N}{M_{Z'}^2}\right) = \frac{N}{2} \quad \Leftrightarrow \quad g_{Z'} \approx 2 \times 10^{-6}\,\frac{M_{Z'}}{\text{MeV}}$$

Light Vector Mediator: Universal Z'



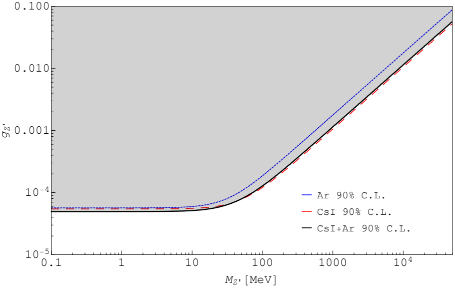


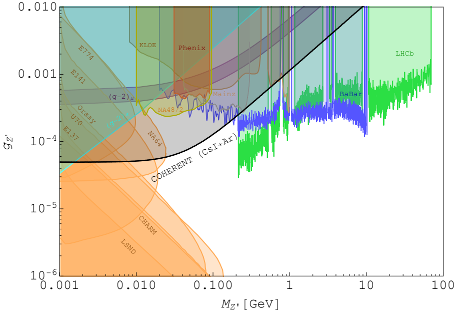
[Cadeddu, Cargioli, Dordei, CG, Li, Picciau, Zhang, arXiv:2008.05022]

[see also: Liao, Marfatia, arXiv:1708.04255; Papoulias, Kosmas, arXiv:1711.09773; Papoulias, arXiv:1907.11644; Khan, Rodejohann, arXiv:1907.12444]

Light Vector Mediator: Z'_{B-L}

Weak charge: $$Q_W = Q_W^{\rm SM} - \frac{g_{Z'}^2}{\sqrt{2}G_F}\left(\frac{ZF_Z(|\vec{q}|)+NF_N(|\vec{q}|)}{|\vec{q}|^2+M_{Z'}^2}\right)$$





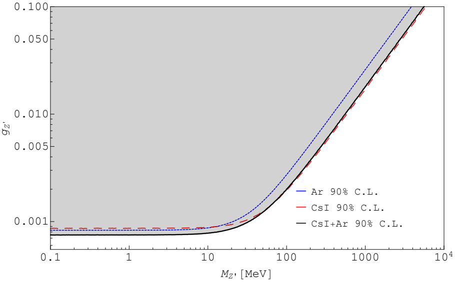
[Cadeddu, Cargioli, Dordei, CG, Li, Picciau, Zhang, arXiv:2008.05022]

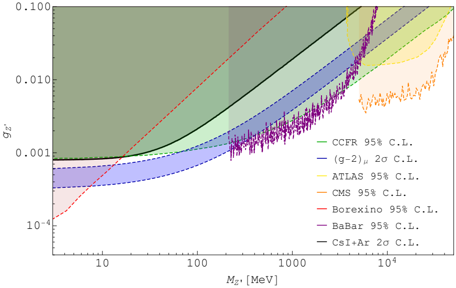
[see also: Miranda, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, arXiv:2003.12050]

Light Vector Mediator: $Z'_{L_\mu - L_\tau}$

$$Q_{W,e} = Q_W^{SM}$$

$$Q_{W,\mu} = g_V^n N F_N(|\vec{q}|^2) + \left[g_V^p - \frac{\alpha g_{Z'}^2}{3\sqrt{2}\pi G_F} \ln\left(\frac{m_\tau^2}{m_\mu^2}\right) \left(\frac{1}{|\vec{q}|^2 + M_{Z'}^2}\right) \right] Z F_Z(|\vec{q}|^2)$$





[Cadeddu, Cargioli, Dordei, CG, Li, Picciau, Zhang, arXiv:2008.05022]

[see also: Amaral, Cerdeno, Foldenauer, Reid, arXiv:2006.11225]

Neutrino Non-Standard Interactions

- Non-renormalizable effective NSI of left-handed neutrinos.

- Charged-Current-like NSI: $(\alpha, \beta, \sigma, \delta = e, \mu, \tau)$

$$\mathcal{H}_{\text{NSI}}^{\text{CC}} = 2\sqrt{2} G_{\text{F}} V_{ud} \sum_{\alpha,\beta} \left(\overline{\ell_{\alpha L}} \gamma_\rho \nu_{\beta L} \right) \left[\varepsilon_{\alpha\beta}^{udL} \overline{u_L} \gamma^\rho d_L + \varepsilon_{\alpha\beta}^{udR} \overline{u_R} \gamma^\rho d_R \right] + \text{H.c.}$$
$$+ 2\sqrt{2} G_{\text{F}} \sum_{\alpha,\beta} \left(\overline{\nu_{\alpha L}} \gamma_\rho \nu_{\beta L} \right) \sum_{\sigma \neq \delta} \left[\varepsilon_{\alpha\beta}^{\sigma\delta L} \overline{\ell_{\sigma L}} \gamma^\rho \ell_{\delta L} + \varepsilon_{\alpha\beta}^{\sigma\delta R} \overline{\ell_{\sigma R}} \gamma^\rho \ell_{\delta R} \right]$$

- Neutral-Current-like or Matter NSI: $(\varepsilon_{\alpha\beta}^{fP} = \varepsilon_{\beta\alpha}^{fP*})$

$$\mathcal{H}_{\text{NSI}}^{\text{NC}} = 2\sqrt{2} G_{\text{F}} \sum_{\alpha,\beta} \left(\overline{\nu_{\alpha L}} \gamma_\rho \nu_{\beta L} \right) \sum_{f=e,u,d} \left[\varepsilon_{\alpha\beta}^{fL} \overline{f_L} \gamma^\rho f_L + \varepsilon_{\alpha\beta}^{fR} \overline{f_R} \gamma^\rho f_R \right]$$

- The ε couplings weight the NSI with respect to SM CC and NC weak interactions.

- NSI are obtained in Effective Field Theory from operators of dimension 6 and higher:

$$\begin{aligned}\mathscr{O}_6 \;=\; & \sum_{\alpha,\beta,\sigma,\delta} C^1_{\alpha\beta\sigma\delta} \left(\overline{L_\alpha}\gamma^\rho L_\beta\right) \left(\overline{L_\sigma}\gamma_\rho L_\delta\right) \\ & + \sum_{\alpha,\beta,\sigma,\delta} C^3_{\alpha\beta\sigma\delta} \left(\overline{L_\alpha}\gamma^\rho \vec{\tau} L_\beta\right) \left(\overline{L_\sigma}\gamma_\rho \vec{\tau} L_\delta\right) \\ & + \ldots\end{aligned}$$

- Constraints are required to suppress unobserved large charged lepton transitions as $\mu \to 3e$. [see: Gavela, Hernandez, Ota, Winter, arXiv:0809.3451]

- Phenomenological analysis: free NSI ε couplings.

Neutrino NSI in CEνNS

- Effective NSI Hamiltonian:

$$\mathcal{H}_{\text{NSI}}^{\text{CE}\nu\text{NS}} = 2\sqrt{2} G_{\text{F}} \sum_{\alpha,\beta=e,\mu,\tau} \left(\overline{\nu_{\alpha L}} \gamma^{\rho} \nu_{\beta L}\right) \sum_{f=u,d} \varepsilon_{\alpha\beta}^{fV} \left(\overline{f} \gamma_{\rho} f\right)$$

- Axial NSI are negligible in CEνNS with heavy nuclei because the spin up and down contribution cancel.
- Only vector NSI, with $\varepsilon_{\alpha\beta}^{fV} = \varepsilon_{\beta\alpha}^{fV*} \Longrightarrow$ real ε_{ee}^{fV}, $\varepsilon_{\mu\mu}^{fV}$, $\varepsilon_{\tau\tau}^{fV}$
- NSI contributions to ν_{ℓ}–$\mathcal{N}$ CEνNS:

$$\frac{d\sigma_{\nu_{\alpha}\text{-}\mathcal{N}}}{dT}(E, T) = \frac{G_{\text{F}}^2 M}{\pi} \left(1 - \frac{MT}{2E^2}\right) Q_{\text{W},\alpha}^2$$

- Weak charge:

$$\begin{aligned} Q_{\text{W},\alpha}^2 = & \left[\left(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}\right) Z F_Z(|\vec{q}|^2) + \left(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV}\right) N F_N(|\vec{q}|^2)\right]^2 \\ & + \sum_{\beta\neq\alpha} \left|\left(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}\right) Z F_Z(|\vec{q}|^2) + \left(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV}\right) N F_N(|\vec{q}|^2)\right|^2 \end{aligned}$$

- Flavor-diagonal NSI interaction add coherently to weak interactions.
- Antineutrinos have the same cross section, because

$$g_V^f \to -g_V^f \quad \text{and} \quad \varepsilon_{\alpha\beta}^{qV} \to -\varepsilon_{\alpha\beta}^{qV}$$

- COHERENT: flux of ν_e, ν_μ, $\bar{\nu}_\mu$ $\Longrightarrow$ $\begin{cases} \text{Initial flavor: } \alpha = e, \mu \\ \text{Final flavor: } \beta = e, \mu, \tau \end{cases}$

- 10 effective NSI couplings: $\begin{cases} \varepsilon_{ee}^{uV} & \varepsilon_{\mu\mu}^{uV} & \varepsilon_{e\mu}^{uV} = \varepsilon_{\mu e}^{uV*} & \varepsilon_{e\tau}^{uV} & \varepsilon_{\mu\tau}^{uV} \\ \varepsilon_{ee}^{dV} & \varepsilon_{\mu\mu}^{dV} & \varepsilon_{e\mu}^{dV} = \varepsilon_{\mu e}^{dV*} & \varepsilon_{e\tau}^{dV} & \varepsilon_{\mu\tau}^{dV} \end{cases}$

$$F_u(|\vec{q}|^2) = \left(2ZF_Z(|\vec{q}|^2) + NF_N(|\vec{q}|^2)\right)$$
$$F_d(|\vec{q}|^2) = \left(ZF_Z(|\vec{q}|^2) + 2NF_N(|\vec{q}|^2)\right)$$

$$\begin{aligned} Q_e^2 = & \left[g_V^p ZF_Z(|\vec{q}|^2) + g_V^n NF_N(|\vec{q}|^2) + \varepsilon_{ee}^{uV} F_u(|\vec{q}|^2) + \varepsilon_{ee}^{dV} F_d(|\vec{q}|^2)\right]^2 \\ & + \left|\varepsilon_{e\mu}^{uV} F_u(|\vec{q}|^2) + \varepsilon_{e\mu}^{dV} F_d(|\vec{q}|^2)\right|^2 + \left|\varepsilon_{e\tau}^{uV} F_u(|\vec{q}|^2) + \varepsilon_{e\tau}^{dV} F_d(|\vec{q}|^2)\right|^2 \end{aligned}$$

$$\begin{aligned} Q_\mu^2 = & \left[g_V^p ZF_Z(|\vec{q}|^2) + g_V^n NF_N(|\vec{q}|^2) + \varepsilon_{\mu\mu}^{uV} F_u(|\vec{q}|^2) + \varepsilon_{\mu\mu}^{dV} F_d(|\vec{q}|^2)\right]^2 \\ & + \left|\varepsilon_{e\mu}^{uV} F_u(|\vec{q}|^2) + \varepsilon_{e\mu}^{dV} F_d(|\vec{q}|^2)\right|^2 + \left|\varepsilon_{\mu\tau}^{uV} F_u(|\vec{q}|^2) + \varepsilon_{\mu\tau}^{dV} F_d(|\vec{q}|^2)\right|^2 \end{aligned}$$

$$Q^2_{\mathrm{W},\alpha} = \left[g_V^p Z F_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2) + \varepsilon_{\alpha\alpha}^{uV} F_u(|\vec{q}|^2) + \varepsilon_{\alpha\alpha}^{dV} F_d(|\vec{q}|^2) \right]^2 + \sum_{\beta\neq\alpha} \left| \varepsilon_{\alpha\beta}^{uV} F_u(|\vec{q}|^2) + \varepsilon_{\alpha\beta}^{dV} F_d(|\vec{q}|^2) \right|^2$$

- NSI couplings with u and d quarks can cancel each other:

$$\varepsilon_{\alpha\beta}^{dV} = -\frac{F_u(|\vec{q}|^2)}{F_d(|\vec{q}|^2)} \varepsilon_{\alpha\beta}^{uV} \quad \Leftrightarrow \quad \varepsilon_{\alpha\beta}^{dV} \simeq -\frac{3.4}{3.8} \simeq -0.89\, \varepsilon_{\alpha\beta}^{uV} \quad \text{for CsI}$$

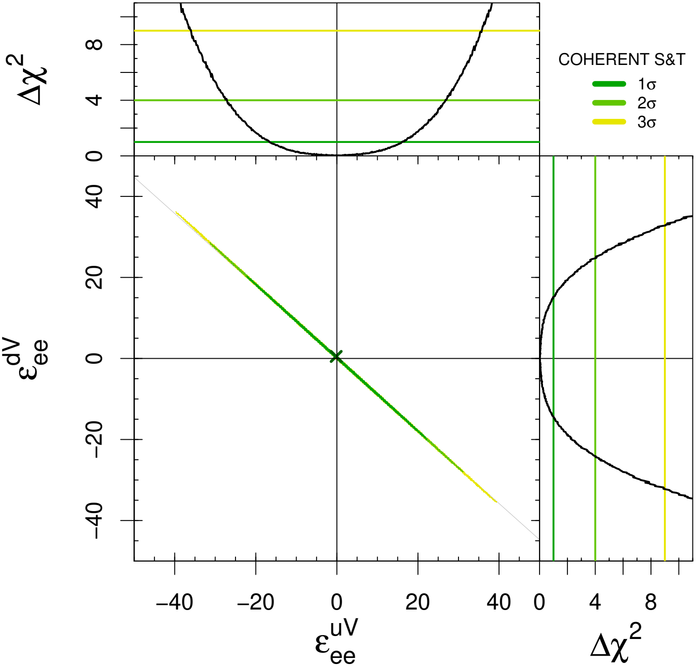
- Cancellations can be large, but not exact, because
  - Cs and I have slightly different $F_u(|\vec{q}|^2)/F_d(|\vec{q}|^2)$.
  - $F_u(|\vec{q}|^2)/F_d(|\vec{q}|^2)$ depends on $|\vec{q}|^2$, whereas $\varepsilon_{\alpha\beta}^{dV}/\varepsilon_{\alpha\beta}^{uV}$ is a constant.

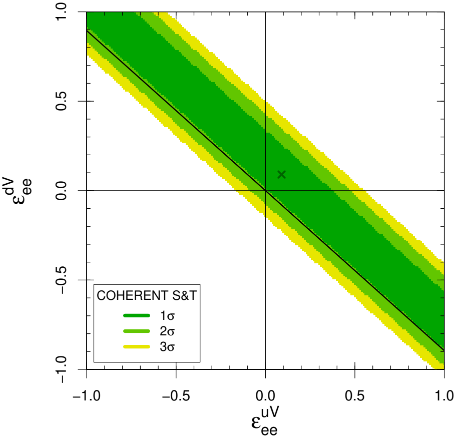
- The diagonal NSI couplings can cancel the weak interaction contribution. Therefore, the signs are important for

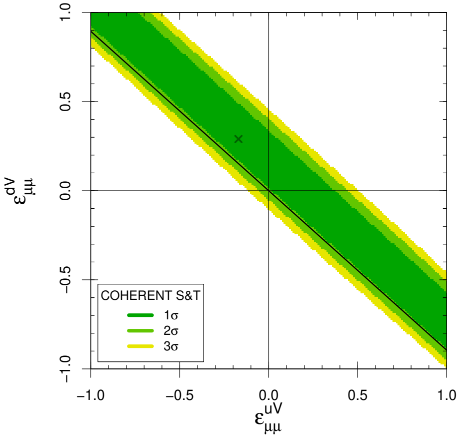
$$\varepsilon_{ee}^{uV} \quad \varepsilon_{\mu\mu}^{uV} \qquad \varepsilon_{ee}^{dV} \quad \varepsilon_{\mu\mu}^{dV}$$

- The maximum contribution of each off-diagonal NSI coupling depend on its absolute value. Therefore, we can get bounds only on

$$|\varepsilon_{e\mu}^{uV}| \quad |\varepsilon_{e\tau}^{uV}| \quad |\varepsilon_{\mu\tau}^{uV}| \qquad |\varepsilon_{e\mu}^{dV}| \quad |\varepsilon_{e\tau}^{dV}| \quad |\varepsilon_{\mu\tau}^{dV}|$$


COHERENT S&T
1σ
2σ
3σ
$\Delta\chi^2$
ε_{ee}^{dV}
ε_{ee}^{uV}
$\Delta\chi^2$

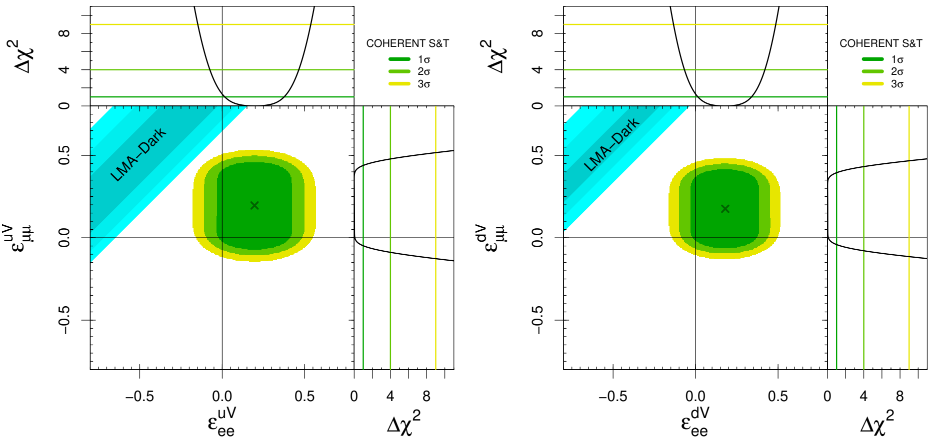




[CG, arXiv:1909.00466]

[see also: Liao, Marfatia, arXiv:1708.04255; Dutta, Liao, Newstead, Strigari, Walker, arXiv:1711.03521; Papoulias, Kosmas, arXiv:1711.09773; Papoulias, arXiv:1907.11644; Khan, Rodejohann, arXiv:1907.12444; Canas, Garces, Miranda, Parada, Sanchez Garcia, arXiv:1911.09831; Dutta, Lang, Liao, Sinha, Strigari, Thompson, arXiv:2002.03066; Miranda, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, arXiv:2003.12050]

NSI with up or down quarks only



- LMA-Dark fit of solar neutrino data is excluded at 5.6σ for NSI with up quark only, and 7.2σ for NSI with down quark only. [CG, arXiv:1909.00466]

[see also: Coloma, Gonzalez-Garcia, Maltoni, Schwetz, arXiv:1708.02899;
Coloma, Esteban, Gonzalez-Garcia, Maltoni, arXiv:1911.09109; Chaves, Schwetz, arXiv:2102.11981]

Conclusions

- The observation of CEνNS in the COHERENT experiment opened the way for new powerful measurements of weak interactions, nuclear structure, non-standard neutrino properties.
- There are several new experiments which use reactor $\bar{\nu}_e$'s: CONUS, CONNIE, NU-CLEUS, MINER, Ricochet, TEXONO, νGEN, ...
- It is important to continue and improve CEνNS observation not only with $\bar{\nu}_e$ from reactors, but also with ν_μ beams (as in COHERENT) in order to explore the properties of ν_μ, that are typically less constrained than the properties of ν_e.
- Future: new COHERENT CEνNS measurements with 1 ton LAr detector, a large array of NaI detectors, and an array of Germanium detectors.
- Powerful project at the European Spallation Source (ESS) in Lund, Sweden, with an order of magnitude increase in neutrino flux with respect to the Oak Ridge SNS.