New Physics Searches with CEvNS (Theory)

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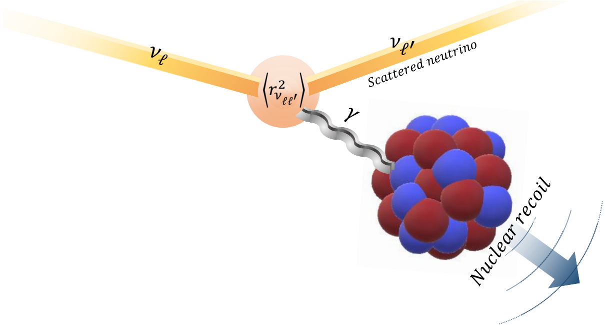
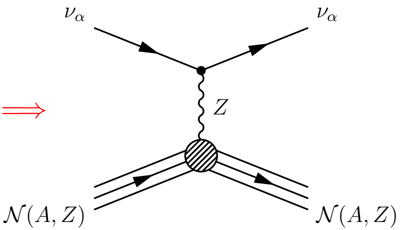
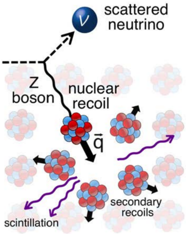


Coherent Elastic Neutrino-Nucleus Scattering

- 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!
- Experimental difficulty: low nuclear recoil kinetic energy $T \lesssim 10\,\mathrm{keV}$
- Prediction: 1974! [Freedman, PRD 9 (1974) 1389]
- First observation: 43 years later, in 2017 with the COHERENT CsI detector and a $\nu_\mu + \nu_e$ beam produced by $\pi + \mu$ decay at rest [COHERENT, arXiv:1708.01294]
- Second observation: in 2020 with the COHERENT Ar detector [COHERENT, arXiv:2003.10630]
- Third observation: in 2022 with a Ge detector and the $\bar{\nu}_e$ flux produced by the Dresden-II reactor [Colaresi, Collar, Hossbach, Lewis, Yocum, arXiv:2202.09672]

CEνNS Cross Section

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

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

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

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

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

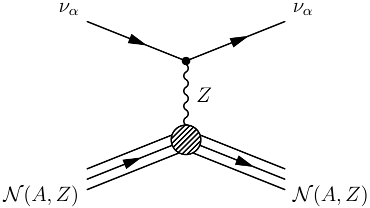
The neutron contribution is dominant! $\Longrightarrow \dfrac{d\sigma_{\mathrm{CE}\nu\mathrm{NS}}}{dT} \propto\hspace{-0.7em}\sim N^2$

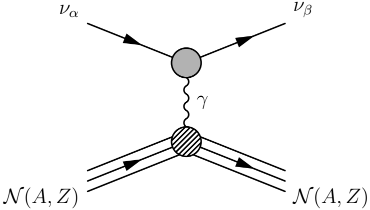
[Freedman, PRD 9 (1974) 1389; Drukier, Stodolsky, PRD 30 (1984) 2295; Barranco, Miranda, Rashba, hep-ph/0508299]

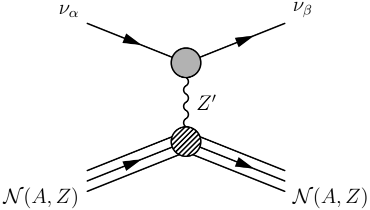
- The coherent nuclear recoil gives a big cross section enhancement for heavy nuclei: $\sigma_{\mathrm{NC}}^{\mathrm{incoherent}} \propto\hspace{-0.7em}\sim N \Longrightarrow \sigma_{\mathrm{CE}\nu\mathrm{NS}}/\sigma_{\mathrm{NC}}^{\mathrm{incoherent}} \propto\hspace{-0.7em}\sim N$

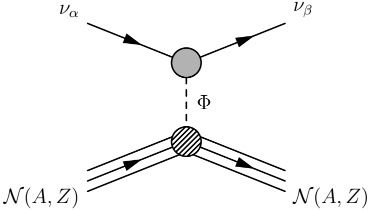
- The nuclear form factors $F_N(|\vec{q}|)$ and $F_Z(|\vec{q}|)$ describe the loss of coherence for $|\vec{q}|R \gtrsim 1$. [Patton et al, arXiv:1207.0693; Bednyakov, Naumov, arXiv:1806.08768; Papoulias et al, arXiv:1903.03722; Ciuffoli et al, arXiv:1801.02166; Canas et al, arXiv:1911.09831; Van Dessel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

SM and BSM CEνNS Neutrino Interactions


Standard Model NC

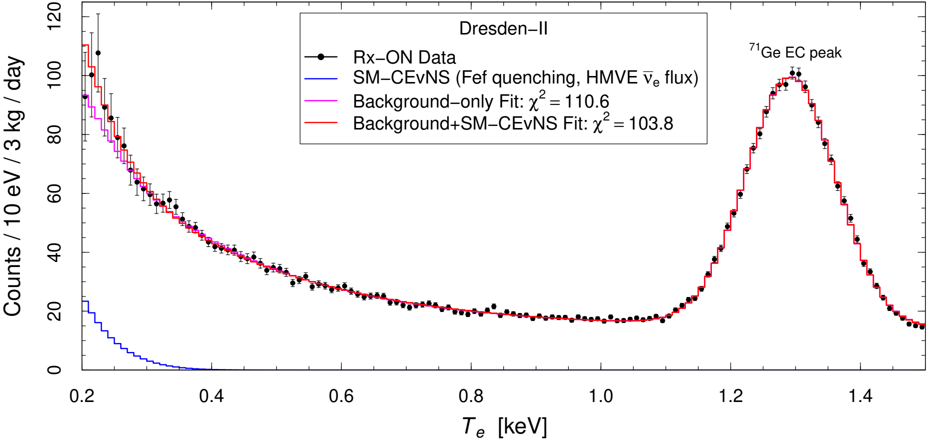

Electromagnetic Interactions


BSM Vector Mediator

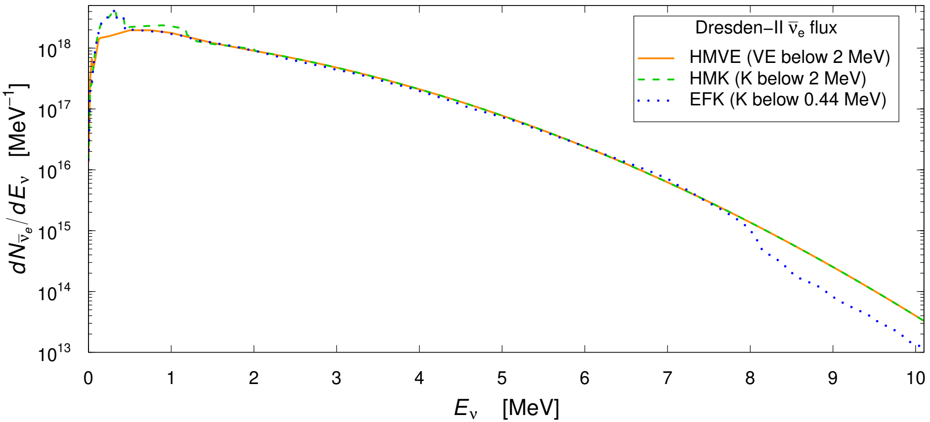

BSM Scalar Mediator

Recent First Observation of Reactor $\bar{\nu}_e$ CEvNS

[Colaresi, Collar, Hossbach, Lewis, Yocum, arXiv:2202.09672]



- For a proper analysis the background must be fitted with signal using the information in the data release in the arXiv ancillary files. Thanks!
- BSM analyses that use the residuals obtained from the official SM fit are not correct and may obtain misleading results.
- Special thanks to the COHERENT Collaboration for the excellent data releases and the availability to help!

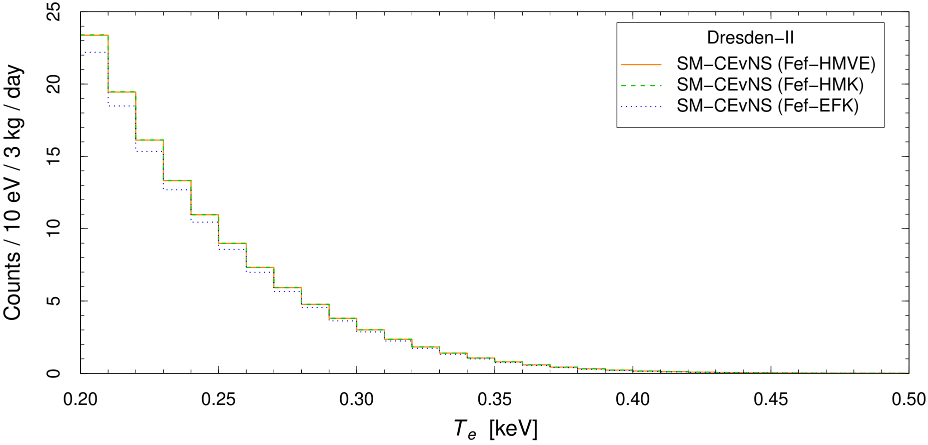


Kopeikin (2012): Usual $\bar{\nu}_e$ fluxes from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu fission daughter nuclei plus low energy $\bar{\nu}_e$'s from

$$n + {}^{238}\text{U} \to {}^{239}\text{U} + \gamma$$

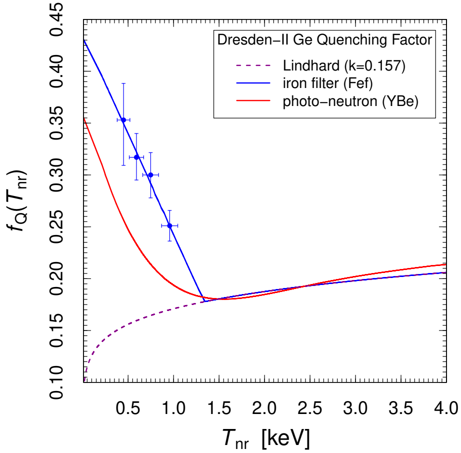
$$ {}^{239}\text{U} \to {}^{239}\text{Np} + e^- + \bar{\nu}_e$$

$$ {}^{239}\text{Np} \to {}^{239}\text{Pu} + e^- + \bar{\nu}_e$$



- Small dependence of the predicted SM CEvNS signal on the difference between the HM and EF fluxes at high energy.

$$E_\nu^{\text{min}}(\text{CEvNS}) \simeq \sqrt{\frac{MT_{\text{nr}}}{2}}: \text{ e.g., } T_{\text{nr}} \simeq 0.2 \text{ keV} \quad \Longrightarrow \quad E_\nu^{\text{min}}(\text{CEvNS}) \simeq 2.5 \text{ MeV}$$



- The Quenching Factor describes the suppression of the ionization yield produced by a nuclear recoil compared to an electron recoil.
- Electron-equivalent energy:

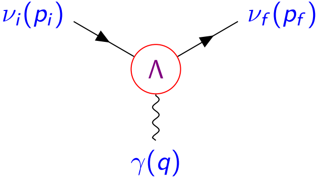
$$T_e = f_Q(T_{nr})\, T_{nr}$$

- Dresden-II Ge Quenching Factor models:
  - Fef: iron filtered neutron beam
  - YBe: photo-neutron $^{88}\mathrm{Y}/\mathrm{Be}$ source [Colaresi et al, arXiv:2202.09672]
- The difference between Fef and YBe is considered as the Quenching Factor systematic uncertainty [Coloma et al, arXiv:2202.10829]

Neutrino Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}^{(\nu)}_{\text{em}}(x) = j^{(\nu)}_{\mu}(x) A^{\mu}(x) = \sum\limits_{k,j=1} \overline{\nu_k}(x) \Lambda^{kj}_{\mu} \nu_j(x) A^{\mu}(x)$

- Effective electromagnetic vertex:



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

$$q = p_i - p_f$$

- Vertex function (mass basis):

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

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

$q^2 = 0$ ⟹ Q, A, μ, ε

helicity-conserving: Q, A

helicity-flipping: μ, ε

- Ultrarelativistic neutrinos at low q^2:

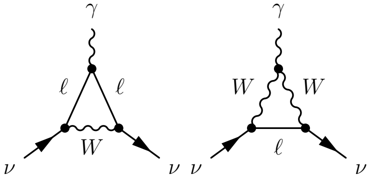
$$\Lambda_{\mu}(q) \simeq \left(\gamma_{\mu} - q_{\mu} \not{q}/q^2\right) \left[F_Q(q^2) - A q^2\right] - i \sigma_{\mu\nu} q^{\nu} \left[\mu - i \varepsilon\right]$$

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

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



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

- In the Standard Model:

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

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

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

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

$$\frac{d\sigma_{\nu_\alpha\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left\{\left[\underbrace{-\frac{1}{2}}_{g_V^n} N F_N(|\vec{q}|) + \left(\underbrace{\frac{1}{2} - 2\sin^2\vartheta_W}_{g_V^p \simeq 0.023} - \frac{2}{3}\, m_W^2 \sin^2\vartheta_W \langle r_{\nu_{\alpha\alpha}}^2\rangle\right) Z F_Z(|\vec{q}|)\right]^2 + \frac{4}{9}\, m_W^4 \sin^4\vartheta_W Z^2 F_Z^2(|\vec{q}|) \sum_{\beta\neq\alpha} |\langle r_{\nu_{\beta\alpha}}^2\rangle|^2\right\}$$

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

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

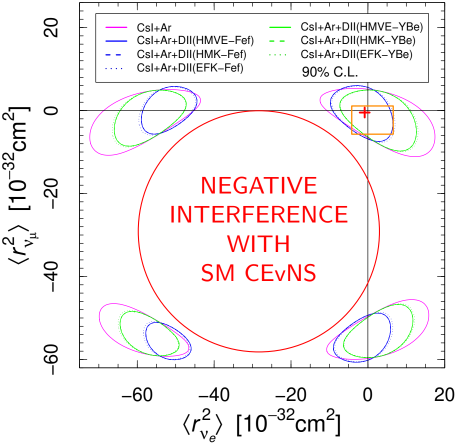
- Transition charge radii generate the incoherent contribution

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

[Kouzakov, Studenikin, arXiv:1703.00401]

Bounds on Diagonal Neutrino Charge Radii

- The transition charge radii are assumed to be zero or negligible.
- Test of SM prediction and search for lepton flavor conserving BSM physics.



[Atzori Corona et al, arXiv:2205.09484]

Dresden-II data analysis options:

- Reactor $\bar{\nu}_e$ flux:
  - **HMVE**: Huber-Mueller (2011) + Vogel-Engel (1989) ($E_\nu < 2$ MeV)
  - **HMK**: Huber-Mueller + Kopeikin (2012) ($E_\nu < 2$ MeV)
  - **EFK**: Estienne-Fallot (2019) + Kopeikin (2012) ($E_\nu < 0.44$ MeV)
- Quenching factor:
  - **Fef**: iron filter
  - **YBe**: photo-neutron
- Previous bounds (orange):
  - Reactor $\bar{\nu}_e \, e^-$: TEXONO
  - Accelerator $\nu_\mu \, e^-$: BNL-E734

Bounds on Diagonal Neutrino Charge Radii

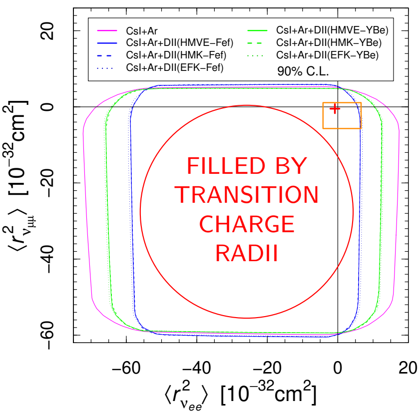
Method	Experiment	Limit $[10^{-32}\ \text{cm}^2]$	C.L.	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\lvert\langle r_{\nu_e}^2\rangle\rvert < 7.3$	90%	1992
	TEXONO	$-4.2 < \langle r_{\nu_e}^2\rangle < 6.6^{a}$	90%	2009
Accelerator $\nu_e\, e^-$	LAMPF	$-7.12 < \langle r_{\nu_e}^2\rangle < 10.88^{a}$	90%	1992
	LSND	$-5.94 < \langle r_{\nu_e}^2\rangle < 8.28^{a}$	90%	2001
Accelerator $\nu_\mu\, e^-$	BNL-E734	$-5.7 < \langle r_{\nu_\mu}^2\rangle < 1.1^{a,b}$	90%	1990
	CHARM-II	$\lvert\langle r_{\nu_\mu}^2\rangle\rvert < 1.2^{a}$	90%	1994
CEvNS [arXiv:2205.09484]	COHERENT + Dresden-II	$-7.1 < \langle r_{\nu_e}^2\rangle < 11.2$ $-8.1 < \langle r_{\nu_\mu}^2\rangle < 4.3$	90%	2022

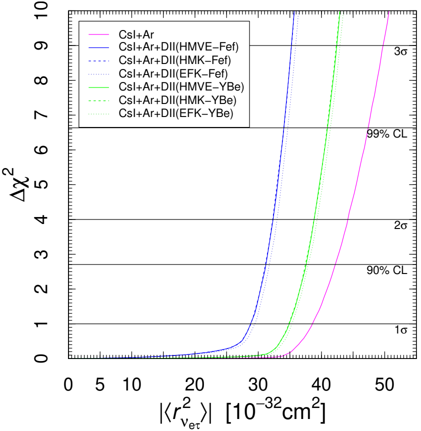
[a] Corrected by a factor of two due to a different convention.

[b] Corrected in Hirsch, Nardi, Restrepo, hep-ph/0210137.

[Previous CEvNS results: Papoulias et al, arXiv:1711.09773, arXiv:1907.11644, arXiv:2003.12050; Khan and Rodejohann, arXiv:1907.12444; Cadeddu et al, arXiv:1810.05606, arXiv:1908.06045, arXiv:2005.01645]

General CEvNS Constraints on Neutrino Charge Radii





$$|\langle r^2_{\nu_{e\mu}} \rangle| < 33 \times 10^{-32}\,\mathrm{cm}^2$$
$$|\langle r^2_{\nu_{e\tau}} \rangle| < 43 \times 10^{-32}\,\mathrm{cm}^2 \qquad (3\sigma)$$
$$|\langle r^2_{\nu_{\mu\tau}} \rangle| < 36 \times 10^{-32}\,\mathrm{cm}^2$$

[Atzori Corona et al, arXiv:2205.09484]

Effective charge radii
in the flavor basis:

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

Neutrino Magnetic and Electric Moments

- Effective dimension-5 Lagrangian:

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

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

$$\mu^{\text{D}}_{kk} \simeq 3.2 \times 10^{-19} \mu_{\text{B}} \left(\frac{m_k}{\text{eV}}\right) \qquad \text{Strongly suppressed by small } m_k!$$

- $\mathcal{N} = 3$ and $N_{Rj} = \nu^c_{Lj}$ $\Longrightarrow$ 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"

- Neutrino magnetic (and electric) moment contributions to CEνNS:

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

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

- Effective magnetic moment of flavor neutrinos:

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

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

- Neglecting the electric moments:

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

- Neutrino-electron elastic scattering (ES) contribution in the COHERENT CsI and Dresden-II Ge detectors. [Coloma et al, arXiv:2202.10829]

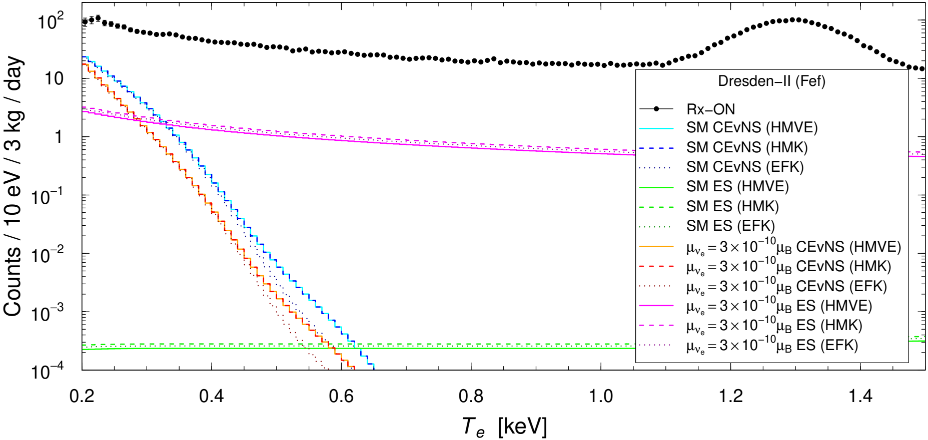
- Negligible SM contribution:

$$\frac{d\sigma^{\text{ES}}_{\nu_\alpha-\mathcal{A}}}{dT_\text{e}}(E, T_\text{e}) = Z^{\mathcal{A}}_{\text{eff}}(T_e)\,\frac{G_\text{F}^2 m_e}{2\pi}\left[\left(g_V^{\nu_\alpha}+g_A^{\nu_\alpha}\right)^2 + \left(g_V^{\nu_\alpha}-g_A^{\nu_\alpha}\right)^2\left(1-\frac{T_e}{E}\right)^2 - \left(\left(g_V^{\nu_\alpha}\right)^2-\left(g_A^{\nu_\alpha}\right)^2\right)\frac{m_e T_e}{E^2}\right]$$

$$g_V^{\nu_e} = 2\sin^2\theta_W + \frac{1}{2}, \quad g_A^{\nu_e} = \frac{1}{2}, \quad g_V^{\nu_\mu} = 2\sin^2\theta_W - \frac{1}{2}, \quad g_A^{\nu_\mu} = -\frac{1}{2}$$

- Significant neutrino magnetic moment contribution for small T_e:

$$\frac{d\sigma^{\text{ES, MM}}_{\nu_\alpha\text{-}\mathcal{A}}}{dT_\mathrm{e}}(E, T_\mathrm{e}) = Z^{\mathcal{A}}_{\text{eff}}(T_\mathrm{e})\frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e}-\frac{1}{E}\right)\left|\frac{\mu_{\nu_\alpha}}{\mu_\text{B}}\right|^2$$

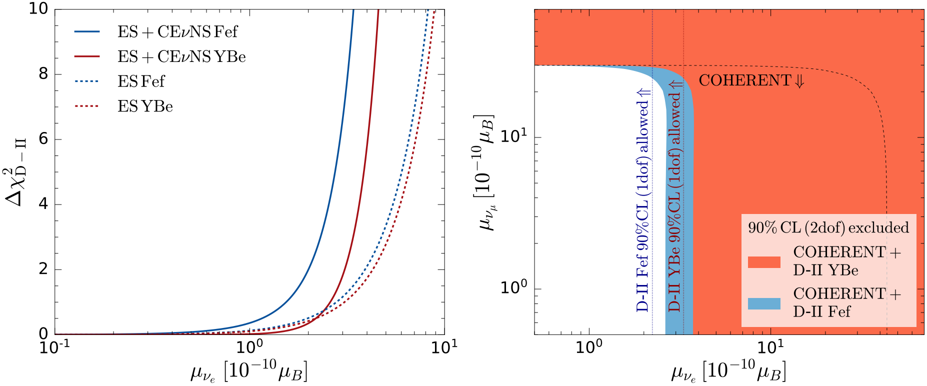


- SM ES are practically negligible, whereas magnetic moment ES are not negligible.

- ES predictions are flatter than CEvNS and depend more on the reactor flux model because

$$E_\nu^{\min}(\text{ES}) \simeq \sqrt{m_e T_e/2}: \text{ e.g., } T_e \simeq 0.5 \text{ keV} \implies E_\nu^{\min}(\text{ES}) \simeq 10 \text{ keV}$$

$$E_\nu^{\min}(\text{CEvNS}) \simeq \sqrt{M T_{\text{nr}}/2}: \text{ e.g., } T_{\text{nr}} \simeq 0.5 \text{ keV} \implies E_\nu^{\min}(\text{CEvNS}) \simeq 4 \text{ MeV}$$

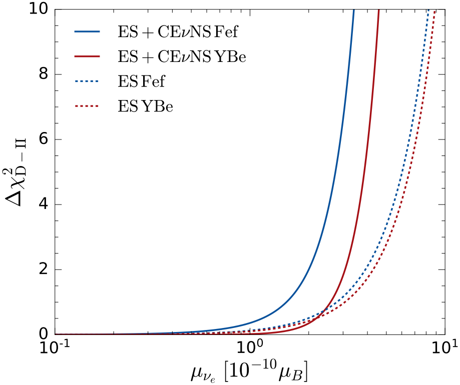


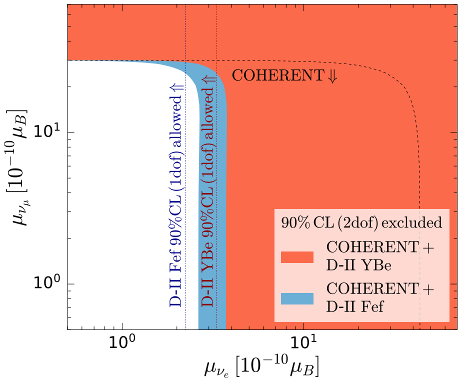
[Coloma, Esteban, Gonzalez-Garcia, Larizgoitia, Monrabal, Palomares-Ruiz, arXiv:2202.10829]

$|\mu_{\nu_e}| < 2.2 \times 10^{-10}\,\mu_{\mathrm{B}}$ HMVE CEvNS+ES Fef 90% C.L.

$$\frac{|\mu_{\nu_e}|}{10^{-10}\,\mu_{\mathrm{B}}} < \left\{ \begin{array}{l} \left.\begin{array}{l} 2.3\,(\text{HMVE or HMK}) \\ 2.5\,(\text{EFK}) \end{array}\right\} \text{CEvNS} \\ \left.\begin{array}{l} 2.1\,(\text{HMVE or HMK}) \\ 2.2\,(\text{EFK}) \end{array}\right\} \text{CEvNS+ES} \end{array} \right\} \quad \text{Fef} \quad 90\%\ \text{C.L.}$$

[Atzori Corona et al, arXiv:2205.09484]





[Coloma, Esteban, Gonzalez-Garcia, Larizgoitia, Monrabal, Palomares-Ruiz, arXiv:2202.10829]

$|\mu_{\nu_e}| < 3.3 \times 10^{-10}\,\mu_B$ HMVE CEvNS+ES YBe 90% C.L.

$$\frac{|\mu_{\nu_e}|}{10^{-10}\,\mu_B} < \left\{ \begin{array}{l} \left.\begin{array}{l} 3.7\,(\text{HMVE or HMK}) \\ 3.8\,(\text{EFK}) \end{array}\right\} \text{CEvNS} \\ \left.\begin{array}{l} 3.2\,(\text{HMVE or HMK}) \\ 3.3\,(\text{EFK}) \end{array}\right\} \text{CEvNS+ES} \end{array} \right\}$$

YBe 90% C.L.

[Atzori Corona et al, arXiv:2205.09484]

Bounds on $|\mu_{\nu_e}|$ and $|\mu_{\nu_\mu}|$

Method	Experiment	Limit $[\mu_B]$	CL	Year
Reactor ES $(\bar{\nu}_e\, e^-)$	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
Reactor CEvNS+ES	Dresden-II [Coloma et al, arXiv:2202.10829] [Atzori Corona et al, arXiv:2205.09484]	$|\mu_{\nu_e}| < 3.3 \times 10^{-10}$	90%	2022
Accelerator ES $(\nu_\mu\, e^-)$	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 CEvNS+ES	COHERENT [Coloma et al, arXiv:2202.10829] [Atzori Corona et al, arXiv:2205.09484]	$|\mu_{\nu_\mu}| < 2 \times 10^{-9}$	90%	2022

[See also: Liao et al, arXiv:2202.10622; Aristizabal Sierra et al, arXiv:2203.02414; Khan, arXiv:2203.08892]

[Previous CEvNS results: Papoulias et al, arXiv:1711.09773, arXiv:1905.03750, arXiv:1907.11644, arXiv:2003.12050; Khan and Rodejohann, arXiv:1907.12444; Cadeddu et al, arXiv:1908.06045, arXiv:2005.01645; CONUS, arXiv:2201.12257]

[Future prospects: Miranda et al, arXiv:1905.03750]

Vector-Mediated Non-Standard Interactions

- General CEvNS cross section:

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

- Very heavy vector mediator: Effective neutral-current NSI Hamiltonian:

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

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

- Many parameters with possible cancellation effects.

- Several phenomenological analyses: general or simplified by assumptions on the parameters.

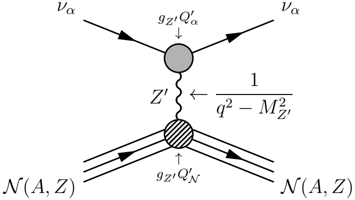
[COHERENT, arXiv:1708.01294, arXiv:2003.10630, arXiv:2110.07730; Coloma et al, arXiv:1708.02899, arXiv:1911.09109, arXiv:2202.10829; Liao et al, arXiv:1708.04255, arXiv:1711.03521, arXiv:2002.03066; Papoulias et al, arXiv:1711.09773, arXiv:1907.11644, arXiv:2003.12050; Khan and Rodejohann, arXiv:1907.12444; CG, arXiv:1909.00466; Canas et al, arXiv:1911.09831; Denton and Gehrlein, arXiv:2008.06062; CONUS, arXiv:2110.02174; Chaves and Schwetz, arXiv:2102.11981]

Light Vector Mediator Models

- Non-standard interactions mediated by a vector boson Z' with mass $M_{Z'} \lesssim 100$ GeV, associated with a new $U(1)'$ gauge symmetry.
- Generic lepton flavor conserving Lagrangian:

$$\mathcal{L}_{Z'}^{V} = -g_{Z'}\, Z'_{\mu} \left[\sum_{\alpha=e,\mu,\tau} Q'_{\alpha}\, \overline{\nu_{\alpha L}} \gamma^{\mu} \nu_{\alpha L} + \sum_{q=u,d} Q'_{q}\, \overline{q} \gamma^{\mu} q \right]$$

- CEvNS:



- Many models, that can be divided in
  - Anomaly-free models generated by appropriate combinations of

$$B,\ L_e,\ L_\mu,\ L_\tau$$

  - Anomalous models, assuming that the anomalies are canceled by the contributions of non-standard fermions an extended theory.

Light Vector Mediator: Universal Z'

- Cross section: $\dfrac{d\sigma_{\nu\text{-}\mathcal{N}}}{dT}(E_\nu, T) = \dfrac{G_{\text{F}}^2 M}{\pi}\left(1 - \dfrac{MT}{2E_\nu^2}\right) Q_{\text{W}}^2$

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

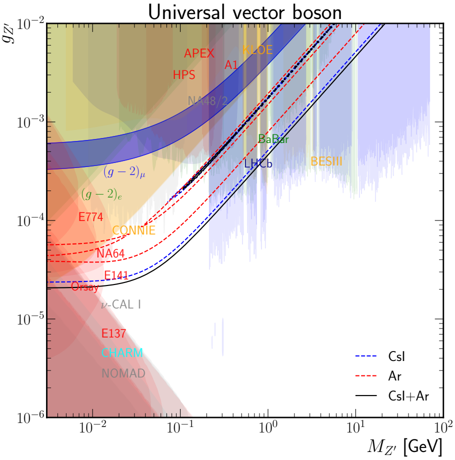
- Since $Q_{\text{W}}^{\text{SM}} \simeq -N/2$, for $M_{Z'} \gg |\vec{q}| \approx 30 MeV$ there is a cancellation for

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

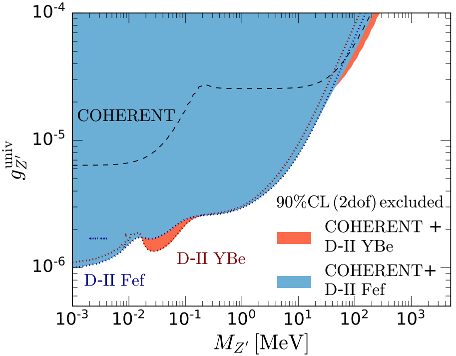
- There is a degeneracy with the SM contribution for

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

Light Vector Mediator: Universal Z'



[Atzori Corona et al, arXiv:2202.11002]



[Coloma et al, arXiv:2202.10829]

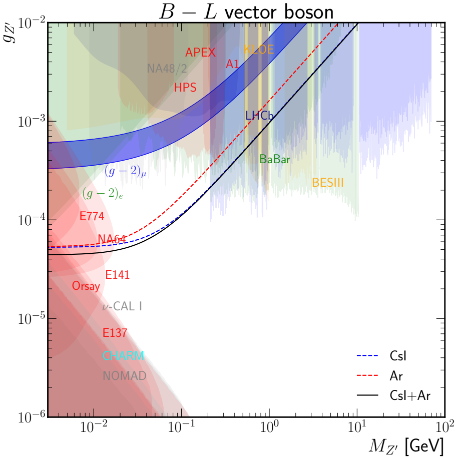
CEvNS: $|\vec{q}|^2 \simeq 2MT_{\mathrm{nr}}$

ES: $|\vec{q}|^2 \simeq 2m_e T_e$

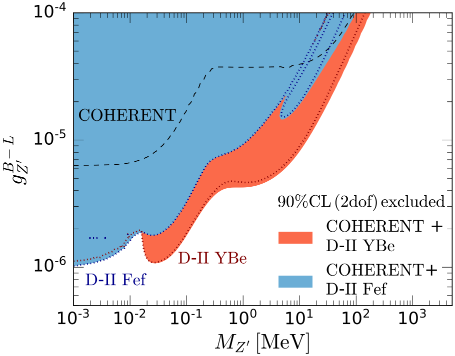
[Previous CEvNS results: Liao and Marfatia, arXiv:1708.04255; Papoulias et al, arXiv:1711.09773, arXiv:1907.11644; Khan and Rodejohann, arXiv:1907.12444; CONNIE, arXiv:1910.04951; Cadeddu et al, arXiv:2008.05022; CONUS, arXiv:2110.02174]

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

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



Anomaly Free!



[Atzori Corona et al, arXiv:2202.11002]

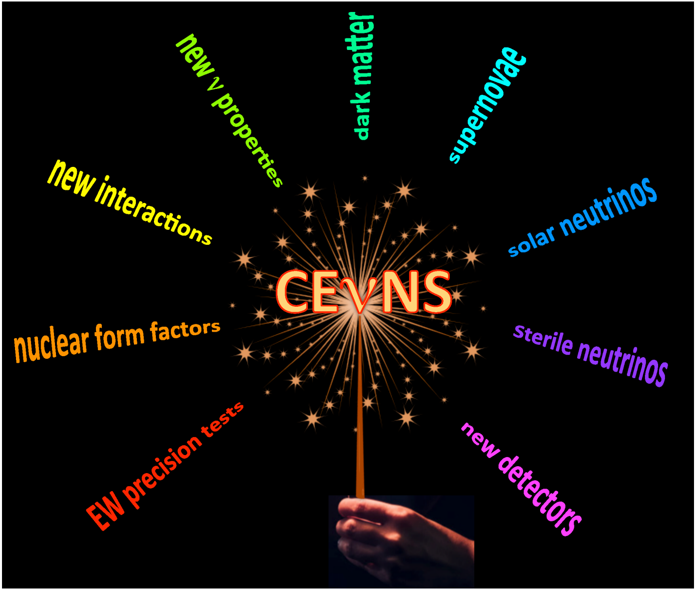
[Coloma et al, arXiv:2202.10829]

[Previous CEvNS results: Miranda et al, arXiv:2003.12050; Cadeddu et al, arXiv:2008.05022]

Short Final Remarks

- The ES effects in Dresden and Coherent CsI lead to dramatic improvements of the bounds on the electric charges of ν_e and ν_μ.
  [Atzori Corona et al, arXiv:2205.09484]
- CEvNS can probe neutrino interactions with BSM scalars.
  [Cerdeno et al, arXiv:1604.01025; Farzan et al, arXiv:1802.05171; Aristizabal Sierra et al, arXiv:1806.07424; Khan and Rodejohann, arXiv:1907.12444; Aristizabal Sierra et al, arXiv:1910.12437; Miranda et al, arXiv:2003.12050; Suliga and Tamborra, arXiv:2010.14545; CONUS, arXiv:2110.02174; Li and Xia, arXiv:2201.05015; Atzori Corona et al, arXiv:2202.11002; Liao et al, arXiv:2202.10622; Coloma et al, arXiv:2202.10829]
- CEvNS can probe general BSM neutrino interactions.
  [Lindner et al, arXiv:1612.04150; Aristizabal Sierra et al, arXiv:1806.07424; Brdar and Rodejohann, arXiv:1810.03626; Chang and Liao, arXiv:2002.10275; Li et al, arXiv:2005.01543; CONUS, arXiv:2110.02174]
- CEvNS can determine the neutron distribution in the nucleus.
  [Cadeddu et al, arXiv:1710.02730, arXiv:2005.01645, arXiv:1908.06045; Aristizabal Sierra et al, arXiv:1902.07398; Huang and Chen, arXiv:1902.07625; Papoulias et al, arXiv:1903.03722, arXiv:1907.11644; Miranda et al, arXiv:2003.12050]
- CEvNS can determine the value of the electroweak mixing angle.
  [Papoulias et al, arXiv:1711.09773, arXiv:1907.11644; Cadeddu et al, arXiv:1808.10202, arXiv:2005.01645, arXiv:1908.06045, arXiv:2205.09484; Huang and Chen, arXiv:1902.07625; Miranda et al, arXiv:1902.09036, arXiv:2003.12050; Khan and Rodejohann, arXiv:1907.12444; COHERENT, arXiv:2110.07730]
- CEvNS can probe active neutrino disappearance into sterile states.
  [Papoulias and Kosmas, arXiv:1711.09773; Blanco et al, arXiv:1901.08094; Miranda et al, arXiv:1902.09036]
- In the future it may be possible to observe Coherent Elastic Neutrino-Atom Scattering (CEvAS) with a very low energy threshold of a few meV. [Sehgal and Wanninger, PLB 171 (1986) 107; Cadeddu et al, arXiv:1907.03302]

CEvNS magic, to be continued ...



[E. Lisi, Neutrino 2018]

Talk dedicated to the memory of Samoil Bilenky

Great Physicist, Mentor, Friend

Neutrino Pioneer

Regular participant in the Neutrino Conferences

23 May 1928, Zmerinka (Ukraine), USSR

5 November 2020, Vancouver, Canada