CEvNS: Theory and Phenomenology

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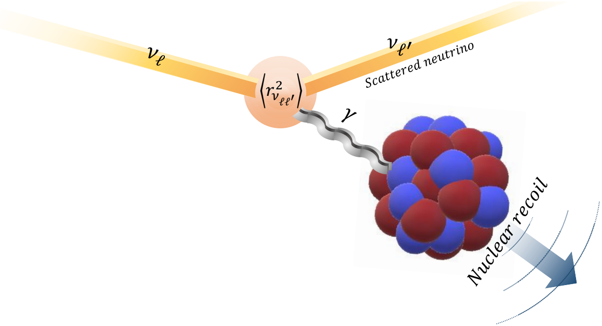
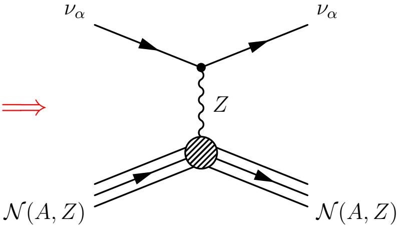
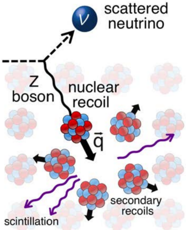


Coherent Elastic Neutrino-Nucleus Scattering

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

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

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

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

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

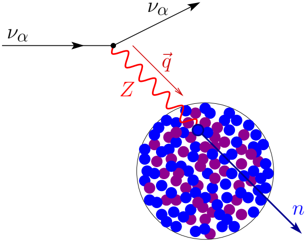
The neutron contribution is dominant! $\Longrightarrow$ $\frac{d\sigma_{\mathrm{CE}\nu\mathrm{NS}}}{dT} \propto\!\!\!\!\sim N^2$

[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: $\sigma_{\mathrm{NC}}^{\mathrm{incoherent}} \underset{\sim}{\propto} N \Longrightarrow \sigma_{\mathrm{CE}\nu\mathrm{NS}}/\sigma_{\mathrm{NC}}^{\mathrm{incoherent}} \underset{\sim}{\propto} N$

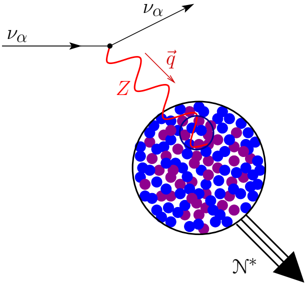
- The nuclear form factors $F_N(|\vec{q}|)$ and $F_Z(|\vec{q}|)$ describe the loss of coherence for $|\vec{q}|R \gtrsim 1$. [Patton et al, arXiv:1207.0693; Bednyakov, Naumov, arXiv:1806.08768; Papoulias et al, arXiv:1903.03722; Ciuffoli et al, arXiv:1801.02166; Canas et al, arXiv:1911.09831; Van Dessel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

Neutrino-Nucleus Scattering



Inelastic Incoherent

$\lambda_Z \ll R$



Elastic Incoherent

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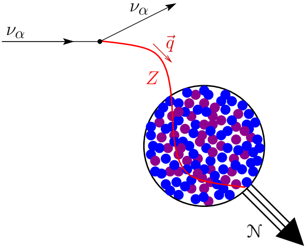


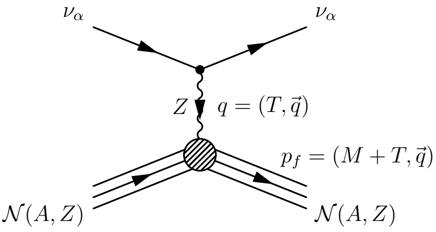
Elastic Coherent

$\lambda_Z \gtrsim 2R$

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

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

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



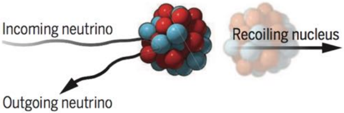
- Heavy target nucleus $\mathcal{N}(A, Z)$:

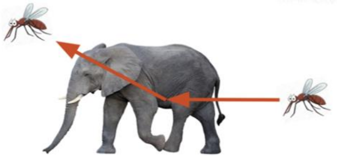
$$A \sim 100 \qquad M \sim 100\,\text{GeV}$$

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

- CEνNS for $|\vec{q}| \lesssim 40\,\text{MeV}$
- Non-Relativistic nuclear recoil:

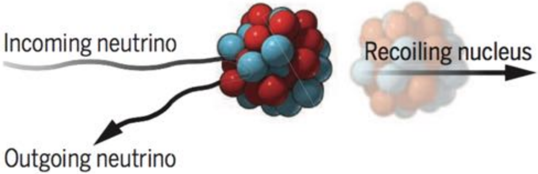
$$|\vec{q}| \simeq \sqrt{2\, M\, T} \qquad\qquad q^0 = T \quad \leftarrow \quad \text{Kinetic Energy}$$





- 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 $\vec{p}_{\nu_f} = -\vec{p}_{\nu_i}$

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

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

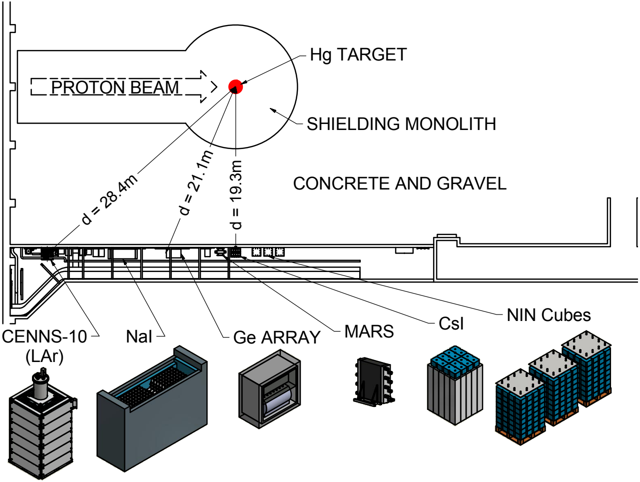
Low-energy neutrinos are needed!

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

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

The COHERENT Experiment

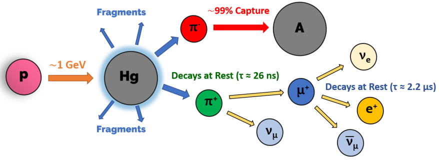
Oak Ridge Spallation Neutron Source

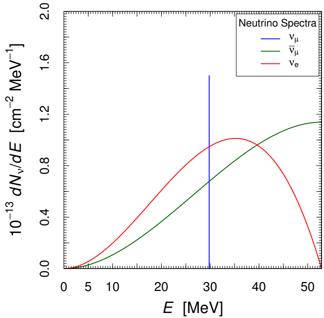


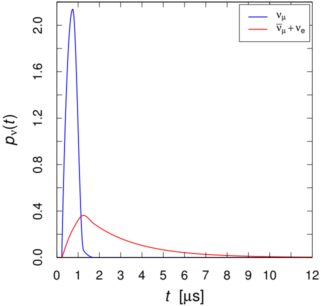
14.6 kg CsI
scintillating crystal

[COHERENT, arXiv:1803.09183]

COHERENT Stopped-Pion Neutrino Source



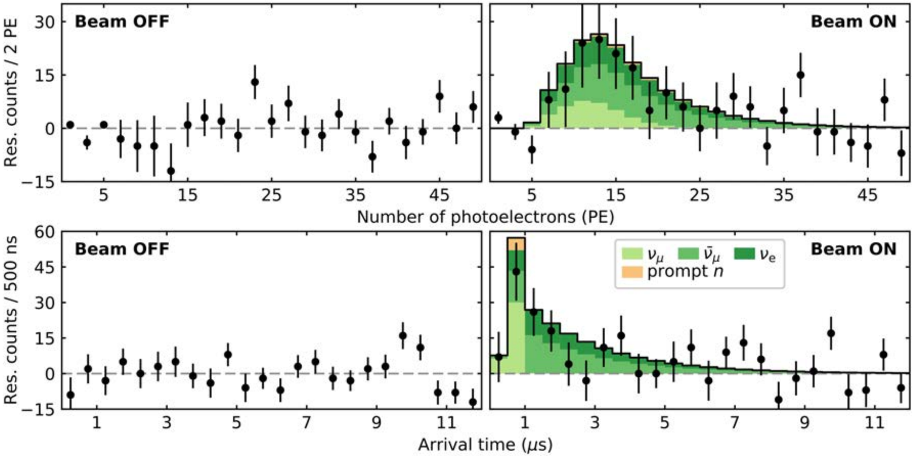




- Prompt monochromatic ν_μ from stopped pion decays:
$$\pi^+ \to \mu^+ + \nu_\mu$$
- Delayed $\bar{\nu}_\mu$ and ν_e from the subsequent muon decays:
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$
- Allows to probe SM and BSM neutral current ν_e and ν_μ interactions, that are distinguished by different energy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

COHERENT 2017: Cesium Iodide (CsI)

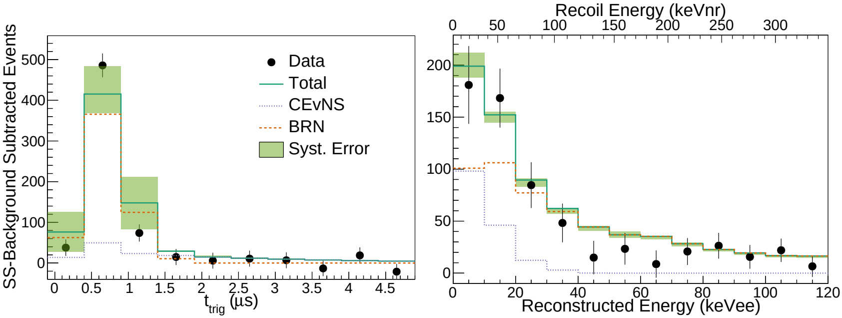
[arXiv:1708.01294]

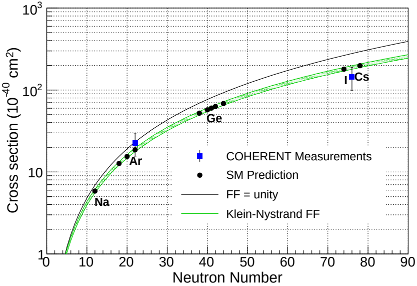


${}^{133}_{55}\mathrm{Cs}_{78}$ and ${}^{127}_{53}\mathrm{I}_{74}$ ← Heavy nuclei well suited for CEνNS

COHERENT 2020: Argon (Ar)

[arXiv:2003.10630]



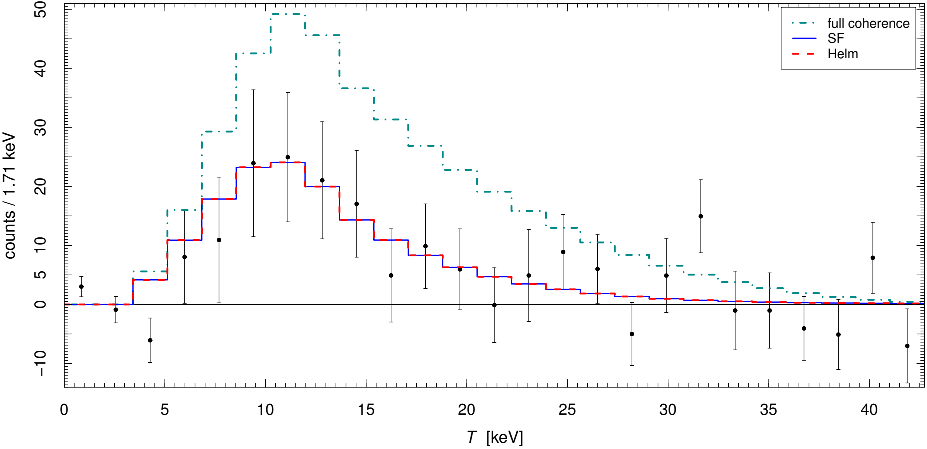


$^{40}_{18}\mathrm{Ar}_{22}$ not so heavy

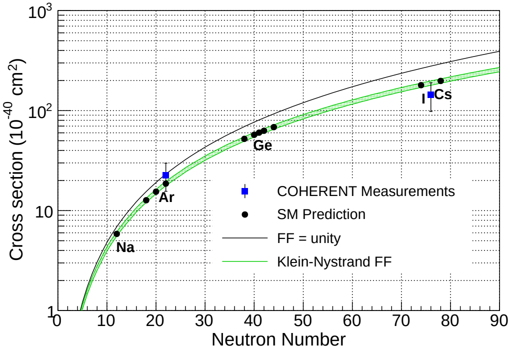
Verified theoretical $\boxed{\sigma \underset{\approx}{\propto} N^2}$

- In the COHERENT experiment the scattering is not completely coherent

$$\text{CsI:}\left\{\begin{array}{l}|\vec{q}| \sim 30 - 80\,\text{MeV} \sim 0.1 - 0.4\,\text{fm}^{-1} \\ R \approx 1.2\,A^{1/3}\,\text{fm} \approx 5\,\text{fm}\end{array}\right\} \Longrightarrow |\vec{q}|R \sim 0.5 - 2$$



[Cadeddu, CG, Li, Zhang, arXiv:1710.02730]



[COHERENT, arXiv:2003.10630]

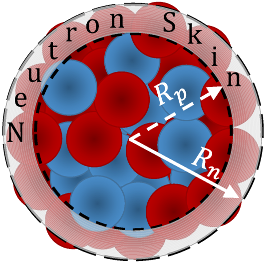
- Partial coherency is described by the nuclear neutron form factor $F_N(|\vec{q}|)$
- Fourier transform of the neutron distribution in the nucleus $\rho_N(r)$:

$$F_N(|\vec{q}|) = \int e^{-i\vec{q}\cdot\vec{r}}\,\rho_N(r)\,d^3r$$

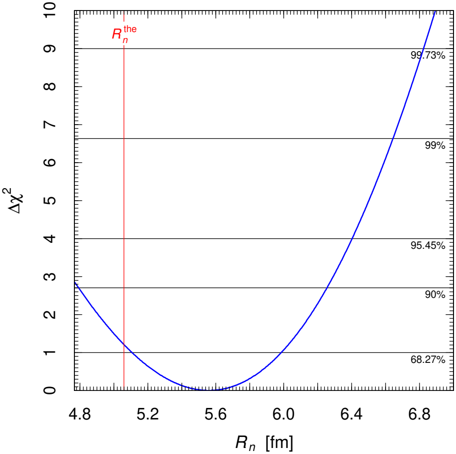
- Measurable parameter: the radius R_n of the nuclear neutron distribution

The Nuclear Proton and Neutron Distributions

- The nuclear proton distribution (charge density) is probed with electromagnetic interactions.
- Most sensitive are electron-nucleus elastic scattering and muonic atom spectroscopy.
- Hadron scattering experiments give information on the nuclear neutron distribution, but their interpretation depends on the model used to describe non-perturbative strong interactions.
- More reliable are neutral current weak interaction measurements.
  But they are more difficult.
- Before 2017 there was only one measurement of R_n with neutral-current weak interactions through parity-violating electron scattering:
  $R_n(^{208}\text{Pb}) = 5.78^{+0.16}_{-0.18}\,\text{fm}$ [PREX, arXiv:1201.2568]
  Larger than $R_p(^{208}\text{Pb}) = 5.5028 \pm 0.0013\,\text{fm} \Longrightarrow$ Neutron Skin



$$\boxed{\Delta R_{np} = R_n - R_p}$$



- Fit of the 2017 COHERENT CsI data:

$$\boxed{R_n(\mathrm{CsI}) = 5.55 \pm 0.44\,\mathrm{fm}}$$

[Cadeddu et al, arXiv:2102.06153, arXiv:1710.02730]

- $R_n(\mathrm{CsI}) \simeq R_n({}^{133}\mathrm{Cs}) \simeq R_n({}^{127}\mathrm{I})$
- Neutron skin:

$$\Delta R_{np}(\mathrm{CsI}) = 0.76 \pm 0.44\,\mathrm{fm}$$

- Predictions of nuclear models:

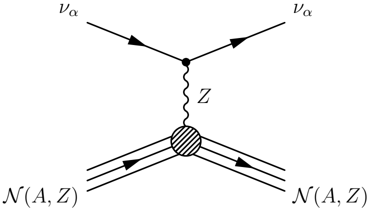
$$\Delta R_{np}(\mathrm{CsI}) \approx 0.1 - 0.3\,\mathrm{fm}$$

- A large neutron skin has important implications for:
  - Nuclear physics: a larger pressure of neutrons
  - Astrophysics: a larger size of neutron stars

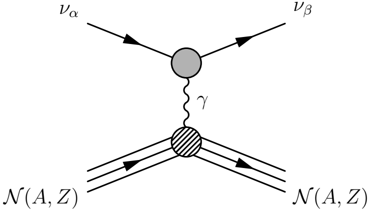
[see also: Papoulias, Kosmas, Sahu, Kota, Hota, arXiv:1903.03722; Papoulias, arXiv:1907.11644; Khan, Rodejohann, arXiv:1907.12444; Coloma, Esteban,Gonzalez-Garcia, Menendez, arXiv:2006.08624]

SM and BSM CEνNS Neutrino Interactions

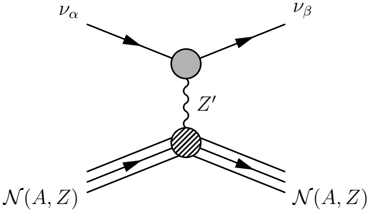
Standard Model NC



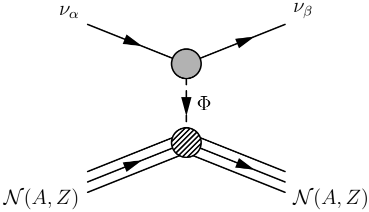
Electromagnetic Interactions



BSM Vector Mediator



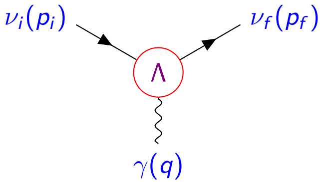
BSM Scalar Mediator



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 $\uparrow$ anapole $\uparrow$ magnetic $\uparrow$ electric $\uparrow$

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

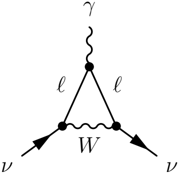
helicity-conserving (q, a) helicity-flipping (μ, ε)

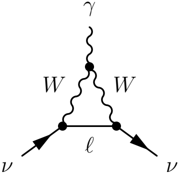
Neutrino Charge Radius

- 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:

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

- 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

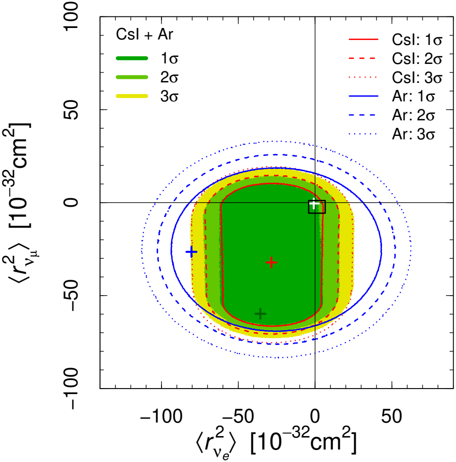
$$\sin^2\vartheta_W \to \sin^2\vartheta_W\left(1+\frac{1}{3}m_W^2\langle r^2_{\nu_\ell}\rangle\right) \quad \Longleftrightarrow \quad \nu_\ell + \mathcal{N} \to \nu_\ell + \mathcal{N}$$

- 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



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

[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]

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.