Shedding light on neutrino charge radius with CEνNS data

In collaboration with
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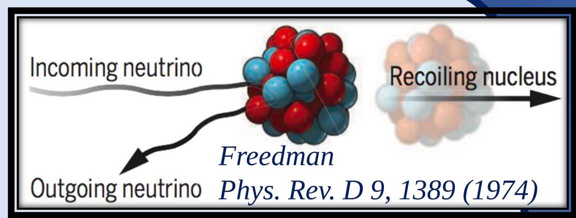
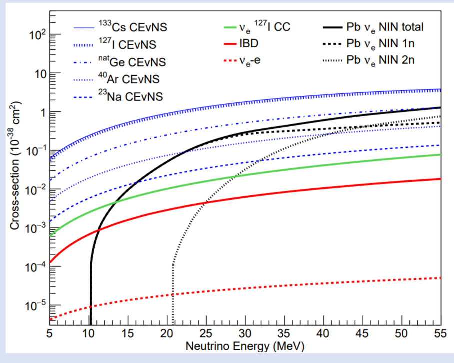
CEνNS

Coherent Elastic Neutrino-Nucleus Scattering
Weak-neutral-current process
The de Broglie wavelength of the exchanged Z^0 boson mediator is of the order of the radius of the nucleus.



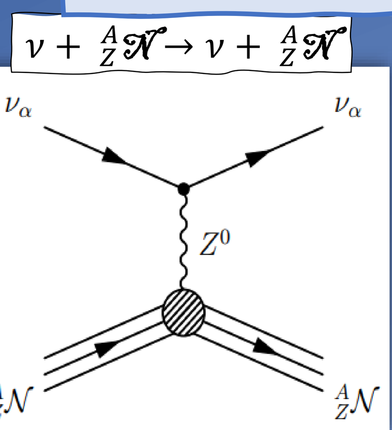
- All the nucleons respond coherently (recoils as a whole)
- "**Large**" cross section ($\propto N^2$) compared to other low energy neutrino interactions



CEνNS Cross Section

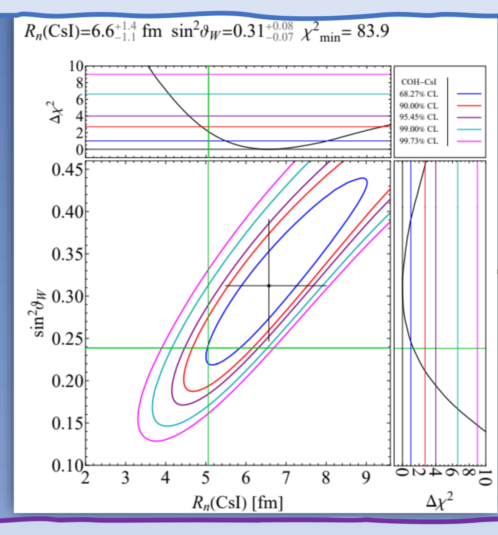
$$\frac{d\sigma}{dT_{\rm nr}} \cong \frac{G_F^2 m_N}{\pi}\left(1-\frac{m_N T_{\rm nr}}{2E_\nu^2}\right)\left[g_V^p(\sin^2\theta_W) Z F_Z(q^2) + g_V^n N F_N(q^2)\right]^2$$

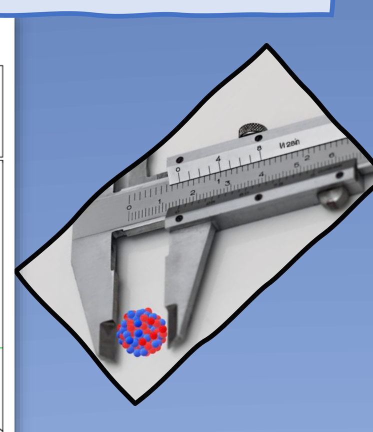
$g_V^p \sim -0.0227$, $g_V^n \sim -0.5117$



Room to study **electroweak** and **nuclear physics**

MAC. et al. Eur.Phys.J.C 83 (2023) 7, 683



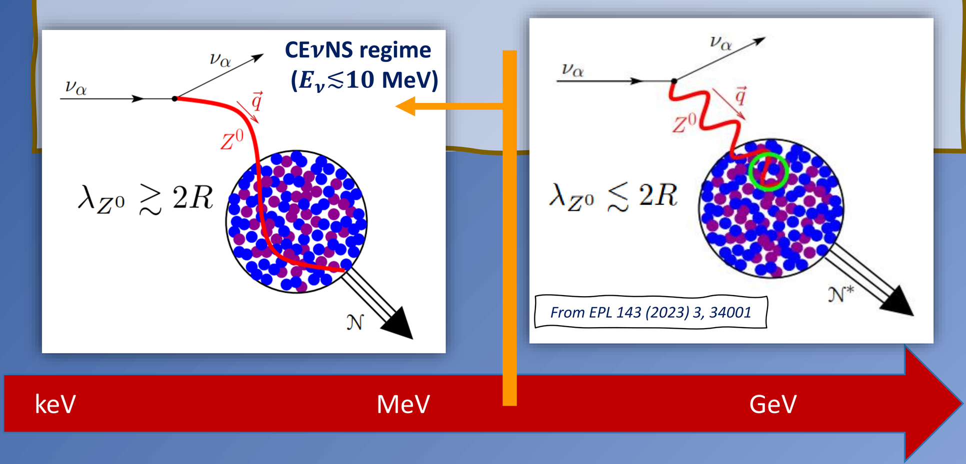


Coherency condition

$$qR_N \lesssim 1$$

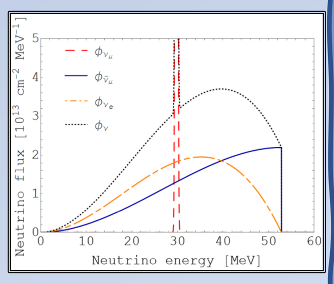
- $E_\nu \sim \frac{200\ \text{MeV fm}}{5\ \text{fm}} \sim 40$ MeV

- Neutrinos with energies of the order of few tens of MeV see the nucleus as a whole (not its constituents)
- Low energy neutrinos produce small nuclear recoils ($\sim$ keV$_{\rm nr}$): low experimental threshold needed

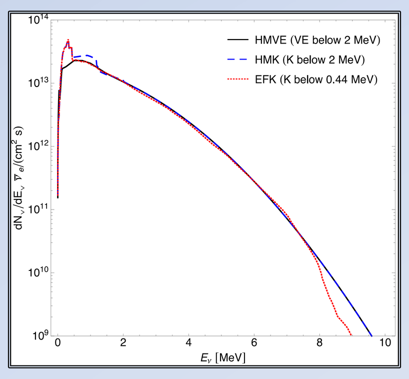


Neutrino Sources

Spallation Neutron Source (SNS)
π decay-at-rest ($\sim$ 30 MeV)
Pulsed neutrino source $\nu_e, \nu_\mu, \bar{\nu}_\mu$



Reactor Neutrinos
Produced at nuclear power plant ($\sim 1-10$ MeV)
Only $\bar{\nu}_e$



Experimental Measurements

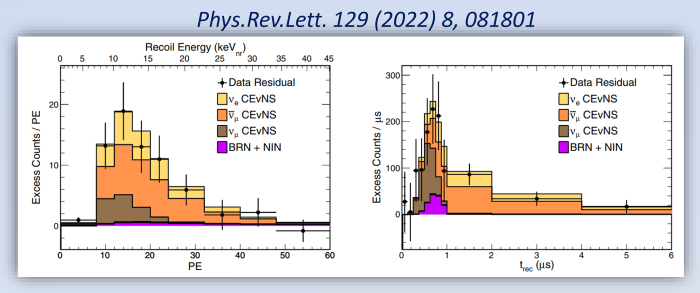
COHERENT EXPERIMENT

CsI detector: first measurement in 2017, updated results in 2021
- Data reject no-CEνNS hypothesis at **11.6 σ**
- 14.6 kg; $\sim$ 7 keV$_{\rm nr}$ threshold
- About 320 events observed consistent with the SM at 1 σ.

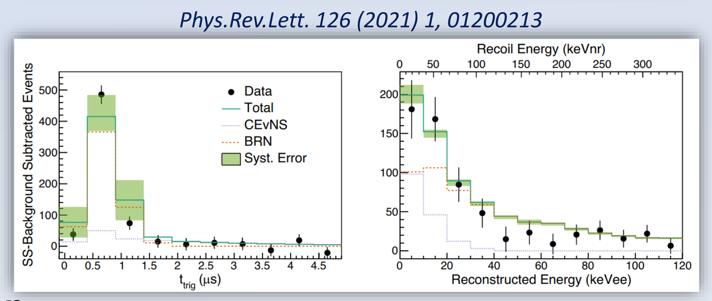
Liquid Argon (LAr) detector observed CEνNS in 2020
- Single Phase detector (24.4 kg)
- $\sim$ 20 keV$_{\rm nr}$ threshold
- **3.5 σ** significance with about 120 events consist with the SM.

In both cases, strong constraints from both energy and timing information

Phys.Rev.Lett. 129 (2022) 8, 081801



Phys.Rev.Lett. 126 (2021) 1, 01200213



Reactor Data
- Observation of CEνNS with a 3 kg Ge detector, 10.39 meters from the 2.96 GW$_{\rm th}$ Dresden-II nuclear power plant.
- 3 kg ultra low-noise Ge detector, 0.2 keV$_{\rm ee}$

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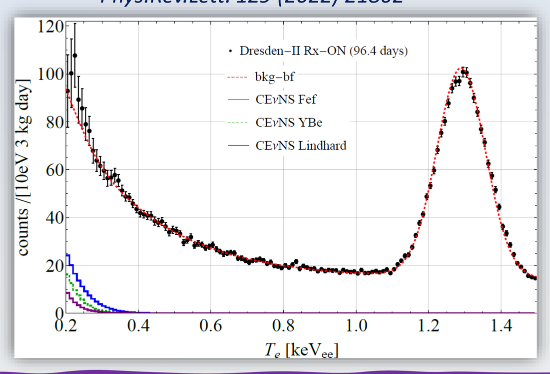
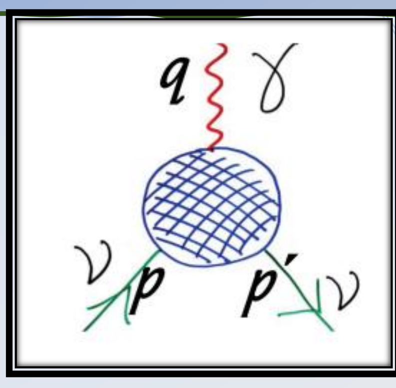


Non-standard behavior of the quenching factor at very low recoils (discussions ongoing in the community). See *MAC et al. Phys.Lett.B 852 (2024) 138627*

Neutrino Electromagnetic Properties

ν-electromagnetic property: ν interaction mediated by a photon (**electromagnetic interaction**).
In the most general form, the neutrino electromagnetic vertex function Λ_μ^{ij} is



$$\Lambda_\mu(q) = \mathbb{f}_Q(q^2)\gamma_\mu - \mathbb{f}_M(q^2)i\sigma_{\mu\nu}q^\nu + \mathbb{f}_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + \mathbb{f}_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

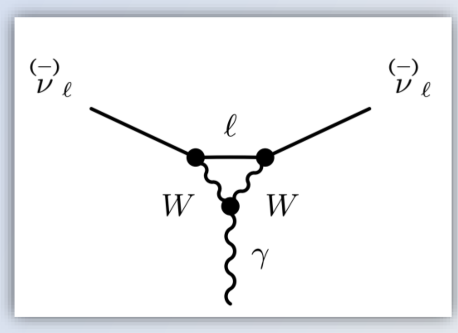
Charge Form Factor | **Magnetic Moment** | **Electric Form Factor** | **Anapole Moment**

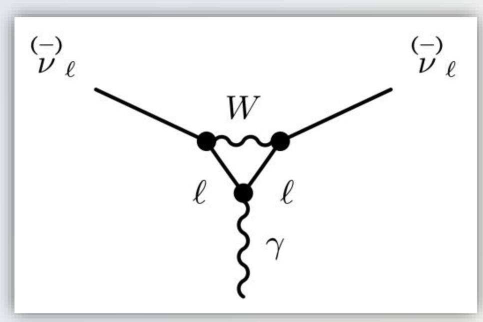
See the review Rev.Mod.Phys. 87 (2015) 531

Neutrino Charge Radius

νEM in the standard model: do we have such diagrams?

YES!





Neutrinos are neutral particles, therefore, they can not couple directly with photons
$\rightarrow$ **1 loop diagrams** are needed!

Expanding the charge form factor in a series of powers of q^2 we get

$$\mathbb{f}_Q(q^2) = \mathbb{f}_Q(0) + q^2 \frac{d\mathbb{f}_Q(q^2)}{dq^2}\Big|_{q^2=0} + \dots$$

and we define **the neutrino charge radius (NCR)** as

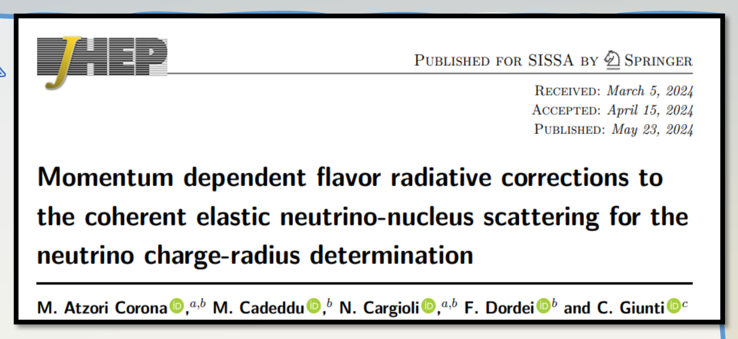
$$\langle r^2\rangle \equiv 6\frac{d\mathbb{f}_Q(q^2)}{dq^2}\Big|_{q^2=0}$$

Note that it is defined at zero momentum transfer!

This quantity can be well evaluated within the standard model and gives

$$\langle r^2_{\nu_\ell}\rangle_{SM} = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3-2\log\left(\frac{m_\ell^2}{m_W^2}\right)\right] \rightarrow \begin{cases}\langle r^2_{\nu_e}\rangle_{SM} = -8.2\times 10^{-33} cm^2\\ \langle r^2_{\nu_\mu}\rangle_{SM} = -4.8\times 10^{-33} cm^2\\ \langle r^2_{\nu_\tau}\rangle_{SM} = -3.0\times 10^{-33} cm^2\end{cases}$$

Neutrino charge radius and CEνNS


JHEP
Published for SISSA by Springer
Received: March 5, 2024
Accepted: April 15, 2024
Published: May 23, 2024

Momentum dependent flavor radiative corrections to the coherent elastic neutrino-nucleus scattering for the neutrino charge-radius determination

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The NCR modifies the neutrino-proton coupling through the radiative correction $\phi_{\nu_\ell - W}$, that can be expressed in terms of $\langle r^2_{\nu_\ell}\rangle$:

$$g_V^p \simeq \frac{1}{2} - 2\sin^2\theta_W - 2\phi_{\nu_\ell - W} + \text{flavor independent radiative correction (See Eur.Phys.J.C 83)}$$

$$g_V^p \simeq \frac{1}{2} - 2\sin^2\theta_W - \frac{\sqrt{2}\pi\alpha_{EM}}{3G_F}\langle r^2_{\nu_\ell}\rangle + \text{flavor independent radiative correction}$$

We can let it free to vary in the fit to obtain a constraint.

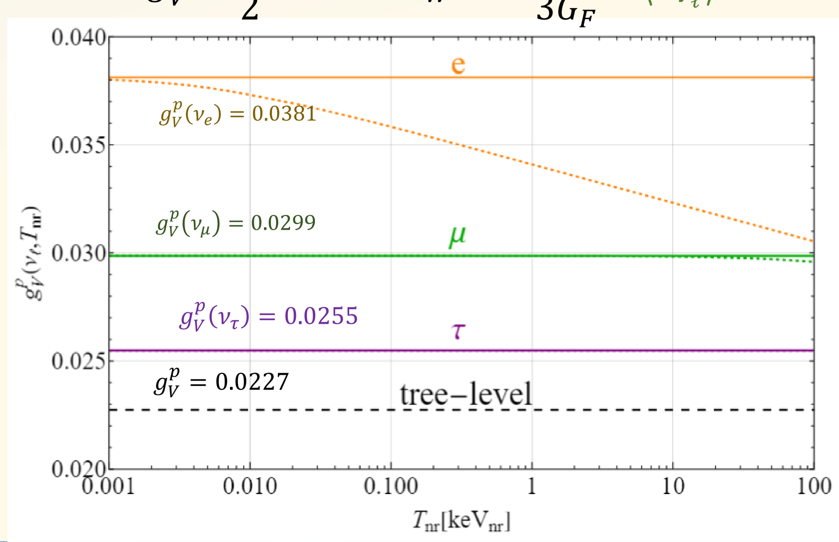
To deal with experiments performed at $q^2 \neq 0$, we define a **radiative correction associated to the NCR** dependent the momentum transfer (recall $q^2 = -2T_{nr}$)

$$\langle r^2_{\nu_\ell}\rangle^{\rm eff} = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3 - 12R_\ell(q^2)\right]$$

$$R_\ell(q^2) = \int_0^1 dx\, x(1-x)\ln\left[\frac{m_\ell^2 - q^2 x(1-x)}{M_W^2}\right]$$

The new neutrino-proton coupling is:

$$g_V^p \simeq \frac{1}{2} - 2\sin^2\theta_W - \frac{\sqrt{2}\pi\alpha_{EM}}{3G_F}\langle r^2_{\nu_\ell}\rangle^{\rm eff}$$

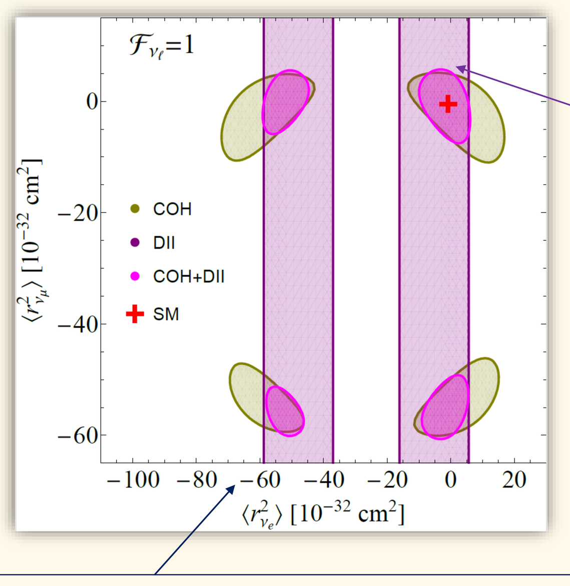


Warning:
CEνNS experiments allow the extraction of $\langle r^2_{\nu_\ell}\rangle^{\rm eff}$, but the physical NCR is defined at zero momentum transfer.

$$\mathcal{F}_{\nu_\ell}(T_{\rm nr}) = \frac{\langle r^2_{\nu_\ell}\rangle^{\rm eff}(T_{\rm nr})}{\langle r^2_{\nu_\ell}\rangle^{\rm eff}(0)} \equiv \frac{\langle r^2_{\nu_\ell}\rangle^{\rm eff}(T_{\rm nr})}{\langle r^2_{\nu_\ell}\rangle^{\rm SM}}$$

State-Of-The-Art Constraints

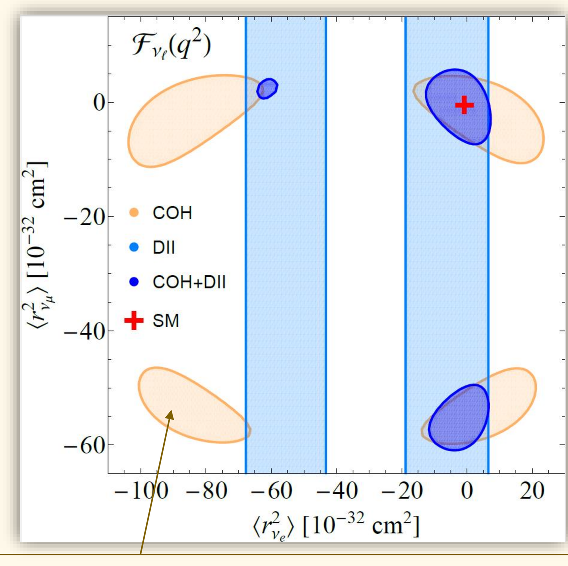
No momentum dependence (*JHEP 09 (2022) 164*)



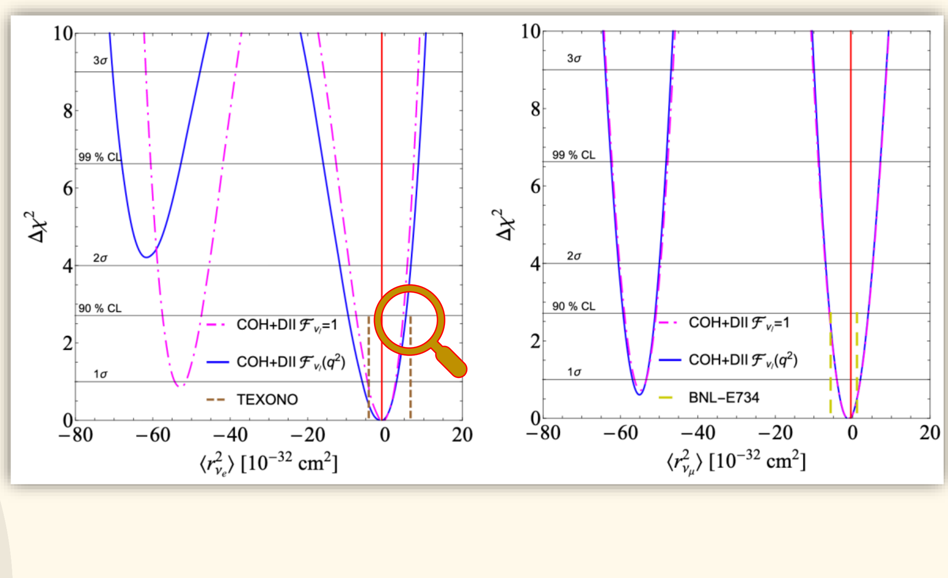
Dresden-II constraints from reactor $\bar{\nu}_e$

Negative large values produce a degeneracy in the cross section

With momentum dependence



COHERENT results are more affected than reactors due to the larger momentum transfer



- By combining measurements **at different momentum transfer**, due to the impact of the NCR form factor, the allowed **regions in the parameter space are reduced.**

At 90% C.L.

Improved best limit!

$$-9.5 < \langle r^2_e[10^{-32}\text{cm}^2]\rangle < 5.5$$

$$-59.2 < \langle r^2_{\nu_\mu}[10^{-32}\text{cm}^2]\rangle < -51.0$$

$$-5.9 < \langle r^2_{\nu_\mu}[10^{-32}\text{cm}^2]\rangle < 4.1$$

World leading limits:

$2 < \langle r^2_e[10^{-32}\text{cm}^2]\rangle < 6.6$ TEXONO

$-5.7 < \langle r^2_{\nu_\mu}[10^{-32}\text{cm}^2]\rangle < 1.1$ BNL

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