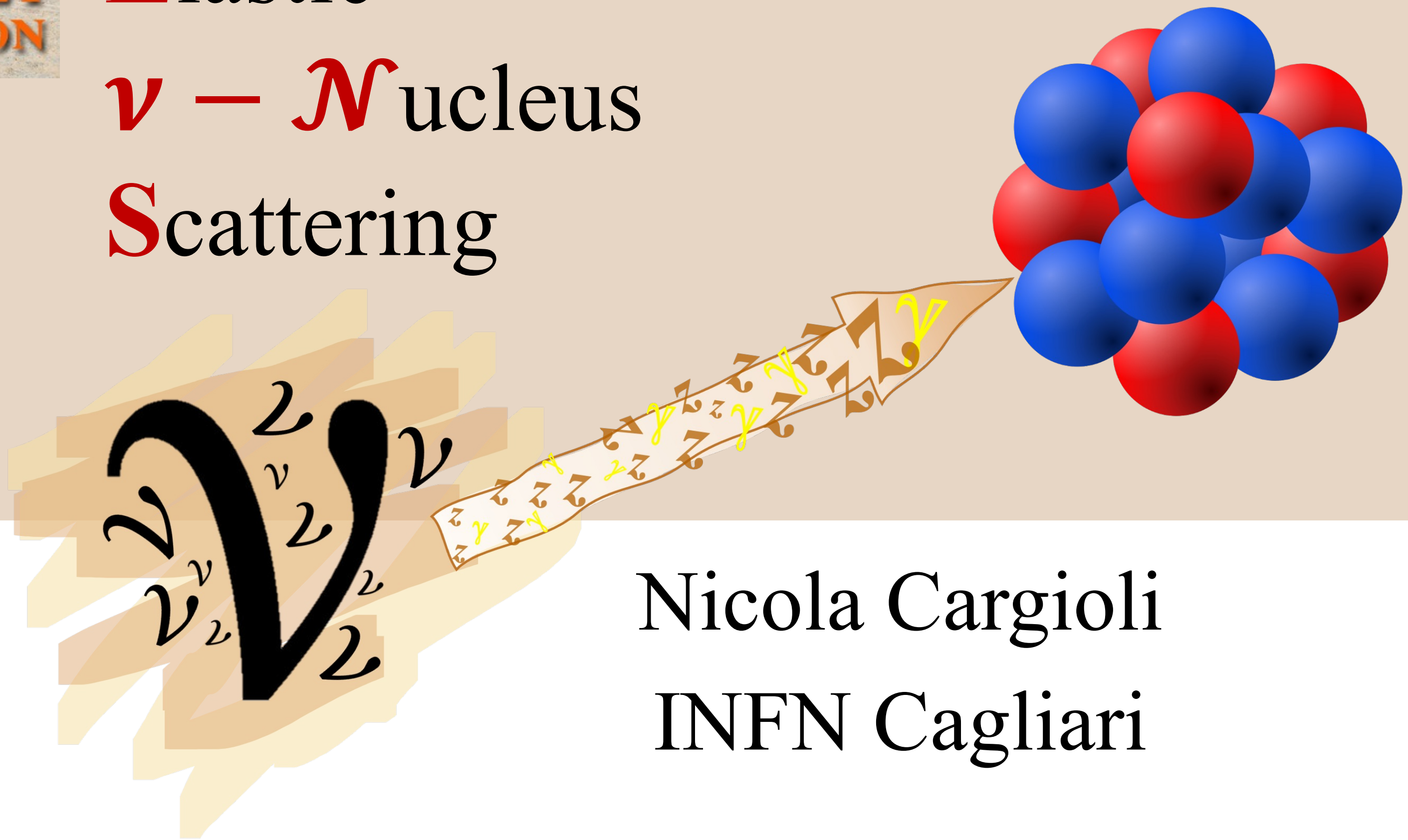
Flavor «unblinding» CEνNS: the Neutrino Charge Radius contribution to

Coherent
Elastic
ν – $\mathcal{N}$ucleus
Scattering



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The Neutrino Charge Radius

Based on:
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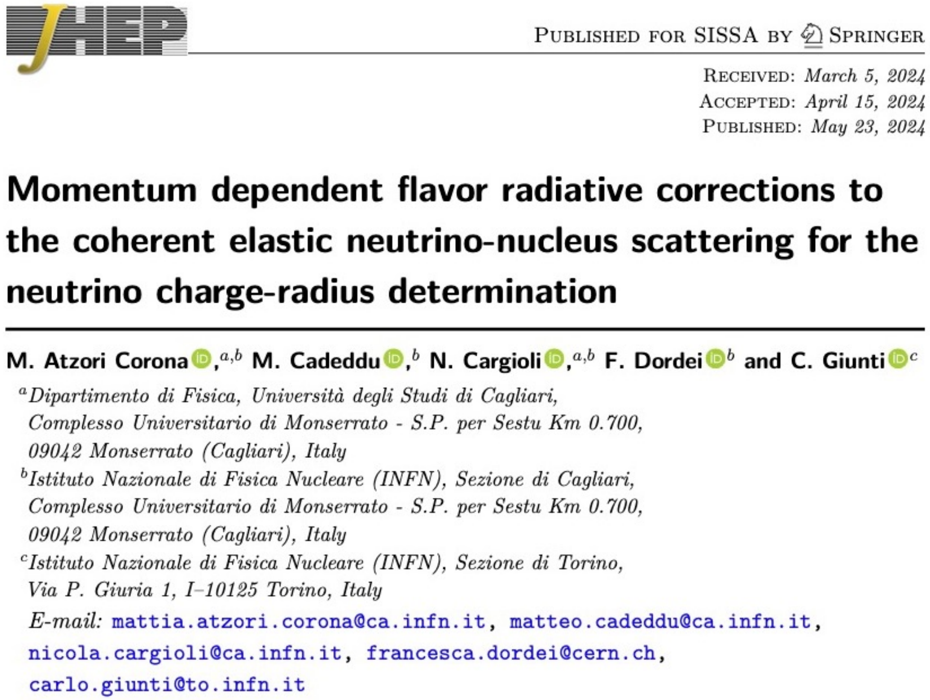

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Momentum dependent flavor radiative corrections to the coherent elastic neutrino-nucleus scattering for the neutrino charge-radius determination

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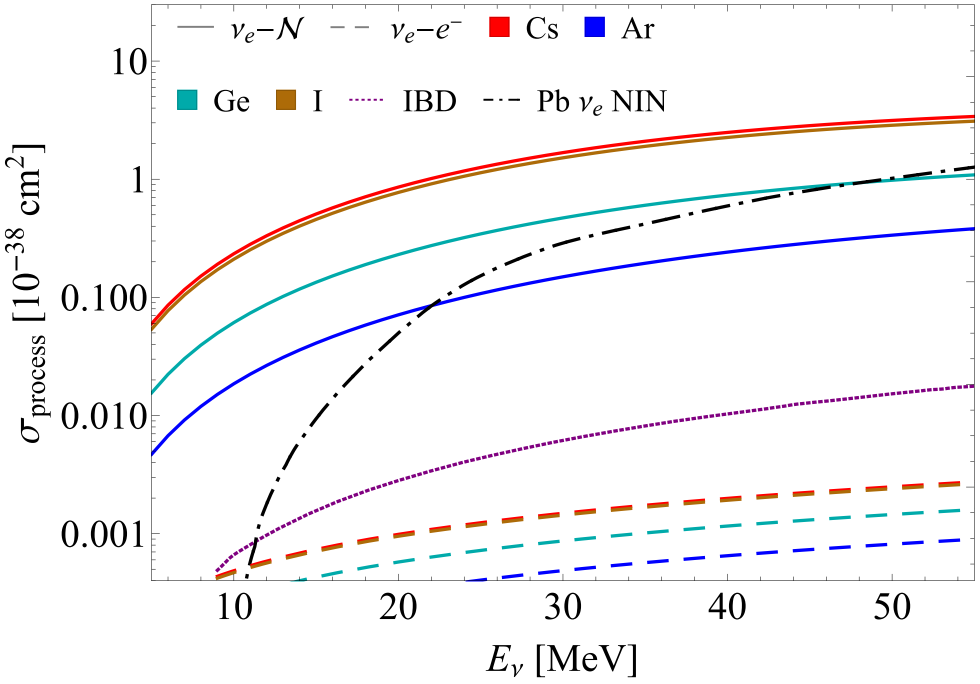
CEvNS

CEvNS: **C**oherent **E**lastic **N**eutrino-**N**ucleus **S**cattering

- Weak-neutral-current process
- "Coherency": the nucleons respond as a whole →
- ✅ "Large" cross section ($\propto N^2$)

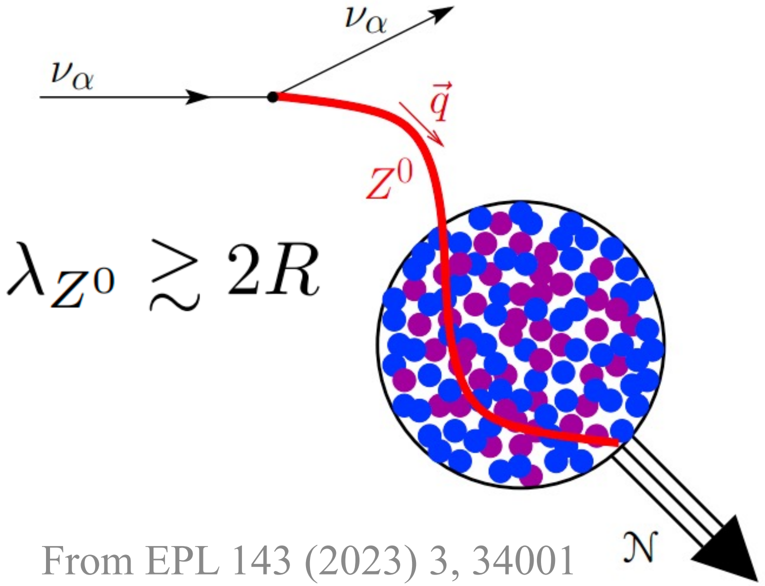


The de Broglie wavelength of the Z^0 boson is of the order of the nuclear radius

$$qR_N \lesssim 1$$

Low momentum transfer (MeV scale) needed, MeV scale neutrinos required!

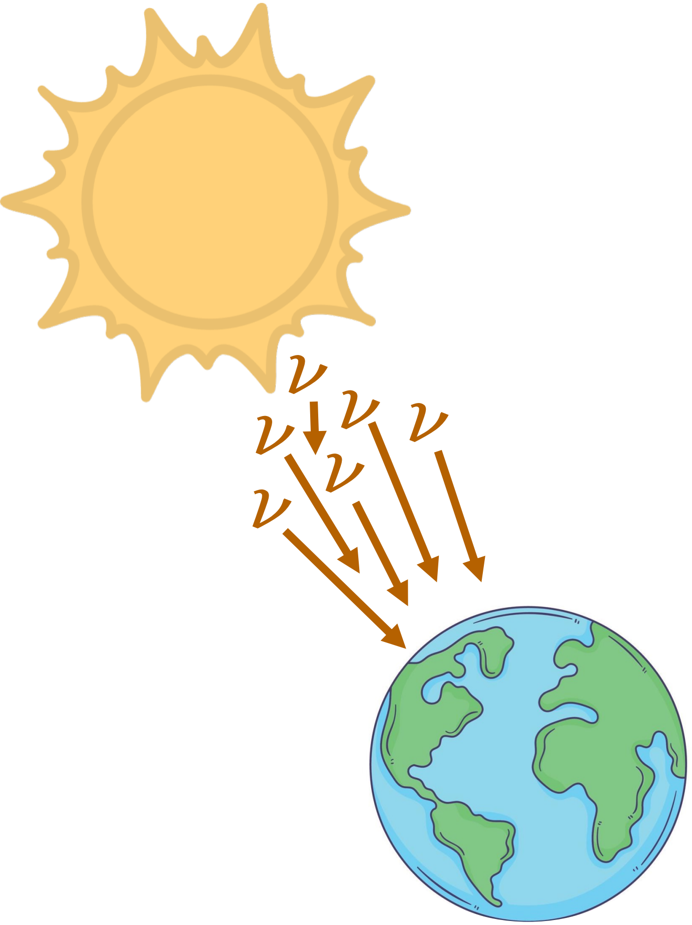
❌ The outcome is a tiny nuclear recoil



From EPL 143 (2023) 3, 34001

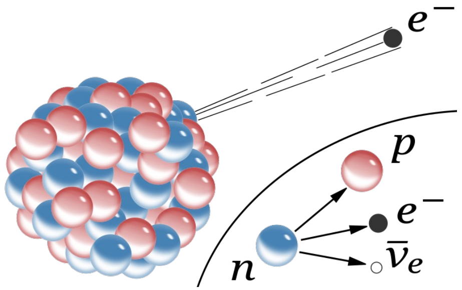
Low Energy Neutrinos

Solar Neutrinos



*Solar neutrino CEvNS has not been observed yet

Reactor Neutrinos

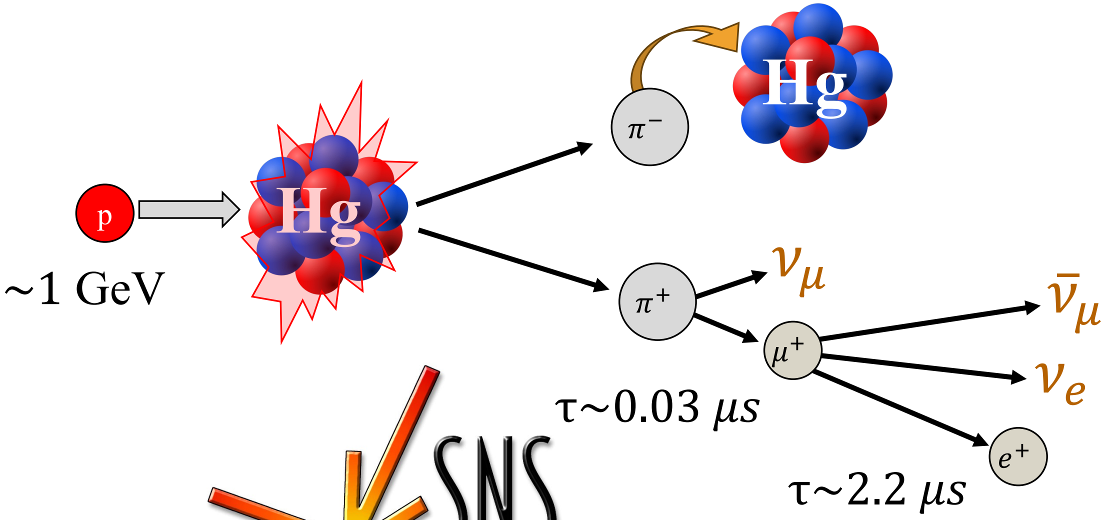


High Flux

Only $\bar{\nu}_e$

$E_\nu \sim 1 - 10$ MeV

Decay-at-rest Neutrinos



SNS
SPALLATION NEUTRON SOURCE

Pulsed beam

Time structure

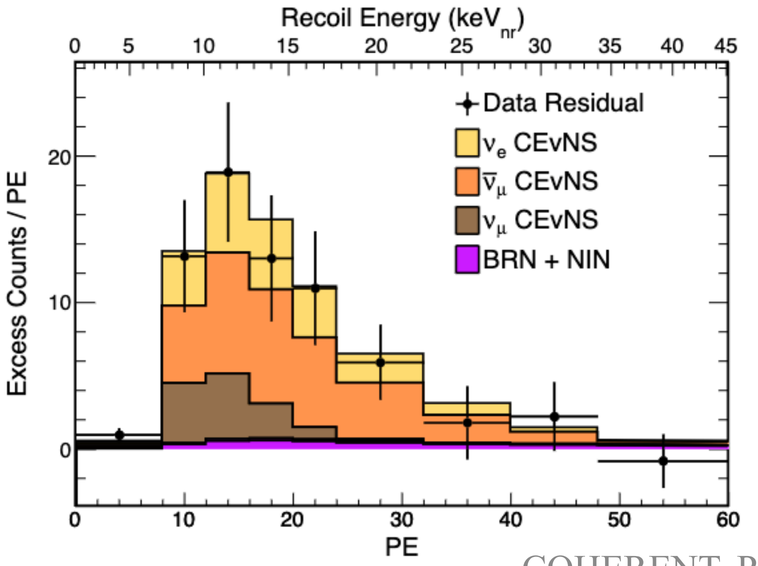
Three kind of ν

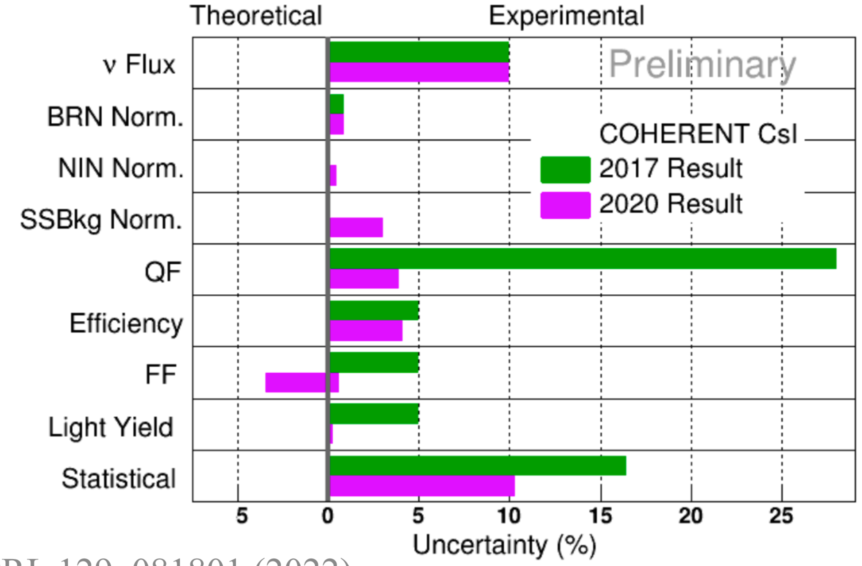
$E_\nu \sim 30$ MeV (up to 50 MeV)

CEvNS measurements @COHERENT: CsI

First CEvNS measurement achieved in 2017 with a 14.6 kg CsI scintillating crystal and neutrinos from πDAR by the COHERENT Collaboration

- Full dataset in 2020
- 306 ± 20 CEvNS events: 11.6σ significance
- To be compared with prediction: $333 \pm 11\ (th) \pm 42\ (ex)$ events
- Flux uncertainty dominates the systematic uncertainty, level 10-13%

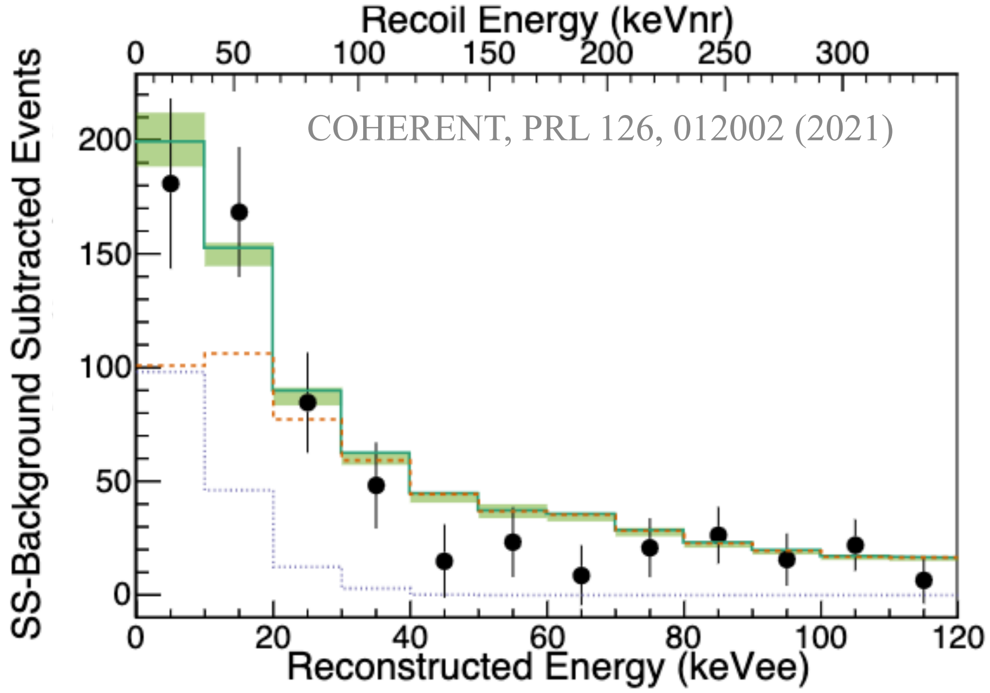




COHERENT, PRL 129, 081801 (2022)

CEvNS measurements @COHERENT: LAr

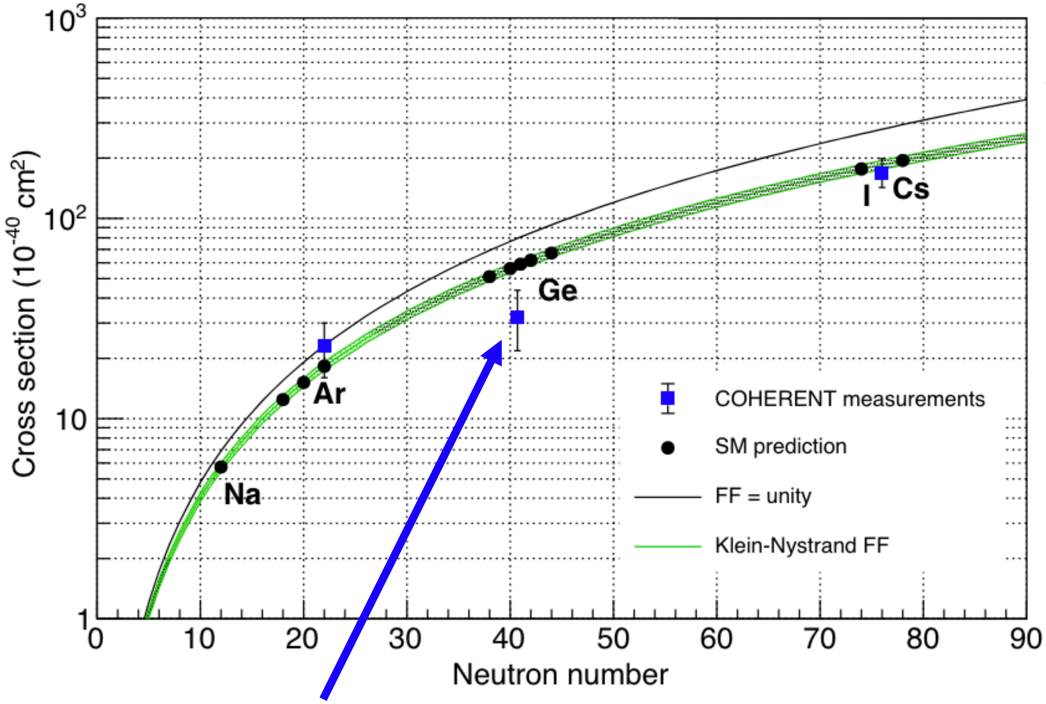
- 2020 first results using Ar (CENNS-10 detector)
- 24 kg active mass of atmospheric argon
- Single phase only (scintillation), thr. ~ 20 keV$_{nr}$
- More than 3σ evidence over background
- Still analyzing data, more results expected soon.



COHERENT, PRL 126, 012002 (2021)

- New targets expected soon!

Test of the expected $\propto N^2$ dependence



R. Bouabid (COHERENT) @ Magnificent CEvNS 2024

New COHERENT measurement on Ge crystal (arXiv:2406.13806)

NEw

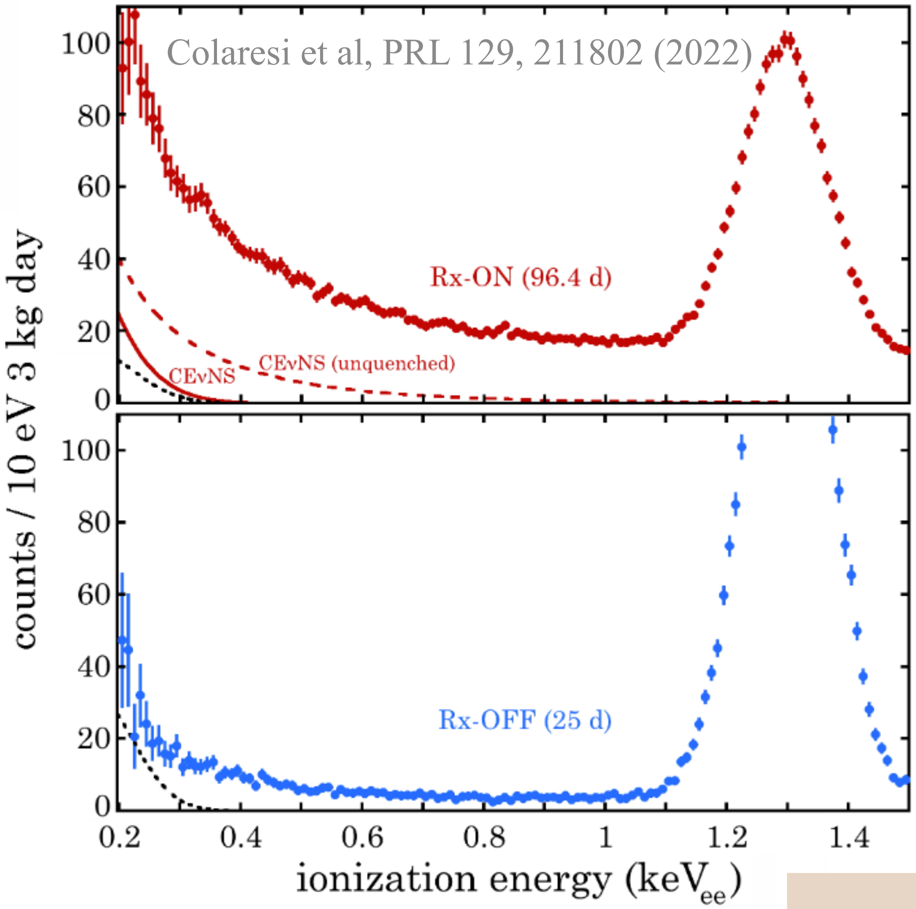
CEvNS evidence at 3.9σ

In agreement with the SM at 2σ

CEvNS measurements @Reactors: Ge

- 2022 First evidence for CEvNS from reactor anti-neutrinos
- 94.6 day (Rx-ON) exposure of a 3 kg ultra-low noise germanium detector (NCC-1701)
- 10.39 m away from the Dresden-II boiling water reactor ($P = 2.96\ \mathrm{GW_{th}}$)
- Low energy threshold: 0.2 $\mathrm{keV_{ee}}$
- The background comes from the elastic scattering of epithermal neutrons and the electron capture in ^{71}Ge

$$\frac{dN^{\mathrm{bkg}}}{dT_\mathrm{e}} = N_{\mathrm{epith}} + A_{\mathrm{epith}} e^{-T_\mathrm{e}/T_{\mathrm{epith}}} + \sum_{i=\mathrm{L1,L2,M}} \frac{A_i}{\sqrt{2\pi}\sigma_i} e^{-\frac{(T_\mathrm{e}-T_i)^2}{2\sigma_i^2}}$$



- Strong preference for the presence of CEvNS is found
- How well do we know the quenching factor model at low energies?

CEvNS cross section

Neutrino energy

Mass of the target nucleus

Proton Form Factor

Neutron Form Factor

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

Nuclear recoil energy

SM vector proton coupling: Weinberg angle

SM vector neutron coupling

For more physics with CEvNS look at M. Cadeddu's talk

At tree-level the CEvNS process is completely flavour-blind and the SM vector couplings are:

$$\boxed{\begin{aligned} g_V^p(\nu_{e,\mu,\tau}) &= \frac{1}{2} - 2\sin^2\vartheta_W \cong 0.0227 \\ g_V^n(\nu_{e,\mu,\tau}) &= -\frac{1}{2} = -0.5 \end{aligned}}$$

$^*\sin^2\vartheta_W\,(q^2 \approx 0) = 0.23863(5)$

There is a plethora of other experiments expecting to detect CEvNS soon! → Precision frontier to be reached soon! → We need **radiative corrections**!

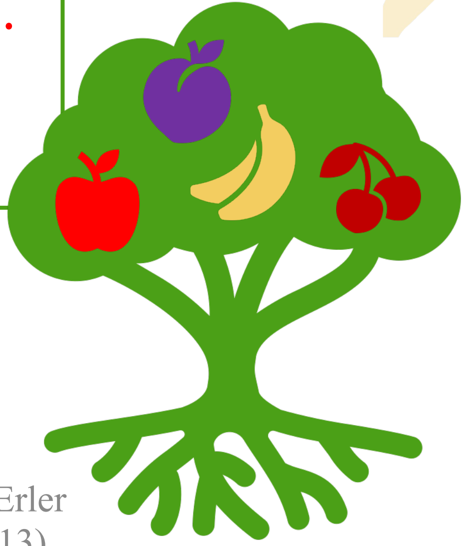
Radiative Corrections to CEvNS

$$g_V^p(\nu_{e,\mu,\tau}) = \frac{1}{2} - 2\sin^2\vartheta_W \cong 0.0227$$

$$g_V^n(\nu_{e,\mu,\tau}) = -\frac{1}{2} = -0.5$$

$$g_V^p(\nu_{e,\mu,\tau}) = \frac{1}{2} - 2\sin^2\vartheta_W + \cdots$$

$$g_V^n(\nu_{e,\mu,\tau}) = -\frac{1}{2} + \cdots$$



At increasing precision, one needs to consider radiative corrections due to higher-order vertex contributions

- In Erler & Su, a strategy is proposed for EW processes to calculate most of these corrections in a universal way that is valid at all orders

See the RGE formalism in Erler & Su, arXiv 1303.5522 (2013)

- For neutral current neutrino processes, the corrections are absorbed in the definitions of the low-energy EW couplings

$\boldsymbol{g_V^p}$ and $\boldsymbol{g_V^n}$

- Remaining smaller corrections are assumed to be applied individually for each experiment, i.e. EW coupling parameters are defined at some common reference scale μ (they choose μ=0), and have the experimental collaborations correct for effects due to $q^2 \neq 0$.

Overlooked for CEvNS experiments so far!

Radiative Corrections to CEvNS

When including the universal radiative corrections the couplings become

$$g_V^p(\nu_\ell) = \rho\left(\frac{1}{2} - 2\sin^2\vartheta_{\mathrm{W}}\right) + 2\text{⧖}_{WW} + \square_{WW} - 2\phi_{\nu_\ell W} + \rho(2\boxtimes_{ZZ}^{uL} + \boxtimes_{ZZ}^{dL} - 2\boxtimes_{ZZ}^{uR} - \boxtimes_{ZZ}^{dR})$$

$$g_V^n = -\frac{\rho}{2} + 2\square_{WW} + \text{⧖}_{WW} + \rho(2\boxtimes_{ZZ}^{dL} + \boxtimes_{ZZ}^{uL} - 2\boxtimes_{ZZ}^{dR} - \boxtimes_{ZZ}^{uR}).$$

*

RGE formalism in Erler & Su, arXiv 1303.5522 (2013)

Where $\rho = 1.00063$ represents a low-energy correction for neutral current processes and:

WW box

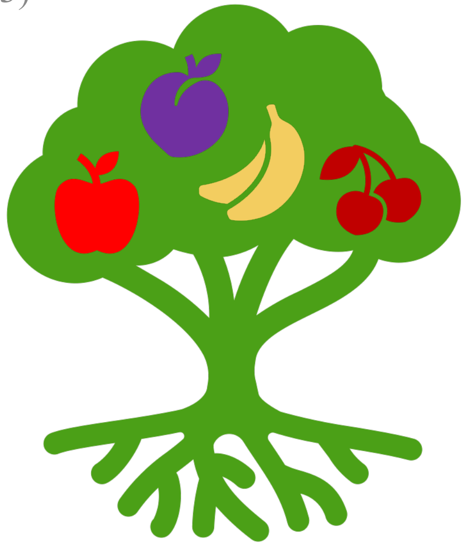
$$\square_{WW} = -\frac{\hat{\alpha}_Z}{2\pi\hat{s}_Z^2}\left[1 - \frac{\hat{\alpha}_s(M_W)}{2\pi}\right]$$

$$\text{⧖}_{WW} = \frac{\hat{\alpha}_Z}{8\pi\hat{s}_Z^2}\left[1 + \frac{\hat{\alpha}_s(M_W)}{\pi}\right]$$

WW crossed-box

$$\boxtimes_{ZZ}^{fX} = -\frac{3\hat{\alpha}_Z}{8\pi\hat{s}_Z^2\hat{c}_Z^2}(g_{LX}^{\nu_\ell f})^2\left[1 - \frac{\hat{\alpha}_s(M_Z)}{\pi}\right]$$

ZZ box



While the remaining radiative term is related to the so-called **Neutrino Charge Radius** (NCR)

$$\phi_{\nu_\ell W} = -\frac{\alpha}{6\pi}\left(\ln\frac{M_W^2}{m_\ell^2} + \frac{3}{2}\right)$$

The NCR adds a flavor-dependence in $g_V^p \to \boldsymbol{g_V^p(\nu_\ell)}$

* $g_V^p(\nu_e) \simeq 0.0381$ $g_V^p(\nu_\mu) \simeq 0.0299$ $g_V^p(\nu_e) \simeq 0.0255$ $g_V^n \simeq -0.5117$

Up to 67% difference wrt tree-level

The Neutrino Charge Radius

- In the SM, the NCR is the only electromagnetic property of neutrinos that is different from zero.
- A neutral particle can be seen as the superposition of two charge distributions of opposite signs described by a charge form factor which is nonzero only for $q^2 \neq 0$

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

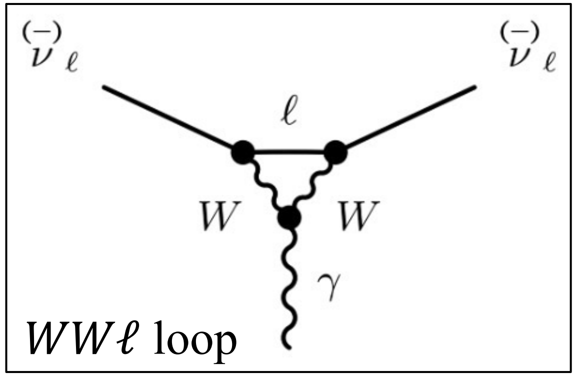
=0 since ν is neutral

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

Neutrino Charge Radius
i.e. the radius of the electric charge distribution
It is a physical observable, being finite and gauge invariant

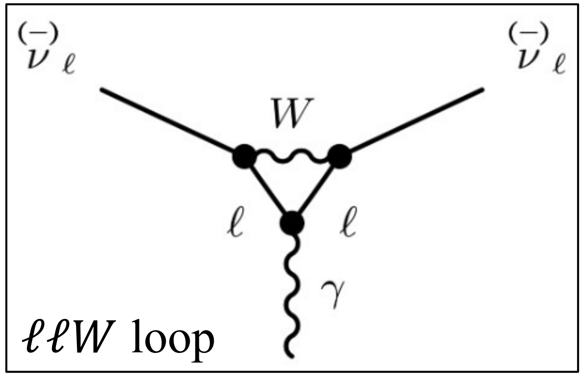
Bernabeu et al, Phys.Rev.D62:113012 (2000)

The charge radius is generated by a loop insertion into the ν_ℓ line, where W boson and charged lepton ℓ can enter



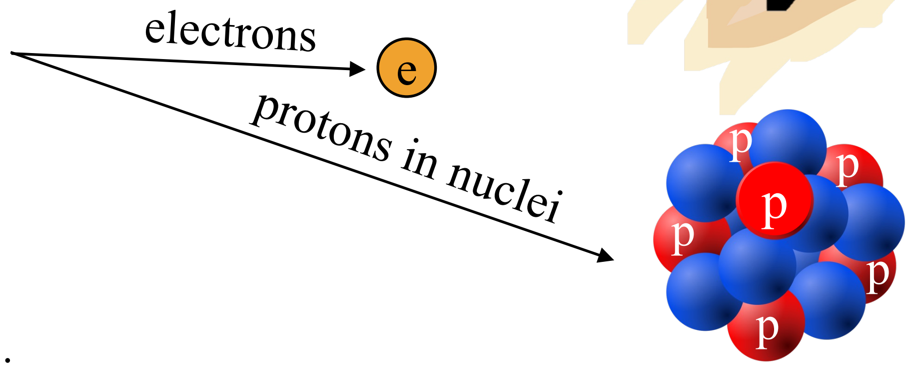
$$\boxed{\langle r^2_{\nu_\ell} \rangle_{\mathrm{SM}} = -\frac{G_{\mathrm{F}}}{2\sqrt{2}\pi^2}\left[3 - 2\ln\left(\frac{m_\ell^2}{m_W^2}\right)\right]}$$

$$* \ \langle r^2_{\nu_e} \rangle \simeq -8.3 \times 10^{-33}\,\mathrm{cm}^2$$
$$\langle r^2_{\nu_\mu} \rangle \simeq -4.8 \times 10^{-33}\,\mathrm{cm}^2$$
$$\langle r^2_{\nu_\tau} \rangle \simeq -3.0 \times 10^{-33}\,\mathrm{cm}^2$$



NCR practical guide

- The neutrino CR affects the scattering of neutrinos with charged particles
- In CEvNS only effects on the neutrino-proton coupling



CE*ν*NS:

$$g_V^p \to \tilde{g}_V^p - \frac{2}{3} M_W^2 \langle r_{\nu_\ell}^2 \rangle \sin^2 \vartheta_W = \tilde{g}_V^p - \underbrace{\frac{\sqrt{2}\pi\alpha}{3G_F} \langle r_{\nu_\ell}^2 \rangle}_{}{}^{*}$$

Effectively we can see the NCR contribution as an **effective shift of the weak mixing angle**

- Interesting quantity to measure:
  - Precision test of the SM at low energies
  - New particles entering the loops could modify it
- So far, only constraints!

$$^{*}\boxed{\langle r^2 \rangle \equiv 6 \frac{d\mathbb{f}_Q(q^2)}{dq^2}\bigg|_{q^2=0}} \Longrightarrow \boxed{\langle r_{\nu_\ell}^2 \rangle_{\mathrm{SM}} = -\frac{G_\mathrm{F}}{2\sqrt{2}\pi^2}\left[3 - 2\ln\left(\frac{m_\ell^2}{m_W^2}\right)\right]}$$

However, the neutrino charge radius is defined at $q^2 = 0$, while **none of the experiments is performed at null-momentum transfer**!

The momentum transfer must be taken into account when implementing radiative corrections in CEvNS processes and when trying to extract the charge radius!

see also Tomalak et al, JHEP 2102, 097 (2021)

Q^2-Dependence in the NCR correction

- Marciano et al. in arXiv:0403168 discuss **process-dependent radiative corrections**

$$\sin^2\vartheta_W(q^2) = k_{\nu_\ell}(q^2)\sin^2\vartheta_W(M_Z) \longrightarrow$$

Everything hidden in the weak mixing angle running!

- For neutrino scattering

$$k_{\nu_\ell}(q^2) = 1 - \frac{\alpha}{2\pi\hat{s}_Z^2}\left[2\sum_f (T_{3f}Q_f - 2\hat{s}_Z^2 Q_f^2)J_f(q^2) + \frac{\hat{c}_Z^2}{3} + \frac{1}{\hat{c}_Z^2}\left(\frac{19}{8} + \frac{17}{4}\hat{s}_Z^2 + 3\hat{s}_Z^4\right) - \left(\frac{7}{2}\hat{c}_Z^2 + \frac{1}{12}\right)\ln\hat{c}_Z^2\right] \boxed{- \frac{\alpha}{\pi\hat{s}_Z^2}\left[-R_\ell(q^2) + \frac{1}{4}\right]}$$

Reminds of the NCR radiative correction

$$\boxed{\begin{aligned}\phi^{\text{eff}}_{\nu_\ell W}(q^2) &= -\frac{\alpha}{\pi}\left(-R_\ell(q^2) + \frac{1}{4}\right)\\ &= -\frac{\alpha}{\pi}\left(-\int_0^1 dx\, x(1-x)\ln\left[\frac{m_\ell^2 - q^2x(1-x)}{M_W^2}\right] + \frac{1}{4}\right)\end{aligned}}$$

$$\boxed{\langle r^2_{\nu_\ell}\rangle^{\text{eff}} = \frac{6G_F}{\sqrt{2}\pi\alpha}\phi^{\text{eff}}_{\nu_\ell W}(q^2) = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3 - 12R_\ell(q^2)\right]}$$

Effective NCR definition to account for the momentum dependence in the radiative corrections

$q^2 \to 0$

✅ $$\phi_{\nu_\ell W} = -\frac{\alpha}{6\pi}\left(\ln\frac{M_W^2}{m_\ell^2} + \frac{3}{2}\right)$$

We obtain the SM NCR in the null momentum transfer limit

Q^2-Dependence in the NCR correction

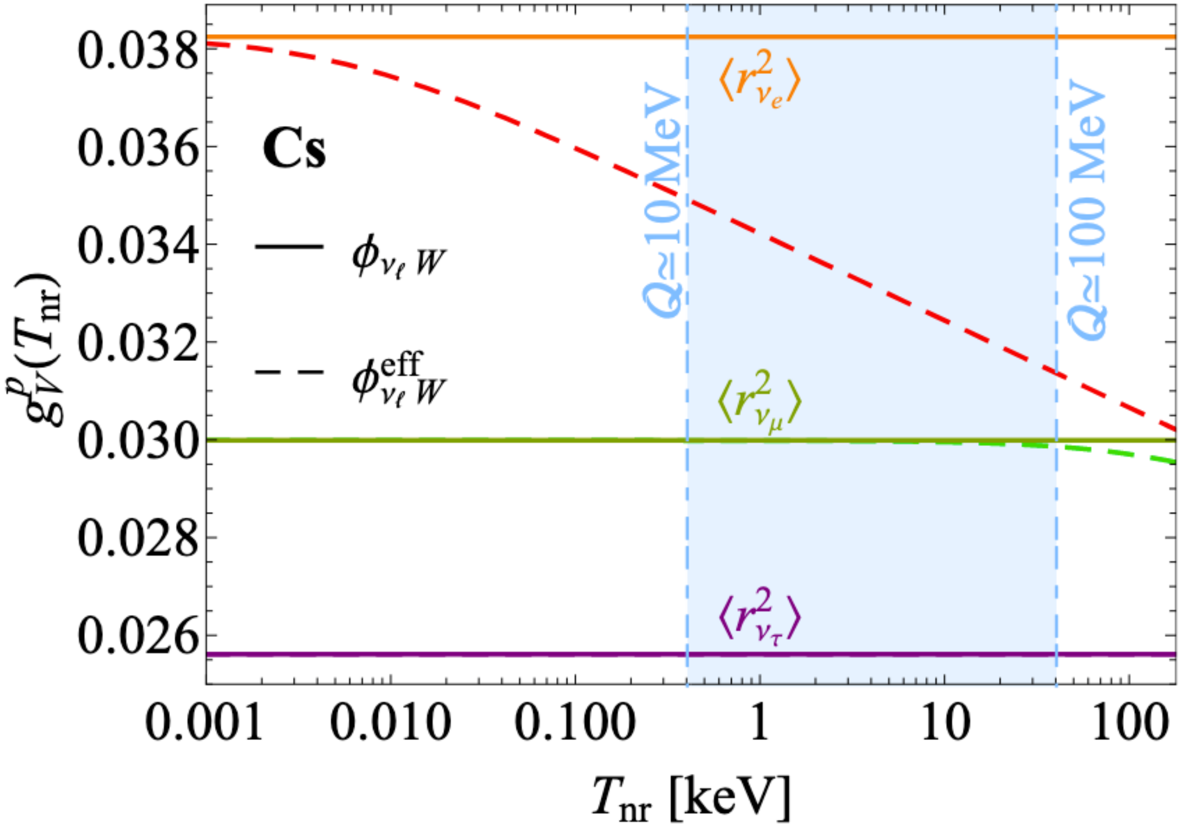
$$\boxed{\langle r^2_{\nu_\ell}\rangle^{\mathrm{eff}} = \frac{6G_F}{\sqrt{2}\pi\alpha}\phi^{\mathrm{eff}}_{\nu_\ell W}(q^2) = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3 - 12R_\ell(q^2)\right]}$$

Considering the latter NCR correction inside the calculation of the neutrino-proton coupling

M. Atzori Corona, M. Cadeddu, N.C., F. Dordei, C. Giunti, JHEP05(2024)271

The impact of the momentum transfer becomes visible for $\boldsymbol{q^2 \gtrsim m_\ell^2}$:

- For ν_e processes the correction is relevant for $q \gtrsim 0.5$ MeV
- For ν_μ only above $\sim$100 MeV
- COHERENT probes $q \sim 10 - 100$ MeV



10-20% difference in the proton coupling!

~1% effect on the cross section

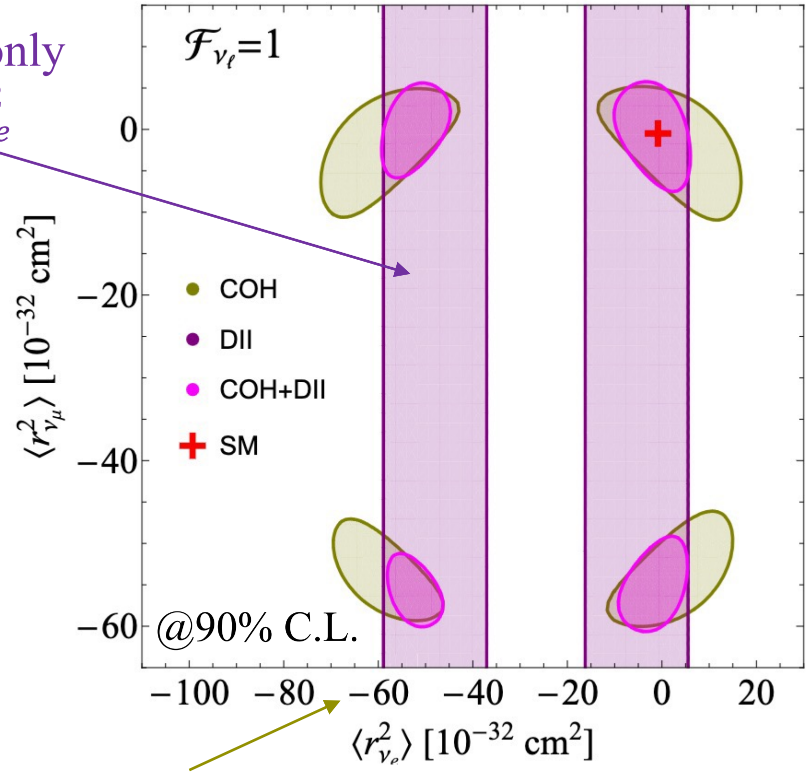
~ 0.5% effect on the rate

Results – NCR from CEvNS data

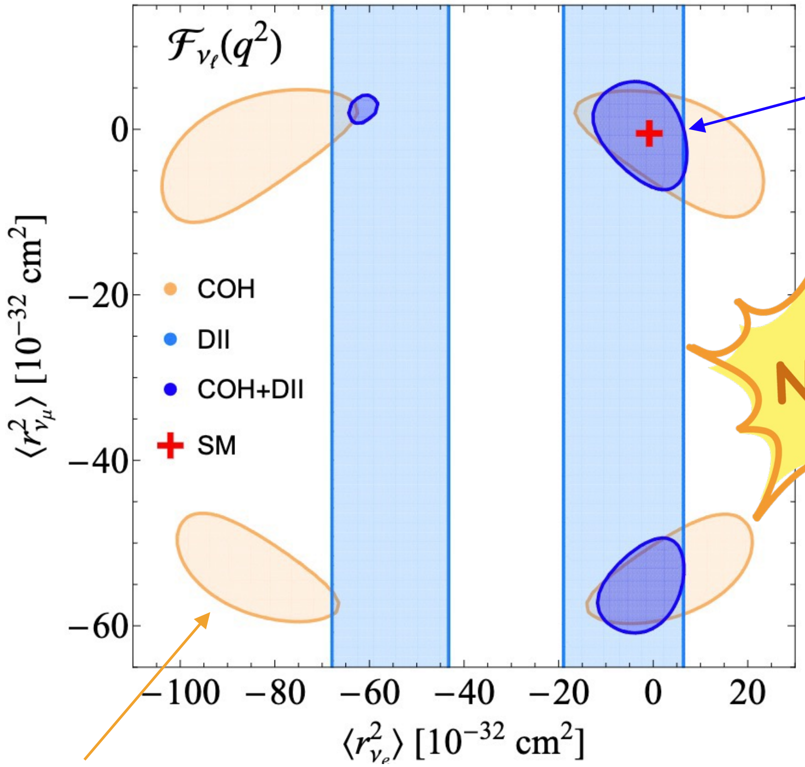
To extract NCR from data, we introduce a form factor

$$\mathcal{F}_{\nu_\ell}(T_{\mathrm{nr}}) = \frac{\langle r^2_{\nu_\ell}\rangle^{\mathrm{eff}}(T_{\mathrm{nr}})}{\langle r^2_{\nu_\ell}\rangle^{\mathrm{eff}}(0)} \equiv \frac{\langle r^2_{\nu_\ell}\rangle^{\mathrm{eff}}(T_{\mathrm{nr}})}{\langle r^2_{\nu_\ell}\rangle^{\mathrm{SM}}} \xrightarrow{q\,\to\,0} \mathcal{F}_{\nu_\ell}(T_{\mathrm{nr}}) = 1$$

No-momentum dependence



With momentum dependence



Reactors are only sensitive to $r^2_{\nu_e}$

Muonic contours are only mildly affected

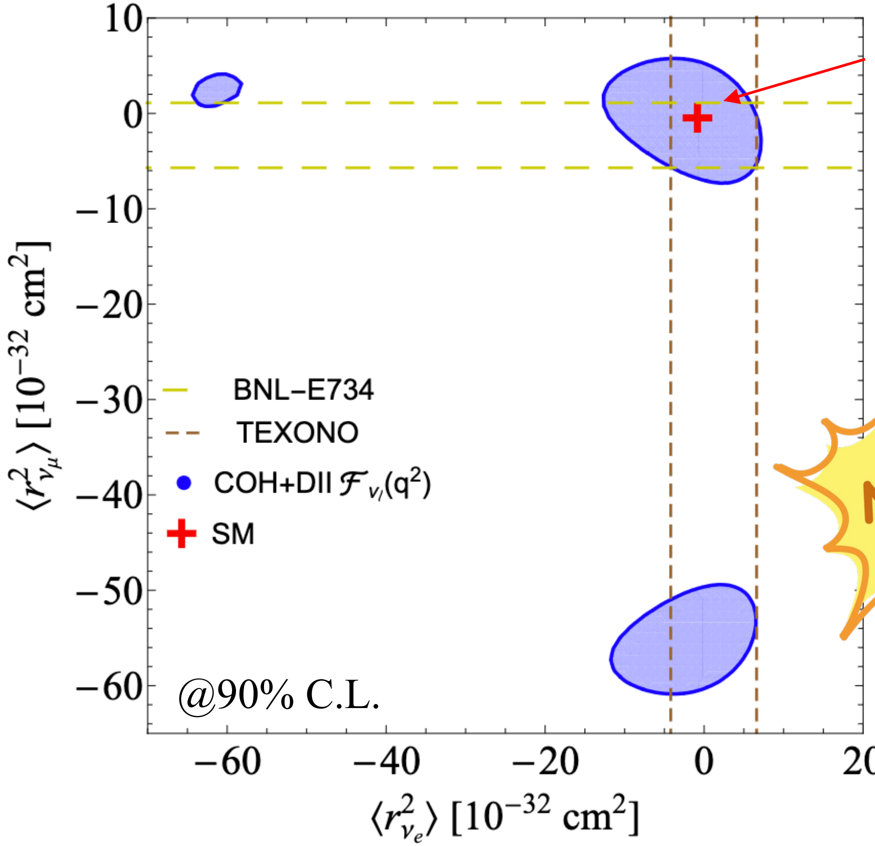
M. Atzori Corona, M. Cadeddu, N.C., F. Dordei, C. Giunti, JHEP05(2024)271

These largely negative values are due to a degeneracy in the cross section

COH Ar+CsI results are more affected due to the larger momentum transfer

Results – A global view on NCR

The main impact of accounting for NCR form factor is that, by combining different measurements, the **allowed regions in the parameter space from CEvNS data are significantly reduced!**



SM within the allowed regions from all the experimental data

Current best limits from accelerator $\nu_{e/\mu} - e$ scattering

Also shown: **TEXONO** $-4.2 < \langle r^2_{\nu_e}\rangle < 6.6\,[10^{-32}\text{cm}^2]$

BNL-E734 $-5.7 < \langle r^2_{\nu_\mu}\rangle < 1.1\,[10^{-32}\text{cm}^2]$

CEvNS data (COH Ar+CsI + Dresden-II)

At 90% C.L.

$$-9.5 < \langle r^2_{\nu_e}\rangle < \boxed{5.5}\,[10^{-32}\text{cm}^2]$$

$$\boxed{-59.2 < \langle r^2_{\nu_\mu}\rangle < 51} \wedge -5.9 < \langle r^2_{\nu_\mu}\rangle < 4.1\,[10^{-32}\text{cm}^2]$$

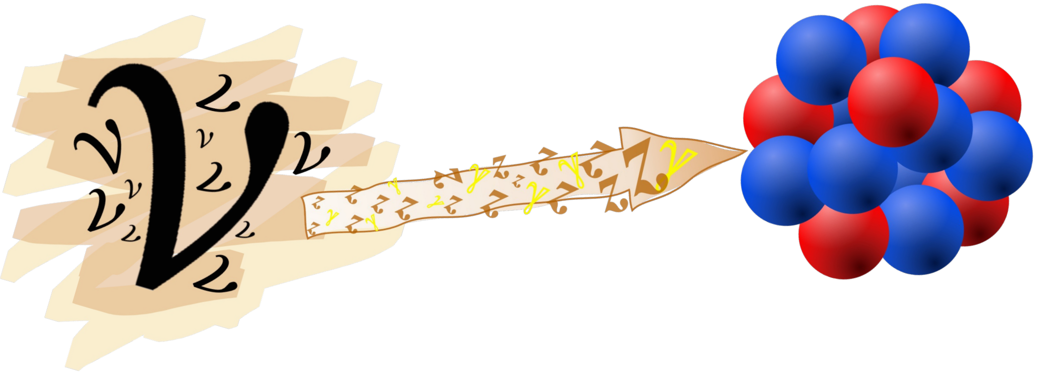
Almost excluded the large negative values

Best upper limit!

M. Atzori Corona, M. Cadeddu, N.C., F. Dordei, C. Giunti, JHEP05(2024)271

Conclusions

- Radiative corrections cannot be neglected anymore!
- **Need to properly account for the non-null momentum transfer of the experiments** in the calculation of the neutrino charge radius radiative correction
- The systematic bias of the $\nu_e \mathcal{N}$ scattering cross section is around 1%, which is an effect of ~10% with respect to the current systematic uncertainties affecting CEvNS
- **Mandatory to consider the momentum dependence to extract unbiased charge radii**: moreover it restricts the available phase space when combining different measurements



Thank you for your attention!