The devil is in the details: the role of the radiative corrections

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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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Abstract: Despite being neutral particles, neutrinos can have a non-zero charge radius, which represents the only non-null neutrino electromagnetic property in the standard model theory. Its value can be predicted with high accuracy and its effect is usually accounted for through the definition of a radiative correction affecting the neutrino couplings to electrons and nucleons at low energy, which results effectively in a shift of the weak mixing angle. Interestingly, it introduces a flavour-dependence in the cross-section. Exploiting available neutrino-electron and coherent elastic neutrino-nucleus scattering (CEνNS) data, there have been many attempts to measure experimentally the neutrino charge radius. Unfortunately, the current precision allows one to only determine constraints on its value. In this work, we discuss how to properly account for the neutrino charge radius in the CEνNS cross-section including the effects of the non-null momentum-transfer in the neutrino electromagnetic form factor, which have been usually neglected when deriving the aforementioned limits. We apply the formalism discussed to a re-analysis of the COHERENT cesium iodide and argon samples and the NCC-1701 germanium data from the Dresden-II nuclear power plant. We quantify the impact of this correction on the CEνNS cross-section and we show that, despite being small, it can not be neglected in the analysis of data from future high-precision experiments. Furthermore, this momentum dependence can be exploited to significantly reduce the allowed values for the neutrino charge radius determination.

Keywords: Non-Standard Neutrino Properties, Neutrino Interactions

ArXiv ePrint: 2402.16709

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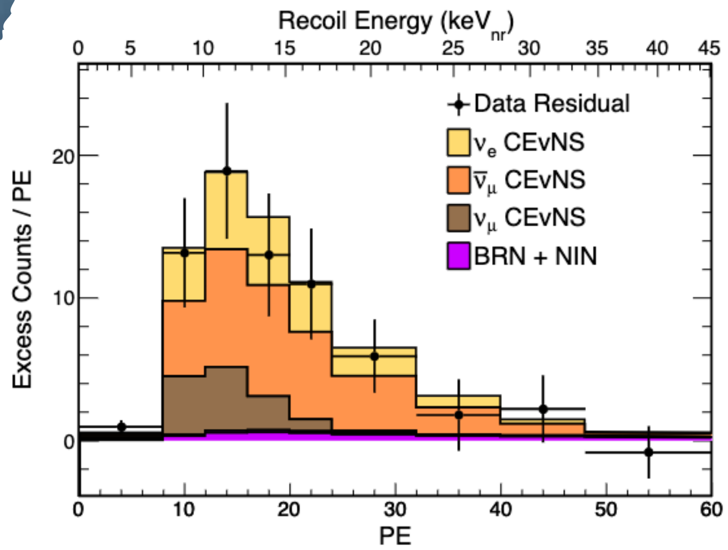
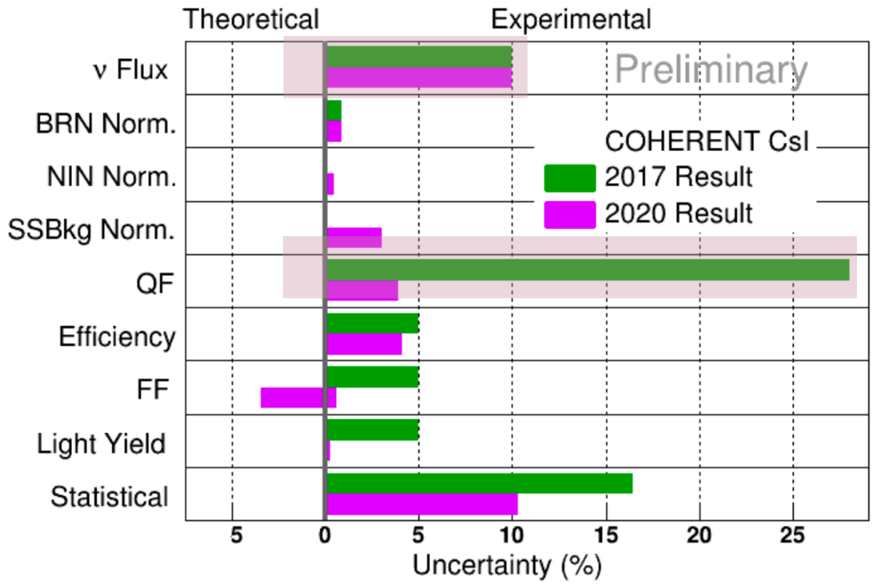
JHEP05(2024)271

Leading actor I

- Full CEνNS dataset with 14.6 kg CsI scintillating crystal and neutrinos from πDAR
- **306 ± 20 CEνNS** events: 11.6σ significance
- To be compared with prediction: **333±11(th)±42(ex)** events

✓ Result is consistent with SM prediction at 1σ
✓ Double exposure wrt 2017 and updated quenching factor model
✓ Flux uncertainty now dominates the systematic uncertainty.
✓ Overall systematic uncertainty reduced: 28% →13%



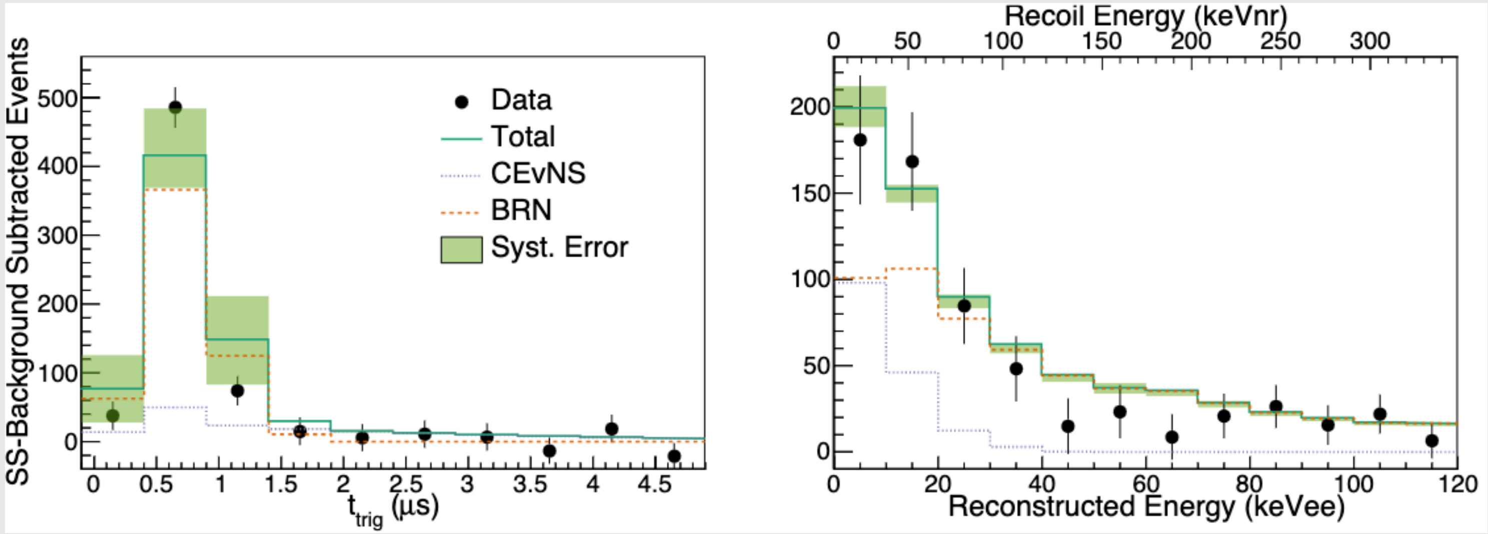


COHERENT, PRL 129, 081801 (2022)

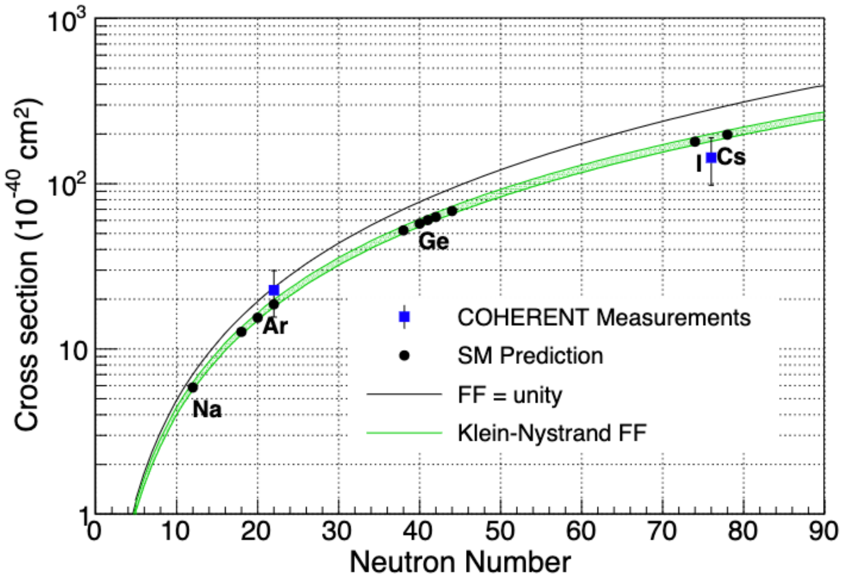
Leading actor II 

- 2020 first results using Ar, aka CENNS-10.
- Active mass of 24 kg of atmospheric argon
- Single phase only (scintillation), thr. ~20 keV_{nr}

✓ Two independent analyses observed a more than 3σ excess over background
✓ Still collecting data, more precise results expected soon.



Verify the **expected neutron-number dependence** of cross-section



The form factor unity assumption is compared to the Klein-Nystrand parameterization that is used for this analysis with the green band representing a ±3% variation on the neutron radius.

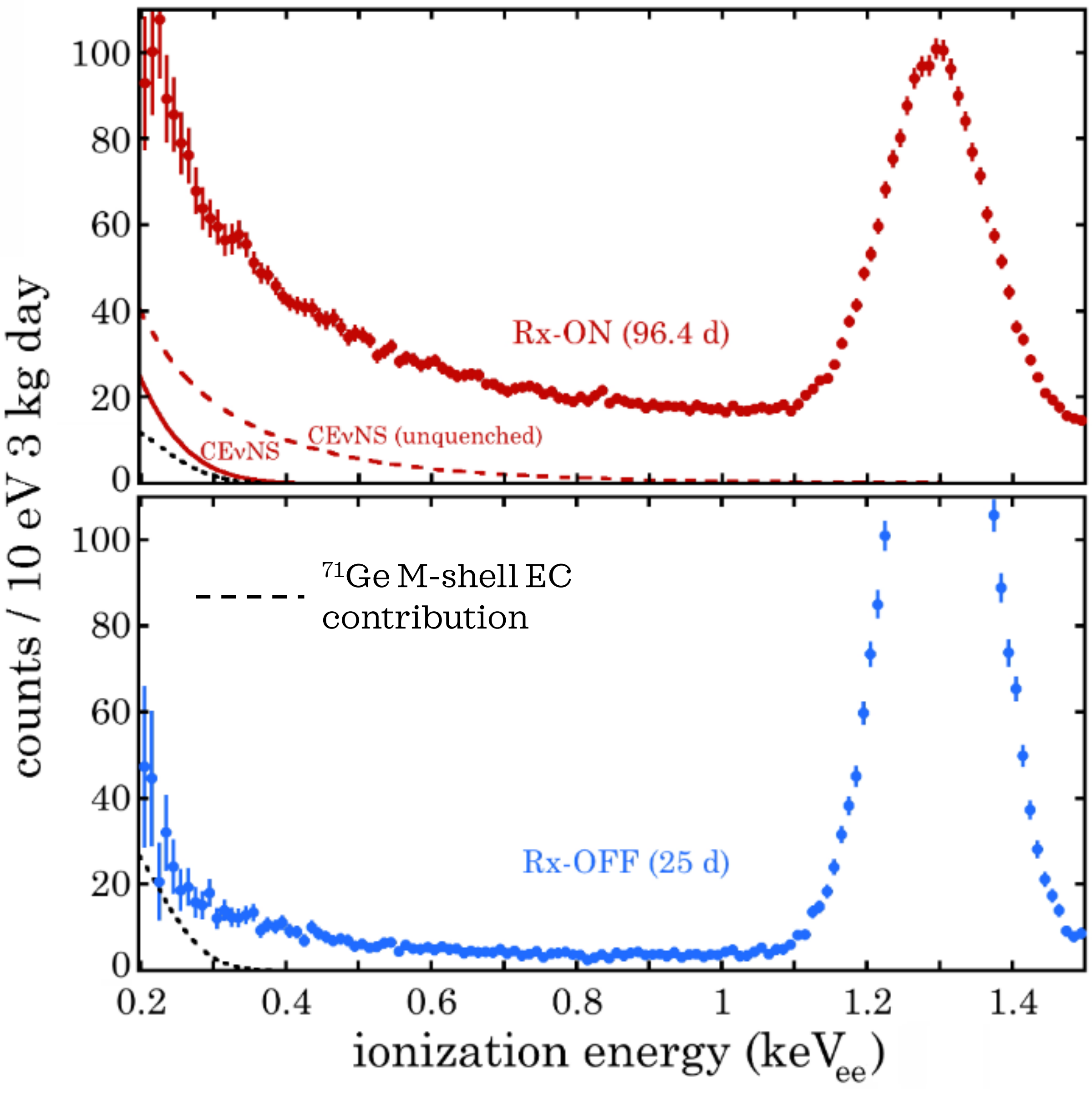
 COHERENT, PRL 126, 012002 (2021)

Leading actor III

- 96.4 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 ($P=2.96 GW_{th}$)
- **Low energy threshold**: 0.2 keVee
- 25 days of reactor off (Rx-OFF)
- The background comes from the elastic scattering of epithermal neutrons and the electron capture in ^{71}Ge

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

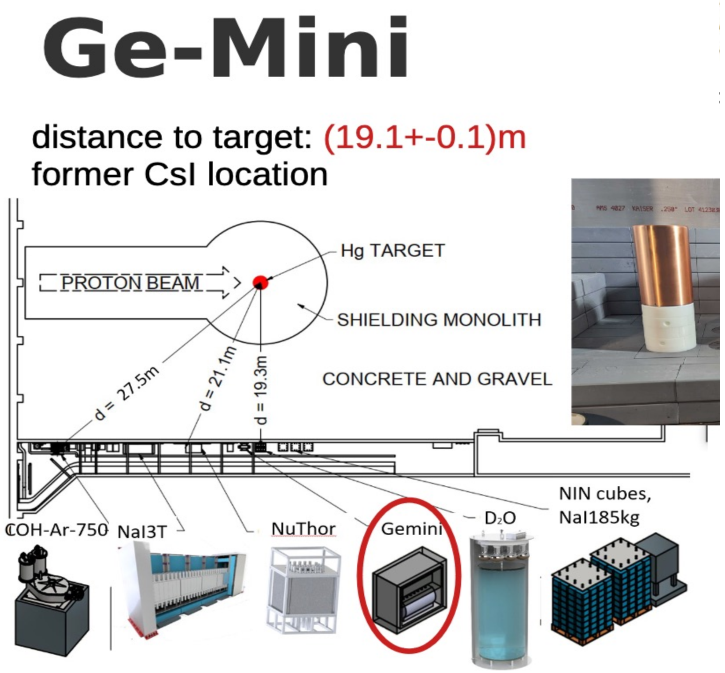
- **Strong preference** ($p<1.2\times10^{-3}$) for the presence of CEνNS is found, when compared to a background-only model.



Colaresi et al, PRL 129, 211802 (2022)

Many other results in the pipeline or expected soon…

- The first measurement of CEνNS events on Germanium by COHERENT with the Ge-Mini detector *See R. Bouabid talk!*
- SNS neutrino flux uncertainty reduction from 10% to 2-3% in 5 years thanks to D_2O at the neutrino alley, upgrade of the SNS (higher beam power and energy)
- **NaIvETe**: CEνNS on lighter nucleus Na, **COH-Ar-10** with 3 times more statistics and **CO-Ar-750** (ton scale), **COH-CryoCsI** with a significantly lower threshold (~0.5 KeVnr), …



J. Hakenmueller, JEPT Seminar

Plethora of other experiments expecting to detect CEνNS soon!

Just looking at the agenda of Mag7's 2024: CONUS(+), NUCLEUS, MINER, vGEN, RED-100, CONNIE, RICOCHET, NEON, CEvNS @ ESS, Dark Matter experiments…

Soon, we can not afford to be sloppy anymore since we will reach the precision frontier!

LET'S HAVE A CLOSER LOOK TO THE INGREDIENTS NEEDED

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

- Neutrino energy: E_ν
- Nuclear recoil energy: T_{nr}
- Mass of the nucleus: m_N
- SM vector proton coupling: g_V^p
- Weinberg angle: ϑ_W
- Proton Form Factor: $F_Z(|\vec{q}|^2)$
- SM vector neutron coupling: g_V^n
- Neutron Form Factor: $F_N(|\vec{q}|^2)$

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

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

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

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

BEYOND TREE LEVEL

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 processes, the corrections are **absorbed in the definitions of the low-energy EW couplings**

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

- **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 CEνNS experiments so far.

NEED TO GO BEYOND TREE LEVEL

When including the **UNIVERSAL radiative corrections** the couplings become:

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

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

Following the RGE formalism in Erler & Su, arXiv 1303.5522 (2013) as used in the PDG.

Where ρ=1.00063 represents a low-energy correction for neutral current processes and:

WW box

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

WW crossed-box

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

ZZ box

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

while the remaining radiative term is related to the so-called **neutrino charge radius**

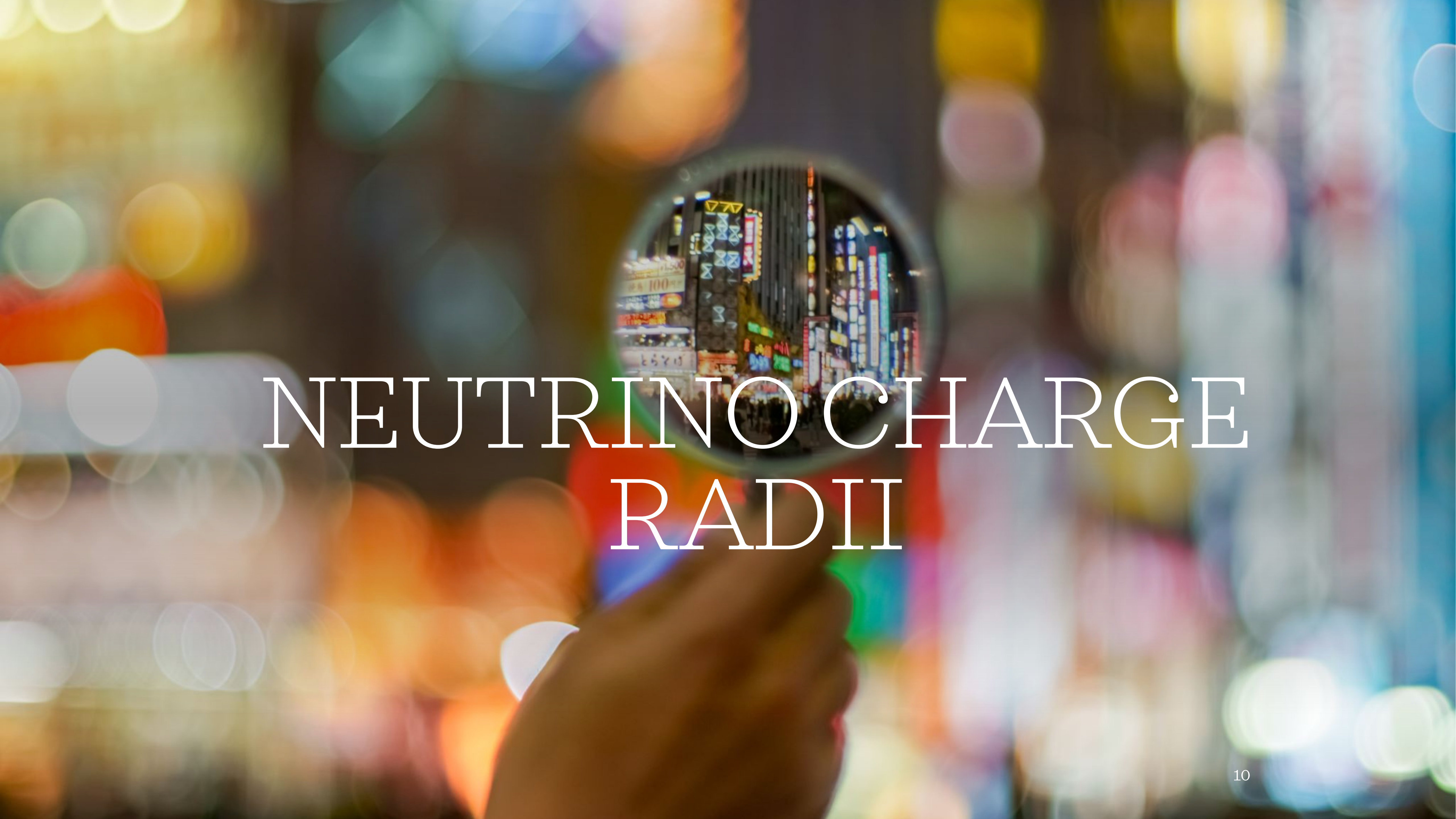
$$\phi_{\nu_\ell W} = -\frac{\alpha}{6\pi}\left(\ln\frac{M_W^2}{m_\ell^2} + \frac{3}{2}\right)$$

In this scenario, **the couplings become flavour-dependent and different from tree-level**:

Up to 67% difference wrt tree-level

$$g_V^p(\nu_e) \simeq 0.0381 \qquad g_V^p(\nu_\mu) \simeq 0.0299$$

$$g_V^p(\nu_\tau) \simeq 0.0255 \qquad g_V^n \simeq -0.5117$$



NEUTRINO CHARGE RADII

Neutrino charge radius - definition

- In the SM, the neutrino charge radii (CR) are the **only electromagnetic properties of neutrinos that are different from zero**.
- A neutral particle can be seen as the superposition of two charge distributions of opposite signs described by an **electric form factor** which is nonzero only for momentum transfers q^2 different from zero

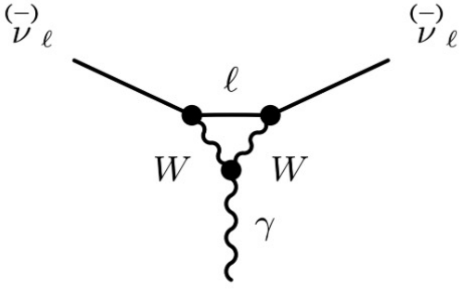
$$\mathfrak{f}_Q(q^2) = \mathfrak{f}_Q(0) + q^2 \frac{d\mathfrak{f}_Q(q^2)}{dq^2}\Big|_{q^2=0} + \dots .$$

=0 since νs are neutral

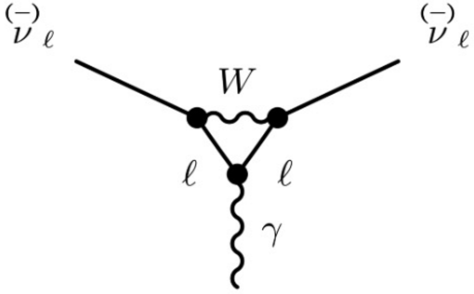
$$\langle r^2 \rangle \equiv 6 \frac{d\mathfrak{f}_Q(q^2)}{dq^2}\Big|_{q^2=0}$$

Neutrino charge radius
i.e. the radius of the electric charge distribution

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



W W ℓ loop



$\ell\ell$W loop

The **NCR is a physical observable**, being finite and gauge invariant!

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

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

W W ℓ loop **$\ell\ell$W loop**

The $\ell\ell$W loop introduces a **dependence of the neutrino CR from the lepton flavour:**

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

Neutrino charge radius – practically speaking

- The neutrino CR affects the scattering of neutrinos with charged particles.
- In the case of CEνNS **it contributes only to the neutrino-proton coupling**, and not to the neutron one.

CEνNS case:

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

$\simeq$ 0.0184 ν-proton coupling without the contribution of the SM CR

Effective shift of the weak mixing angle

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

- Interesting quantity to measure, as **new particles entering the loops could modify it**!
- So far, **only constraints** have been put on its value
- However, keep in mind that the neutrino charge radius is defined at $q^2 \equiv 0$, while **none of the experiments is performed at null-momentum transfer**!

⇨ Must be taken into account when implementing radiative corrections in CEνNS processes and when measuring the ν charge radius!

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

How to deal with non-null momentum transfers?

- Look at **process - dependent radiative corrections** defined by Marciano et al. in arXiv:0403168.

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

where for **neutrino scattering**:

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

with:

$$R_\ell(0) = \frac{1}{6}\ln\frac{m_\ell^2}{M_W^2}$$

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

For $q^2 \to 0$ we retrieve the same radiative correction as in the RGE formalism:

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

$$\phi_{\nu_\ell W} = -\frac{\alpha}{\pi}\left(-R_\ell(0) + \frac{1}{4}\right)$$

with a clear advantage:

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

The radiative correction includes the momentum dependence!

The effective charge radius form factor

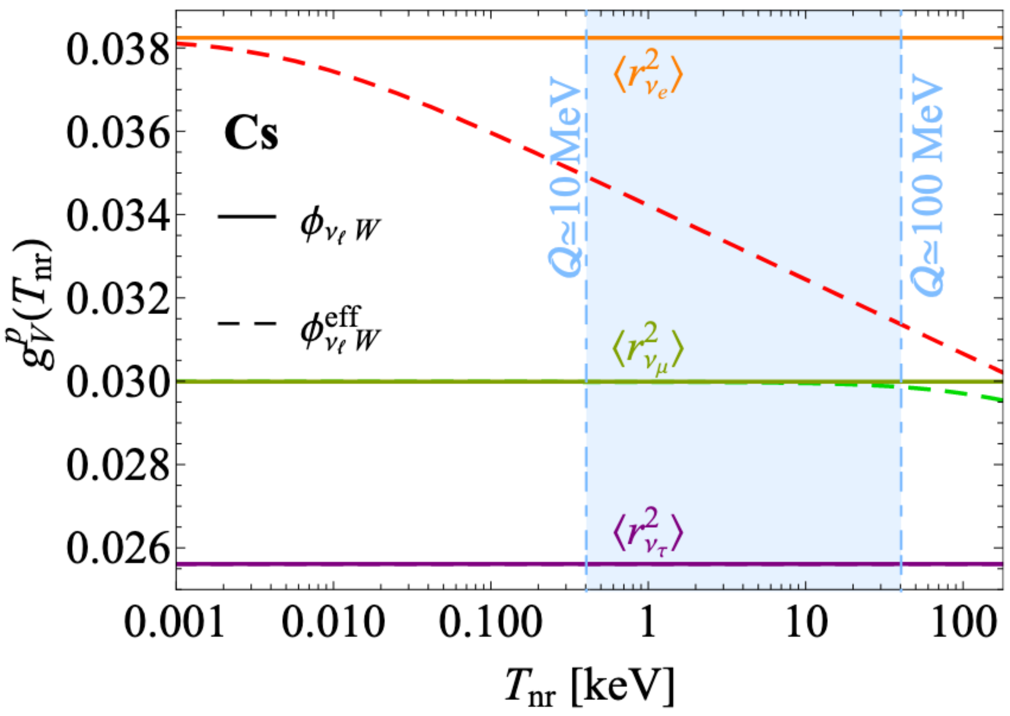
We introduce a **neutrino charge radius form factor** $\mathcal{F}_{\nu_\ell}(T_{\rm nr}) = \frac{\langle r^2_{\nu_\ell}\rangle^{\rm eff}(T_{\rm nr})}{\langle r^2_{\nu_\ell}\rangle^{\rm eff}(0)} \equiv \frac{\langle r^2_{\nu_\ell}\rangle^{\rm eff}(T_{\rm nr})}{\langle r^2_{\nu_\ell}\rangle^{\rm SM}}$

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

From which we obtain an updated proton coupling:

Impact visible for $q^2 \gtrsim m_\ell^2$:

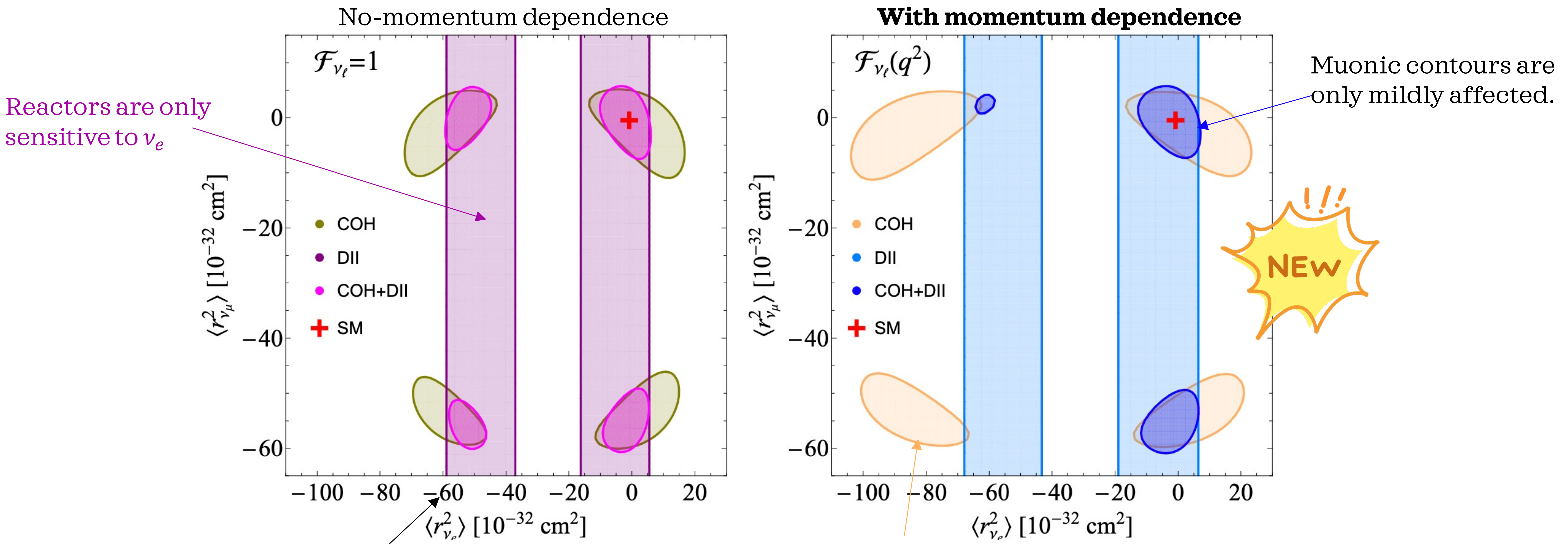
- for ν_e processes the correction becomes visible for $q \gtrsim 0.5$ MeV
- for ν_μ only above ~ 100 MeV!



10-20% difference in the proton coupling!

Neutrino charge radius results

- Dataset used: latest COHERENT cesium iodide and argon with the germanium NCC-1701 data (DII).

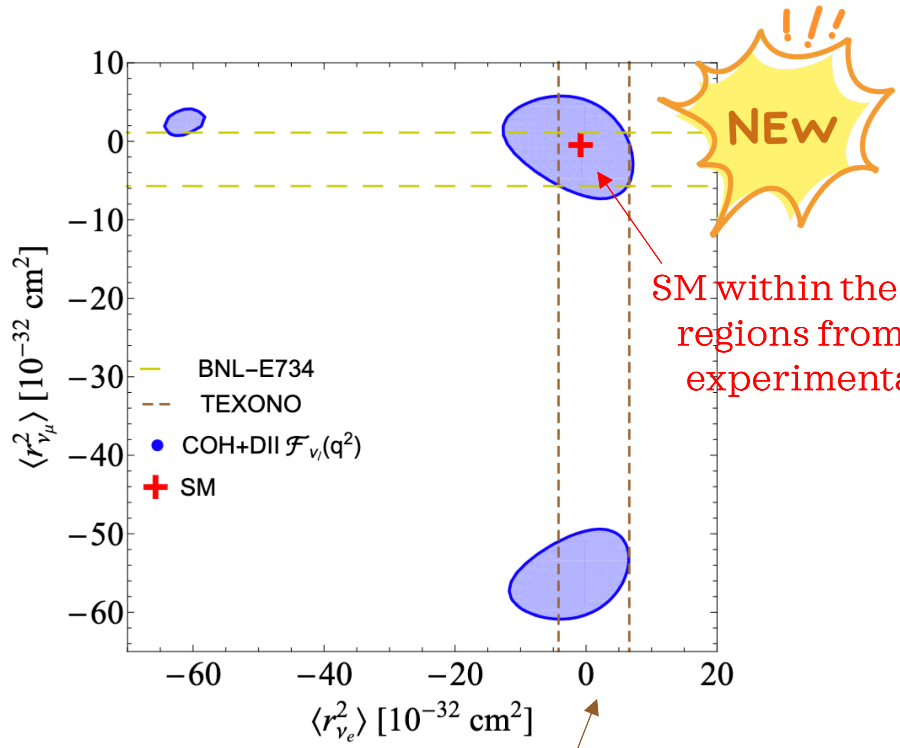


These largely negative values produce a degenerate cross-section

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

Results

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



SM within the allowed regions from all the experimental data

	1σ	90%	2σ	3σ
		COHERENT (CsI+Ar)		
$\langle r^2_{\nu_e} \rangle$	$(-95.0, -77.4)$ $(0.09, 12.8)$	$(-100.0, -69.8)$ $(-8.6, 19.1)$	$(-102.6, -64.8)$ $(-13.9, 22.2)$	$(-110.4, 30.7)$
$\langle r^2_{\nu_\mu} \rangle$	$(-6.8, 0.5)$	$(-57.6, -48.9)$ $(-9.3, 2.9)$	$(-59.2, -47.1)$ $(-10.7, 4.2)$	$(-63.3, -42.3)$ $(-15.2, 8.1)$
		Dresden-II		
$\langle r^2_{\nu_e} \rangle$	$(-62.5, -53.7)$ $(-9.0, 1.8)$	$(-65.7, -48.5)$ $(-13.8, 4.5)$	$(-67.2, -45.0)$ $(-17.2, 6.0)$	$(-71.1, 9.7)$
		COHERENT (CsI+Ar) + Dresden-II		
$\langle r^2_{\nu_e} \rangle$	$(-5.8, 3.1)$	$(-9.5, 5.5)$	$(-11.6, 6.8)$	$(-70.3, -47.7)$ $(-19.8, 10.1)$
$\langle r^2_{\nu_\mu} \rangle$	$(-56.8, -53.3)$ $(-4.0, 2.1)$	$(-59.2, -51.0)$ $(-5.9, 4.1)$	$(-60.4, -49.9)$ $(-6.9, 5.3)$	$(-63.8, -46.8)$ $(-9.9, 8.7)$

At 90% CL:

$$-9.5 < \langle r^2_{\nu_e} \rangle \, [10^{-32}\,\text{cm}^2] < 5.5,$$ **Best upper limit!**

$$-59.2 < \langle r^2_{\nu_\mu} \rangle \, [10^{-32}\,\text{cm}^2] < -51.0 \;,\; -5.9 < \langle r^2_{\nu_\mu} \rangle [10^{-32}\,\text{cm}^2] < 4.1$$

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** $-5.7 < \langle r^2_{\nu_\mu} \rangle < 1.1\,[10^{-32}\text{cm}^2]$ @90% CL

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 ν_e N scattering cross section is around 1 -2%, which is an **effect of ~20% with respect to the current systematic uncertainties** affecting CEνNS.
- **For future measurements, it will become imperative to include the momentum dependence!**
- **Mandatory to consider it to extract unbiased charge radii:** moreover it restricts the available phase space.

THANKS FOR YOUR ATTENTION

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EPIC 2024 is the first workshop dedicated to **precision electroweak physics**, with focus on:

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- **Lepton- and neutrino-nucleus interactions**
- **Nuclear matter across energy scales and multi-messenger astronomy**

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- Dedicated poster session for students at the workshop with teaser-talk event.

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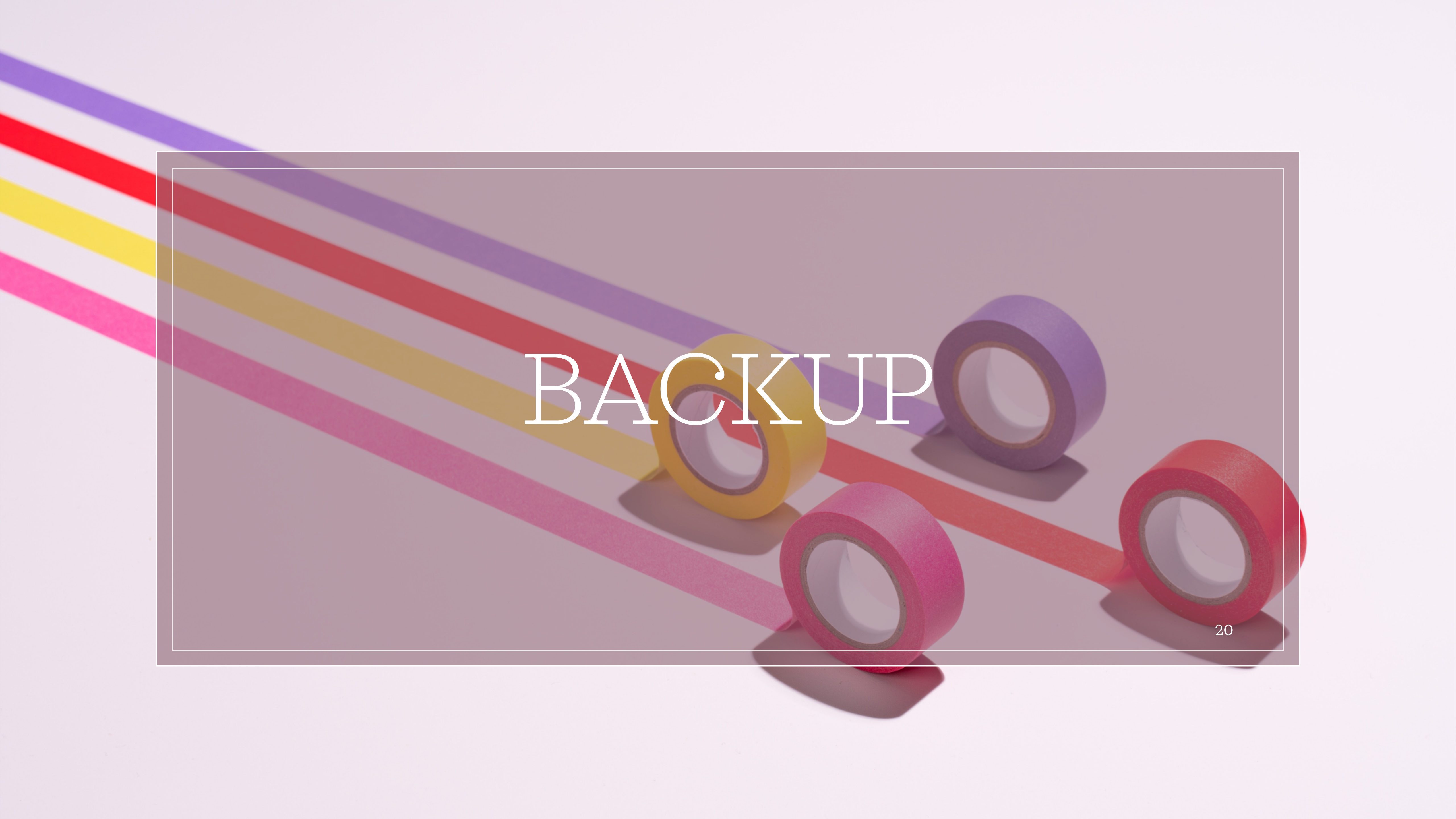
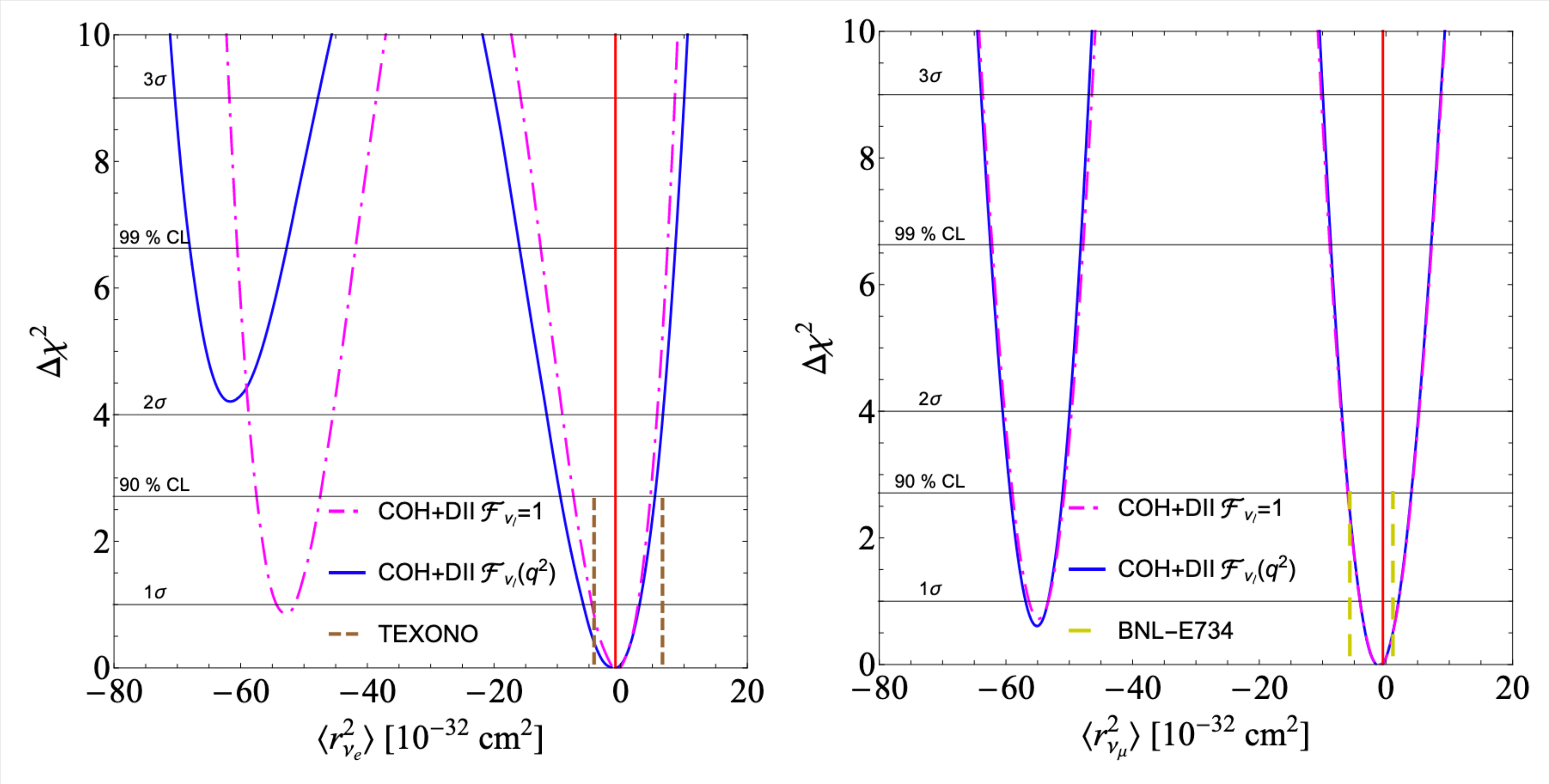


BACKUP

1D PROJECTIONS



Agreement between the two formalisms

It can be noticed that the difference of the weak mixing angle values consists only of a small constant term:

$$k_{\nu_\ell}(q^2=0)\hat{s}_Z^2 - \hat{s}_0^2(\mathrm{RGE}) = -\frac{2\alpha}{9\pi} + \mathcal{O}(\alpha^2)$$

See also Appendix A of arXiv: 2309.04060

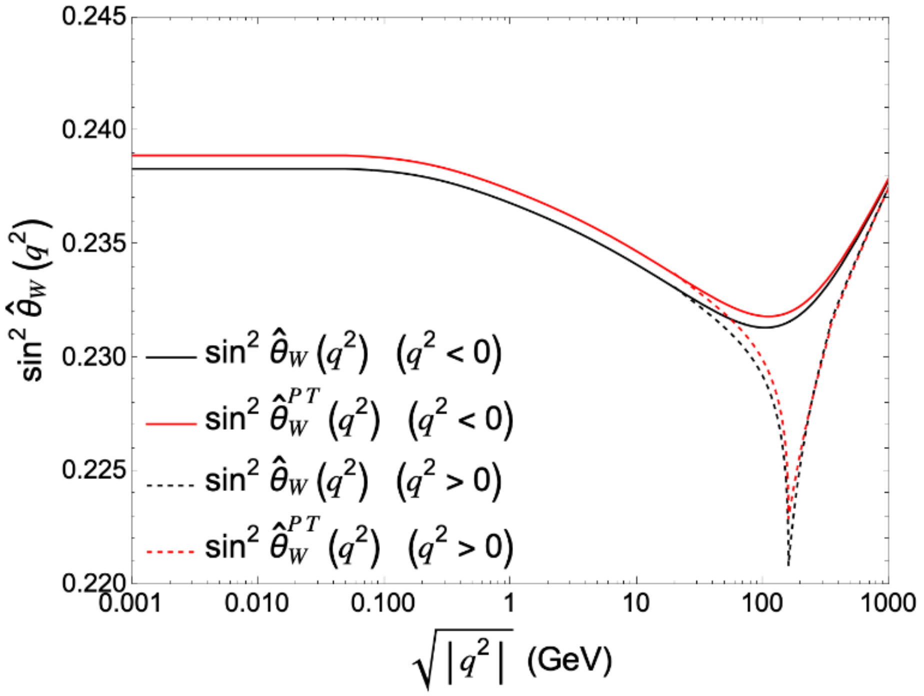
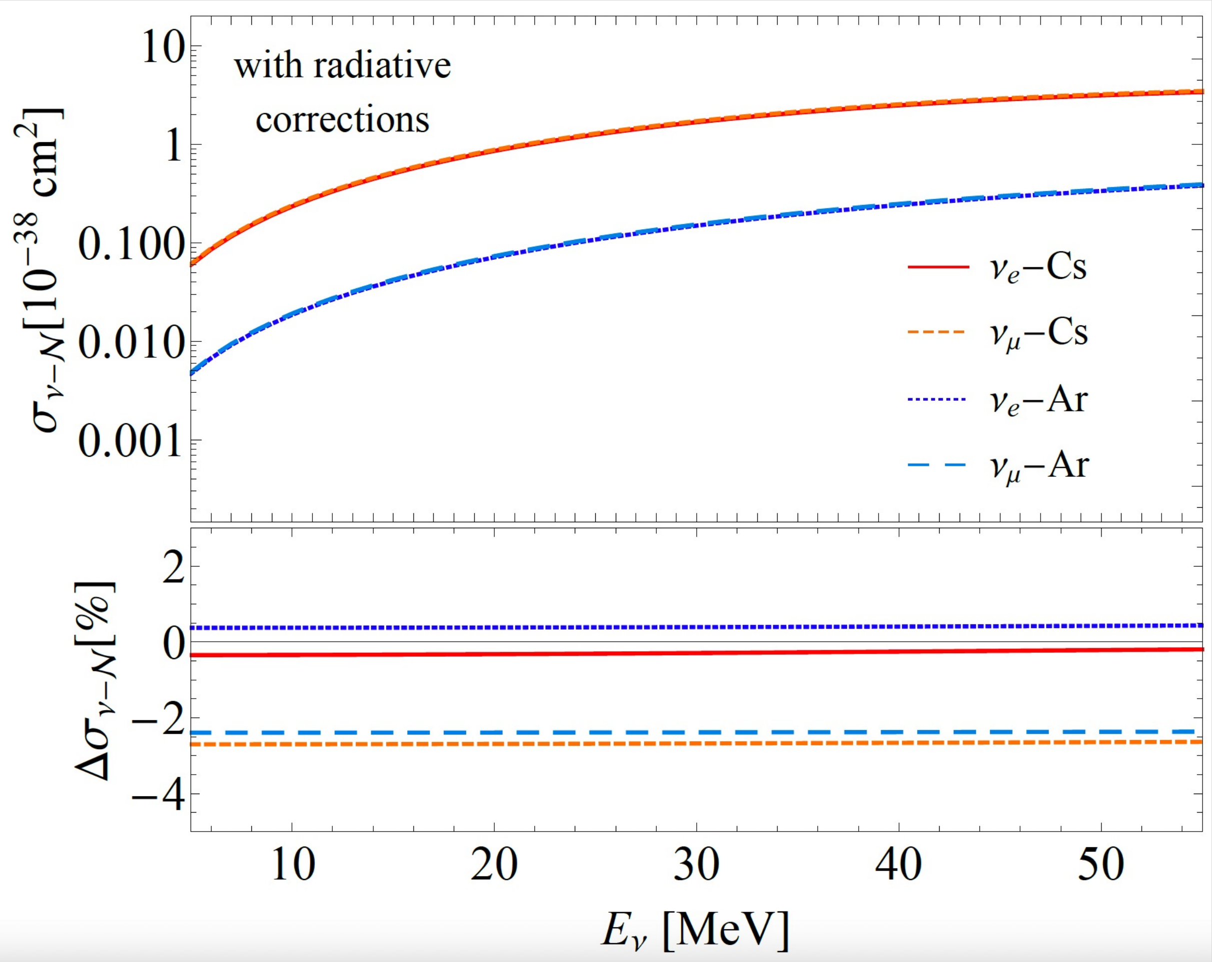


FIG. 9. A comparison of typical form $\sin^2\hat{\theta}_W(q^2)$ in black and PT form $\sin^2\hat{\theta}_W^{\mathrm{PT}}(q^2)$ in red. Solid (dashed) curves represent spacelike (timelike) momenta. The curves for timelike momenta are shown only in a domain $\sqrt{|q^2|} > 20$ GeV.

Impact of radiative corrections @ q^2=0



From N. Cargioli PhD's thesis

The effective charge radius form factor

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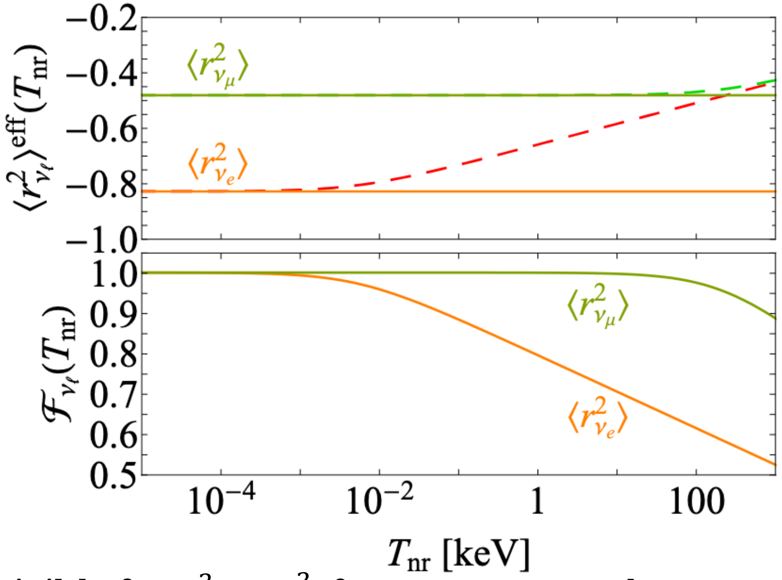
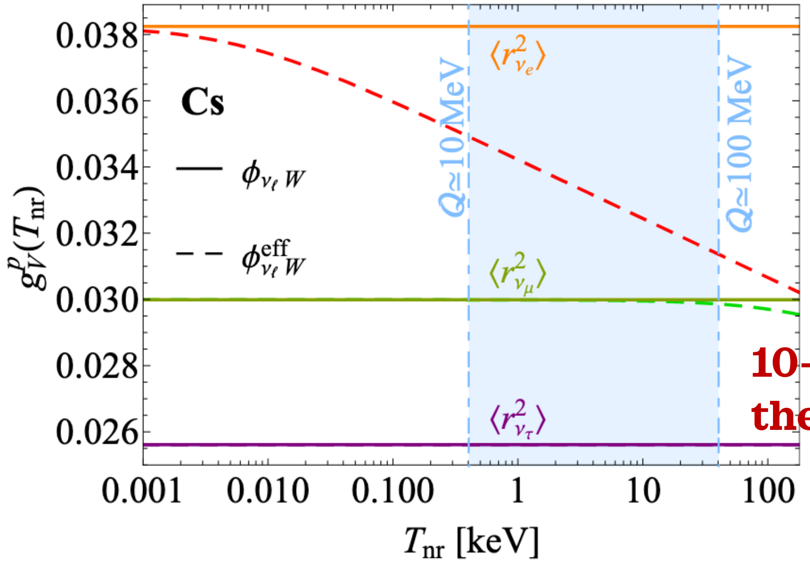
From which we obtain an updated proton coupling:



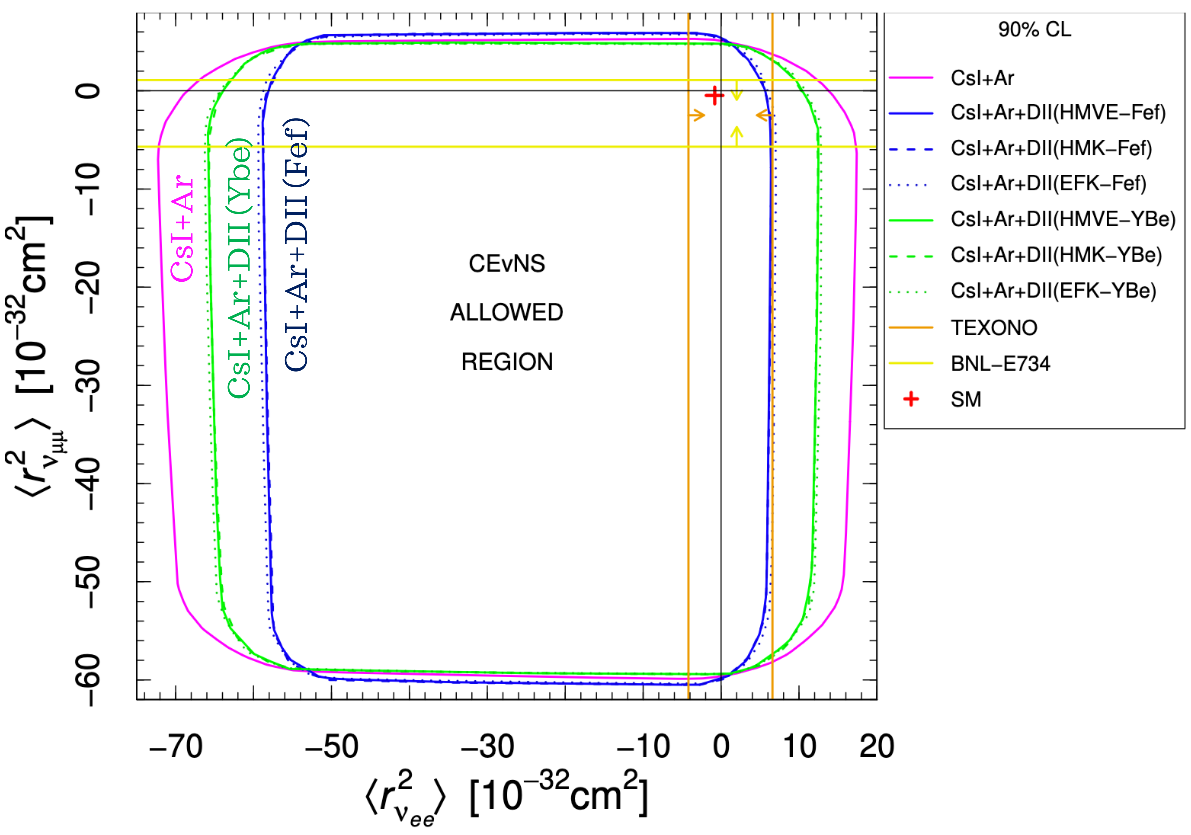


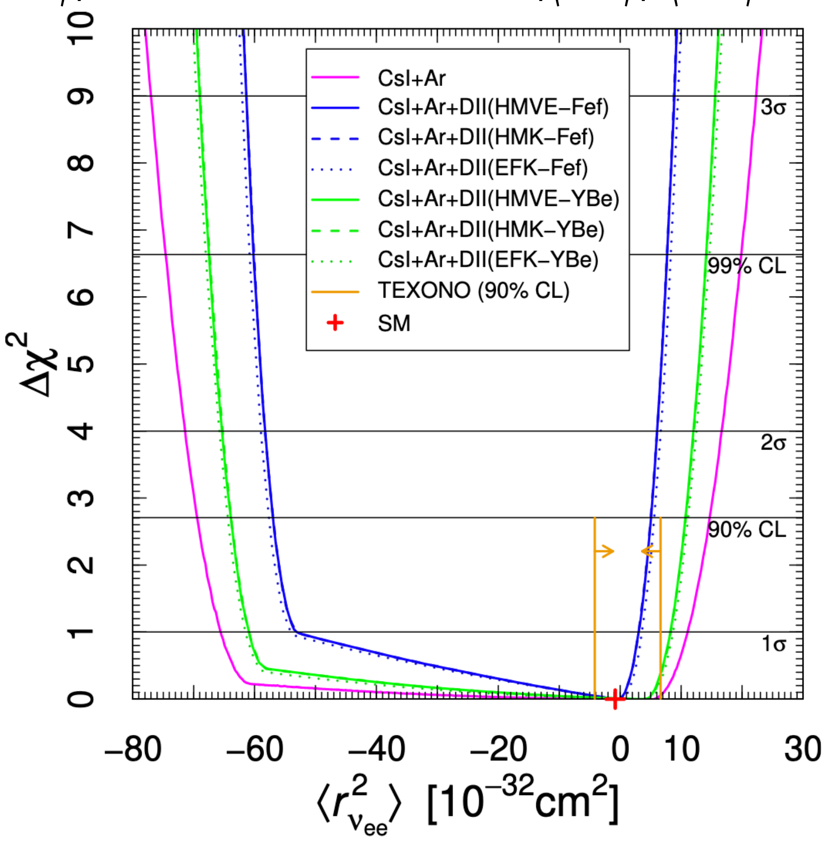
10-20% difference in the proton coupling!

Impact visible for $q^2 \gtrsim m_\ell^2$, for ν_e processes the correction to the couplings becomes visible for $q \gtrsim 0.5$ MeV, while for ν_μ only above ~ 100 MeV!

Neutrino charge radius – previous results

Assuming the **presence of transition CR**, **DRESDEN-II** can measure $\langle r^2_{\nu_{ee}} \rangle$, $|\langle r^2_{\nu_{e\mu}} \rangle|$, $|\langle r^2_{\nu_{e\tau}} \rangle|$ **COHERENT** also $|\langle r^2_{\nu_{\mu\tau}} \rangle|$, $\langle r^2_{\nu_{\mu\mu}} \rangle$

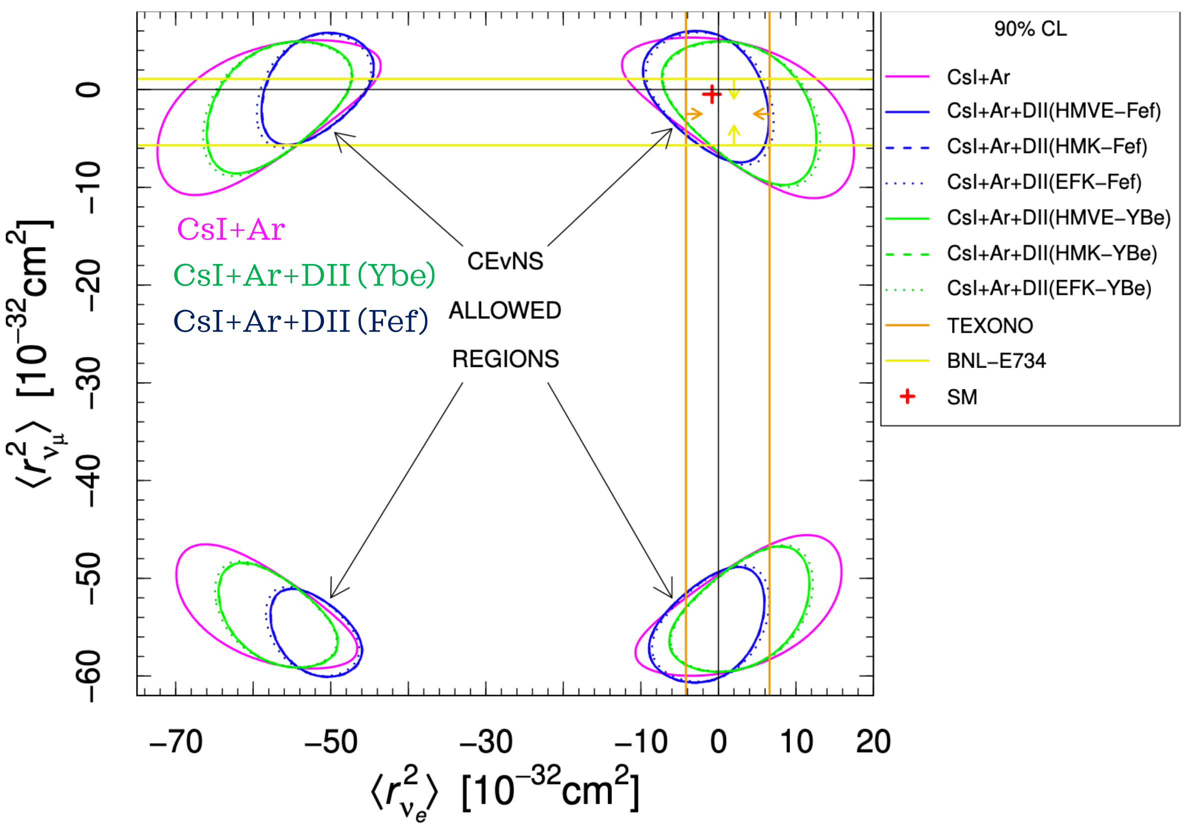


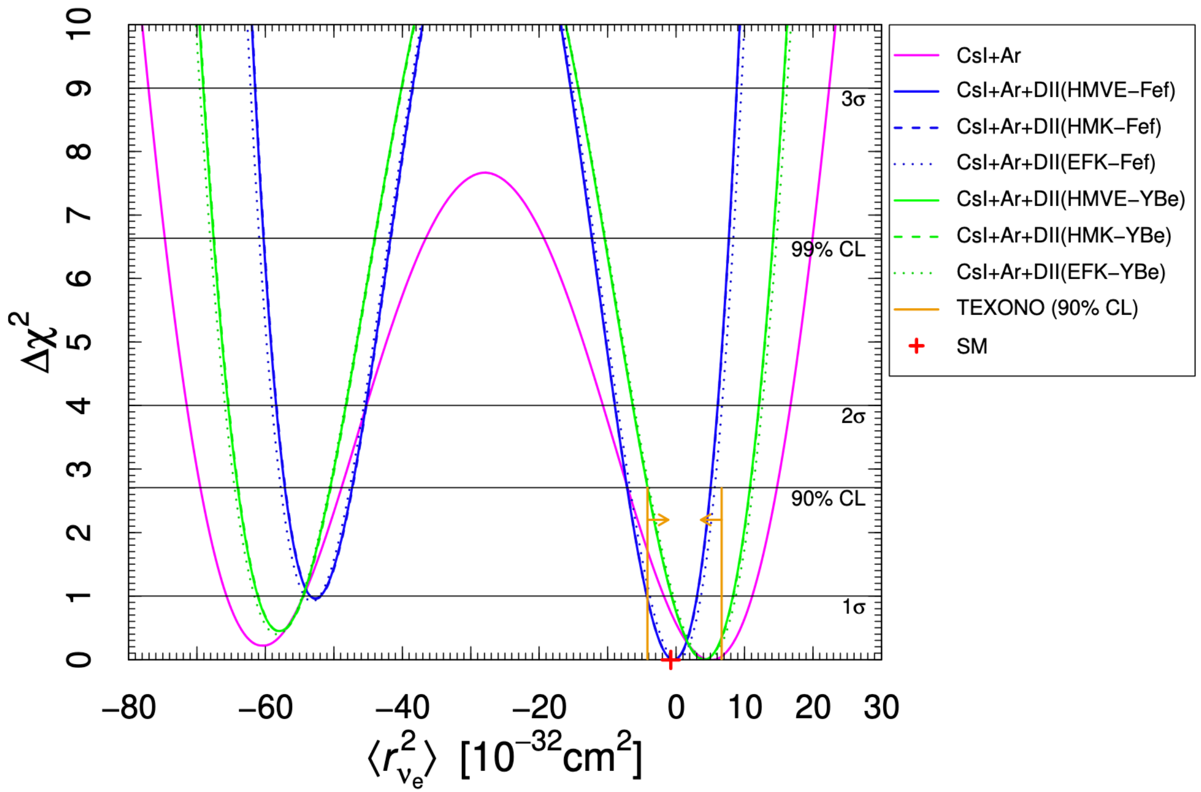


- The CsI + Ar COHERENT combination is **vastly dominated by CsI**.
- **Dresden-II** and **CsI** datasets contribute with **roughly same precision**.
- **HMVE, HMK, EFK** different flux parametrization: practically independent, **highly sensistive to the QF used**.

Neutrino charge radius – previous results

Assuming the **absence of transition CR**: $\langle r^2_{\nu_e} \rangle \equiv \langle r^2_{\nu_{ee}} \rangle$ and $\langle r^2_{\nu_\mu} \rangle \equiv \langle r^2_{\nu_{\mu\mu}} \rangle$

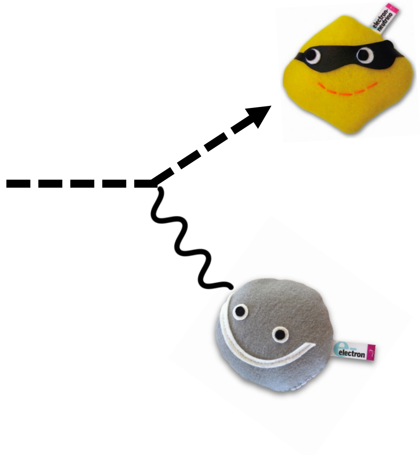




$-7.1 < \langle r^2_{\nu_e} \rangle < 5$ $[10^{-32}\,\mathrm{cm}^2]$ **COHERENT + DRESDEN-II @ 90% CL**

- When using the Fef QF we **set a better upper bound with respect to that set by TEXONO** ($6.6\times10^{-32}\,\mathrm{cm}^2$)
- **No effect is found due to ES** on the neutrino CR, thus the results are independent of its inclusion

ELASTIC ν –ELECTRON SCATTERING



- ν-electron elastic scattering (ES) is a **concurrent process to CEvNS**
- In the SM, its contribution to the total event rate is small and can be neglected
- **In certain BSM scenarios the ES contribution increases significantly** ⇒ Allows us to achieve stronger constraints !

Neutrino energy

Mass of the electron

SM neutrino electron coupling

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

\+ radiative corrections

$$\frac{d\sigma^{ES}(E_\nu, T_e)}{dT_e} = Z_{eff}^A(T_e)\,\frac{G_F^2\, m_e}{2\pi}\left[(g_V^{\nu_\iota}+g_A^{\nu_\iota})^2 + (g_V^{\nu_\iota}-g_A^{\nu_\iota})^2\left(1-\frac{T_e}{E_\nu}\right)^2 - \left((g_V^{\nu_\iota})^2-(g_A^{\nu_\iota})^2\right)\frac{m_e T_e}{E_\nu^2}\right]$$

Electron recoil energy

The interaction is not with free electrons but atomic electrons! Quantifies the **number of electrons that can be ionized by a certain energy deposit T_e.**

- ➢ The $Z_{eff}^A(T_e)$ term is needed to correct the cross section derived under the Free Electron Approximation (FEA) hypothesis, where electrons are considered to be free and at rest (would just scale as Z).
- ➢ Alternative ab-initio approach: **multi-configuration relativistic random phase approximatio**n (MCRRPA) able to improve the description of the atomic many-body effects
- ➢ We do not include such contribution for Ar, where the f_{90} parameter removes electron recoils due to ES

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The Z_{eff} term

$$Z_{\rm eff}^{\rm Cs} = \begin{cases} 55, & T_e > 35.99\,{\rm keV} \\ 53, & 35.99\,{\rm keV} \geq T_e > 5.71\,{\rm keV} \\ 51, & 5.71\,{\rm keV} \geq T_e > 5.36\,{\rm keV} \\ 49, & 5.36\,{\rm keV} \geq T_e > 5.01\,{\rm keV} \\ 45, & 5.01\,{\rm keV} \geq T_e > 1.21\,{\rm keV} \\ 43, & 1.21\,{\rm keV} \geq T_e > 1.07\,{\rm keV} \\ 41, & 1.07\,{\rm keV} \geq T_e > 1\,{\rm keV} \\ 37, & 1\,{\rm keV} \geq T_e > 0.74\,{\rm keV} \\ 33, & 0.74\,{\rm keV} \geq T_e > 0.73\,{\rm keV} \\ 27, & 0.73\,{\rm keV} \geq T_e > 0.23\,{\rm keV} \\ 25, & 0.23\,{\rm keV} \geq T_e > 0.17\,{\rm keV} \\ 23, & 0.17\,{\rm keV} \geq T_e > 0.16\,{\rm keV} \\ 19, & T_e < 0.16\,{\rm keV} \end{cases} \qquad Z_{\rm eff}^{\rm I} = \begin{cases} 53, & T_e > 33.17\,{\rm keV} \\ 51, & 33.17\,{\rm keV} \geq T_e > 5.19\,{\rm keV} \\ 49, & 5.19\,{\rm keV} \geq T_e > 4.86\,{\rm keV} \\ 47, & 4.86\,{\rm keV} \geq T_e > 4.56\,{\rm keV} \\ 43, & 4.56\,{\rm keV} \geq T_e > 1.07\,{\rm keV} \\ 41, & 1.07\,{\rm keV} \geq T_e > 0.93\,{\rm keV} \\ 39, & 0.93\,{\rm keV} \geq T_e > 0.88\,{\rm keV} \\ 35, & 0.88\,{\rm keV} \geq T_e > 0.63\,{\rm keV} \\ 31, & 0.63\,{\rm keV} \geq T_e > 0.62\,{\rm keV} \\ 25, & 0.62\,{\rm keV} \geq T_e > 0.19\,{\rm keV} \\ 23, & 0.19\,{\rm keV} \geq T_e > 0.124\,{\rm keV} \\ 21, & 0.124\,{\rm keV} \geq T_e > 0.123\,{\rm keV} \\ 17, & T_e < 0.123\,{\rm keV} \end{cases}$$

Table 1. The effective electron charge of the target atom, $Z_{\rm eff}^{\mathcal{A}}(T_e)$, for Cs and I.

$$Z_{\rm eff}^{\rm Ge} = \begin{cases} 32, & T_e > 11.103\,{\rm keV} \\ 30, & 11.103\,{\rm keV} \geq T_e > 1.4146\,{\rm keV} \\ 28, & 1.4146\,{\rm keV} \geq T_e > 1.2481\,{\rm keV} \\ 26, & 1.2481\,{\rm keV} \geq T_e > 1.217\,{\rm keV} \\ 22, & 1.217\,{\rm keV} \geq T_e > 0.1801\,{\rm keV} \\ 20, & 0.1801\,{\rm keV} \geq T_e > 0.1249\,{\rm keV} \\ 18, & 0.1249\,{\rm keV} \geq T_e > 0.1208\,{\rm keV} \\ 14, & 0.1208\,{\rm keV} \geq T_e > 0.0298\,{\rm keV} \\ 10, & 0.0298\,{\rm keV} \geq T_e > 0.0292\,{\rm keV} \\ 4, & T_e \leq 0.0292\,{\rm keV} \end{cases}$$

Table 2. The effective electron charge of the target atom, $Z_{\rm eff}^{\mathcal{A}}(T_e)$, for Ge.

Specific for each atom, obtained using edge energies from photo-absorption data.

A. Thompson et al., X-ray data booklet, https://xdb.lbl.gov/, Lawrence Berkeley National Laboratory, U.S.A. (2009)

The charge radii summary

Process	Collaboration	Limit $[10^{-32}\ \mathrm{cm}^2]$	C.L.	Ref.
Reactor $\bar{\nu}_e$-e	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3$	90%	[94]
	TEXONO	$-4.2 < \langle r^2_{\nu_e}\rangle < 6.6$	90%	[91] [a]
Accelerator ν_e-e	LAMPF	$-7.12 < \langle r^2_{\nu_e}\rangle < 10.88$	90%	[95] [a]
	LSND	$-5.94 < \langle r^2_{\nu_e}\rangle < 8.28$	90%	[96] [a]
Accelerator ν_μ-e and $\bar{\nu}_\mu$-e	BNL-E734	$-5.7 < \langle r^2_{\nu_\mu}\rangle < 1.1$	90%	[92] [a, b]
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2$	90%	[97] [a]
COHERENT + Dresden-II	w/o transition CR	$-7.1 < \langle r^2_{\nu_e}\rangle < 5$	90%	This work [c]
	w transition CR	$-56 < \langle r^2_{\nu_e}\rangle < 5$	90%	This work [c]
COHERENT + Dresden-II	w/o transition CR	$-5.9 < \langle r^2_{\nu_\mu}\rangle\rvert < 4.3$	90%	This work [c]
	w transition CR	$-58.2 < \langle r^2_{\nu_\mu}\rangle < 4.0$	90%	This work [c]

[a] Corrected by a factor of two due to a different convention, see ref. [21].
[b] Corrected in ref. [93].
[c] Using the Fef quenching factor.

Table 7. Experimental limits for the neutrino charge radii.