Probing Neutrino Charge Radii with Coherent Elastic Solar Neutrino-Nucleus Scattering

Onur Başlı
collaborated with M. Demirci
(Karadeniz Technical University)

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- Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)
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Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

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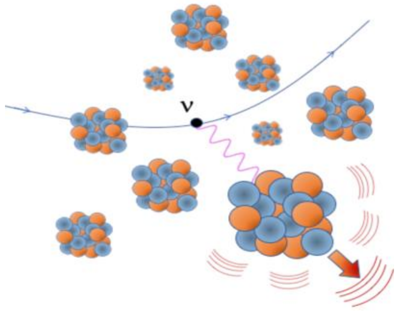
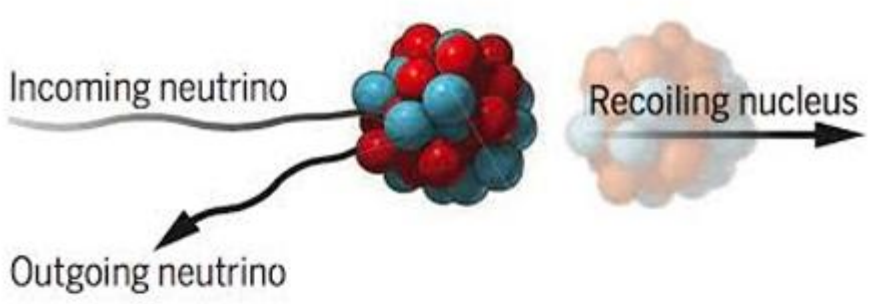
Coherent effects of a weak neutral current

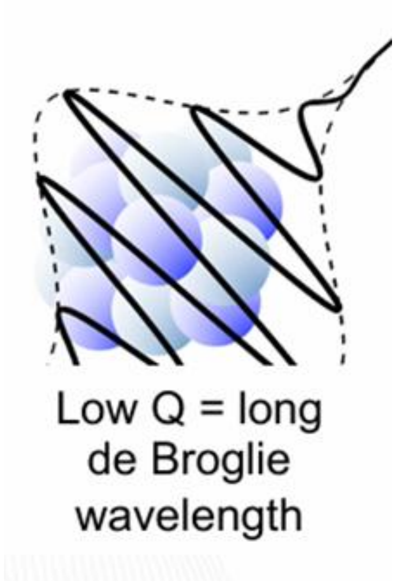
Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

- A neutral current weak interaction process that occurs at low energies in the Standard Model (SM) framework.
- Theoretically proposed in 1974 by Daniel Freedman, firstly.
- Hard to detect; the nuclear recoil energy, T_{nr}, is around a few keV.
- Successfully detected by the COHERENT experiment at Oak Ridge National Laboratory [D. Akimov et al., Science 357.1123 (2017)].

In the process, neutrinos are scattered from the nucleus via the exchange of Z^0 boson, and the nucleus recoils as a whole.

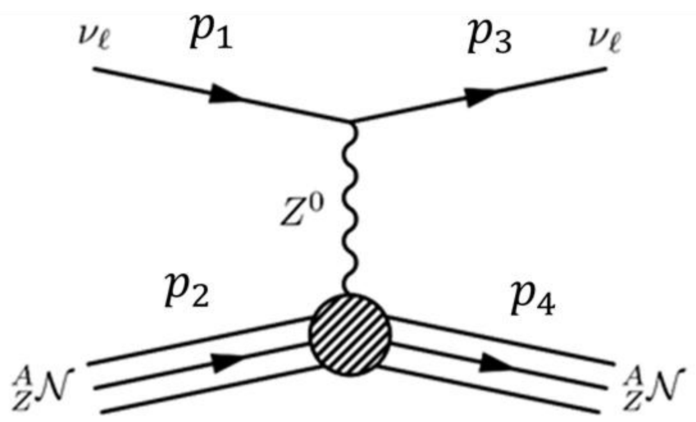






Incoming neutrinos interact with nucleus as a whole without changing its internal state.

For momentum transfer smaller than the inverse of nuclear size, $|\vec{q}|R \ll 1$, along-wavelength Z^0 boson can probe the entire nucleus.



$$\nu(p_1)\mathcal{N}(p_2) \to \nu(p_3)\mathcal{N}(p_4)$$

$$Q_V^{SM} = Z g_V^p + N g_V^n$$

$$|\vec{q}| = \sqrt{2 m_{\mathcal{N}} T_{nr}}/197.3\ \text{fm}^{-1}$$

Tree level:

$$g_V^p = \frac{1}{2} - 2\sin^2\theta_W$$

$$g_V^n = -\frac{1}{2}$$

With radiative Corrections:

$$g_V^p(\nu_e) \simeq 0.0382$$

$$g_V^p(\nu_\mu) \simeq 0.0300$$

$$g_V^n \simeq -0.5117$$

CEνNS cross section is cleanly predicted by the SM !!!

$$\mathcal{M} = \frac{G_F}{2\sqrt{2}} Q_V^{SM} F(|\vec{q}|^2)\bar{\nu}(p_3)\gamma^\mu(1-\gamma^5)\nu(p_1)\bar{u}(p_4)\gamma_\mu u(p_2)$$

$$\frac{d\sigma_{SM}}{dT_{nr}}(E_\upsilon, T_{nr}) = \frac{{G_F}^2}{\pi} m_{\mathcal{N}} (Q_V^{SM})^2 \left(1 - \frac{m_{\mathcal{N}} T_{nr}}{2E_\upsilon^2}\right) F^2(|\vec{q}|^2)$$

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form factor. $F(|\vec{q}|^2) = 3\frac{j_1(|\vec{q}|R_0)}{|\vec{q}|R_0} e^{-\frac{1}{2}|\vec{q}|^2 s^2}$

(Helm, 1956, Phys. Rev., 104(5), 1466)

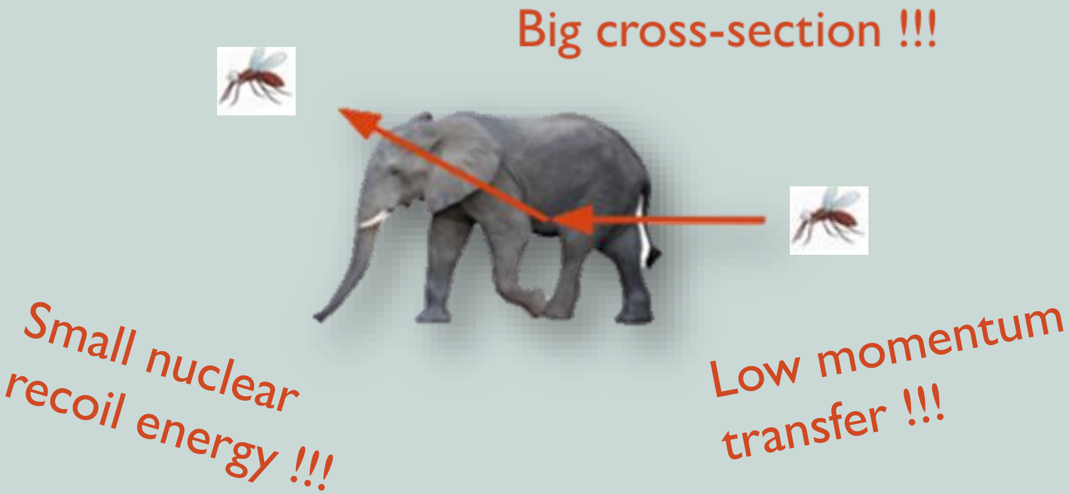
diffraction radius. $R_0^2 = \frac{5}{3}R^2 - 5s^2$

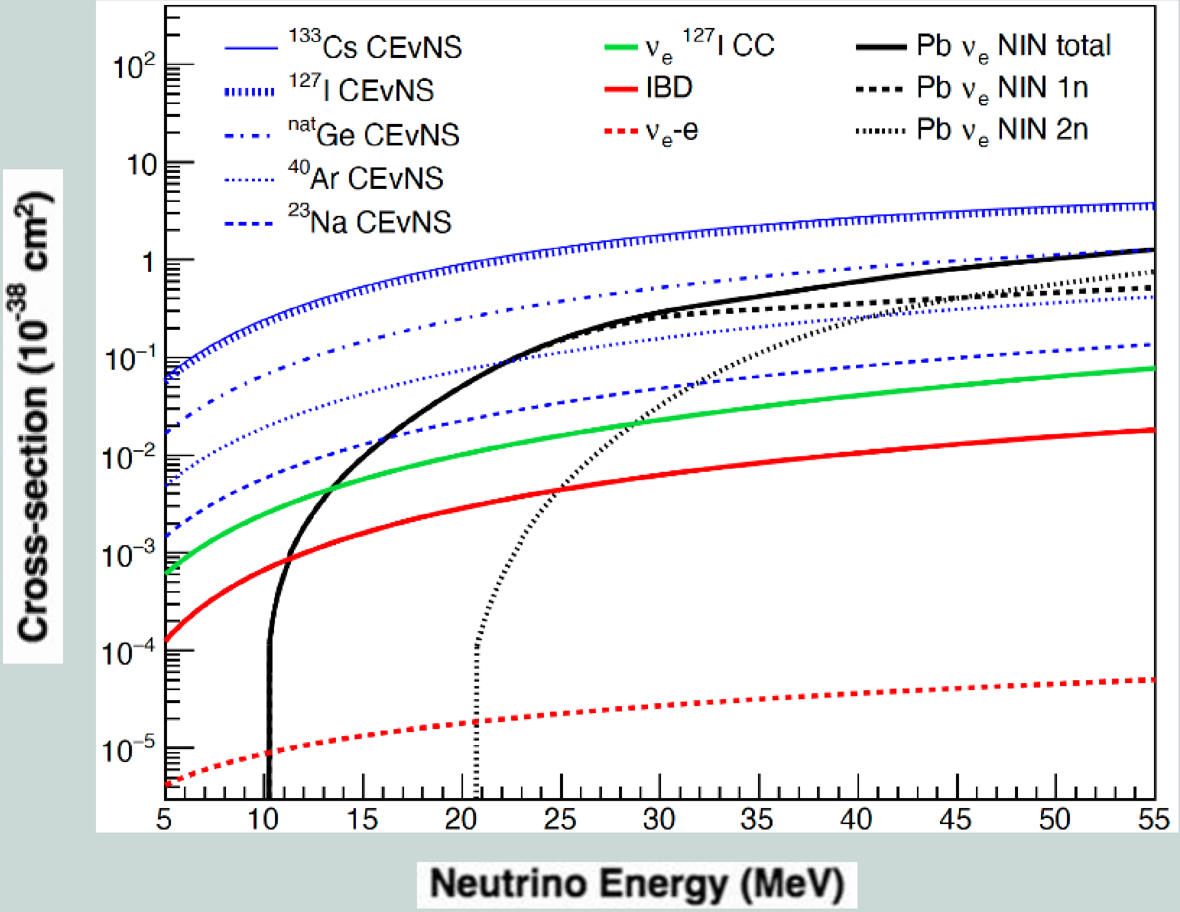
nuclear radius. $R = 1.23\ A^{1/3}$

surface thickness. $s = 0.9\ \text{fm}$

CEνNS provides relatively large σ among other neutrino interaction processes.

Since it is well predicted in the SM framework, a deviation here would represent the new physics.





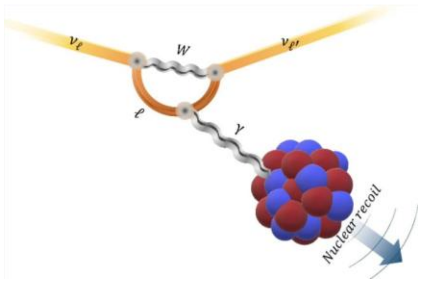
(D. Akimov et al. Science 357.6356, 2017)

The success of experimental observations and improvements made in these observations triggered both experimental and theoretical scientific activities regarding CEνNS.

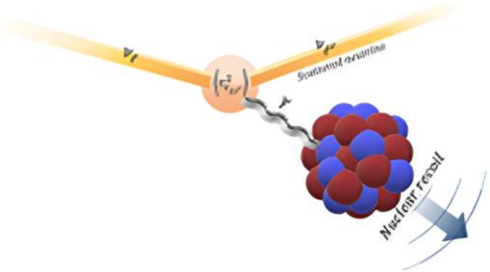
New opportunities to study neutrino physics !!!

CEνNS has opened a new window on beyond the SM (BSM) physics with the experimental constraints it obtained. Possible BSM physics scenarios accessible for CEνNS experiments include:

- Non-standard neutrino interactions (NSI) (Sierra, 2018; Demirci, 2021),
- New light mediators (Xia, 2022; Demirci, 2024),
- Dark matter research (Schwemberger and T.T. Yu, 2022, Phys. Rev. D 106, 015002).
- Neutrino electromagnetic properties (Khan, 2023; Giunti and Ternes, 2023, Phys. Rev. D 108, 095044), etc.



Neutrino Charge Radius (NCR)



A neutral particle can be characterized by a superposition of two charge distributions of the opposite signs, so that the particle form factor $F_Q(q^2)$ can be non-zero for $q^2 \neq 0$.

The mean charge radius (in fact, it is the charge radius squared) of an electrically neutral neutrino is given by

$$\langle r_\nu^2 \rangle = -6 \frac{dF_Q(q^2)}{dq^2}\bigg|_{q^2=0}$$

The neutrino charge radius is the only electromagnetic property of the neutrino that can have a non-zero value.

$$\langle r^2_{\nu_\alpha} \rangle_{SM} = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3 - 2\ln\left(\frac{m^2_\alpha}{m^2_W}\right)\right] \; (\alpha = e, \mu, \tau)$$

$$\langle r^2_{\nu_e} \rangle_{SM} = -0.83 \times 10^{-32}\ cm^2$$

$$\langle r^2_{\nu_\mu} \rangle_{SM} = -0.48 \times 10^{-32}\ cm^2$$

$$\langle r^2_{\nu_\tau} \rangle_{SM} = -0.30 \times 10^{-32}\ cm^2$$

(Bernabeu vd., 2000; Hirsch vd., 2003)

Even in the SM framework, neutrinos have charge radii through contributions from radiative corrections including loop corrections of the W and Z bosons and $\gamma - Z$ boson mixing diagrams !!!

Among the other electromagnetic properties of the neutrino (millicharge, magnetic and anapol moment), the most accessible one for experimental studies is the neutrino charge radius !!!

Bernabeu, Papavassiliou, Vidal, 2004

Contribution of the NCR to the CEνNS

In the CEνNS process, the matrix element

$$\mathcal{M} = \left[\frac{2\pi Z e^2}{3} < r_{\nu_e}^2 > \bar{u}(p_3)\gamma^{\mu} u(p_1)\right] j_{\mu}^{\mathcal{N}}$$

is used for the contribution of the neutrino charge radius, and the differential cross section is calculated as

$$\frac{d\sigma_{\upsilon_\alpha CR}}{dT_{nr}} = \frac{\pi Z^2 e^4}{36} |F(q^2)|^2 \left(< r_{\nu_e}^2 >\right)^2 m_{\mathcal{N}} \left(1 - \frac{T_{nr}}{E_\nu} - \frac{m_{\mathcal{N}} T_{nr}}{2E_\nu^2}\right)$$

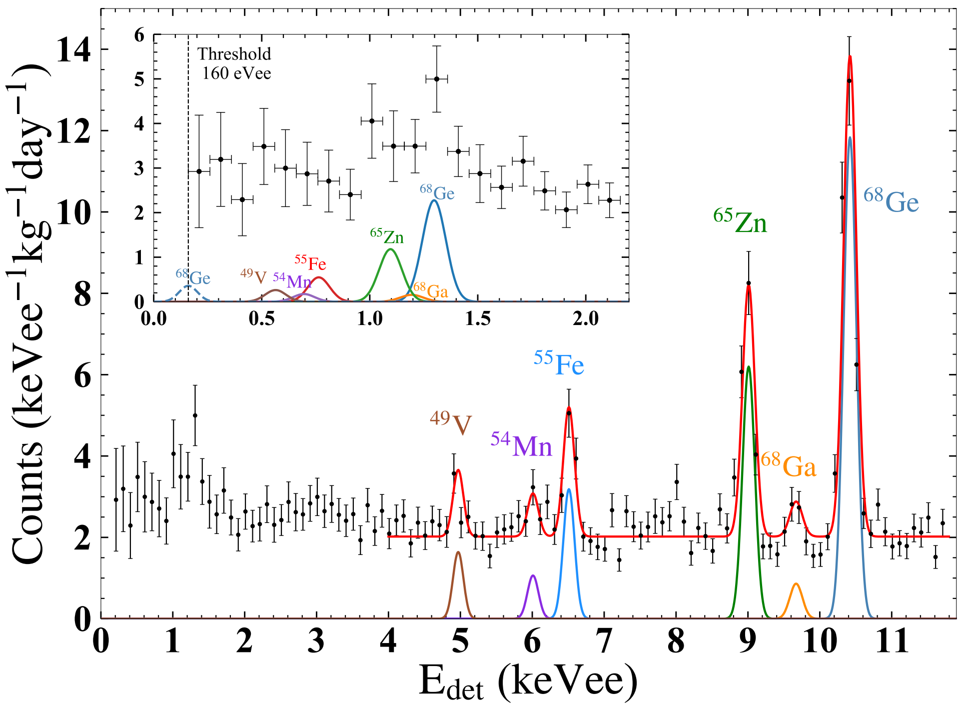
The NCR contribution can be included as a correction for the CEνNS cross section !!!

The total differential cross section, including the interference of this contribution with the SM CEνNS process, is found as

$$\frac{d\sigma_{\nu_\alpha CR}}{dT_{nr}} = \frac{d\sigma_{SM}}{dT_{nr}}\left(1 + \frac{\sqrt{2}e^2 Z}{12 G_F Q_V^{SM}}(< r_{\nu_\alpha}^2 >)\right)^2$$

Method	Experiment	Limit $[10^{-32}\mathrm{cm}^2]$	C.L.	Reference
Reactor $\bar{\nu}_e - e^-$	Krasnoyarsk	$\lvert\langle r_{\nu_e}^2\rangle\rvert < 7.3$	90%	(Vidyakin et al., 1992)
	TEXONO	$-4.2 < \langle r_{\nu_e}^2\rangle < 6.6$	90%	(Deniz et al., 2010)
Accelerator $\nu_e - e^-$	LAMPF	$-7.12 < \langle r_{\nu_e}^2\rangle < 10.88$	90%	(Allen et al., 1993)
	LSND	$-5.94 < \langle r_{\nu_e}^2\rangle < 8.28$	90%	(Auerbach et al., 2001)
Accelerator $\nu_\mu - e^-$	BNL-E734	$-4.22 < \langle r_{\nu_\mu}^2\rangle < 0.48$	90%	(Ahrens et al., 1990)
	CHARM-II	$\lvert\langle r_{\nu_\mu}^2\rangle\rvert < 1.2$	90%	(Vilain et al., 1995)
CEνNS	COHERENT (CsI)	$-67 < \langle r_{\nu_e}^2\rangle < 10$	90%	(Khan, 2023[a])
		$-60 < \langle r_{\nu_\mu}^2\rangle < 5$	90%	(Khan, 2023[a])
	COHERENT (CsI+LAr)	$\langle r_{\nu_e}^2\rangle \in [-61.2, -48.2] \cup [-4.7, 2.2]$	90%	(De Romeri et al., 2023)
		$\langle r_{\nu_\mu}^2\rangle \in [-58.2, -52.1]$	90%	(De Romeri et al., 2023)
Dark matter DD	PandaX4T+LZ+XENONnT	$-99.5 < \langle r_{\nu_e}^2\rangle < 12.8$ $-82.2 < \langle r_{\nu_{\mu/\tau}}^2\rangle < 88.7$	90%	(Giunti & Ternes, 2023)

Numerical Results



In this study, data from the current CDEX-10 experiment on the CEνNS process (Kang et al., 2013; Jiang et al., 2018; She et al., 2020; Geng et al., 2023) **were used !!!**

In the recent CDEX-10 study (Geng et al., 2023), event rates of coherent neutrino-nucleus scattering along with neutrino-electron scattering were published.

The event rates of the process is calculated by integrating the neutrino flux and the cross section:

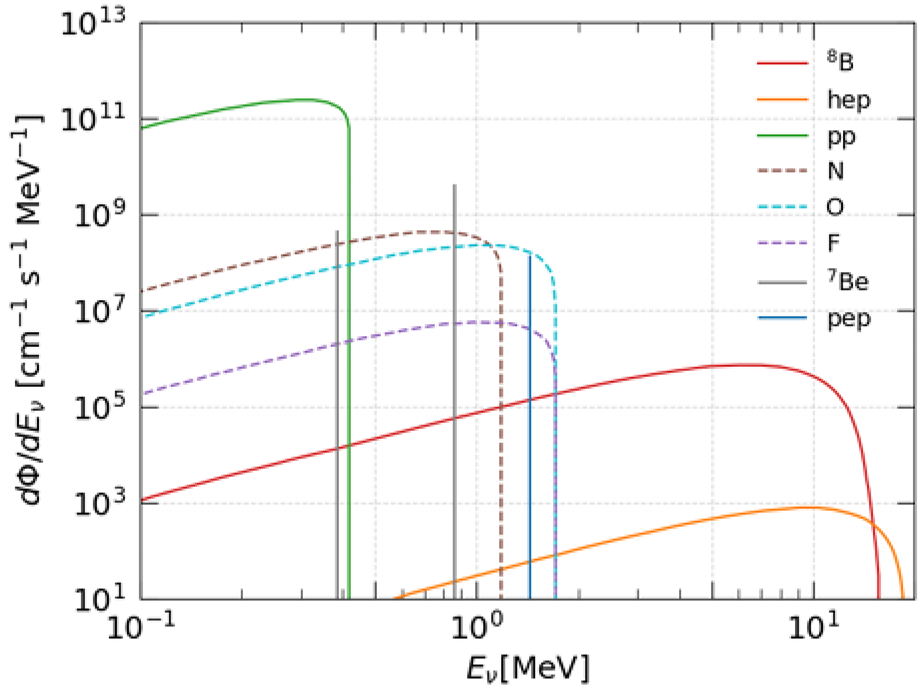
$$\frac{dR}{dT_{nr}} = N_T \int_{E_\nu^{min}}^{E_\nu^{max}} dE_\nu \frac{d\Phi(E_\nu)}{dE_\nu} \frac{d\sigma(E_\nu, T_{nr})}{dT_{nr}}$$

where $d\Phi(E_\nu)/dE_\nu$ is the differential neutrino flux and $N_T = m_t N_A / m_A$.

Solar Neutrino Flux : A huge flux of neutrinos from the Sun !!!

Solar neutrino fluxes with their uncertainties from the high-metallicity solar neutrino model BS05(OP).

Components	Flux [$cm^{-2}s^{-1}$]	Uncertainty [%]
pp	5.99×10^{10}	0.8%
pep	1.42×10^{8}	1.3%
hep	7.93×10^{3}	15.4%
^{8}B	5.69×10^{6}	12.6%
^{7}Be	4.84×10^{9}	9.3%
^{13}N	3.07×10^{8}	20.2%
^{15}O	2.33×10^{8}	23.3%
^{17}F	5.84×10^{6}	25.1%



CDEX-10 data are given in terms of electron equivalent recoil energy T_{ee}. These are first converted to nuclear recoil energy T_{nr} with the help of the quenching factor:

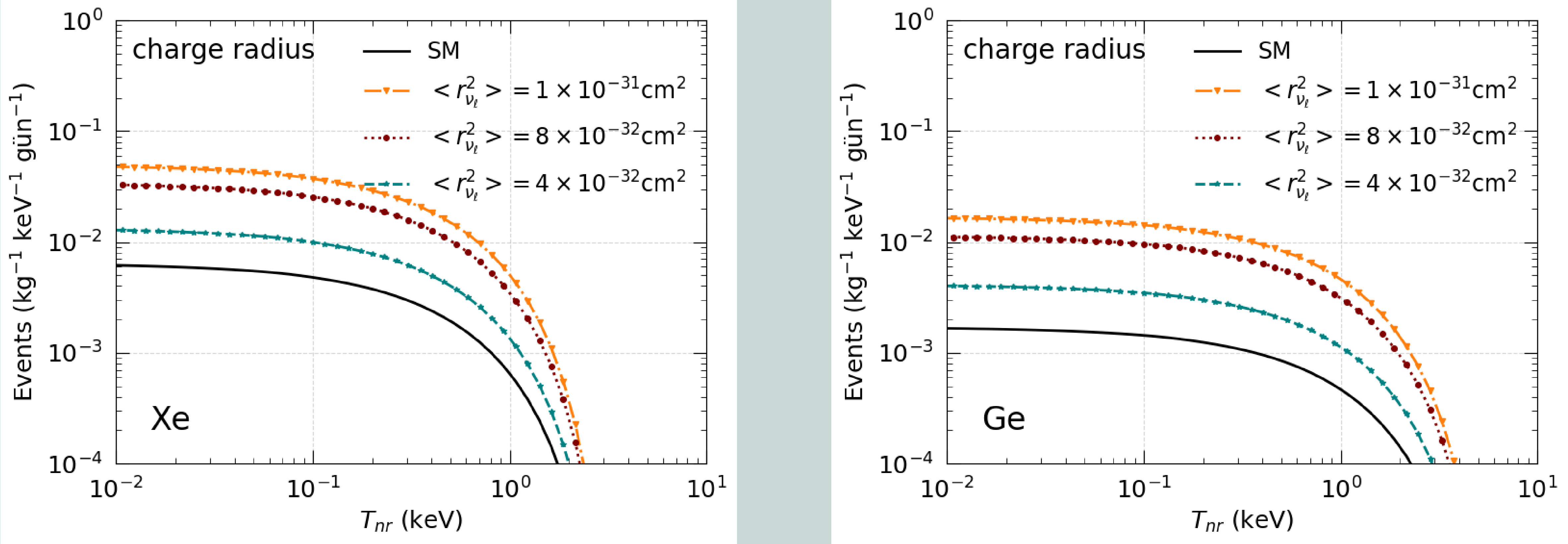
$$T_{ee} = Y(T_{nr})T_{nr}$$

Here we use the Lindhard quencing factor (Lindhard et al., 1963) for $Y(T_{nr})$. Thus, the differential rate can be expressed as

$$\frac{dR}{dT_{ee}} = \frac{dR}{dT_{nr}}\left[Y(T_{nr}) + T_{nr}\frac{dY(T_{nr})}{dT_{nr}}\right]^{-1}$$

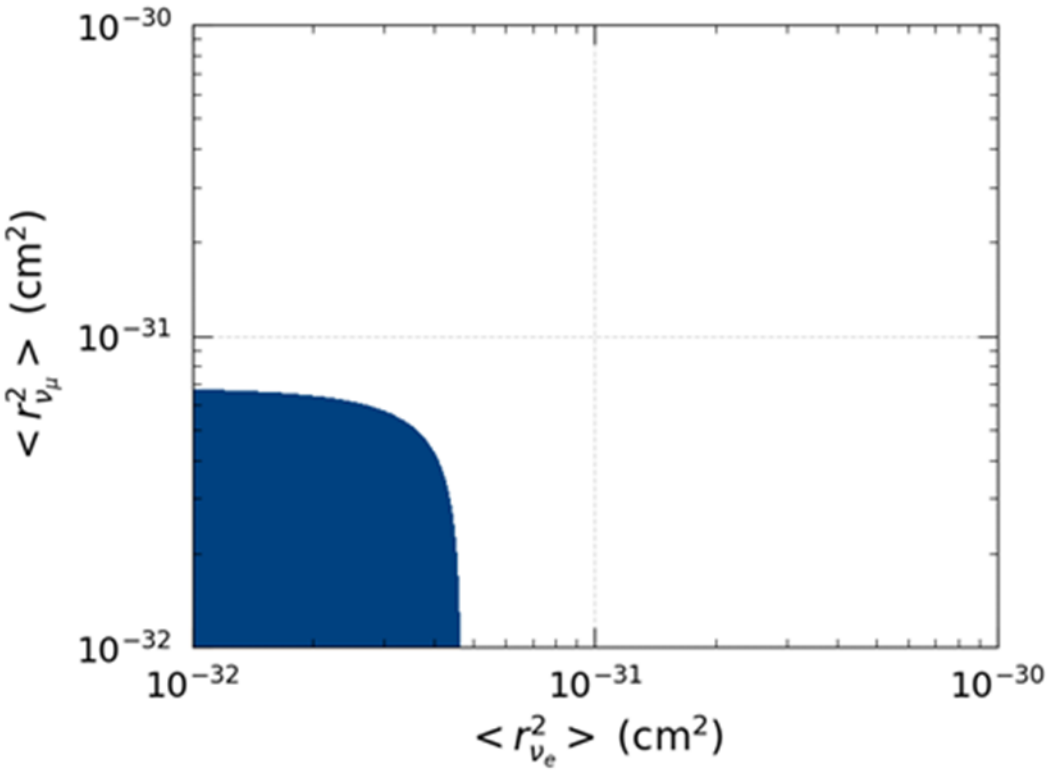
We adopt the pull approach of the χ^2 function (Fogli et al., 2002) to derive constraints on the free parameter space of BSM models:

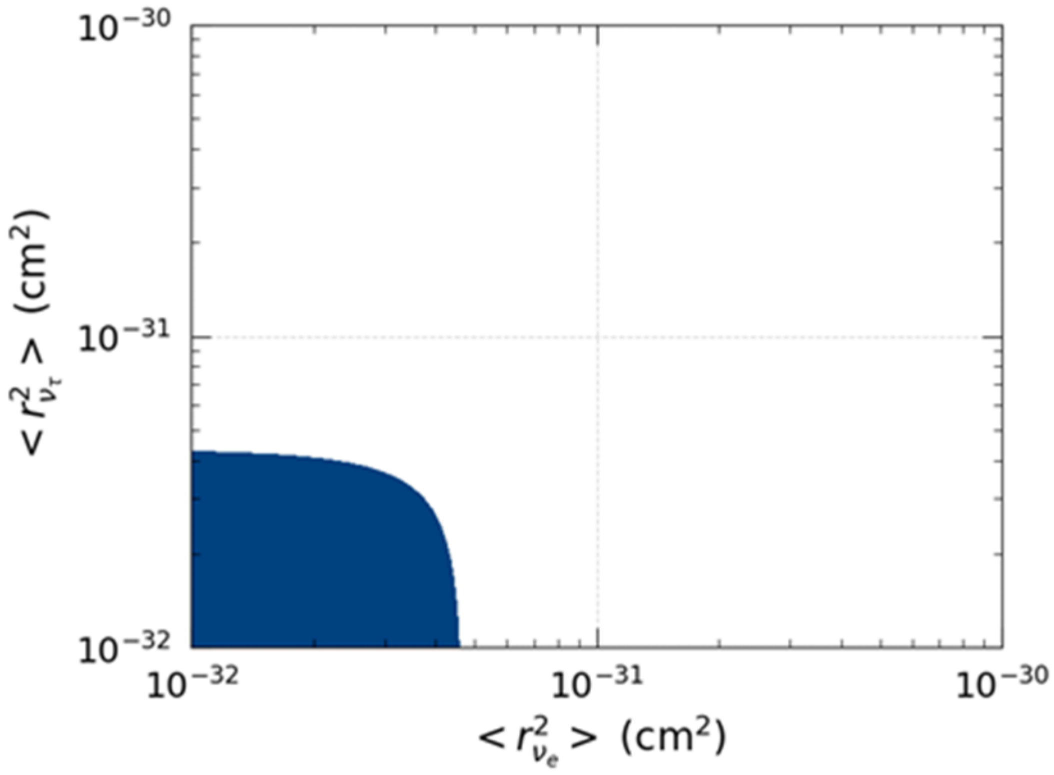
$$\chi^2 = \min_{(\xi_j)} \sum_{i=1}^{20} \left(\frac{R_{obs}^i - R_{exp}^i - B - \sum_j \xi_j c_j^i}{\Delta^i}\right)^2 + \sum_j \xi_j^2$$



The predicted event rates for individual contributions from the neutrino charge radius in the CEνNS process were calculated as a function of the nuclear recoil energy for Ge and Xe target nuclei.

New limits on the neutrino charge radius were derived from CDEX-10 data analysis !!!





Experimental limits on the neutrino charge radius

CDEX-10 Data Analysis ($\times 10^{-32} \mathrm{cm}^2$)
$\lvert < r^2_{\nu_e} > \rvert < 4.65$
$\lvert < r^2_{\nu_\mu} > \rvert < 6.80$
$\lvert < r^2_{\nu_\tau} > \rvert < 4.32$

Current results show competitive behavior with reactor and accelerator results.

According to COHERENT-(CsI) analysis data, an improvement of approximately 1 order of magnitude was achieved.

In the COHERENT-(CsI LAr) data, the same order of constraint is provided compared to the results obtained for the charge radius of the electron neutrino, and approximately 1 order better than the results obtained for the charge radius of the muon neutrino.

Conclusions

In this study, the new upper limit values for the neutrino charge radius have been derived using the latest data from the CDEX-10 experiment.

Analysis results for the neutrino charge radius are presented in two-dimensional parameter space according to neutrino flavours.

It is seen that the analysis results obtained for the neutrino charge radius investigated within the framework of CEνNS are compatible with the literature.

THANKS FOR YOUR ATTENTION!

Onur Başlı

onurbasli@uludag.edu.tr

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