PREDICTING NEUTRINO MILLICHARGE SENSITIVITY WITH COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

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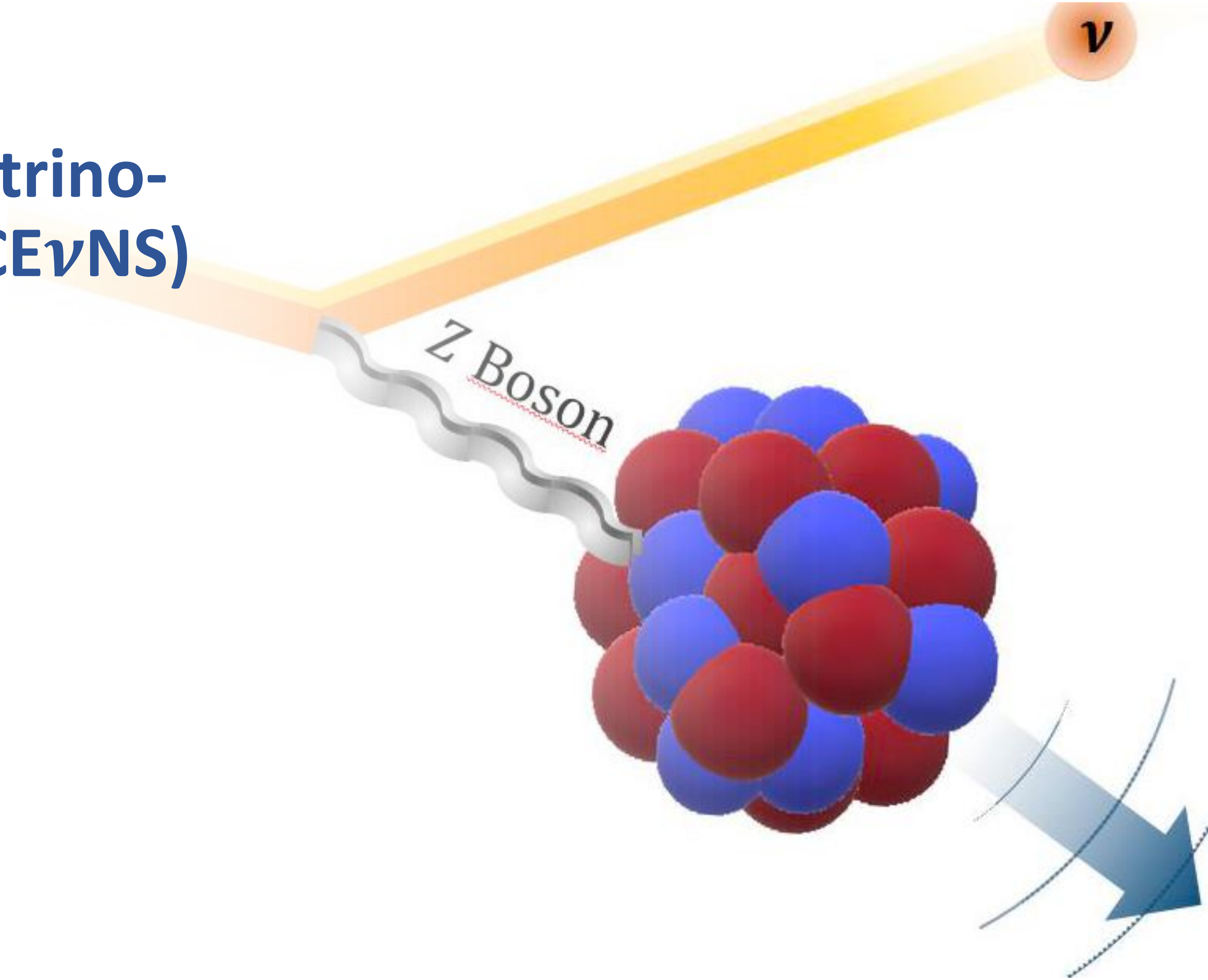
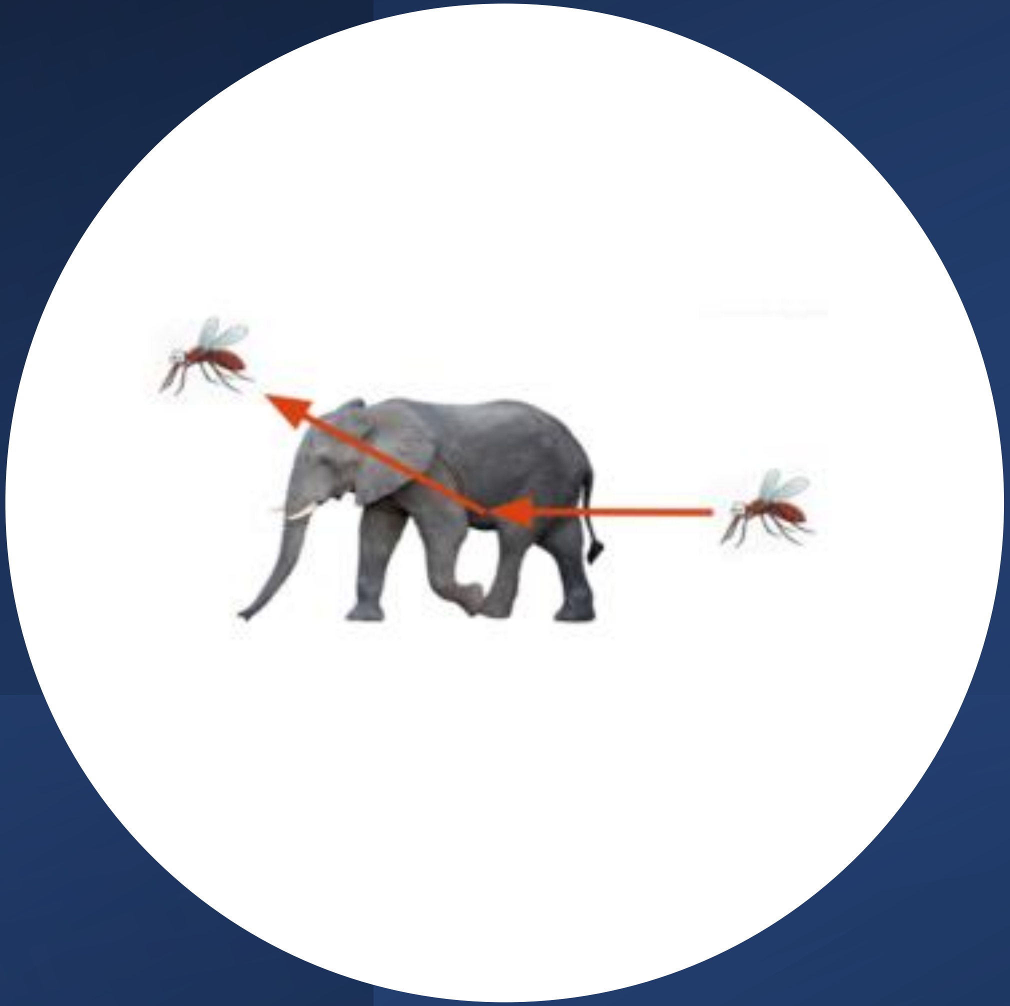
- Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)
- Neutrino Millicharge
- Numerical Results
- Conclusions



Coherent Elastic Neutrino-Nucleus Scattering
(CEνNS)



Prediction

- CEνNS predicted theoretically in 1974 by Daniel Freedman, firstly.
- A neutral current weak interaction process that occurs at low energies in the Standard Model (SM) framework.
- The aim was to propose a class of experiments that could provide information about the isospin structure of the neutral current that cannot be obtained elsewhere.

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Coherent effects of a weak neutral current

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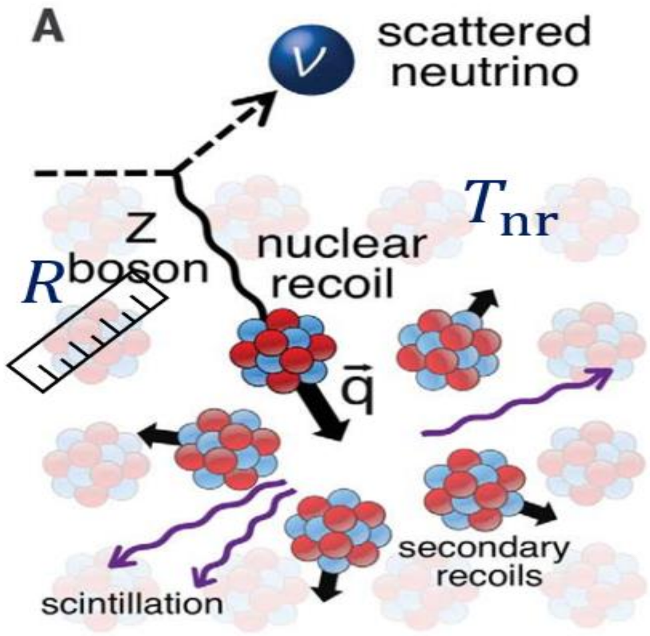
Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering.

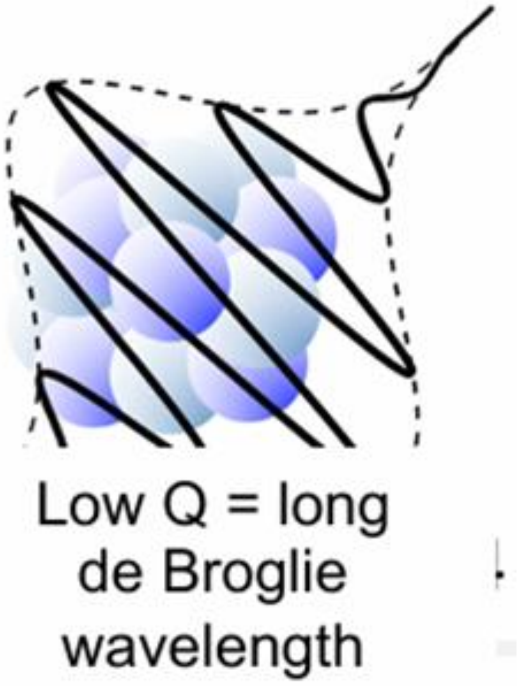
Process

- A neutrino is scattered from the nucleus via the exchange of a Z^0 boson, and the nucleus recoils as a whole.

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

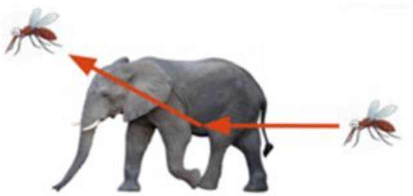
- Incoming neutrinos interact with nucleus as a whole without changing its internal state.

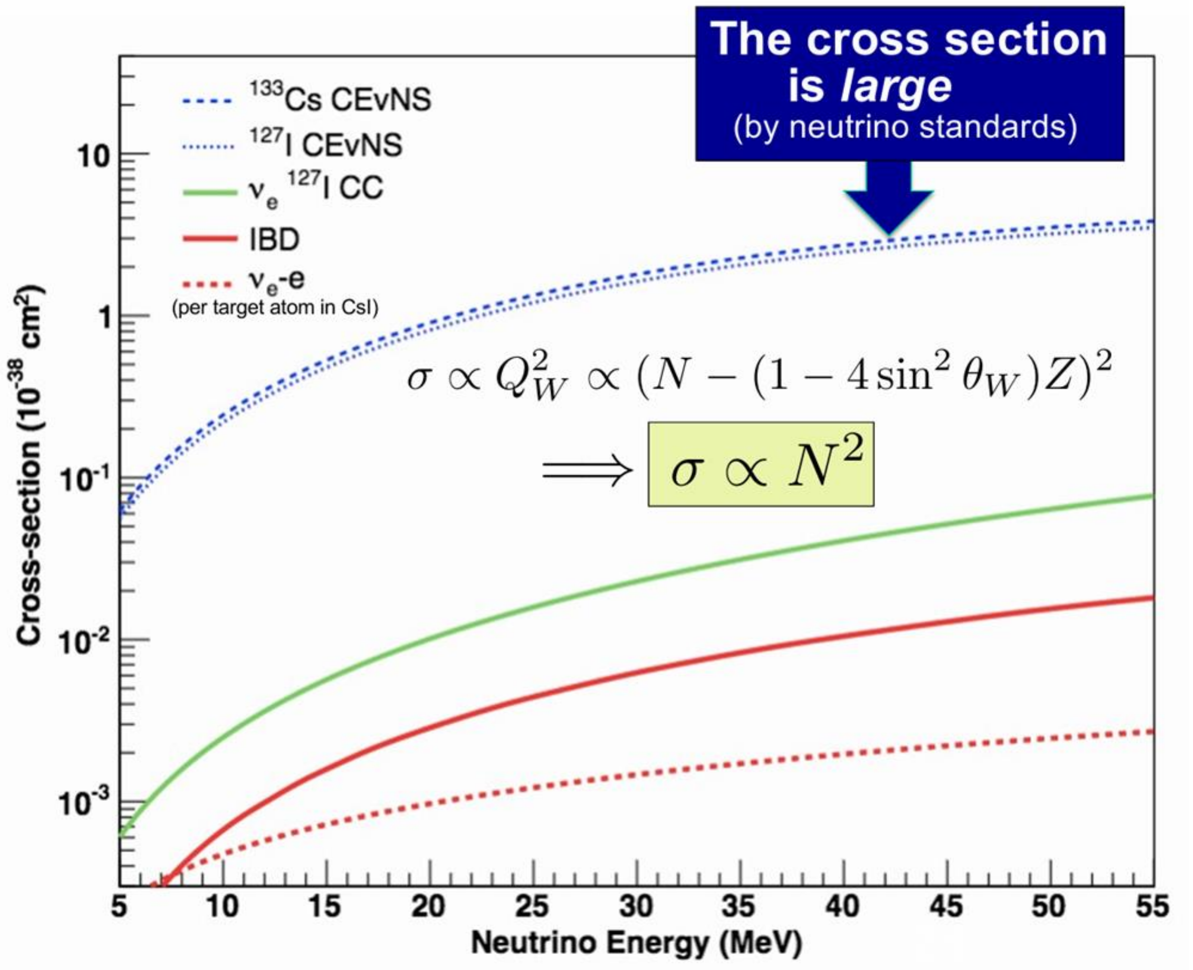




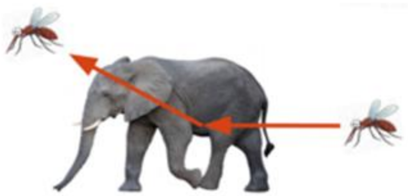
CEνNS - Challenging Process to Observe

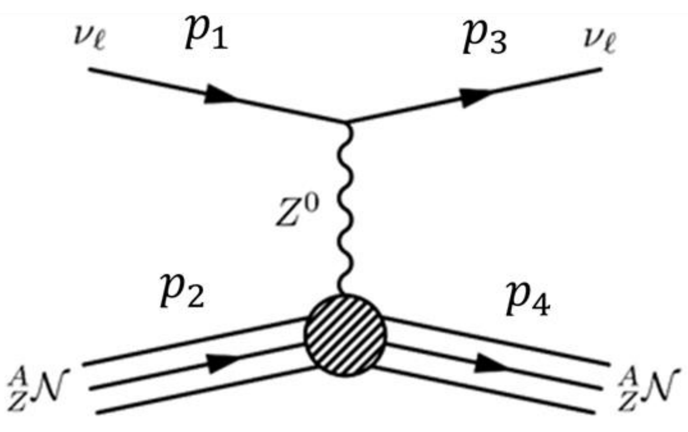
- It provides relatively large σ among other neutrino interaction processes.
- Hard to detect; the nuclear recoil energy, T_{nr}, is around a few keV.
- First observation in 2017 by the COHERENT experiment at Oak Ridge National Laboratory. [D. Akimov et al., Science 357.1123 (2017)].





Differential Cross-section





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

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

$$\frac{d\sigma}{dT_{nr}}(E_\upsilon\,, T_{nr}) = \frac{{G_F}^2}{\pi} m_{\mathcal{N}} \left(\mathrm{Q}_{\mathrm{SM}}^{\mathrm{V}}\right)^2 \left(1 - \frac{m_{\mathcal{N}} T_{nr}}{2E_\upsilon^2}\right) |F(q^2)|^2$$

Weak charge of the nucleus:

$$\mathrm{Q}_{\mathrm{SM}}^{\mathrm{V}} = Z g_p^V + N g_n^V$$

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

with the proton and neutron couplings at tree-level.

Tree level:

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

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

With radiative Corrections:

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

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

$$g_V^n \simeq -0.5117$$

- The heavier target nucleus, the greater boost in the cross-section but the smaller the nuclear recoil.

$\sin^2\theta_W = 0.23863$ (PDG, 2022)

Motivation

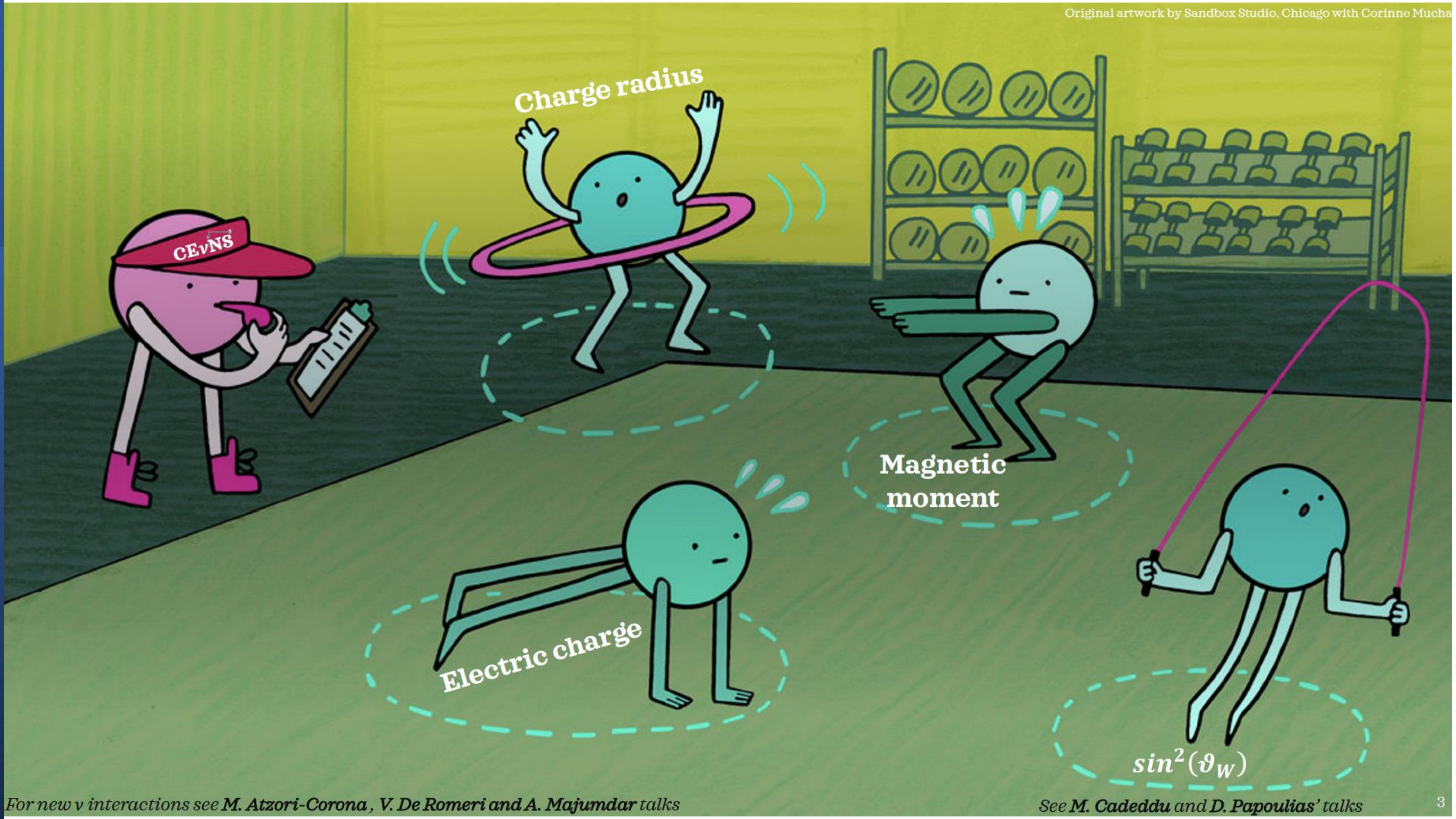
- Since CEνNS is well predicted in the SM framework, a deviation here would represent new physics.

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

- This process provides a promising new framework for investigating the fundamental parameters of the SM and new physics beyond the SM, such as neutrino millicharges.

- CEνNS, in particular, also provides a background for the dark matter direct-detection (DD) experiments.

Neutrino Millicharge



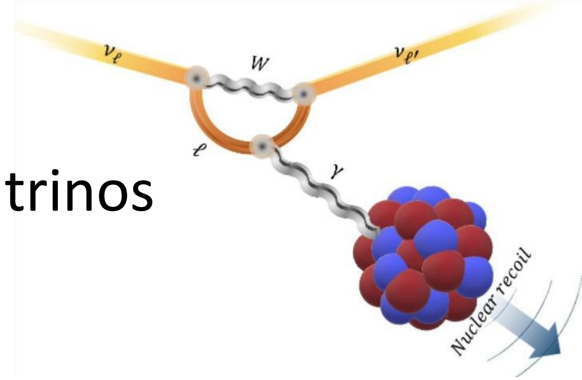
- Non vanishing mass of neutrinos are indicated by neutrino oscillation process (Pontecorvo, 1957; Maki et. al. 1962).

- This fact leads to the requirement of SM extension, since neutrinos are massless in the SM.

- Electromagnetic properties (magnetic moment, charge radius, millicharge) are one of the possibilities (Giunti & Studenikin, 2015).

- For neutrinos the electric charge is zero and there are no electromagnetic interactions at tree-level.

- Such interactions comes from quantum loops effects that allow neutrinos direct interaction with photon and charged particles.



- Neutrinos can have non-zero electric charge. The inclusion of right-handed neutrinos (ν_R) in the SM introduces a new hypercharge parameter into the anomaly equations that destroys the charge quantization.

- For the CEνNS process, the electromagnetic contribution from neutrinos to the SM weak interaction, expressed in terms of neutrino millicharge q_{ν_α} ($\alpha = e, \mu, \tau$) with α flavor is defined by (Giunti & Studenikin, 2015)

$$\mathcal{L}_\alpha^{em} = -ie\,(q_{\nu_\alpha}\bar{\nu}_\alpha\gamma_\mu\nu_\alpha + \bar{N}\gamma_\mu N)A^\mu$$

where A^μ is the photon field and e is the unit electric charge.

- The matrix element for the contribution of neutrino millicharge in the CEνNS process is written as

$$\mathcal{M} = \frac{4\pi Z e}{q^2} q_{\nu_\alpha} \bar{u}(p_3)\, \gamma^{\mu}\, u(p_1)\, j_{\mu}^{\mathcal{N}}$$

where $j_{\mu}^{\mathcal{N}} = \left(p_{2\mu} + p_{4\mu}\right) F(q^2)$ is the nucleus current. From here, the differential cross section that contributes to the neutrino millicharge (MC) to the CEνNS process is found as

$$\frac{d\sigma_{\nu_\alpha MC}}{dT_{nr}} = \pi Z^2 e^2 |F(q^2)|^2 \left(\frac{q_{\nu_\alpha}}{m_{\mathcal{N}} T_{nr}}\right)^2 2 m_{\mathcal{N}} \left(1 - \frac{T_{nr}}{\mathrm{E}_{\nu}} - \frac{m_{\mathcal{N}} T_{nr}}{2\mathrm{E}_{\nu}^2}\right)$$

- The neutrino millicharge is more sensitive to low-energy recoils (Khan, 2021; Aprile et al., 2020) because it interferes with the SM contribution and the coupling constant is inversely proportional to the square of the recoil energy.

- The total differential cross section, including the interference of this contribution with the SM, is written as

$$\left[\frac{d\sigma}{dT_{nr}}\right] = \left[\frac{d\sigma}{dT_{nr}}\right]_{\text{SM}} \left(1 - \frac{\sqrt{2}Ze}{4G_F Q_{SM}}\left(\frac{q_{\nu_\alpha}}{m_{\mathcal{N}} T_{nr}}\right)\right)^2$$

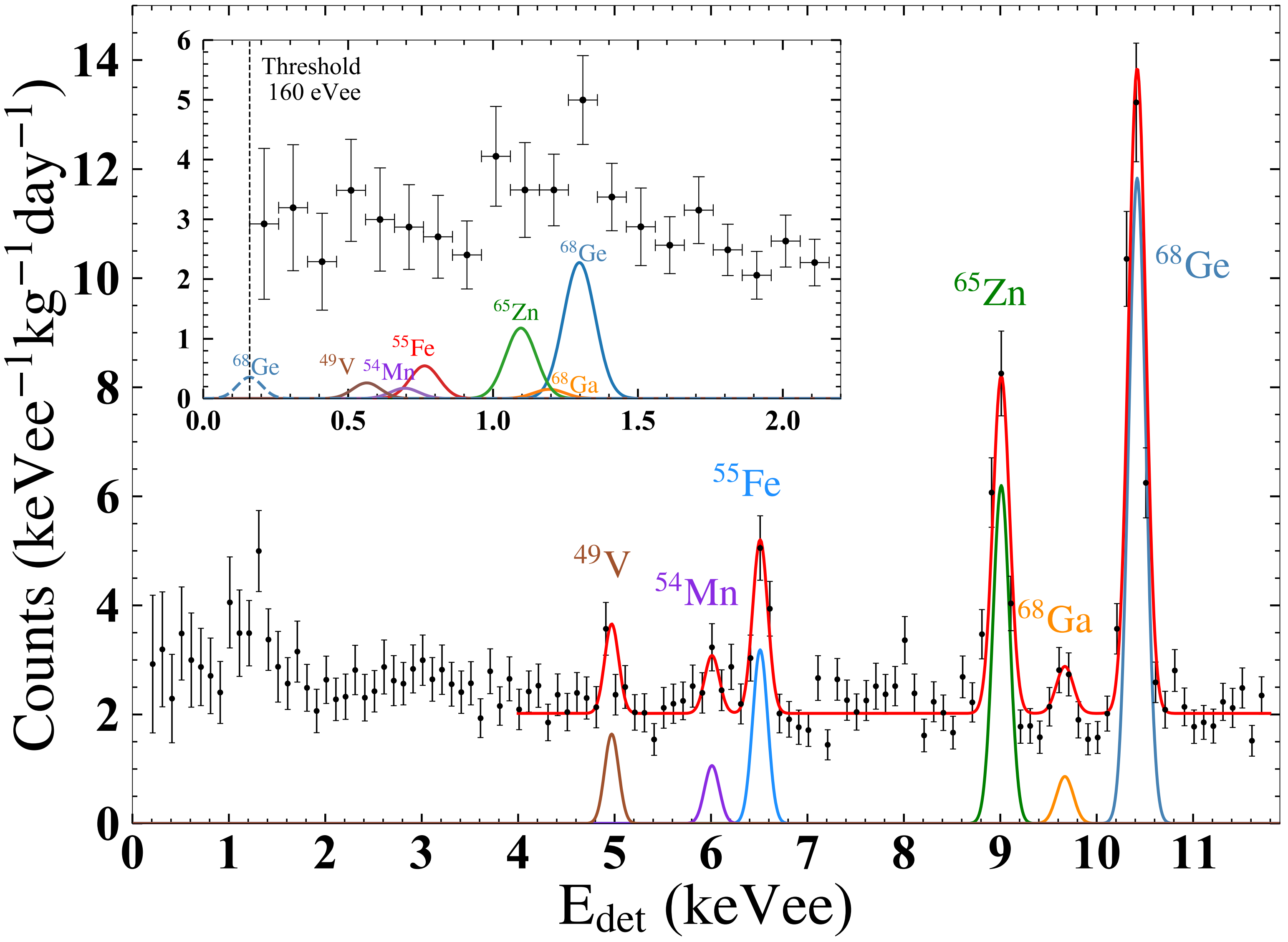
- Moreover, since the electromagnetic interaction terms add coherently to the vector part of the weak interaction, the contribution of the neutrino millicharge can also be calculated directly by

$$\sin^2\theta_W \to \sin^2\theta_W \left(1 - \frac{\pi\alpha_{EM}}{\sqrt{2}\sin^2\theta_W G_F\, m_{\mathcal{N}} T_{nr}} Q_{\alpha\alpha}\right)$$

changing for the weak mixing angle θ_W in the SM CEνNS cross section.

Method/Experiment	Limit	Reference
SLAC e^-	$\lvert q_{\nu_\tau}\rvert \lesssim 3 \times 10^{-4} e$	(Davidson et al., 1991)
BEBC	$\lvert q_{\nu_\tau}\rvert \lesssim 4 \times 10^{-4} e$	(Babu et al., 1994)
Solar cooling (plasmon decay)	$\lvert q_\nu\rvert \lesssim 6 \times 10^{-14} e$	(Raffelt, 1999)
Red giant cooling (plasmon decay)	$\lvert q_\nu\rvert \lesssim 2 \times 10^{-14} e$	(Raffelt, 1999)
Neutrality of matter	$\lvert q_{\nu_e}\rvert \lesssim 3 \times 10^{-21} e$	(Raffelt, 1999)
Electric charge asymmetry of the universe	$\lvert q_\nu\rvert < 4 \times 10^{-35} e$	(Caprini & Ferreira, 2005)
TEXONO	$\lvert q_{\bar{\nu}_e}\rvert \lesssim 3.7 \times 10^{-12} e$	(Gninenko et al., 2007)
GEMMA	$\lvert q_{\nu_e}\rvert \lesssim 1.5 \times 10^{-12} e$	(Studenikin, 2014)
COHERENT (CsI)	$-1.10 \times 10^{-7} e < q_{\nu_e} < 3.90 \times 10^{-7} e$ $-0.55 \times 10^{-7} e < q_{\nu_\mu} < 0.75 \times 10^{-7} e$	(Khan, 2023)
COHERENT (CsI+LAr)	$q_{\nu_e} \in (-6.9, 5.6) \times 10^{-8} e$ $q_{\nu_\mu} \in (-3.3, 2.5) \times 10^{-8} e$	(De Romeri et al., 2023)
PandaX-4T + LZ + XENONnT	$q_{\nu_e} \in (-2.0, 7.0) \times 10^{-13} e$ $q_{\nu_{\mu/\tau}} \in (-7.5, 7.3) \times 10^{-13} e$	(Giunti & Ternes, 2023)

Numerical Results



- We analysis the recent CDEX-10 data (Kang et al., 2013; Jiang et al., 2018; She et al., 2020; Geng et al., 2023) with associated to CEνNS process.

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

- 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 $Y(T_{nr})$:

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

- 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)

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

for constraining the corresponding model parameters.

- Here, R^i_{obs} and R^i_{exp} are the observed and expected event rates (that consists of SM + new physics contribution) respectively, in the i th energy bin.

- Δ^i denotes the experimental uncertainty which includes statistical and systematic uncertainties, and the solar neutrino flux uncertainty is represented by c^i_j .

- The function is minimized with respect to all pull parameters ξ_j.

Projected Scenarios

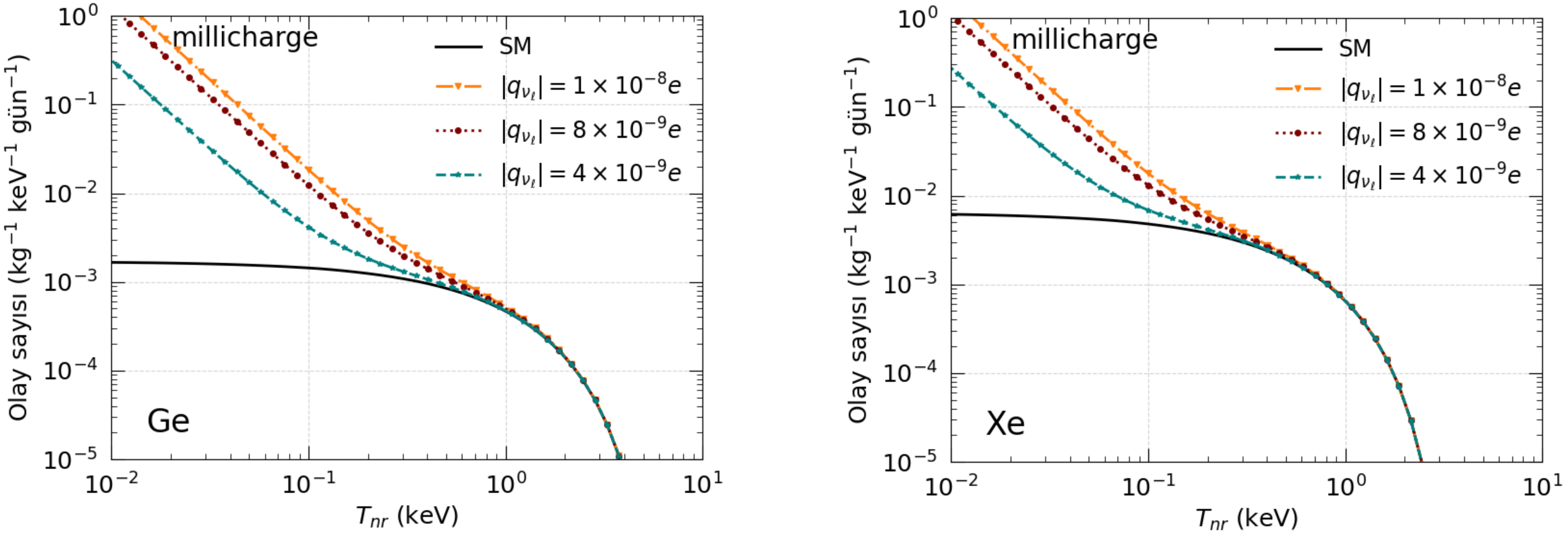
- Future experimental configurations may further constrain new physics parameters. Regarding these developments, two scenarios are suggested (Demirci & Mustamin, 2024):

- The first is the realistic scenario based on the assumption that the experimental uncertainty can reach 10%.

- The second is the optimistic scenario in which the uncertainty is determined as 1.5%.

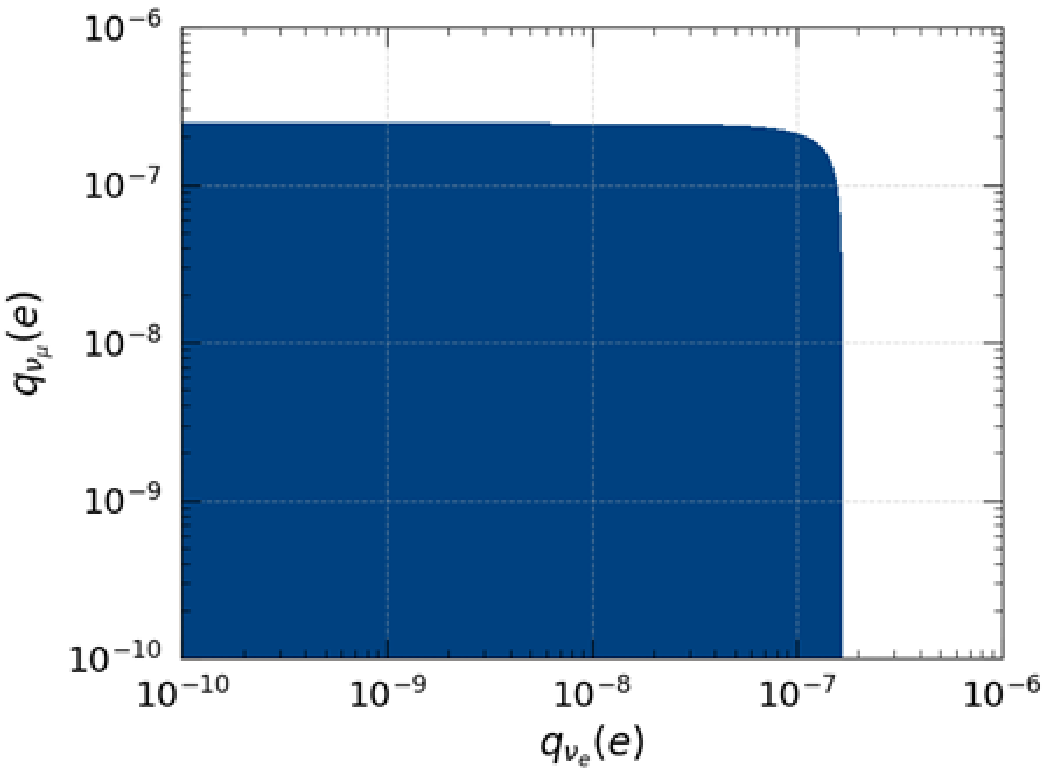
- These scenarios are implemented in the relevant energy region of the observed future recoil energy. In this case, the nuclear recoil energy will be around 0.1 keV and 0.015 keV for the realistic and optimistic scenarios considered, respectively.

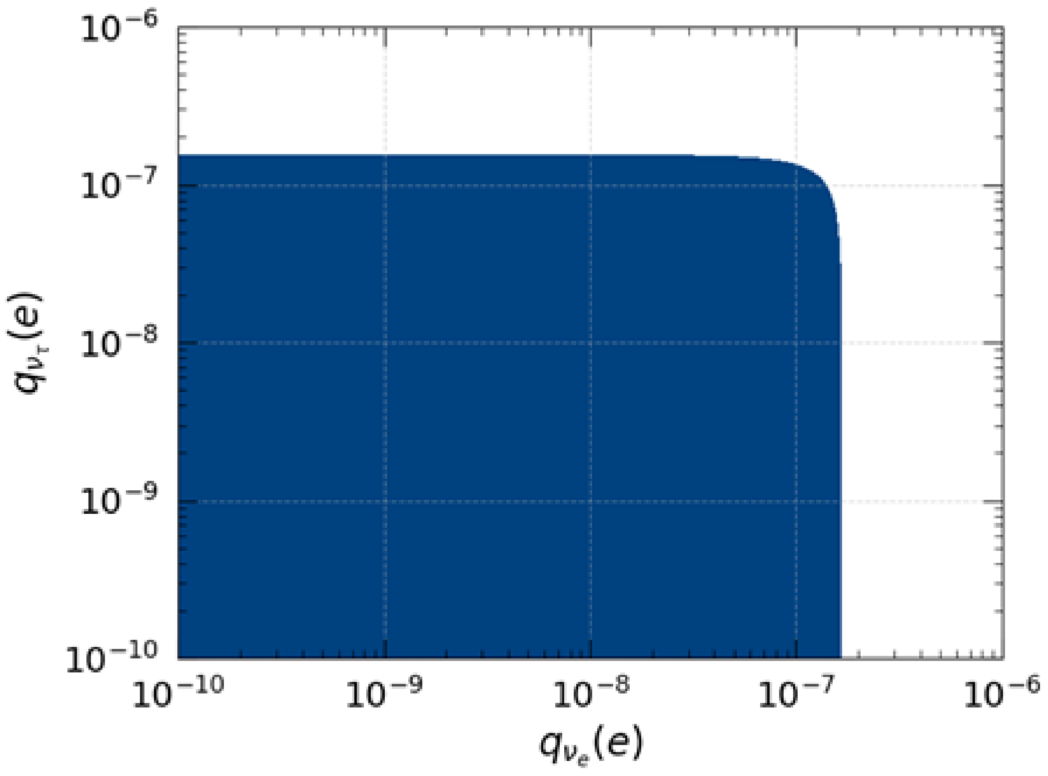
- The predicted event rates for the contribution from the neutrino millicharge in the CEνNS process were calculated as a function of the nuclear recoil energy.



- It should be noted that the neutrino millicharge contribution can be included as a correction for the weak mixing angle.

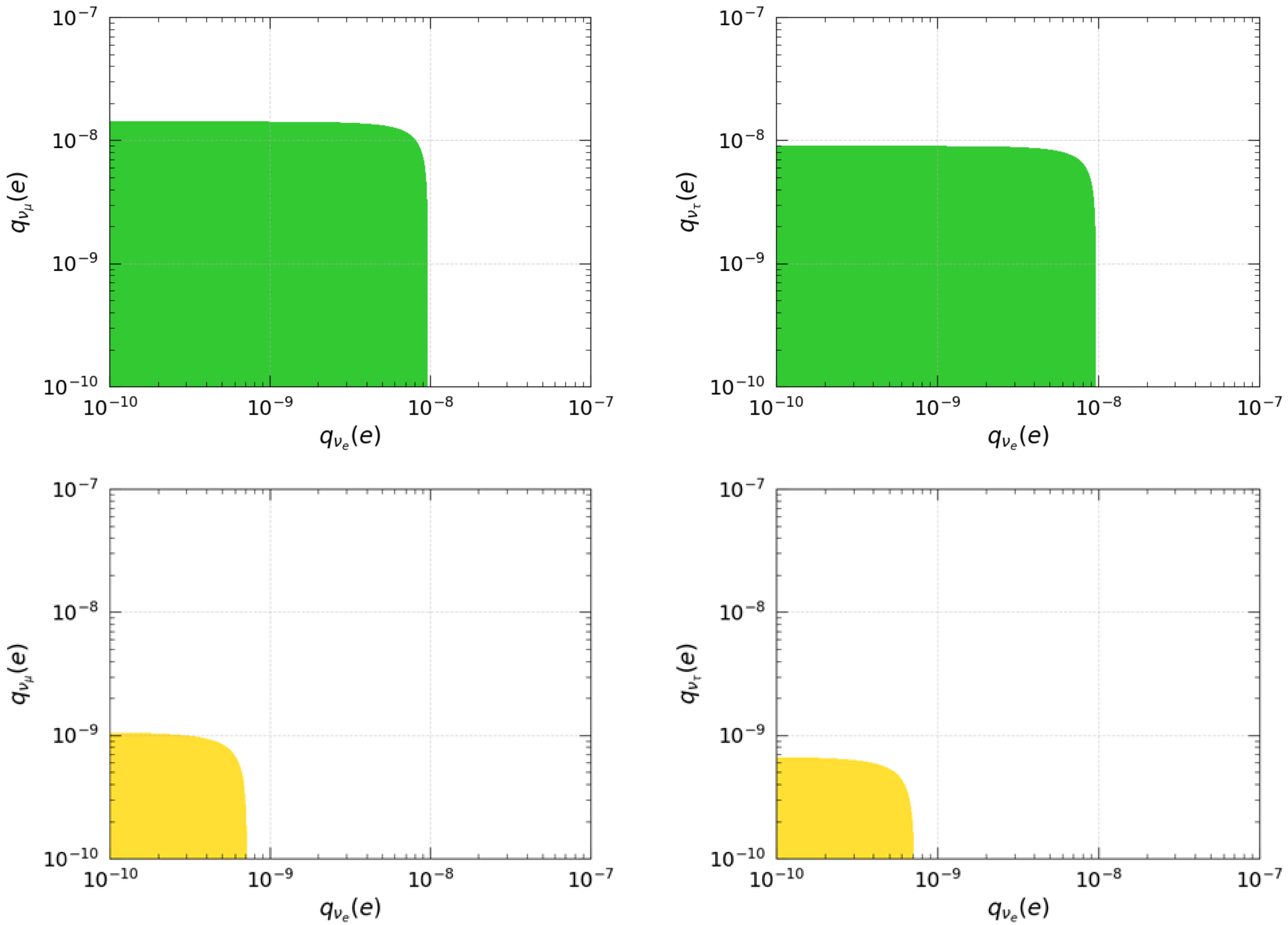
- Upper-limit values were derived from CDEX-10 data analysis in parameter spaces created according to flavor differences for neutrino millicharge.





Realistic scenario

Optimistic scenario

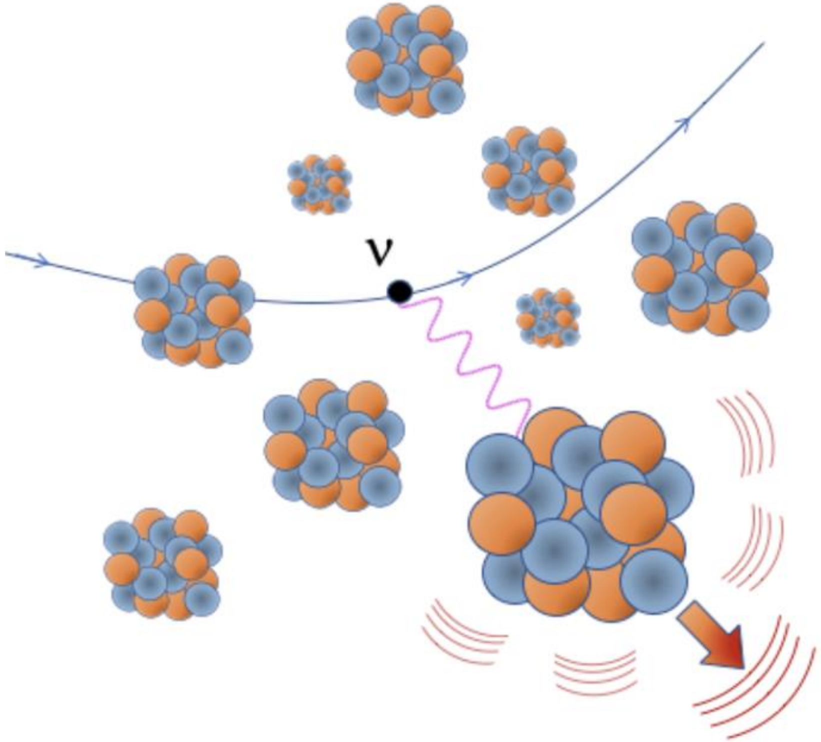


Neutrino millicharge flavors	CDEX-10 data analysis ($\times 10^{-7}$e)	Realistic scenario ($\times 10^{-9}$e)	Optimistic scenario ($\times 10^{-10}$e)
$\lvert q_{\nu_e} \rvert$	< 1.66	< 9.64	< 7.17
$\lvert q_{\nu_\mu} \rvert$	< 2.42	< 14.1	< 10.5
$\lvert q_{\nu_\tau} \rvert$	< 1.54	< 8.94	< 6.65

- Current CDEX-10 data analysis results provide tighter constraints than SLAC and BEBC limits.
- Moreover, it is 1.3 times stronger for q_{ν_e} while approximately 70 % weaker for q_{ν_μ}, according to the limits derived from COHERENT-(CsI) data.
- It shows $\sim$ 1 order of magnitude lower constraint than the limits derived from the COHERENT-(CsI+LAr) combined analysis.
- In the realistic scenario, $\sim$ 1 order of magnitude better constraint is obtained from COHERENT-(CsI) analysis data, showing improvement over the combined analysis of COHERENT-(CsI+LAr) data. In the optimistic scenario, the better upper limit values are obtained compared to both CsI and CsI+LAr data.

Conclusions

- In this study, new upper limit values for the neutrino millicharge have been derived using the latest data from the CDEX-10 experiment.
- The event rates of the SM CEνNS together with the event rates of the individual contribution of the neutrino millicharge are shown as a function of the nuclear recoil energy.
- Analysis results for the neutrino millicharge are presented in two-dimensional parameter space according to neutrino flavours.
- It is seen that the analysis results obtained for the neutrino millicharge investigated within the framework of CEνNS are compatible with the literature.



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