Solar neutrino constraints on U(1)' models via coherent elastic neutrino-nucleus scattering

supported by TÜBITAK Project No: 123F186

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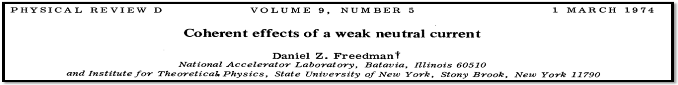
8 November 2023

Outline

Coherent Elastic Neutrino Nucleus Scattering (CEνNS)

CEνNS Process

- A Standard Model (SM) process, where neutrinos interact with the nucleus via Z exchange as a whole, followed by the recoiled nucleus.
- Theoretically proposed around half a century ago (Freedman, 1974),


PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

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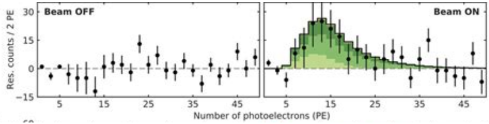
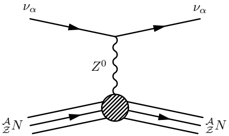
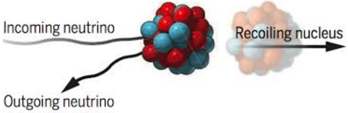
experimentally observed recently by COHERENT collaboration (Akimov *et al*, 2017).





- Some characteristics: $E_\nu \lesssim 50$ MeV, $T_{nr} \lesssim 50$ keV.



- It is the largest observable among other processes involving neutrinos.
- Difficult to observe, its nuclear recoil energy lies in low keV scales.
- Hence, it provides a promising novel framework to investigate fundamental parameters of the SM and new physics beyond the SM (BSM).
- It triggers developments of sensitive detector technology.

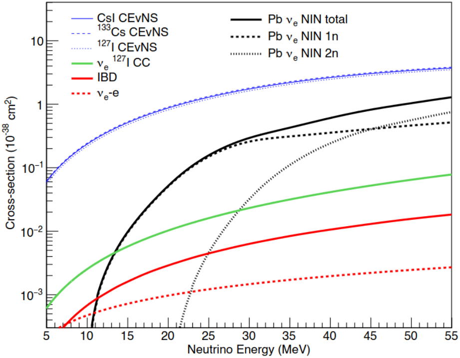


Figure from Akimov *et. al.*, 2017.

CEνNS Cross-Section

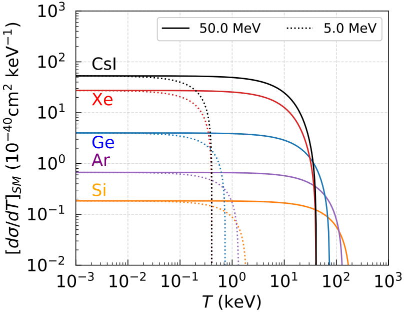
The differential cross section of CEνNS is

$$\left[\frac{d\sigma}{dT_{nr}}\right] = \frac{G_F^2 m_N}{\pi} Q_{\rm SM}^2 \left(1 - \frac{m_N T_{nr}}{2E_\nu^2}\right) \times \left|F(|\vec{q}|^2)\right|^2, \qquad (1)$$

G_F : Fermi constant; m_N : nucleus mass. The weak charge coupling:

$$Q_{\rm SM} = g_V^p \mathcal{Z} + g_V^n \mathcal{N} \qquad (2)$$

$g_V^p = 1/2(1 - 4\sin^2\theta_W)$, $g_V^n = -1/2$. Form factor: the Helm parameterization (Helm, 1956)



$$F(q^2) = 3j_1(qR)e^{-\frac{1}{2}q^2 s^2}/(qR), \qquad (3)$$

with $Q^2 \equiv -q^2 = 2m_N T_{nr}$.

Worldwide Efforts to Measure CEνNS

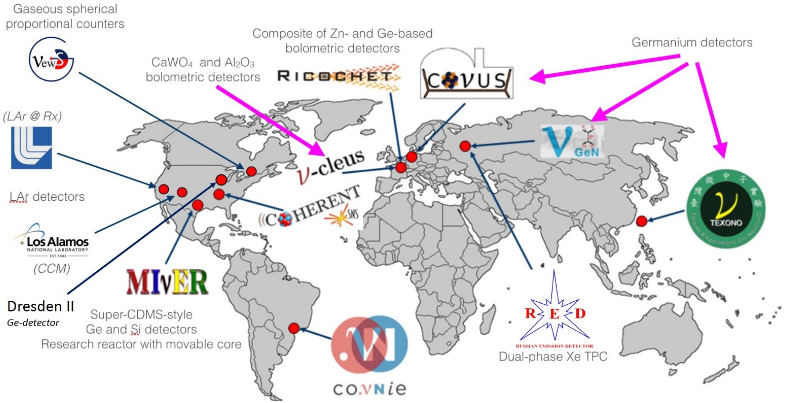


Figure from R. Dmitrii's talk@Magnificent CEvNS2023

- Except for COHERENT and Captain Mills, all others are attempting to use nuclear reactors as a neutrino source.
- Reactors provide a large constant energy neutrino flux.
- CEνNS and Dark Matter Community are both making a great effort to improve and increase the number of available experimental probes.

Neutrino Sources

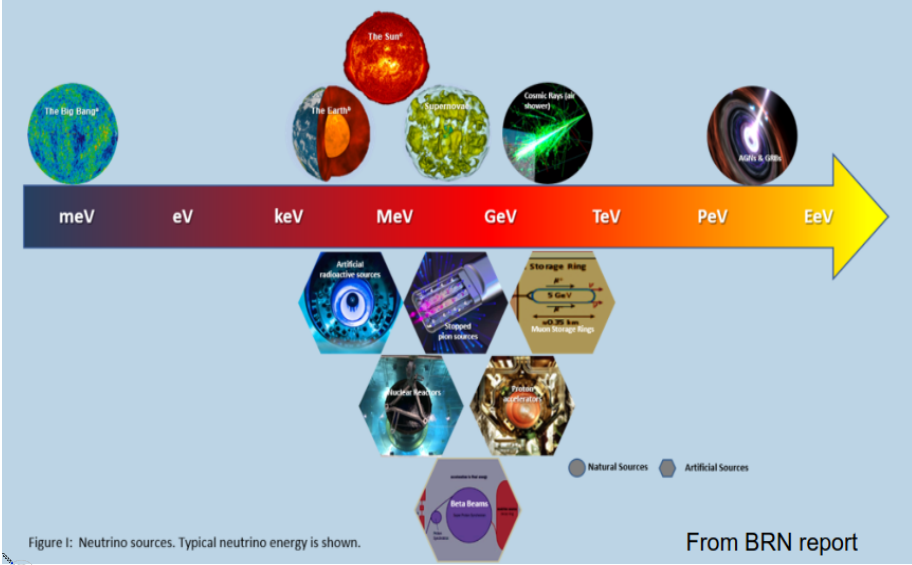
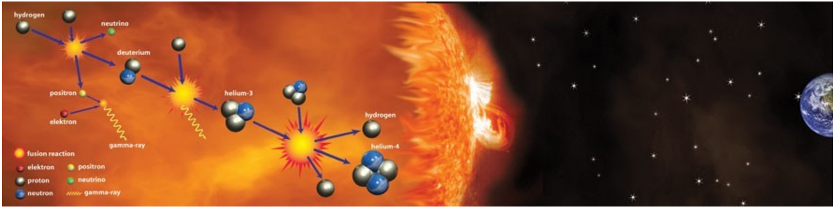


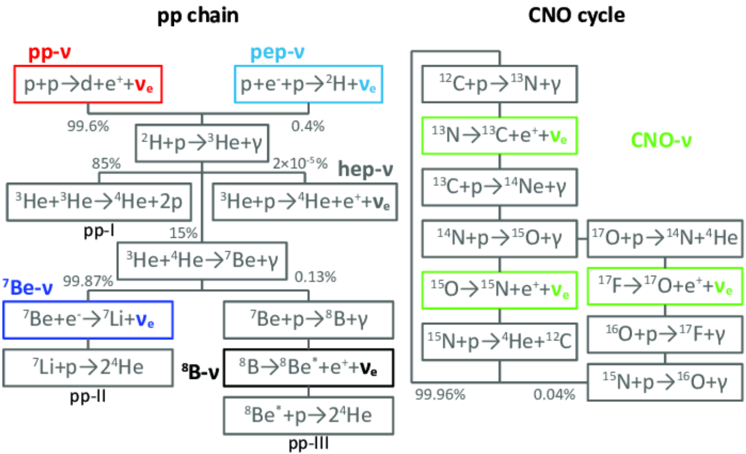
Figure I: Neutrino sources. Typical neutrino energy is shown.

Solar Neutrinos

Neutrinos from the Sun



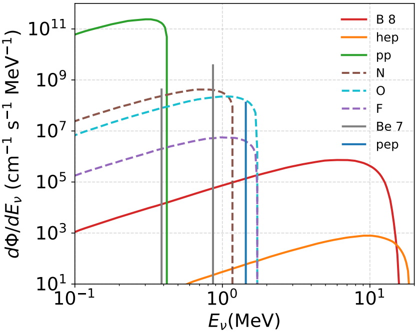
- It is one of the most intensive natural neutrino sources on the earth.
- Neutrinos are produced as electron neutrinos by the nuclear fusion inside the Sun.
- The general information of solar neutrino is part of the Standard Solar Model.
- Two main processes: pp chain and CNO cycle.



pp chain
CNO cycle
pp-ν
$p+p \rightarrow d+e^{+}+\nu_e$
pep-ν
$p+e^{-}+p \rightarrow {}^{2}H+\nu_e$
99.6%
0.4%
${}^{2}H+p \rightarrow {}^{3}He+\gamma$
85%
$2\times10^{-5}\%$
hep-ν
${}^{3}He+{}^{3}He \rightarrow {}^{4}He+2p$
${}^{3}He+p \rightarrow {}^{4}He+e^{+}+\nu_e$
pp-I
15%
${}^{3}He+{}^{4}He \rightarrow {}^{7}Be+\gamma$
^{7}Be-ν
99.87%
0.13%
${}^{7}Be+e^{-} \rightarrow {}^{7}Li+\nu_e$
${}^{7}Be+p \rightarrow {}^{8}B+\gamma$
${}^{7}Li+p \rightarrow 2\,{}^{4}He$
^{8}B-ν
${}^{8}B \rightarrow {}^{8}Be^{*}+e^{+}+\nu_e$
pp-II
${}^{8}Be^{*}+p \rightarrow 2\,{}^{4}He$
pp-III
${}^{12}C+p \rightarrow {}^{13}N+\gamma$
${}^{13}N \rightarrow {}^{13}C+e^{+}+\nu_e$
CNO-ν
${}^{13}C+p \rightarrow {}^{14}Ne+\gamma$
${}^{14}N+p \rightarrow {}^{15}O+\gamma$
${}^{17}O+p \rightarrow {}^{14}N+{}^{4}He$
${}^{15}O \rightarrow {}^{15}N+e^{+}+\nu_e$
${}^{17}F \rightarrow {}^{17}O+e^{+}+\nu_e$
${}^{15}N+p \rightarrow {}^{4}He+{}^{12}C$
${}^{16}O+p \rightarrow {}^{17}F+\gamma$
${}^{15}N+p \rightarrow {}^{16}O+\gamma$
99.96%
0.04%

- Solar neutrino fluxes with uncertainties from the high-metallicity solar neutrino model BS05(OP) (Bahcall & Serenelli, 2005).

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%



Vector Mediator from $U(1)'$ Symmetry

The U(1)' Symmetry

$$SU(2)_{\mathrm{L}} \otimes U(1)_{Y} \otimes SU(3)_{\mathrm{c}} \rightarrow SU(2)_{\mathrm{L}} \otimes U(1)_{Y} \otimes SU(3)_{\mathrm{c}} \otimes U(1)'$$

- We consider the SM extensions with the addition of a $U(1)'$ gauge group with an associated neutral gauge boson Z' (Mohapatra & Pati, 1975).
- The SM is expanded by adding three right-handed neutrinos so that the anomaly-free requirement is satisfied (Basso *et. al.*, 2009).
- This addition simultaneously explains the smallness of neutrino mass through the see-saw mechanism (Mohapatra & Senjanovic, 1980).
- Other unsolved puzzles in the SM that can be explained in such models: grand unified theory, nature of DM, leptogenesis, etc.

The Lagrangians

- For general Z' mediator, the interaction Lagrangian with SM particles is given by (Cerdeon *et. al.*, 2016):

$$\mathcal{L}_{Z'} = Z'_\mu \left[\sum_{q=u,d} Q'_q g^{q}_{Z'} \bar{q} \gamma^\mu q + Q'_\ell g^{\nu_\ell}_{Z'} \bar{\nu}_{\ell L} \gamma^\mu \nu_{\ell L} \right]. \tag{4}$$

- The differential cross-section is given by:

$$\left[\frac{d\sigma}{dT_{nr}} \right]_{\mathrm{SM}+Z'} = \left[1 + \frac{Q_{Z'}}{\sqrt{2} G_F Q_{\mathrm{SM}} (m^2_{Z'} + 2 m_N T_{nr})} \right]^2 \left[\frac{d\sigma}{dT_{nr}} \right]_{\mathrm{SM}}. \tag{5}$$

- The weak vector charge is

$$Q_{Z'} = \left[\mathcal{Z}(2Q'_u + Q'_d) + \mathcal{N}(Q'_u + 2Q'_d) \right] g^{q}_{Z'} g^{\nu_\ell}_{Z'} Q'_\ell. \tag{6}$$

The $B-L$ and $B-3L_{e,\mu,\tau}$ Models

- We consider vector Z' mediator with an associated $U(1)'$ gauge group for a variety of models including $U(1)_{B-L}$ (Mohapatra, 1975), $U(1)_{B-3L_e}$, $U(1)_{B-3L_\mu}$, and $U(1)_{B-3L_\tau}$ (Ma & Sarkar, 1998; Chang *et. al.*, 2001).
- These models differ in terms of the charges of the fermions with the associated gauge group.
- This difference determines the contributions of each model to CEνNS, mediated by the Z' vector boson.

Model	Q'_u	Q'_d	Q'_e	Q'_μ	Q'_τ
universal	1	1	1	1	1
$B-L$	1/3	1/3	−1	−1	−1
$B-3L_e$	1/3	1/3	−3	0	0
$B-3L_\mu$	1/3	1/3	0	−3	0
$B-3L_\tau$	1/3	1/3	0	0	−3

- Since the $U(1)_{B-3L_e}$, $U(1)_{B-3L_\mu}$, and $U(1)_{B-3L_\tau}$ models depend on different neutrino flavors, we consider the solar neutrino survival probabilities.
- These are:

$$P_{ee} = \cos^4\theta_{13} P_{eff} + \sin^4\theta_{13}, \tag{7}$$

$$P_{e\mu} = (1 - P_{ee})\cos^2\theta_{23}, \tag{8}$$

$$P_{e\tau} = (1 - P_{ee})\sin^2\theta_{23}, \tag{9}$$

- The factor P_{eff} is the matter effect that satisfies

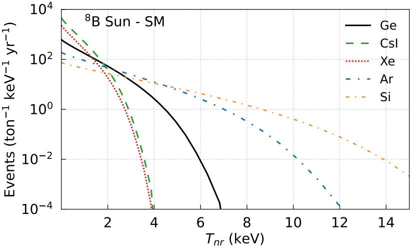
$$P_{eff} = \sin^2\theta_{12}, \tag{10}$$

for solar neutrino in a few MeV energy (PDG, 2022).

Event Rate

Event Rate

- The minimum neutrino energy satisfies $E_\nu^{min} = \frac{T_{nr}}{2}\left(1 + \sqrt{1 + \frac{2m_N}{T_{nr}}}\right)$.
- The maximum nuclear recoil energy obeys $T_{nr}^{max} = \frac{2E_\nu^2}{2E_\nu + m_N}$.
- The differential event rate of the CEνNS:



$$\frac{dR}{dT_{nr}} = N_T \int_{E_\nu^{min}}^{E_\nu^{max}} dE_\nu \frac{d\Phi(E_\nu)}{dE_\nu} \frac{d\sigma(E_\nu, T_{nr})}{dT_{nr}}. \quad (11)$$

Quenching Factor

- The observed physical quantity is electron-equivalent energy. To relate this with nuclear recoil energy, quenching factor $Y(T_{nr})$ is needed.
- For this purpose, we utilize the Lindhard quenching factor (Lindhard *et. al.*, 1963):

$$Y(T_{nr}) = \frac{kg(\epsilon)}{1 + kg(\epsilon)}, \tag{12}$$

with

$$\begin{aligned} g(\epsilon) &= 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon \\ \epsilon &= 11.5\mathcal{Z}^{-7/3} T_{nr}, \end{aligned} \tag{13}$$

where $k = 0.16$, closely matches the recent low-energy measurement (Bonhomme *et. al.*, 2022).

- The Linhard formula is acceptable for high recoil energy, namely 0.254 keV $< T_{nr} <$ 10 keV.
- Below this range, in the range of 0.04 keV $< T_{nr} <$ 0.254 keV, we consider for Ge target (Essig *et. al.*, 2018)

$$Y(T_{nr}) = 0.18\left[1 - \exp\left(\frac{15 - T_{nr}}{71.03}\right)\right] \tag{14}$$

- The T_{nr}(keV) can be converted into T_{ee}(keV) by

$$T_{ee} = Y(T_{nr})T_{nr}. \tag{15}$$

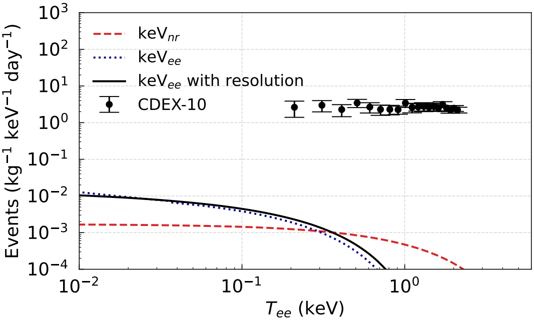
- Hence, the differential rate as the electron equivalency is given by

$$\frac{dR}{dT_{ee}} = \frac{dR}{dT_{nr}}\frac{1}{Y(T_{nr}) + T_{nr}\frac{dY(T_{nr})}{dT_{nr}}}. \tag{16}$$

Analysis and Results

χ^2-Analysis

- In this study, we are interested in the CEνNS with solar neutrinos from the recent CDEX-10 experiment (Geng *et. al.*, 2023).
- We use 20 data points, related to neutrino-nucleus scattering.
- The electron-equivalent recoil energy data are converted to nuclear recoil with the Linhard quenching factor.



- We adopt the pull approach of the χ^2 function (Fogli *et. al.*, 2002):

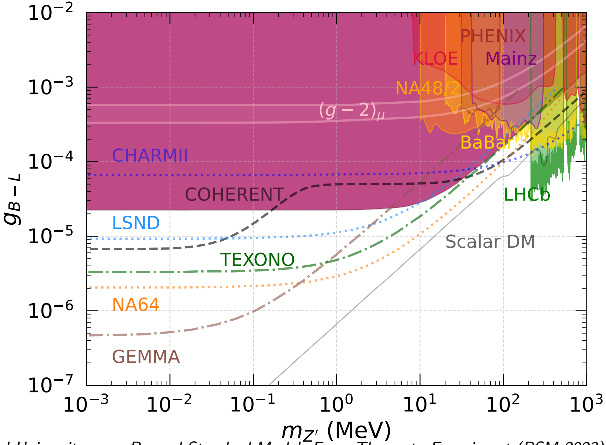
$$\chi^2 = \min_{(\xi_j)} \sum_{i=1}^{20} \left(\frac{R^i_{obs} - R^i_{exp} - B - \sum_j \xi_j c^i_j}{\Delta^i} \right)^2 + \sum_j \xi_j \qquad (17)$$

.

- R^i_{obs} and R^i_{exp} are the observed and expected event rates, respectively. in the i-th energy bin.
- Δ^i denotes the experimental uncertainty.
- The solar neutrino flux uncertainty is represented by c^i_j.

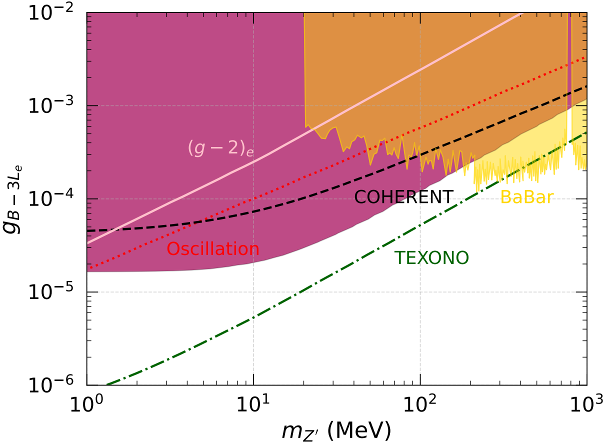
$B - L$

- It addresses an improvement to the considered existing limits.
- Improvement to COHERENT in the intermediate mass scale; outperformed in the low and high mass scales.
- Partially cover collider limits.



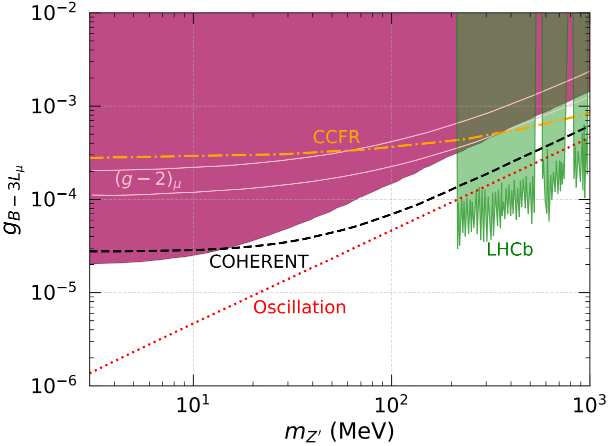
$B - 3L_e$

- It dominates oscillation, and COHERENT, while partially covering Babar and it is outperformed by TEXONO limits.



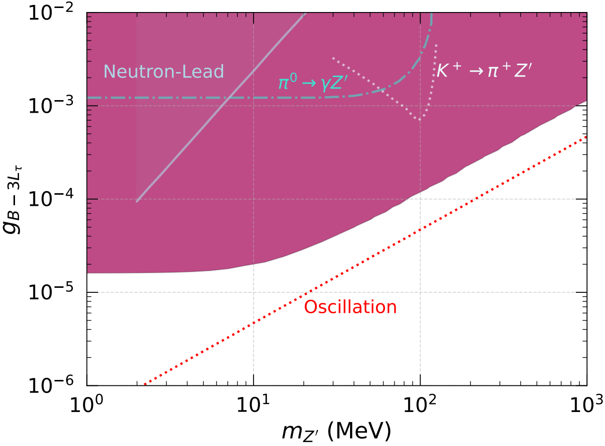
$B - 3L_\mu$

- It improves limits of CCFR, and COHERENT in the low mass region.
- Partially covers LHCb, yet to reach oscillation limit.



$B - 3L_\tau$

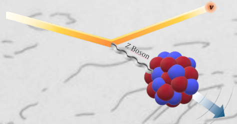
- It dominates neutron-lead, as well as the limits of pion and kaon decays.
- Still outperformed by oscillation limit.



Summary

Summary

- We have presented the constraints on light Z' mediator models from the analysis of the current CDEX-10 data.
- We made comparisons with non-CEνNS constraints and with $(g-2)_\mu$ allowed region.
- Our results indicate the CDEX-10 address improvements to the existing limits of the $B-L$, $B-3L_e$, $B-3L_\mu$, and $B-3L_\tau$ model.
- Such as the COHERENT limit, and more stringent bound are found except for the $B-3L_\tau$ model, while the oscillation limits are still yet to be all covered except for $B-3L_e$.
- Phenomenological analyses of the recent CDEX-10 data can uncover new insights into the beyond SM, placing complementary constraints on a small range of parameters.
- CEνNS is a powerful tool to explore new physics scenarios beyond SM.
- Another talk from our team will address the neutrino magnetic moment effect in CEνNS using solar neutrino flux.



Thank You for Your Attention

Acknowledgment: This work was supported by the Scientific and Technological Research Council of Turkey under Project 123F186.