First results of LZ and XENONnT: A comparative study of neutrino properties and light mediators

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Next generation direct dark matter detection experiments are favorable facilities to probe neutrino properties and light mediators beyond the Standard Model. We explore the implications of the recent data reported by LUX-ZEPLIN (LZ) and XENONnT collaborations on electromagnetic neutrino interactions and neutrino generalized interactions (NGIs). We show that LZ places the most stringent upper limits on the neutrino magnetic moment (of the order of few \(\times10^{-12}\) \(\mu_B\)) as well as stringent constraints to neutrino millicharge (of the order of \(\sim10^{-13}\) e)–competitive to XENONnT–and improved by about one order of magnitude in comparison to existing constraints coming from Borexino and TEXONO. We furthermore explore the LZ and XENONnT sensitivities to simplified models with light NGIs and find improved constraints in comparison to those extracted from Borexino-Phase II data.

Introduction.— The LUX-ZEPLIN (LZ) collaboration has recently reported its first results on the search for Weakly Interacting Massive Particles (WIMPs), with a data accumulation corresponding to an exposure of 5.5 ton for 60 live days (from 23 Dec 2021 to 11 May 2022) [1]. At the same time, the XENONnT experiment [2] also reported its blind science results, collected with a total exposure of 1.16 ton \(\cdot\) yr. Interestingly, the upgraded experiment has managed to rule out the so-called XENON1T excess [3] by using a new larger liquid xenon (LXe) detector with a fiducial mass of 5.9 ton and an achieved background reduction of about 50% with respect to its predecessor.

Both experiments are based on a dual-phase LXe cylindrical time projection chamber (TPC) and have reached a very low electron recoil (ER) energy threshold of \(\sim 1\ \text{keV}_{ee}\). This makes them ideal facilities for probing new physics phenomena involving spectral distortions at low energies. The two observables in the TPC LXe detector are the so called S1 and S2 signals, triggered by scintillation photons and subsequent ionization electrons respectively, in the aftermath of a WIMP-nucleus or background event. The first WIMP searches of LZ and XENONnT are consistent with the null hypothesis (background-only). The main background sources in their reconstructed ER region of interest (ROI) arise from \(\beta\)-decay events and elastic neutrino-electron scattering (E\(\nu\)ES) due to the pp and \(^{7}\text{Be}_{0.861}\) components of the solar neutrino spectrum. Another important background source may potentially come due to \(^{37}\text{Ar}\) events originating from xenon exposure to cosmic rays before filling up the TPC detector and getting transferred underground. However, for the case of XENONnT this component has a negligible contribution to the background model.

Apart from being state-of-the-art direct dark matter detection experiments by analyzing the first LZ and XENONnT data–we show that they have also reached a better sensitivity on low-energy neutrino physics, surpassing dedicated neutrino experiments by up to an order of magnitude. Prompted by the lack of WIMP-induced events in the ROI, in this work we are motivated to explore potential deviations from the Standard Model (SM) E\(\nu\)ES cross section with the new data available. Indeed, as recently pointed out in Ref. [4] the new LZ data can be used to set the most stringent limits on effective neutrino magnetic moments, further constraining previous limits [5] from the analysis of Borexino Phase-II data [6] by about a factor 5. These results are competitive, though slightly more stringent,
to those obtained in Ref. [7] using the recent XENONnT data. In addition to the latter works, here we also provide the corresponding constraints on the fundamental transition magnetic moments (TMMs) [8], improving previous constraints obtained from laboratory based experiments reported in Ref. [9]. We furthermore note that TMMs are more interesting since they have the advantage of being directly comparable with existing constraints from different laboratory experiments [10] and astrophysics [11]. We then demonstrate that the LZ data can be exploited to probe additional electromagnetic (EM) neutrino properties such as the neutrino millicharge and charge radius [12].

For the first time we show that they can be used for obtaining the most severe upper limits on neutrino millicharges, which we found to be of the order of $10^{-13} \, e$. On the other hand, we stress that LZ and XENONnT are placing weak sensitivities on the neutrino charge radii. We finally point out that the new data can be used to probe neutrino generalized interactions (NGIs) due to light mediators, improving previous constraints set by Borexino.

**Theory.**— Within the framework of the SM the tree-level differential $\text{EvES}$ cross section with respect to the electron recoil energy $E_{er}$, takes the form [13]

$$
\frac{d\sigma_{\nu_e}}{dE_{er}} = G_F^2 \frac{m_e}{2\pi} \left( (g_V \pm g_A) \right)^2 
+ (g_V \mp g_A) \left( 1 - \frac{E_{er}}{E_{\nu_e}} \right)^2 - \left( g_V^2 - g_A^2 \right) \frac{m_e E_{er}}{E_{\nu_e}^2},
$$

where $m_e$ is the electron mass, $E_{\nu_e}$ the incoming neutrino energy, $G_F$ the Fermi constant, while the $\pm$ sign accounts for neutrino (antineutrino) scattering. The vector and axial vector couplings are given by

$$
g_V = -\frac{1}{2} + 2\sin^2 \theta_W + \delta_{\alpha e}, \quad g_A = \frac{1}{2} + \delta_{\alpha e},
$$

with the Kronecker delta $\delta_{\alpha e}$ term accounting for the charged-current contributions to the cross section, present only for $\nu_e\rightarrow e^-$ and $\bar{\nu}_e\rightarrow e^-$ scattering.

The existence of nonzero neutrino mass, established by the observation of neutrino oscillations in propagation [14, 15] stands up as the best motivation for exploring nontrivial EM neutrino properties [16–19]. The most general EM neutrino vertex is expressed in terms of the EM neutrino form factors $F_\alpha(q)$, $F_\nu(q)$, $F_\rho(q)$ and $F_\pi(q)$ (for a detailed review see Ref. [12]). The observables at a low energy scattering experiment are the charge, magnetic moment, electric moment and anapole moment, respectively, which coincide with the aforementioned EM form factors evaluated at zero momentum transfer $q = 0$.

The helicity-flipping neutrino magnetic moment contribution to the $\text{EvES}$ cross section adds incoherently to the SM and reads [20]

$$
\frac{d\sigma_{\nu_e}}{dE_{er}} = \frac{\pi a_{\text{EM}}^2}{m_e^2} \left( \frac{1}{E_{\nu_e}} - \frac{1}{E_{er}} \right) \left( \frac{\mu_{\nu_e}^{\text{eff}}}{\mu_B} \right)^2,
$$

with $a_{\text{EM}}$ denoting the fine structure constant. Note that the so-called effective magnetic moment is expressed in terms of the fundamental neutrino magnetic ($g_j$) and electric ($e$) dipole moments, which for solar neutrinos takes the form

$$
\mu_{\nu_e}^{\text{eff}} = \sum_j | \sum_j U_{\nu_e}^j \lambda_{jk} |^2,
$$

where $\lambda_{jk} = [g_{jk} - ie_{jk}]$ represent the TMMs [8, 10]. On the other hand the helicity-preserving EM contributions for millicharge ($q_{\nu_e}$), anapole moment ($a_{\nu_e}$) and neutrino charge radius

$$
\langle r_{\nu_e}^2 \rangle \quad \text{are taken via the substitution [12]:}
$$

$$
\nu \rightarrow \nu + \frac{\sqrt{2} \pi a}{G_F} \left[ \frac{\langle r_{\nu_e}^2 \rangle}{3} - \frac{a_{\nu_e}}{18} - \frac{1}{m_e E_{er}} \left( \frac{q_{\nu_e}}{e} \right) \right],
$$

where $e$ is the electric charge of electron.

Sensitive experiments with extremely low-energy threshold capabilities such as LZ and XENONnT constitute excellent probes of new physics interactions that involve spectral features induced in the presence of novel mediators. Many such beyond the SM physics scenarios can be accommodated in the context of model independent NGIs. Let us note that in this framework all Lorentz invariant forms $X = \{ S, P, V, A, T \}$ employing Wilson coefficients of dimension-six effective operators can be incorporated [21]. Here, we consider the $\text{EvES}$ contributions of light scalar ($S$), pseudoscalar ($P$), vector ($V$), axial vector ($A$) and tensor ($T$) bosons with mass $m_X$ and coupling $g_X = \sqrt{g_{\nu X} g_{e X}}$, and explore how well they fit...
can be constrained in the light of the recent data. For $X = \{V, A\}$ interactions, the corresponding differential cross sections can be obtained from Eq.(1) and the replacements [22]

$$g'_{V/A} = g_{V/A} + \frac{g_{eV/A} \cdot g_{eV/A}}{4\sqrt{2G_F} (2m_eE_{er} + m_{V/A}^2)}.$$  

(5)

For the case of $X = \{S, P, T\}$ interaction there is no interference with the SM cross section and the relevant contributions read [23]

$$\frac{d\sigma_{\nu_e}}{dE_{er}}^\xi_S = \left[ \frac{g^2_{eS} \cdot g^2_S}{4\pi(2m_eE_{er} + m^2_S)} \right] \frac{m_e^2 E_{er}}{E^2_{er}},$$  

(6)

$$\frac{d\sigma_{\nu_e}}{dE_{er}}^\xi_P = \left[ \frac{g^2_{eP} \cdot g^2_P}{8\pi(2m_eE_{er} + m^2_P)} \right] \frac{m_e^2 E_{er}}{E^2_{er}},$$  

(7)

$$\frac{d\sigma_{\nu_e}}{dE_{er}}^\xi_T = \frac{m_e \cdot g^2_{eT} \cdot g^2_T}{\pi(2m_eE_{er} + m^2_T)} \cdot \left[ \frac{E^2_{er}}{E^2_{er}} \right] \left[ 1 + 2 \left( 1 - \frac{E_{er}}{E^2_{er}} \right) \right] + \left( 1 - \frac{E_{er}}{E^2_{er}} \right)^2 - \frac{m_e}{E^2_{er}}.$$  

(8)

Statistical analysis.— At LZ and XENONnT the differential event rate for the different interactions $\xi = \{\text{SM, EM, NGI}\}$ is calculated, as [24]

$$\frac{dR}{dE_{cr}}^\xi = \mathcal{E} N_T \sum_{i=\text{solar}} \int_{E^\text{min}_{\nu}}^{E^\text{max}_{\nu}} dE_{\nu} \frac{d\Phi_{\nu}^i(E_{\nu})}{dE_{\nu}} \left[ \frac{d\sigma}{dE_{er}} \right]^\nu \xi_{\nu_e}$$  

(9)

where $\mathcal{E}$ and $N_T$ are $Z_{\text{eff}} m_{\text{det}} N_A/m_{\text{Xe}}$ denote the exposure and number of electron targets respectively, with $m_{\text{det}}$ being the fiducial mass of the detector, $N_A$ the Avogadro number and $m_{\text{Xe}}$ the molar mass of $^{131}\text{Xe}$. Due to atomic binding, $Z_{\text{eff}}(E_{er})$ accounts for the number of electrons that can be ionized for an energy deposition $E_{er}$. The latter is approximated through a series of step functions that depend on the single particle binding energy of the $i$th electron, evaluated from Hartree-Fock calculations [25]. In the ROI of LZ and XENONnT experiments, $E_{er}$ES populations are mainly due to $pp$ neutrinos with a subdominant contribution coming from $^7\text{Be}_{0.861}$ neutrinos, while the rest fluxes of the solar neutrino spectrum [26], $(d\Phi_{\nu}/dE_{\nu})$, contribute negligibly. Since solar neutrinos undergo oscillations in propagation before reaching the Earth, the cross section in Eq.(9) is weighted with the relevant oscillation probability and reads

$$\left[ \frac{d\sigma}{dE_{er}} \right]_{\nu_e}^\nu_{\xi} = P_{ee} \left[ \frac{d\sigma_{\nu_e}}{dE_{er}} \right]_{\nu_e}^\nu_{\xi} + \sum_{j=\mu,\tau} P_{ej} \left[ \frac{d\sigma_{\nu_e}}{dE_{er}} \right]_{\nu_e}^\nu_{\xi},$$  

(10)

where $(P_{ee})$ is solar neutrino survival probability, while $P_{e\mu} = (1 - P_{ee}) \cos^2 \theta_{23}$ and $P_{e\tau} = (1 - P_{ee}) \sin^2 \theta_{23}$ are the corresponding transition probabilities with the atmospheric mixing angle $\theta_{23}$ taken from [27]. The minimum neutrino energy required to induce an electronic recoil $E_{er}$ is trivially obtained from the kinematics of the process, as $E^\text{min}_{er} = (E_{er} + \sqrt{E^2_{er} + 2m_eE_{er}})/2$.

In order to accurately simulate the LZ signal, the true differential event rate of Eq.(9) is then smeared with a normalized Gaussian resolution function with width $\sigma(E^\text{reco}_{cr}) = K/\sqrt{E^2_{cr}}$ [28] $(E^\text{reco}_{cr}$ is the reconstructed recoil energy and $K = 0.323 \pm 0.001$ (keV$_{ee}$)$^{3/2}$) and converted to a reconstructed spectrum. Finally, the reconstructed spectrum is weighted by the efficiency function, $A(E^\text{reco}_{cr})$ taken from the LZ data release [1]. Since the efficiency function provided in the data release is given in units of nuclear recoil energy, we convert it to ER units through the standard Lindhard quenching factor $(Q_{\nu})$ [29] as, $E_{er} = Q_{\nu}(E_{nr}) \cdot E_{nr}$. For the case of XENONnT, a similar procedure is followed, while the efficiency is taken from Ref. [2] and the resolution function from Ref. [3].

In order to explore the new physics parameter(s) of interest $S$ with the LZ data, our statistical analysis is based on the Poissonian $\chi^2$ function [38]

$$\chi^2(S) = 2 \sum_{i=1}^{51} \left[ R^i_{\text{pred}}(S) - R^i_{\text{exp}} + R^i_{\text{exp}} \ln \left( \frac{R^i_{\text{exp}}}{R^i_{\text{pred}}(S)} \right) \right] + \left( \frac{\alpha}{\sigma_\alpha} \right)^2 + \left( \frac{\beta}{\sigma_\beta} \right)^2 + \left( \frac{\delta}{\sigma_\delta} \right)^2,$$  

(11)

where $R^i_{\text{exp}}$ stands for the experimental differential events in ith bin reported in [1], while the predicted differential spectrum—which contains ErES and background components—is taken as $R^i_{\text{pred}}(S; \alpha, \beta, \delta) = (1 + \alpha)R^i_{\text{bgk}} + (1 + \beta)R^i_{\text{ErES}}(S) + (1 + \delta)R^i_{\text{37Ar}}$. Here, the nuisance parameters $\alpha$, $\beta$ and $\delta$ are introduced to incorporate the uncertainty on background, flux normalization and $^{37}\text{Ar}$ contributions with $\sigma_\alpha = 13\%$, $\sigma_\beta = 7\%$ and $\sigma_\delta = 100\%$ (see Refs. [1, 4]). Following Ref. [4], the $R^i_{\text{bgk}}$ spectrum is taken by subtracting the SM and $^{37}\text{Ar}$ contributions from
The total background reported in [1] by normalizing the integrated spectrum of $^{37}$Ar to its nominal value given by the LZ collaboration, i.e. 97 events. For the case of XENONnT we employ a Gaussian $\chi^2$ function

$$\chi^2 = \sum_i \left( \frac{R_{i,\text{pred}}(S, \beta) - R_{i,\text{exp}}}{\sigma_i} \right)^2 + \left( \frac{\beta}{\sigma_\beta} \right)^2, \quad (12)$$

where $R_{i,\text{pred}}(S, \beta) = (1 + \beta) R_{i,\text{ES}}(S) + B_0$. Here, $B_0$ represents the modeled background reported in [2] from which we have subtracted the SM $\nu e$ES contribution.

In the left panel of Fig. 1 we show the one-dimensional $\Delta \chi^2$ profiles corresponding to the effective neutrino magnetic moment, obtained from the analysis of LZ and XENONnT data. Differently from Ref. [4] where a universal effective neutrino magnetic moment has been consid-

| Flavor | $|\mu_e| \ 10^{-11} \mu_B$ | $q_{\nu} \ 10^{-12} e$ | $(r^2) \ 10^{-32} \text{cm}^2$ |
|--------|-----------------|----------------|------------------|
| $\nu_e$ | $\leq 0.69$ (LZ) | $[-0.08, 0.26]$ (LZ) | $[-92.7, 12.8]$ (LZ) |
|        | $\leq 0.9$ (XENONnT) | $[-0.13, 0.64]$ (XENONnT) | $[-96.1, 10.1]$ (XENONnT) |
|        | $\leq 3.7$ (Borexino) [5] | $\leq 1$ (Reactor) [30] | $[-4.2, 6.6]$ (TEXONO) [31] |
|        | $\leq 7.4$ (TEXONO) [32] | $[-9.3, 9.5]$ (Dresden-II) [33] | $[-5.9, 8.28]$ (LSND) [34] |
|        | $\leq 2.9$ (GEMMA) [35] | | $[-7.1, 5]$ (COHERENT + Dresden-II) [33] |
| $\nu_\mu$ | $\leq 1.13$ (LZ) | $[-0.28, 0.27]$ (LZ) | $[-48.3, 71.7]$ (LZ) |
|        | $\leq 1.47$ (XENONnT) | $[-0.62, 0.61]$ (XENONnT) | $[-48.7, 54.9]$ (XENONnT) |
|        | $\leq 5$ (Borexino) [5] | $\leq 11$ (XMASS-I) [36] | $[-1.2, 1.2]$ (CHARM-II) [37] |
|        | | | $[-5.9, 4.3]$ (COHERENT + Dresden-II) [33] |
| $\nu_\tau$ | $\leq 0.98$ (LZ) | $[-0.24, 0.23]$ (LZ) | $[-31, 61.9]$ (LZ) |
|        | $\leq 1.27$ (XENONnT) | $[-0.54, 0.52]$ (XENONnT) | $[-41.4, 47.7]$ (XENONnT) |
|        | $\leq 5.9$ (Borexino) [5] | $\leq 11$ (XMASS-I) [36] | |
|        | | | |

**TABLE I**: Summary of 90% C.L. limits on EM neutrino parameters neutrino magnetic moment (in units $10^{-11} \mu_B$), millicharge (in units $10^{-12} e$), charge radius (in units $10^{-32} \text{cm}^2$) extracted in the present analysis (bold font) using the LZ and XENONnT data. For comparison, also shown are the existing limits from other experiment.

**FIG. 1**: $\Delta \chi^2$ profiles of the flavor dependent neutrino magnetic moment (left) and millicharge (right) parameters from the analysis of LZ (solid lines) and XENONnT (dashed lines) data.
erred, here we present the individual limits on the flavored effective magnetic moments according to Eq. \((10)\). At 90% C.L. we find the upper limits \(\{\mu_{\nu_e}^{\text{eff}}, \mu_{\nu_\mu}^{\text{eff}}, \mu_{\nu_\tau}^{\text{eff}}\}\)=\(\{6.9 (9), 11.3 (14.7), 9.8 (12.7)\}\),\(10^{-12}\) for the case of LZ (XENONnT). The latter constitute the most severe limits extracted from laboratory-based experiments to date, surpassing existing limits from the analysis of Borexino Phase-II data \([6]\) carried out in Ref. \([5]\) for \(\mu_{\nu_e}^{\text{eff}}, \mu_{\nu_\mu}^{\text{eff}}\) and \(\mu_{\nu_\tau}^{\text{eff}}\) as well as the TEXONO \([32]\) and GEMMA \([39]\) limits on \(\mu_{\nu_e}^{\text{eff}}\). Going one step further, for the first time we derive the corresponding constraints on the fundamental magnetic moments \(\lambda_{ij}\) (see Supplemental material and Refs. \([10, 40]\) for details). Using the definition \(\Lambda_i = \varepsilon_{ijk}\lambda_{jk}\) we find the limits \(\{\Lambda_1, \Lambda_2, \Lambda_3\}\) to be \(\{8.6 (11.1), 6.2 (8), 5.2 (6.6)\}\) at 90% C.L. from the analysis of LZ (XENONnT) data. The latter limits are directly comparable and competitive with astrophysical limits derived from plasmon decay: \(\mu_{\nu_e}^{\text{eff}} = \sqrt{\sum_i |\Lambda_i|^2} = 4.5 \times 10^{-12}\) \(\mu_B\) (95% C.L.) \([11]\).

In the right panel of Fig. \(1\) we present the corresponding sensitivities on the neutrino millicharge. As for the case of the neutrino magnetic moment, the extracted constraints refer to the different flavors and indicate that the LZ data are very sensitive to this EM parameter. For each flavor we find the limits at 90% C.L. \(\{q_{\nu_e}, q_{\nu_\mu}, q_{\nu_\tau}\}\)=\(\{-0.8, 2.6\}, \{-2.8, 2.7\}, \{-2.4, 2.3\}\) \(\times 10^{-13}\), which are by one order of magnitude more severe than existing constraints in the literature i.e. from TEXONO \([30]\) as well as from those extracted in Ref. \([33]\) through a combined analysis of the recent coherent elastic neutrino-nucleus scattering (CEνNS) data by CHERENT \([41, 42]\) and Dresden-II \([43]\). Notice, that the LZ limits are by a factor 4 more stringent in comparison to the XENONnT limits which are found to be \(\{q_{\nu_e}, q_{\nu_\mu}, q_{\nu_\tau}\}\)=\(\{(-1.3, 6.4), (-6.2, 6.1), (-5.4, 5.2)\}\) \(\times 10^{-13}\) \(\text{e}\) at 90% C.L.

Table I summarizes the 90% C.L. limits on EM neutrino properties extracted in the present work from the analysis of the LZ and XENONnT data. Also listed are the corresponding limits on the neutrino charge radii, for which as expected the new data are not placing a competitive sensitivity. This is due to the absence of signal enhancement at low momentum transfer, unlike the case of neutrino magnetic moment and millicharge. For the sake of comparison, also shown in the Table are the most stringent existing limits placed from the different experimental data mentioned above.

We finally turn our attention on simplified NGIs with light \(X = \{S, P, V, A, T\}\) mediators. The corresponding allowed regions by the LZ and XENONnT data in the \((g_X, m_X)\) plane are illustrated at 90% C.L. in Fig. \(2\). We stress that NGI limits from the analysis of LZ data are presented for the first time in this work. As can be seen, for the case of tensor (pseudoscalar) interaction the most (least) stringent bounds are found, in agreement with the projected sensitivities explored in Ref. \([44]\). Compared to Borexino Phase-II limits extracted in Ref. \([5]\) the present analysis leads to improved sensitivities, with the LZ data being slightly more constraining compared to XENONnT.

Conclusions.— Motivated by the low energy ROI as well as the high energy resolution and well-understood background at LZ and XENONnT, we have concentrated on new physics interactions characterized by signal enhancements at low momentum transfer that may lead to sizable signal distortions. In particular, we have analyzed the recent data reported by the two collaborations focusing on potential EeES contributions in the presence of EM neutrino properties and light NGI mediators. We find that in all cases the LZ data are competitive with XENONnT, though yielding slightly improved constraints. Regarding the flavored effective neutrino magnetic moments as
well as the fundamental transition magnetic moments, we show that the LZ data release set the currently best upper limits in the literature \( (6.9, 11.3, 9.8) \times 10^{-12} \mu_B \), being slightly more severe than the corresponding ones set by XENONnT and improving existing upper limits from Borexino and TEXONO. With respect to the neutrino millicharge, the present analysis leads to limits as low as \( \{q_e, q_\mu, q_\tau\} = \{(-0.8, 2.6), (-2.8, 2.7), (-2.4, 2.3)\} \times 10^{-13} \) e, hence improving previous upper limits by \( \frac{1}{2} \times (6.9, 11.3, 9.8) \times 10^{-12} \mu_B \). On the contrary, in the case of simplified models accommodating in the framework of NGIs, the new data lead to improvements by about half an order of magnitude with respect to Borexino limits in the \((g_X, m_X)\) parameter space.

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Supplemental Material

In what follows, all the necessary details regarding our calculational procedure are provided along with further results and extended discussions accompanying the main part of the manuscript. First, in Fig. 3 we present a comparison of the experimental data with the expected signal at LZ (left panel) and XENONnT (right panel) for various new physics scenarios involving EM neutrino properties and NGIs. We have furthermore checked that our integrated SM EνES spectra in the ROI of LZ and XENONnT agree well with those reported by the two collaborations.

FIG. 3: Expected signal and comparison with the experimental data at LZ (left) and XENONnT (right). Various examples of possible new physics contributions to EνES are shown.

Appendix A: Effective and transition neutrino magnetic moments

The most general parametrization of an effective neutrino magnetic moment can be expressed in terms of the transition magnetic moment (TMM) matrix \( \lambda = \mu - i\epsilon \), where \( \mu \) and \( \epsilon \) is the magnetic and electric dipole moments. For Majorana neutrinos, the latter is an antisymmetric Majorana which in the mass basis takes the form \[40\]

\[
\lambda = \begin{pmatrix}
0 & \Lambda_3 & -\Lambda_2 \\
-\Lambda_3 & 0 & \Lambda_1 \\
\Lambda_2 & -\Lambda_1 & 0
\end{pmatrix},
\]
where for simplicity the definition $\Lambda_i = \epsilon_{ijk}\lambda_{jk}$ has been introduced. Then, the most general effective neutrino magnetic moment taking into account also the effect of neutrino oscillations in propagation reads \[45\]

$$
\mu^2_{\nu_{\mu},\nu_e}(L, E_\nu) = \sum_i U_{\alpha i}^* e^{-i \Delta m^2_{ij} L/2E_\nu} \lambda_{ij},
$$
(A2)

with $U_{\alpha i}$ being the entries of the lepton mixing matrix, $\Delta m^2_{ij}$ the neutrino mass splittings and $L$ the distance between the neutrino source and detection points. For the case of solar neutrinos we are interested in this work, the exponential in Eq.(A2) can be safely neglected and the effective neutrino magnetic moment takes the form \[46\]

$$
(\mu_{\nu_{\mu},\nu_e}^{\text{eff}})^2 = |\Lambda|^2 - c_{13}^2 |\Lambda_2|^2 + (c_{13}^2 - 1)|\Lambda_3|^2 + c_{13}^2 P_{e\mu}^2 \left( |\Lambda_2|^2 - |\Lambda_1|^2 \right),
$$
(A3)

with $c_{13} = \cos \theta_{13}$ and $P_{e\mu}^2 = 0.667 \pm 0.017$ which corresponds to the average probability value for pp neutrinos \[27\].

The latter expression is used to map between the effective neutrino magnetic moments and the fundamental TMMs. In the upper panel of Fig. 4 we show the 90% C.L. allowed regions in the ($\mu_{\nu_{\mu}},\mu_{\nu_e}$) plain assuming the third effective magnetic moment to be vanishing, while in the lower panel we demonstrate the corresponding 90% C.L. limits in the TMM parameter space ($\Lambda_i, \Lambda_j$) by marginalizing over $\Lambda_k$.

**Appendix B: Neutrino millicharges, charge radii and anapole moments**

Here we present the allowed regions by the new LZ and XENONnT data in the parameter space of neutrino millicharges ($q_{\nu_{\mu}}, q_{\nu_e}$). A combined analysis allowing two nonzero neutrino millicharges to vary at a time has been performed, assuming vanishing contribution from the third. The allowed regions at 90% C.L. are illustrated in Fig. 5.
FIG. 5: Allowed regions in the $(q_{\nu_\alpha}, q_{\nu_\beta})$ plane at 90% C.L. from the analysis of LZ (blue) and XENONnT (red) data. Two nonvanishing neutrino millicharges are allowed to vary at a time, while the third is set to zero.

FIG. 6: $\Delta \chi^2$ profiles of neutrino charge radii (left) and anapole moments (right) obtained from the analysis of LZ (solid lines) and XENONnT (dashed lines) data.

Figure 6 illustrates the sensitivity reach to neutrino charge radius and anapole moments in the left and right panel, respectively. As mentioned in the main text, LZ and XENONnT data can place only weak limits on the neutrino charge radii. Assuming two nonzero charge radii at a time, the 90% C.L. allowed regions in the parameter space of $(\langle r_{\nu_\alpha}^2 \rangle, \langle r_{\nu_\beta}^2 \rangle)$ are depicted in Fig. 7. Let us finally note that the corresponding limits on the anapole moments can be immediately obtained using the relation $\alpha_{\nu_\alpha} = -\langle r_{\nu_\alpha}^2 \rangle/6$. 
FIG. 7: Same as in Fig. 5 but for the case neutrino charge radii.

Appendix C: Comparison of LZ and XENONnT limits with other experiments

Here, our aim is to provide a better comparison between the NGI limits extracted in the present work from the analysis of LZ and XENONnT data with existing limits in the literature. To this purpose and for the sake of clarity in Fig. 8, we reproduce the limits from Fig. 2 for vector (left panel) and scalar (right panel) NGIs and we superimpose limits coming from other laboratory experiments using CEνNS data from: COHERENT [47], CONNIE [48] and CONUS [49], and through the EνES channel at Borexino [5].

FIG. 8: Sensitivity at 90% C.L. for the the vector mediator model in $(m_V, g_V)$ (left) and scalar mediator model in $(m_S, g_S)$ (right). Existing constraints from other related studies are superimposed for comparison (see the text).