New constraint on neutrino magnetic moment from LZ dark matter search results

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Elastic neutrino-electron scattering represents a powerful tool to investigate key neutrino properties. In view of the recent results released by the LUX-ZEPLIN Collaboration, we provide a first determination of the limits achievable on the neutrino magnetic moment, whose effect becomes non-negligible in some beyond the Standard Model theories. Interestingly, we are able to show that the new LUX-ZEPLIN data allows us to set the most stringent limit on the neutrino magnetic moment when compared to the other laboratory bounds, namely $\mu_\nu < 6.2 \times 10^{-12} \mu_B$ at 90% C.L.. This limit supersedes the previous best one set by the Borexino Collaboration by almost a factor of 5 and it rejects by more than $5\sigma$ the hint of a possible neutrino magnetic moment found by the XENON1T Collaboration.

Introduction.— Recently, the LUX-ZEPLIN (LZ) Collaboration released the results [1] of the first search for so-called Weakly Interacting Massive Particles (WIMPs) [2], one of the most searched candidates to explain dark matter, which is predicted by a large number of theories beyond the Standard Model (SM) [3–5]. The LZ experiment is located at the Sanford Underground Research Facility (SURF) in Lead, South Dakota. Its core is a dual-phase time projection chamber (TPC) filled with about 10 t of liquid xenon (LXe), of which 7 (5.5) t of the active (fiducial) region. The possible interaction of a WIMP inside the detector produces two detectable signals if the nuclear recoil (NR) is above the ~1 keV$_{nr}$ threshold, namely scintillation photons (S1) in the detector bulk and a secondary scintillation signal (S2) produced by the ionized electrons that drift thanks to an electric field to the gas pocket on top of the detector. Both signals are captured by 494 photomultiplier tubes located at the top and the bottom of the TPC. The results reported correspond to 60.3 live days and given that the data are consistent with a background-only hypothesis, permit setting the most stringent limits on the spin-dependent WIMP-nucleon scattering cross-section for masses greater than 9 GeV/$c^2$ [1].

Among the different background components that are kept into account in the data analysis, there is one due to elastic solar neutrino-electron scattering ($\nu$ES) inside the TPC. This component represents about 10% of the total background and it is theoretically well predicted. The total number of such electron recoils (ER) that is found after the combined fit of the background model plus a 30 GeV/$c^2$ WIMP signal is $27.3 \pm 1.6$ [1]. Such a process is extremely sensitive to some neutrino electromagnetic properties beyond the SM (BSM), as the neutrino magnetic moments (MM), which can significantly enhance the $\nu$ES contribution at low recoil energies [6–11]. Thus, in this work, we revisit the fit to the LZ data allowing for a neutrino MM to set competitive limits on this quantity.

Theoretical framework.— Neutrino-electron elastic scattering is a source of background for direct searches of WIMPs. This background is in principle reducible, but in practice hard to remove completely in experiments that use xenon due to the limited discrimination available between NIs and ERs. Luckily, in the SM its contribution to the total event rate at low recoil energies is rather precisely known and flat with respect to the recoil energy and thus it is usually subtracted in standard dark-matter analyses. However, in certain BSM scenarios, the $\nu$ES contribution could increase significantly, making it important to investigate this opportunity. Indeed, stronger constraints can be obtained on many neutrino electromagnetic properties [6–10].

The SM $\nu$ES cross section per xenon atom is obtained multiplying the $\nu$ES cross section per electron with the effective electron charge of the target atom $Z_{\text{eff}}^\nu(T_e)$ [6, 12, 13], and for each neutrino flavour $\nu_\ell$
\( \ell = e, \mu, \tau \) is given by

\[
\frac{d\sigma^{\nu\ell}}{dT_e}(E, T_e) = Z_{\text{eff}}(T_e) \frac{G_F^2 m_e}{2\pi} \left( (g_V^{\nu\ell} + g_A^{\nu\ell})^2 + (g_V^{\nu\ell} - g_A^{\nu\ell})^2 \right) \frac{m_e T_e}{E^2},
\]

where \( G_F \) is the Fermi constant, \( E \) is the neutrino energy, \( m_e \) is the electron mass, \( T_e \) is the electron recoil energy, and the neutrino-flavour dependent electron couplings at tree level are

\[
g_V^{\nu\ell} = 2 \sin^2 \theta_W + 1/2, \quad g_A^{\nu\ell} = 1/2, \quad g_V^{\nu\ell} = 2 \sin^2 \theta_W - 1/2,
\]

They correspond to \( g_V^e = 0.9521, g_A^e = 0.4938, g_V^\mu = -0.0397, g_A^\mu = -0.5062, \) and \( g_V^\tau = -0.0353 \) when taking into account radiative corrections (see Ref. [14] for further information). Here, \( \theta_W \) is the weak mixing angle, also known as the Weinberg angle, whose value at zero momentum transfer is \( \sin^2 \theta_W = 0.23857 \) [15] in the MSS scheme. The \( Z_{\text{eff}}(T_e) \) term [16, 17] quantifies the number of electrons that can be ionized by a certain energy deposit \( T_e \) and is needed to correct the cross section derived under the Free Electron Approximation (FEA) hypothesis. This is especially important for Xe, where one expects a rather big effect from atomic binding [12]. It has been obtained by using the edge energies extracted from photoabsorption data [12, 18] (see Ref. [14] for further information). An alternative method implies the usage of the so-called Relativistic Random-Phase Approximation (RRPA) theory [12, 19–21]. With respect to the FEA corrected with the stepping function \( Z_{\text{eff}}(T_e) \) as used in this work, RRPA provides an ab-initio approach able to give an improved description of the atomic many-body effects. This alternative approach reduces further the \( \nu \)ES number of events by an almost constant value as a function of the recoil energy.

The total SM differential cross section includes the contribution from all neutrino flavours keeping into account the oscillation probability and it is

\[
\frac{d\sigma^{\nu\ell}}{dT_e}(E, T_e) \simeq \frac{d\sigma^{\nu\ell}}{dT_e} P_{ee}(E) + \frac{d\sigma^{\nu\ell}}{dT_e} \left[ 1 - P_{ee}(E) \right],
\]

where \( P_{ee}(E) \simeq 0.55 \) [12, 15] is the average survival probability for solar neutrinos reaching the detector when considering the dominant \( pp \) and \(^7\)Be fluxes.

**Neutrino magnetic moment.**— In the SM, neutrinos are considered massless, and therefore neutrino MMs are vanishing. Nevertheless, from the fact that neutrino oscillates, we know that the SM must be extended to give masses to the neutrinos. In the minimal extension of the SM in which neutrinos acquire Dirac masses through the introduction of right-handed neutrinos, the neutrino MM is given by [22–29]

\[
\mu_\nu = \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \simeq 3.2 \times 10^{-19} \left( \frac{m_\nu}{eV} \right) \mu_B,
\]

where \( \mu_B \) is the Bohr magneton, \( m_\nu \) is the neutrino mass and \( e \) is the electric charge. Taking into account the current upper limit on the neutrino mass [15], this value is less than \( \mu_\nu \sim 10^{-18} \mu_B \), which is too small to be observed experimentally. Nevertheless, given that in some BSM scenarios the neutrino MM is predicted to be larger [23], a positive observation would represent a clear signal of physics beyond the minimally extended SM. For this reason, neutrino MM is the most investigated neutrino electromagnetic property, both theoretically and experimentally.

An enhanced MM would increase the neutrino scattering cross-sections at low energies on both electrons and nuclei, and thus could be observable by low-threshold detectors, such as the liquid xenon dark matter detectors, as discussed in Refs. [30–33]. By considering the enhancement due to \( \nu \)ES, the differential \( \nu \)ES cross section that takes into account the contribution of the neutrino MM is given by adding to the SM cross section in Eq. (1) the MM contribution, namely

\[
\frac{d\sigma^{\nu\ell}}{dT_e}(E, T_e) = Z_{\text{eff}}(T_e) \frac{\pi e^2}{m_e^2} \left( \frac{1}{T_e} - \frac{1}{E} \right) \left| \frac{\mu_{\nu\ell}}{\mu_B} \right|^2,
\]

where \( \mu_{\nu\ell} \) is the effective MM of the flavour neutrino \( \nu_\ell \) in elastic scattering (see Ref. [22]).

**Data analysis strategy.**— For the analysis of the LZ data set, we obtained information on all the quantities used from Ref. [1] and the accompanying

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\(^1\) We note that Eq. (4) is not exact since \( \sigma_{\nu\mu} \neq \sigma_{\nu\nu} \) due to small radiative corrections (see Ref. [14]) and \( P_{\nu\mu} \neq P_{\nu\nu} \), the latter being the \( \nu_e \to \nu_\mu \) and \( \nu_\mu \to \nu_\tau \) oscillation probability, respectively [8]. Nevertheless, the usage of the approximated formula has a negligible impact on the analysis.
The total differential neutrino flux, \( dN_{\nu,j}/dE \), is given by the sum of all the different solar neutrino components \( j \) as from Refs. [15, 34], of which the most relevant for the sensitivity range of LZ are the continuous \( pp \) flux and the monochromatic \( ^{7}\text{Be} \) 861 keV line, even though there are many additional contributions from other mechanisms that are included in the analysis.

In each ER energy-bin \( i \), the theoretical \( \nu\text{ES} \) event number \( N_{\nu}\text{ES}^{i} \) is given by

\[
N_{\nu}\text{ES}^{i} = N(\text{Xe}) \int_{E_{\text{min}}(T_{\nu})}^{E_{\text{max}}(T_{\nu})} dE \sum_{j} dN_{\nu,j}(E) \frac{d\sigma_{\nu}}{dT_{\nu}}(E, T_{\nu}),
\]

where \( N(\text{Xe}) \) is the number of xenon targets contained in the detector, \( T_{\nu} \) is the ER kinetic energy, \( A(T_{\nu}) \) is the energy-dependent detector efficiency, \( E_{\text{min}}(T_{\nu}) = (T_{\nu} + \sqrt{T_{\nu}^{2} + 2m_{e}T_{\nu}})/2 \), and \( E_{\text{max}} \sim 2 \) MeV. The number of target xenon atoms in the detector is given by \( N(\text{Xe}) = N_{A} M_{\text{det}}/M_{\text{Xe}} \), where \( N_{A} \) is the Avogadro number, \( M_{\text{det}} = 5.5 t \) is the detector fiducial mass and \( M_{\text{Xe}} \) is the average xenon molar mass.

The energy observed in the detector is the ER energy \( T_{\nu} \). However, the LZ Collaboration provides the detector acceptance as a function of the NR energy \( T_{\text{nr}} \). Thus, the acceptance as a function of the ER energy is obtained by inverting the relation

\[
T_{\nu} = f_{Q}(T_{\text{nr}}) T_{\text{nr}},
\]

where \( f_{Q} \) is the xenon quenching factor. For the latter, we consider a standard Lindhard model with \( k = 0.166 \) [35]. A possible systematic contribution from the quenching factor is considered in the results section by doubling the uncertainty on the neutrino flux and is seen to have a negligible impact.

Besides the solar \( \nu\text{ES} \), the background components that survive the selection in the region of interest come from different sources, the dominant one being the ERs from radioactive decay of impurities dispersed in the xenon, commonly referred to as \( \beta \) background. Together with a small (< 1%) fraction due to ER from \( \gamma \)-rays originating in the detector components and cavern walls, this background represents about 79% of the total one. Other background sources include the naturally occurring isotopes of xenon, which also contribute to ER events, as well as isotopes that are activated cosmogenically, such as \( ^{127}\text{Xe} \) and \( ^{37}\text{Ar} \). Moreover, the NR background has contributions from radiogenic neutrons and coherent elastic neutrino-nucleus scattering (CE\( \nu \)NS) from \( ^{8}\text{B} \) solar neutrinos. Finally, there is a small component of accidental backgrounds that is also kept into account. Overall, the LZ Collaboration reports a background of 333 ± 17 events, of which 27.3±1.6 are due to solar \( \nu\text{ES} \), see Tab. 1 in Ref. [1].

We performed the analysis of the LZ data using a Poissonian least-squares function [15, 36], given that in some energy bins the number of events is small, namely

\[
\chi^{2} = 2 \sum_{i=1}^{51} [(1 + \alpha)N_{i}^{\text{bkgs}} + (1 + \beta)N_{i}\text{ES}^{i} - N_{i}^{\exp}] + N_{i}^{\exp} \ln \left[ \frac{N_{i}^{\exp}}{(1 + \alpha)N_{i}^{\text{bkgs}} + (1 + \beta)N_{i}\text{ES}^{i}} \right] + \frac{\alpha}{\sigma_{\alpha}}^{2} + \frac{\beta}{\sigma_{\beta}}^{2},
\]

where \( N_{i}^{\text{bkgs}} \) is the number of residual background events found in the \( i \)-th bin fit by the LZ Collaboration minus that due to solar \( \nu\text{ES} \) (both extracted from Fig. 6 of Ref. [1]), \( N_{i}\text{ES}^{i} \) is the prediction in the \( i \)-th bin for the \( \nu\text{ES} \) signal, and \( N_{i}^{\exp} \) is the experimental number of events in the \( i \)-th bin, also extracted from Fig. 6 of Ref. [1]. The nuisance parameter \( \alpha \) takes into account the uncertainty on the neutrino background (with \( \sigma_{\alpha} = 5.1\% \))\(^2\), while \( \beta \) keeps into account the uncertainty on the neutrino flux (with \( \sigma_{\beta} = 7\% \))\(^3\). By using this procedure we ignore that a possible non-zero neutrino MM should also increase the CE\( \nu \)NS contribution from \( ^{8}\text{B} \) solar neutrinos. However, given that the latter contribution is only 0.15 ± 0.01, we verified that we can safely neglect it. For the future, we note that a lower experimental energy threshold would increase the CE\( \nu \)NS contribution, thus contributing

\[^{2}\text{We note that this procedure ignores the fact that the different background contributions have a different relative uncertainty. However, given that the total background is dominated by the \( \beta \) decays this approximation is valid.}\]

\[^{3}\text{The flux uncertainty is about 7\% for \( ^{7}\text{Be} \) and 0.6\% for \( pp \) [37], we conservatively use the first one for both fluxes.}\]
to further strengthening the MM limits.

We highlight that, differently from all the other background sources, the number of $^{37}$Ar events is not well constrained theoretically. It is estimated by calculating the exposure of Xe to cosmic rays before it was brought underground, then correcting for the decay time before the search [38]. A flat constraint of 0 to three times (i.e. 291) the estimate of 97 events is imposed because of large uncertainties in the prediction. The fit to the data using this prior finds $52.1^{+8.9}_{-8.6}$ events. In order to keep into account this large uncertainty, we perform a second analysis in which we separate the $^{37}$Ar contribution from the total background such that the least-squares function becomes

$$
\chi^2_{^{37}\text{Ar}} = 2 \sum_{i=1}^{51} \left[ \alpha_i N_i^{\text{bkg}} + \beta_i N_i^{\text{ES}} + \delta_i N_i^{^{37}\text{Ar}} - N_i^{\text{exp}} \right]^2
$$

$$
+ N_i^{\text{exp}} \ln \left( \frac{N_i^{\text{exp}}}{\alpha_i N_i^{\text{bkg}} + \beta_i N_i^{\text{ES}} + \delta_i N_i^{^{37}\text{Ar}}} \right)
$$

$$
+ \left( \frac{\alpha - 1}{\sigma_\alpha} \right)^2 + \left( \frac{\beta - 1}{\sigma_\beta} \right)^2 + \left( \frac{\delta - 1}{\sigma_\delta} \right)^2,
$$

where $N_i^{\text{bkg}}$ is the number of residual background events minus those due to $\nu$ES and $^{37}$Ar as found in the $i$-th electron recoil energy bin fit by the LZ Collaboration, and $N_i^{^{37}\text{Ar}}$ is the number of $^{37}$Ar background events found in the $i$-th bin fit by the LZ Collaboration, scaled such that the integral is equal to 97 events, as estimated in Ref. [1]. We leave the latter free to vary in the fit with a Gaussian constraint given by the nuisance parameter $\delta$, which takes into account the uncertainty on the $^{37}$Ar background, with $\sigma_\delta = 100\%$. In this case, we set $\sigma_\alpha = 13\%$, which is the uncertainty on the expected number of background events provided in Ref. [1] when non considering the $^{37}$Ar contribution.

In Fig. 1 we show the $\nu$ES predictions for the LZ spectrum compared with the data, under different hypotheses and with the inclusion of the other sources of background. In this way, one can compare the SM $\nu$ES prediction with that obtained in presence of a possible neutrino MM, considering e.g. $\mu_\nu = 2.15 \times 10^{-11} \mu_B$, that is the favoured value of neutrino MM found by the XENON1T Collaboration when interpreting an excess detected in their data at low recoil energies [11].

Results.— Since neutrinos are a mixture of mass eigenstates due to the phenomenon of oscillations, the MM measured for solar $\nu$ES is an effective value given by

$$
\mu_{\nu}^{\text{eff}} = \sum_j \sum_k |A_k(E_\nu, L)|^2,
$$

where $\mu_{jk}$ is an element of the neutrino electromagnetic moments matrix and $A_k(E_\nu, L)$ is the amplitude of the $k$-mass state at the point of scattering [8]. For the Majorana neutrino, only the transition moments are non-zero, while the diagonal elements of the matrix are equal to zero due to CPT-conservation. For the Dirac neutrino, all matrix elements may have non-zero values [39].

The results of our analysis using the $\chi^2$ in Eq. (9) for the neutrino MM are shown in Fig. 2, where we show the marginal $\Delta \chi^2$’s at different confidence levels (C.L.). At 90% C.L., the bound on the neutrino MM obtained in this work is

$$
\mu_{\nu}^{\text{eff}} < 6.2 \times 10^{-12} \mu_B,
$$

with $\chi^2_{\text{min}} = 106.2$, which corresponds to an integrated number of $\sim 40$ $\nu$ES events. This limit can be compared with the bounds obtained by other experiments. The Super-Kamiokande Collaboration achieved a limit of $3.6 \times 10^{-10} \mu_B$ (90% C.L.) by fitting day/night solar neutrino spectra above...
5 MeV. With additional information from other solar neutrino and KamLAND experiments a limit of $1.1 \times 10^{-10} \mu_B$ (90% C.L.) was obtained [40]. The Borexino Collaboration reported the best current limit on the effective MM by laboratory experiments of $2.8 \times 10^{-11} \mu_B$ (90% C.L.) using the ER spectrum from solar neutrinos [8]. The best MM limit from reactor antineutrinos is $2.9 \times 10^{-11} \mu_B$ (90% C.L.) [41]. The analysis of the CEνNS data from Dresden-II and COHERENT Collaborations permits to set limits on $|\mu_{\nu_e}| < 2.13 \times 10^{-10} \mu_B$ and $|\mu_{\nu_x}| < 18 \times 10^{-10} \mu_B$ [6], also exploiting νES. When considering non-laboratory experiments, the most stringent limits on the neutrino MM of up to $\sim 10^{-12} \mu_B$ come from astrophysical observations [42–44], which however are rather indirect. A complete historical record of limits on the neutrino MM can be found in Ref. [15] and it is summarised in Fig. 3. It is possible to see that by our analysis of the LZ data we can set the most stringent limit on the effective neutrino MM compared to the other laboratory bounds. Moreover, this limit excludes by more than 5σ the hint of a possible neutrino MM found by the XENON1T Collaboration [11]. Indeed, at 90% C.L. they find $14 < \mu_{\nu_e}^{\text{eff}}[10^{-12} \mu_B] < 29$, so intriguingly we are able to reject this explanation.

We also analysed the impact of increased systematic uncertainties, by setting $\sigma_\alpha = 20\%$ and $\sigma_\beta = 15\%$. Despite the large values chosen, as it is shown in Fig. 2, the limit obtained is practically the same with $\chi^2_{\text{min}} = 106.1$. Moreover, we checked the impact of introducing the detector energy resolution in Eq. (7), which is measured to be very precise by the LZ Collaboration but is not provided in the current data release. For this check, the theoretical spectra were smeared using a Gaussian distribution with an energy-dependent width, which has been determined using an empirical fit of monoenergetic peaks [45]. In particular, for the latter we employed the value reported in Ref. [46], namely $\sigma(T_e) = K/\sqrt{T_e}$, with $K = 0.323 \pm 0.001$. Thanks to the excellent energy resolution achieved by LZ, we verified that its inclusion does not significantly modify the limit obtained. Finally, we investigated the possibility of leaving the $^{37}$Ar component free to vary in the fit using a prior similar to that implemented by the LZ Collaboration, as defined in Eq. (10). Interestingly, the fit retrieves a number of $^{37}$Ar events similar to that found by LZ, namely 48.4 with $\chi^2_{\text{min}} = 106$. Thus, also in this case, the limits do not significantly change.

**Conclusions.**— In this paper, we describe the search for a possible neutrino MM by exploiting elastic solar neutrino-electron scattering data provided by the LUX-ZEPLIN Collaboration. By using 331.65 t days of data we searched for effects of the neutrino magnetic moment by looking for distortions in the shape and normalization of
the electron recoil spectrum. At 90% C.L. we obtain the new best upper laboratory limit on the effective neutrino magnetic moment, namely $\mu_{\text{eff}} < 6.2 \times 10^{-12} \mu_B$, including background and fluxes uncertainties. It supersedes the previous best limit set by the Borexino Collaboration by almost a factor of 5, and it rejects by more than 5$\sigma$ the hint of a possible neutrino MM found by the XENON1T Collaboration when interpreting their excess at low recoil energies. The limit is stable against significant variations in the background and flux uncertainties as well as when leaving the $^{37}$Ar background component free to vary in the fit.

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Supplemental Material

In the following appendices we provide additional details. In Appendix A we show the values of the term which quantifies the number of electrons that can be ionized by a certain energy deposit; in Appendix B we describe the calculation of the neutrino-electron couplings, taking into account the radiative corrections.

Appendix A: The \( Z_{\text{eff}}^A(T_e) \) term

The \( Z_{\text{eff}}^A(T_e) \) term \cite{1, 2}, which quantifies the number of electrons that can be ionized by a certain energy deposit \( T_e \), is given for xenon in Tab. I. It has been obtained by using the edge energies extracted from photoabsorption data \cite{3, 4}.

| \( T_e > \text{keV} \) |
|---|
| 54 | 34.561 |
| 52 | 34.561 ≥ 4.528 |
| 50 | 4.528 ≥ 5.1037 |
| 48 | 5.1037 ≥ 4.7822 |
| 44 | 4.7822 ≥ 1.1478 |
| 42 | 1.1478 ≥ 1.0021 |
| 40 | 1.0021 ≥ 0.9406 |
| 36 | 0.9406 ≥ 0.6764 |
| 26 | 0.6764 ≥ 0.2132 |
| 24 | 0.2132 ≥ 0.1467 |
| 22 | 0.1467 ≥ 0.1455 |
| 18 | 0.1455 ≥ 0.0695 |
| 14 | 0.0695 ≥ 0.0675 |
| 10 | 0.0675 ≥ 0.0233 |
| 4  | 0.0233 ≥ 0.0134 |
| 2  | 0.0134 ≥ 0.0121 |
| 0  | \( T_e ≤ 0.0121 \) |

TABLE I. The effective electron charge of the target atom, \( Z_{\text{eff}}^A(T_e) \).

Appendix B: Neutrino-electron coupling determination

In order to study the neutrino-electron scattering process, it is necessary to study in detail the calculation of the couplings, taking into account the radiative corrections. The latter are implemented following the formalism given in Ref. \cite{5}. In particular, the \( \ell \) flavour neutrino right and left couplings to fermions, with \( f = e \), are given by

\[
g^{\nu_f}_{LL} = \rho \left( -\frac{1}{2} - Q_f s_0^2 + \Xi_{ZZ}^f \right) - Q_f \varphi_{\nu_f W} + \Box wW
\]

(B1)

\[
g^{\nu_f}_{LR} = -\rho \left( Q_f s_0^2 + \Xi_{ZZ}^R \right) - Q_f \varphi_{\nu_f W}
\]

(B2)

In these relations, \( \rho = 1.00063 \) represents a low-energy correction for neutral-current processes and \( Q_f \) is the fermion charge. Here \( s_0^2 = \sin^2 \theta_{\text{SM}} \), which keeps the same value for \( \mu < \mathcal{O}(0.1 \text{ GeV}) \). The other corrections inserted come from different contributions, such as the charge radii (\( \varphi_{\nu_f W} \)), and EW box diagrams (\( \Xi_{ZZ}^f \)). They can be expressed as

\[
\varphi_{\nu_f W} = -\frac{\alpha}{6\pi} \left( \ln \frac{M_W^2}{m_f^2} + \frac{3}{2} \right),
\]

(B3)

\[
\Box wW = \frac{\alpha}{2\pi s_Z^2} \left[ 1 - \frac{\alpha_s(M_W)}{2\pi} \right],
\]

(B4)

\[
\Xi_{ZZ}^f = \frac{3\alpha}{8\pi s_Z^2} \left( g^{\nu_f}_{LL} \right)^2 \left[ 1 - \frac{\alpha_s(M_Z)}{\pi} \right],
\]

(B5)

where \( X \in \{ L, R \} \), and \( \alpha_s \equiv \alpha(M_Z) \). Note that in Eq. (B5) all the \( (g^{LL}_X)^{\nu_f} \) are evaluated at lowest order but replacing \( s_0^2 \) by \( s_Z^2 \) and are given by \( g^{LL}_L = -\frac{1}{2} + \frac{1}{2} \) and \( g^{LL}_R = s_Z^2 \). For neutrino-electron scattering the couplings are given by

\[
g^{\nu e}_{LL} = \rho \left( -\frac{1}{2} + 2s_0^2 \right) + \Box wW + 2\varphi_{\nu e W}
\]

+B6

\[
g^{\nu e}_{LR} = \rho (\Xi_{ZZ}^L - \Xi_{ZZ}^R),
\]

(B6)

\[
g^{\nu e}_{AA} = \rho \left( -\frac{1}{2} + \Xi_{ZZ}^L + \Xi_{ZZ}^R \right) + \Box wW,
\]

(B7)

where \( g^{\nu e}_{AA} = g^{LL}_{LL} - g^{RR}_{LR} \).

For the numerical SM evaluation we assume the values from Refs. \cite{6, 7}, namely \( s_0^2 = 0.23857 \), \( s_Z^2 = 0.23121 \), \( \alpha_s(M_W) = 0.123 \), \( \alpha_s(M_Z) = 0.1185 \), and \( \alpha_s^{-1} = 127.952 \). We thus obtain the couplings \( g^{\nu e}_{AA} = 0.9521 \), \( g^{\nu e}_{LL} = 0.4398 \), \( g^{\nu e}_{LR} = -0.0397 \), \( g^{\nu e}_{AA} = -0.5062 \), and \( g^{\nu e}_{AA} = -0.0353 \) that take into account all radiative corrections. We note that, for the \( \nu_e \) coupling, an unity factor has been added to the result in order to take into account the charge current contribution.
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