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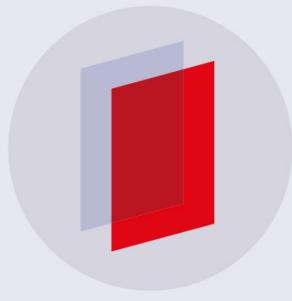
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New scalar contributions to the weak dipole moments of charged leptons

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Abstract. We calculate the contributions of new scalar particles to the weak anomalous dipoles moments in alternative electroweak gauge theories.

1. Introduction

It is well known that the study of the static electromagnetic properties of fermions provides a unique opportunity to look for new physics effects. The theoretical study of both the magnetic dipole moment (MDM) and the electric dipole moment (EDM) of fermions has long received considerable attention, which has been boosted in recent years due to the significant progress in the experimental area. Along with the interest in the study of the electromagnetic properties of a fermion, there has also been interest in the static weak properties, which are associated with its interaction with the Z gauge boson. The analogues of the MDM and the EDM are the weak magnetic dipole moment (WMDM) a_f^W and the weak electric dipole moment (WEDM) d_f^W, respectively, which are defined at the Z-pole via the dipole terms of the $Z\bar{f}f$ vertex function $ie\bar{u}(p)\Gamma_{Z\bar{f}f}^\mu u(p')$

$$\Gamma_{Z\bar{f}f}^\mu\left(q^2\right) = F_2\left(q^2\right)i\sigma^{\mu\nu}q_\nu + F_3\left(q^2\right)\sigma^{\mu\nu}\gamma_5 q_\nu, \tag{1}$$

with $q = p - p'$ the Z transfer momentum. The WMDM is defined as $a_f^W = -2m_f F_2\left(m_Z^2\right)$ and the WEDM is given by $d_f^W = -eF_3\left(m_Z^2\right)$. Only the weak dipole moments (WDMs) of heavy fermions are worth studying as those of lighter fermions would be beyond the reach of experimental detection. In the SM, $a_\tau^W = -(2.10 + 0.61i) \times 10^{-6}$ arises at the one-loop level [3], and $d_\tau^W < 8 \times 10^{-34}$ is induced up to the three-loop level [4]. Although the sensitivity reached at the LEP was beyond such precision level, potentially large contributions from SM extensions can be at the reach of future experiments. In this work we are interested in analyzing new potential contributions arising from models with an extended scalar sector. We will thus calculate the one-loop contributions to the WDMs induced by neutral, singly and doubly charged scalar bosons, which can arise in several models with extended scalar sectors. Our calculation will thus be somewhat general: instead of working out the WDMs within a specific model, we will consider the scenario of a theory with various nondegenerate neutral, singly and doubly charged scalar bosons with the most general renormalizable couplings to leptons and the Z gauge boson that can induce the WDMs at the one-loop level. Because of space limitations, in this report we

only show the contributions to the WMDM, as for the contributions to the WEDM they can be found in [1].

2. New scalar contributions to the WMDM of charged leptons

We first consider lepton number conserving (LNC) interactions mediated by scalar bosons (lepton number violating interactions (LNV) can be induced by the doubly charged scalar bosons). For the couplings of a lepton-antilepton pair with a neutral or singly charged scalar particle (denoted ϕ_i or ϕ_j from now on) we will consider the following renormalizable interaction

$$\mathcal{L} = g\,\bar{\ell}_l \left(S_{ilm} + P_{ilm}\gamma_5\right)\ell_m\phi_i + \text{H.c.}, \tag{2}$$

and a similar expression for any other scalar boson. Here ℓ_l is a charged lepton and ℓ_m is a lepton whose charge depends on that of the scalar boson: if ϕ_i is a neutral (charged) scalar boson, ℓ_m is a charged (neutral) lepton. Note that we are considering the most general case where the neutral scalar bosons are a mixture of CP-even and CP-odd states, which can arise for instance in general THDM with CP violation.

As for the interactions of Z gauge boson with two nondegenerate neutral or charged scalar bosons ϕ_i and ϕ_j, it will be written as follows

$$\mathcal{L} = ig\,g_{Z\phi_i\phi_j}Z^\mu\phi_i^\dagger\overleftrightarrow{\partial_\mu}\phi_j + \text{H.c}, \tag{3}$$

whereas the couplings of the type $ZV\phi_i$, with V a neutral (charged) gauge boson and ϕ_i a neutral (charged) scalar boson, are given by

$$\mathcal{L} = g\,g_{\phi_i VZ}m_Z Z^\mu V_\mu\phi_i + \text{H.c.}, \tag{4}$$

where V stands for a SM gauge boson or another one predicted by a SM extension. Such coupling can be for instance the $\phi_i ZZ$ and the $\phi^\pm ZW^\mp$ ones. The latter can arise at the tree-level in Higgs triplet models. We also need the interaction between a lepton-antilepton pair with a neutral or charged gauge boson V, which we write as

$$\mathcal{L} = g\,\bar{\ell}_l\gamma_\mu\left(g_V^{Vlm} - g_A^{Vlm}\gamma_5\right)V^\mu\ell_m + \text{H.c.} \tag{5}$$

Once a specific model is considered, the couplings S_{ilm}, P_{ilm}, $g_{Z\phi_i\phi_i}$, etc. will acquire a particular form, which will depend on the parameters of such model. Since we are primarily interested on any contributions arising from new hypothetical scalar bosons, we will not consider those contributions that have already been discussed in the context of the SM . At the one-loop level these couplings lead to contributions to the WDMs of a charged lepton via the Feynman diagrams depicted in Fig. 1. We denote the external charged lepton by ℓ_l and the internal lepton (neutral or charged) by ℓ_m, whereas ϕ_i and ϕ_j represent scalar bosons, and V is a gauge boson. Evidently once the electric charge of the scalar bosons are fixed, the charges of the internal lepton ℓ_m and the gauge boson V will also become fixed by charge conservation in each vertex. For instance, if ϕ_i and ϕ_j are neutral scalar bosons, ℓ_m is a charged lepton e, μ, τ. Thus, the contributions of new neutral scalar bosons require the vertices $\phi_i\ell_m\ell_l$, $\phi_i ZZ$, $Z\phi_i\phi_j$ and $Z\bar{\ell}_m\ell_m$. On the other hand, when ϕ_i and ϕ_j are charged scalar bosons, the internal lepton is a neutrino $\ell_m = \nu_m$. This class of contributions requires the vertices $\phi_i^+\bar{\nu}_m\ell_l$, $\phi_i^- W^+ Z$, $Z\phi_i^-\phi_j^-$ and $Z\bar{\nu}_m\nu_m$.

We have obtained the following expressions for the contributions of each type of Feynman diagram to the WMDM of a charged lepton via the Feynman parameter technique.

The contributions to the WMDM can be written as follows

$$a_l^{W-I} = \frac{\alpha\sqrt{x_l}}{4\pi s_W^3}\sum_{i,j,m} 16\left(1 - \delta_{ij}\right)\text{Re}\left[S_{ilm}S_{jlm}^* g_{Z\phi_i\phi_j}^*\right]A_I^{m\phi_i\phi_j} + \begin{pmatrix} \sqrt{x_m} \to -\sqrt{x_m} \\ S_{ilm} \to P_{ilm} \\ S_{jlm} \to P_{jlm} \end{pmatrix}, \tag{6}$$
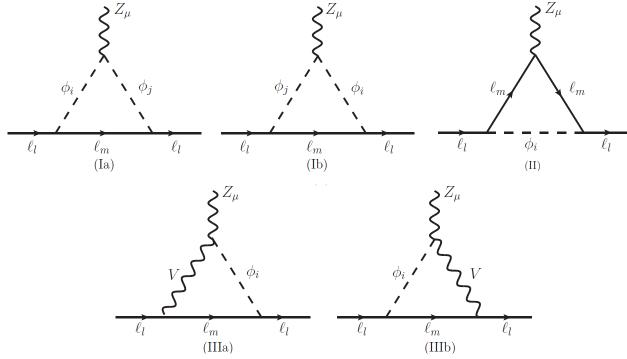
Figure 1. Generic Feynman diagrams for the new scalar contributions to the WDMs of a charged lepton. Here ℓ_l stands for a charged lepton, whereas ℓ_m is a lepton whose charge depends on that of the ϕ_i and ϕ_j scalar bosons (diagrams I and II) and that of the V gauge boson and the ϕ_i scalar boson (diagrams III).

$$
\begin{aligned}
a_l^{W-II} &= \frac{\alpha\sqrt{x_l}}{4\pi s_W^3}\sum_{i,m} 16\left(g_V^{Zmm}\|S_{imm}\|^2 A_{II_1}^{\phi_i mm} + g_A^{Zmm}\sqrt{x_l}\,\mathrm{Re}\left[S_{imm}P_{imm}^*\right]A_{II_2}^{\phi_i mm}\right) \\
&+ \left(\begin{array}{c} \sqrt{x_m}\to-\sqrt{x_m} \\ S_{imm}\leftrightarrow P_{imm}\end{array}\right),
\end{aligned}
\tag{7}
$$

and

$$
a_l^{W-III} = \frac{\alpha\sqrt{x_l}}{4\pi s_W^3}\sum_{i,m,V}\frac{2g_{\phi_i VZ}}{x_V}\mathrm{Re}\left[S_{ilm}\,g_V^{Vlm*}\right]A_{III}^{m\phi_i V} - \left(\begin{array}{c}\sqrt{x_m}\to-\sqrt{x_m} \\ S_{ilm}\to P_{ilm} \\ g_V^{Vlm}\to g_A^{Vlm}\end{array}\right),
\tag{8}
$$

where $x_a = m_a^2/m_Z^2$ and δ_{ij} is the Kronecker delta. It is understood that these sums run over all the possible combinations of internal particles predicted by a particular theory. Furthermore, the term between parenthesis means that the previous term but with the respective substitutions is to be added. As far as the A_i^{ABC} functions are concerned, they depend on the masses of the particles circulating into each triangular loop and that of the external lepton (the superscript letters stand for the distinct particles in the loop), which can be found in [1]. It is also important to mention that our expressions are complementary to those reported in Ref. [2], where the WMDM of a fermion was obtained using the Feynman-'t Hooft gauge along with the Passarino-Veltman reduction scheme.

In addition to the above results, we also need to consider the $\Delta L = 2$ LNV contributions, which can be mediated by a doubly charged scalar boson. This class of interactions can be written as

$$
\mathcal{L}^{\Delta L=2} = g\,\ell_l^T C\left(S_{ilm}' + P_{ilm}'\gamma^5\right)\ell_m\phi^i + \mathrm{H.c}
\tag{9}
$$

where C is the charge conjugation matrix. Doubly charged scalar bosons contribute to the WDMs of charged leptons via the Feynman diagrams shown in Fig. 2, where the fermion-flow arrows either clash or emerge from LNV vertices as opposed to LNC vertices where the fermion flow follows the same direction. Note that we have considered type-III$'$ Feynman diagrams, where Y stands for a doubly charged gauge boson. Some models with Higgs triplets, for instance 331

models, predict such particles. We will consider the following interaction of a doubly charged gauge boson with charged leptons

$$\mathcal{L}_Y^{\Delta L=2} = g\, \ell_l^T C \left(g_V^{Ylm} - g_A^{Ylm}\gamma^5 \right) \gamma^\mu \ell_m Y_\mu^{++} + \text{H.c..} \tag{10}$$
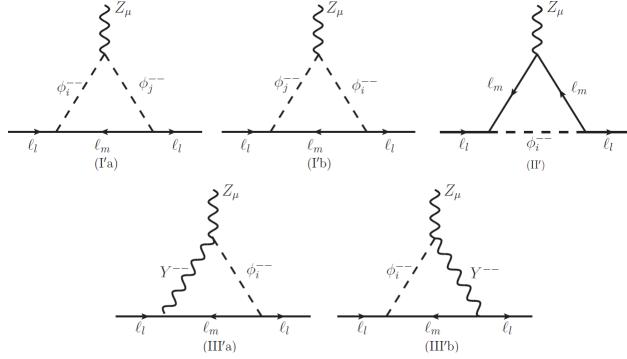

Figure 2. Contributions to the WDMs of charged leptons mediated by doubly charged scalar bosons. Here ℓ_l and ℓ_m are both charged leptons. For completeness we also include the contributions from a doubly charged gauge bosons Y.

Due to the presence of the charge conjugation matrix and the transposed spinors, the application of the Feynman rules to obtain the amplitudes of these Feynman diagrams must be done carefully. We have followed the approach presented in Ref. [5, 6] for calculating amplitudes with fermion number violating vertices. After some algebra we have found that the results arising from the Feynman diagrams of Fig. 1 [i.e. (6)- (8)] hold true for the contributions of a doubly charged scalar bosons except that a multiplicative factor of two for each LNV vertex must be inserted when the leptons are identical ($l = m$):

$$a_l^{W-I'} \;\to\; (1+\delta_{lm})^2 a_l^{W-I} \tag{11}$$

$$a_l^{W-II'} \;\to\; (1+\delta_{lm})^2 a_l^{W-II} \tag{12}$$

$$a_l^{W-III'} \;\to\; (1+\delta_{lm})^2 a_l^{W-III} \tag{13}$$

where it is understood that one must replace the appropriate couplings and masses involved in each contribution. This situation was also noted in the calculation of the anomalous magnetic moment of a lepton [5].

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