Constraints on Four Fermion Contact Interactions from Precise Electroweak Measurements

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Abstract

We establish constraints on a general four–fermion contact interaction from precise measurements of electroweak parameters. We compute the one–loop contribution for the leptonic $Z$ width, anomalous magnetic, weak–magnetic, electric and weak dipole moments of leptons in order to extract bounds on the energy scale of these effective interactions.

12.60.Rc, 12.15.Lk, 12.60.-i
I. INTRODUCTION

Four–fermion contact interactions are able to describe the dominant effect at low energies, arising from the existence of quark and lepton substructure [1]. Such interactions can be generated by the exchange of some common constituents between the fermion currents or by the binding force that keeps the constituents together.

Recently, the phenomenology associated to these four–Fermi contact interactions has become the subject of intense study as they have been proposed as a possible explanation [2,3] to the high–$Q^2$ anomaly in the HERA [4] data. Both H1 and ZEUS experiments at HERA have reported the observation of an excess of events, compared with the Standard Model prediction, in the reaction $e^+p \to e^+ + X$ at very high–$Q^2$. The H1 Collaboration observed events seem to be concentrated at an invariant mass of $\sim 200$ GeV, what could suggest the presence of a s–channel resonant state. The ZEUS Collaboration data, however, are more spread in invariant mass. The probability of a statistical fluctuation seems to be quite small (less than $6 \times 10^{-3}$, for the H1 data). Nevertheless, up to this moment, it is not possible to establish the resonant or continuum aspect of the events although the continuum aspect seems to be slightly favoured by the most recent data [3]. Moreover, the existence of quark substructure could also manifest as the enhancement of the inclusive jet differential cross section at high $E_T$ [1].

In this paper, we study the constraints on general four–fermion contact interactions arising from the precise measurements of the electroweak parameters. We evaluate the one–loop contribution of the four–Fermi Lagrangian to the leptonic $Z$ width, anomalous magnetic, weak–magnetic, electric and weak dipole moments of leptons. The comparison with recent experimental data for these parameters allow to extract bounds on the energy scale of these effective interactions.
II. ONE–LOOP CONTRIBUTION OF THE FOUR–FERMION INTERACTION

We analyse the one–loop contribution of all possible four–fermion contact interactions, \( i.e. \) represented by scalar, vector and tensorial currents,

\[
L_{\text{scalar}} = \eta g^2 \Lambda^2 \left[ \bar{\psi}_m (V^m_S - i A^m_S \gamma_5) \psi_m \right] \left[ \bar{\psi}_n (V^n_S - i A^n_S \gamma_5) \psi_n \right]
\]

\[ (1a) \]

\[
L_{\text{vector}} = \eta g^2 \Lambda^2 \left[ \bar{\psi}_m \gamma^{\mu} (V^m_V - A^m_V \gamma_5) \psi_m \right] \left[ \bar{\psi}_n \gamma^\mu (V^n_V - A^n_V \gamma_5) \psi_n \right]
\]

\[ (1b) \]

\[
L_{\text{tensor}} = \eta g^2 \Lambda^2 \left[ \bar{\psi}_m \sigma^{\mu\nu} (V^m_T - i A^m_T \gamma_5) \psi_m \right] \left[ \bar{\psi}_n \sigma_{\mu\nu} (V^n_T - i A^n_T \gamma_5) \psi_n \right]
\]

\[ (1c) \]

where \( \Lambda \) is the energy scale of the effective interaction, \( m \) and \( n \) are lepton and quark flavors, and \( \eta = \pm 1 \). In general, these Lagrangians do not respect the \( SU(3) \otimes SU(2) \otimes U(1) \) of the Standard Model but solely respect the \( U(1) \) symmetry. In what follows we have assumed that the fermionic currents do not mix flavors, unlike in the case of effective operators that are generated at low energy by the exchange of heavy leptoquarks.

We write the matrix element of a neutral vector boson \((V = \gamma, Z)\) current in the general form:

\[
J^{\mu} = e \bar{u}_f (p_1) \left( F_v \gamma^\mu + F_a \gamma^\mu \gamma_5 + F_m \frac{i}{2m_f} \sigma^{\mu\nu} q_\nu + F_d \frac{1}{2m_f} \sigma^{\mu\nu} \gamma_5 q_\nu \right) v_f (p_2),
\]

\[ (2) \]

where the form factors \( F_i, i = v, a, m, d, \) are functions of \( Q^2 \), with \( Q = p_1 + p_2 \). The form factors \( F_v \) and \( F_a \) are present at tree level in the Standard Model, \( e.g. \) for the photon,

\[
F_v^{\text{tree}} \equiv G_V = Q_f, \quad F_a^{\text{tree}} \equiv G_A = 0
\]

\[ (3) \]

where \( Q_f \) is electric charge of the fermion in unities of the proton charge, while for the \( Z \) boson,

\[
F_v^{\text{tree}} \equiv G_V = \frac{1}{2s_W c_W} (T^f_3 - 2Q_f s_W^2), \quad F_a^{\text{tree}} \equiv G_A = \frac{1}{2s_W c_W} T^f_3
\]

\[ (4) \]

where \( s_W (c_W) = \sin (\cos) \theta_W, \) and \( T^f_3 \) and is the third component of the weak isospin of the fermion.
The four–fermion interaction contribution to the form factors $F_v$ and $F_a$ at one–loop level can alter the $Z$ boson width to fermions. The form factor $F_m$ is responsible for an additional contribution to the anomalous magnetic and weak–magnetic moments of the fermion which are denoted by $a_\gamma^f$ and $a_Z^f$, respectively,

$$F_m(Q^2 = 0) = a_\gamma^f \equiv \frac{(g_f - 2)}{2},$$

$$F_m(Q^2 = M_Z^2) = a_Z^f. \quad (5)$$

The form factor $F_d$ is related to electric ($d_e^f$) and weak dipole moments ($d_w^f$) by,

$$\frac{e}{2m_f} F_d(Q^2 = 0) = d_e^f,$$

$$\frac{e}{2m_f} F_d(Q^2 = M_Z^2) = d_w^f. \quad (6)$$

The contact interactions in Eq. (1) modify these form factors at one-loop through the diagrams presented in Figs. (1) and (2). We obtain for the nonzero one–loop contributions of the scalar Lagrangian (1a) to the $s$–channel diagrams,

$$F_v^S(s) = \eta \frac{g^2}{48\pi^2\Lambda^2} G_V(V_u^u V_l^l + A_u^u A_l^l)Q^2 \log \left( \frac{\Lambda^2}{\mu^2} \right),$$

$$F_a^S(s) = -\eta \frac{g^2}{48\pi^2\Lambda^2} G_A(V_u^u V_l^l + A_u^u A_l^l) \left( 6M^2 - Q^2 \right) \log \left( \frac{\Lambda^2}{\mu^2} \right),$$

$$F_m^S(s) = \eta \frac{g^2}{8\pi^2\Lambda^2} G_V(V_u^u V_l^l - A_u^u A_l^l) M^2 \log \left( \frac{\Lambda^2}{\mu^2} \right),$$

$$F_d^S(s) = \eta \frac{g^2}{4\pi^2\Lambda^2} G_V(V_l^u A_u^l + V_u^l A_l^u) M^2 \log \left( \frac{\Lambda^2}{\mu^2} \right), \quad (7)$$

where $M$ is the internal and external fermion mass, $G_{V,A}$ is the vector (axial) coupling of the gauge boson, c.f. Eq. (3) and (4) and the indexes $u$ ($l$) denote the constants associated to the upper (lower) vertices of Fig. (1). The scalar Lagrangian does not contribute to the $t$–channel.

The contribution of interaction (III) to the $s$–channel is,

$$F_v^V(s) = \eta \frac{g^2}{48\pi^2\Lambda^2} \left\{ \left[ 6G_A M^2 - (G_V + G_A) Q^2 \right] (V_V^l + A_V^l) (V_V^u + A_V^u) \right. \right.$$ 

$$\left. - \left[ 6G_A M^2 + (G_V - G_A) Q^2 \right] (V_V^l - A_V^l) (V_V^u - A_V^u) \right\} \log \left( \frac{\Lambda^2}{\mu^2} \right),$$

4
\[ F_a^V(s) = -\eta \frac{g^2}{48\pi^2\Lambda^2} \left\{ [6G_A M^2 - (G_V + G_A)Q^2] (V_V^l + A_V^l)(V_V^u + A_V^u) \\
+ [6G_A M^2 + (G_V - G_A)Q^2] (V_V^l - A_V^l)(V_V^u - A_V^u) \right\} \log \left( \frac{\Lambda^2}{\mu^2} \right) . \tag{8} \]

and to the t–channel,

\[ F_v^V(t) = \eta \frac{g^2}{12\pi^2\Lambda^2} V_v^c \left[ 6G_A A^c_i A^c_i M_i^2 - (G^c_i A^c_i + G^c_i V^c_i)Q^2 \right] \log \left( \frac{\Lambda^2}{\mu^2} \right) ; \]

\[ F_a^V(t) = -\eta \frac{g^2}{12\pi^2\Lambda^2} A_V^c \left[ 6G_A A^c_i A^c_i M_i^2 - (G^c_i A^c_i + G^c_i V^c_i)Q^2 \right] \log \left( \frac{\Lambda^2}{\mu^2} \right) . \tag{9} \]

where the index \( i \) refers to the mass and coupling constants of the internal fermion running in the loop and \( e \) refers to the external fermion (c.f. Fig. (2)).

Finally, the tensor Lagrangian \( \text{(1c)} \) contributes to the s–channel as,

\[ F_m^T(s) = -\eta \frac{g^2}{2\pi^2\Lambda^2} G_V (V_V^l A_V^u - A_V^l A_V^u) M^2 \log \left( \frac{\Lambda^2}{\mu^2} \right) ; \]

\[ F_d^T(s) = -\eta \frac{g^2}{\pi^2\Lambda^2} G_V (V_V^l A_V^u + A_V^l A_V^u) M^2 \log \left( \frac{\Lambda^2}{\mu^2} \right) ; \tag{10} \]

and to the t–channel as,

\[ F_m^T(t) = -\eta \frac{g^2}{\pi^2\Lambda^2} G_V (V_V^c A_V^c - A_V^c A_V^c) M_e M_i \log \left( \frac{\Lambda^2}{\mu^2} \right) ; \]

\[ F_d^T(t) = -\eta \frac{g^2}{\pi^2\Lambda^2} G_V (A_V^c V_V^c + A_V^c V_V^c) M_e M_i \log \left( \frac{\Lambda^2}{\mu^2} \right) . \tag{11} \]

The loop contributions of the four–fermion interaction were evaluated in \( D = 4 - 2\epsilon \) dimensions using the dimensional regularization method \( [7] \), which is a gauge–invariant regularization procedure. We have adopted the unitary gauge to perform the calculations. The results in \( D \) dimensions were obtained with the aid of the Mathematica package FeynCalc \( [8] \), and the poles at \( D = 4 \ (\epsilon = 0) \) were identified with the logarithmic dependence on the scale \( \Lambda \). We retain only the leading non–analytical contribution from the loop diagram by making the identification \( 2/(4 - d) \to \log(\Lambda^2/\mu^2) \), where \( \mu \) is the scale involved in the process. At the \( Z \) pole we use \( \mu = M_Z \) and for processes involving real photons (\( Q^2 = 0 \)) we choose \( \mu \) equal to the mass of the final state fermion. Notice that the contributions to the photon form factor \( F_v \) cancel at \( Q^2 = 0 \) as required by the the QED Ward identities \( [9] \). Our
bounds on the scale $\Lambda$ were obtained assuming $g^2/4\pi = 1$ for the new contact interaction coupling. When all fermions have the same flavor, i.e. $m = n$ in Eq. (1), we included the normalization $g^2/2\pi = 1$. When quarks are running in the loop the color factor ($N_C = 3$) is taken into account.

In principle, compositeness may not only generate the four–fermion operators (1), which contribute to new physics at one–loop level, but it may also generate effective operators which could give tree–level contributions, which we did not consider here. Thus our bounds are derived under the assumption that it is unnatural that large cancellations occur between the tree–level and the one–loop contributions in all the observables.

III. CONSTRAINTS FROM PRECISE MEASUREMENTS

A. The Leptonic Width of the Z Boson

The decay rate for the process $Z \rightarrow e^+e^-$ arising from the most general vertex expressed in Eq.(4) is,

$$\Gamma(Z \rightarrow e^+e^-) = \frac{\alpha M_Z N_C}{3} \left(1 - \frac{4m_f^2}{M_Z^2}\right)^{1/2} \left[F_v^2 \left(1 + \frac{2m_f^2}{M_Z^2}\right) + F_a^2 \left(1 - \frac{4m_f^2}{M_Z^2}\right)\right]$$

$$+ 3F_m F_v + F_m^2 \left(1 + \frac{8m_f^2}{M_Z^2}\right) M_Z^2 8m_f^2 + F_d^2 \left(1 - \frac{4m_f^2}{M_Z^2}\right) M_Z^2 8m_f^2 \right]. \quad (12)$$

In this equation, we write the form factors as $F_v = F_v^{\text{tree}} + \delta F_v$ and $F_a = F_a^{\text{tree}} + \delta F_a$, where the $\delta$’s denote the radiative corrections to the tree level contribution. When the magnetic and electric dipole contributions are absent, we get the well known result for the extra contribution,

$$\delta \Gamma(Z \rightarrow e^+e^-) = -\frac{2\alpha M_Z N_C}{3} \left[G_v^e \delta F_v(M_Z^2) - G_A^e \delta F_a(M_Z^2)\right] , \quad (13)$$

where $G_{V,A}^e$ is the vector (axial) couplings of electrons to the Z. Interaction (1) also contributes at one–loop to the width $Z \rightarrow q\bar{q}$ but the effect is too small for the present experimental accuracy on the hadronic width of the Z.
The most recent LEP experimental result \cite{10}, $\Gamma_{\ell\ell} = 83.91 \pm 0.10$ MeV, can be compared with the Standard Model predictions for the leptonic width, in order to establish bounds on the scale $\Lambda$ through Eq. (13). The Standard Model result depends on the top quark and Higgs boson masses. In what follows, we present our results for $m_{\text{top}} = 175$ GeV and for Higgs boson mass $M_H = 300$ GeV, which yield $\Gamma_{\ell\ell} = 83.92$ MeV.

In Table I, we show the 95% CL bounds on the scale of the vector current interactions involving an electron pair and any other fermions pair, coming from the measurement of the leptonic $Z$ width. We should notice that the bounds on several interactions structures are more restrictive than the ones that come from direct searches at collider experiments \cite{11}. These cases are denoted in Table I by the numbers in boldface.

In the case of scalar interactions only the four electron Lagrangian contributes to the $Z \to e^+e^-$ width and leads to the bound $\Lambda \gtrsim 0.6$ TeV for $(V_{T}^{2}V_{T}^{i} + A_{T}^{e}A_{T}^{i}) = 1$, while the tensorial current interaction does not contribute to this observable.

**B. Anomalous Magnetic and Weak–Magnetic Moment**

The anomalous magnetic form factor is generated only at one–loop both in the Standard Model and via the four–fermion interaction. The best determination of the anomalous magnetic moment of the muon $a_{\mu}^{\gamma} \equiv (g_{\mu} - 2)/2$ comes from a CERN experiment, \textit{i.e.} $a_{\mu}^{\gamma} = 11 659 230 (84) \times 10^{-10}$ \cite{12}. This result should be compared with the existing theoretical calculations of the QED \cite{13}, electroweak \cite{14}, and hadronic \cite{15} contributions, which are known with high precision.

The main theoretical uncertainty comes from the hadronic contributions which is of the order of $20 \times 10^{-10}$. We use the limits imposed on $\delta a_{\mu}^{\gamma} \equiv a_{\mu}^{\gamma} - a_{\mu}^{\gamma(\text{SM})}$ given in Ref. \cite{16}, $-1.4 \times 10^{-8} \leq \delta a_{\mu}^{\gamma} \leq 2.2 \times 10^{-8}$ at 95% CL. The proposed AGS experiment at the Brookhaven National Laboratory \cite{17} will be able to measure the anomalous magnetic moment of the muon with an accuracy of about $\pm 4 \times 10^{-10}$.

The anomalous magnetic moment of electron is measured with great accuracy $a_{e}^{\gamma} =$
1 159 652 188.4(4.3) × 10^{-12} \textsuperscript{[18]}. From the comparison of this result with the theoretical value \textsuperscript{[19]} the authors of Ref. \textsuperscript{[16]} find the limits: \(-6.9 \times 10^{-11} \leq \delta a^\gamma_e \leq 4.3 \times 10^{-11}\) with 95\% CL. We use these limits in our calculations.

We present in Table \textsuperscript{[4]} the bounds on \(\Lambda\) from the present \(g - 2\) data and also from the forthcoming AGS experiment, for the tensorial current interaction assuming \((V^*_T V^i_T - A^*_e A^i_T) = 1\). For the scalar current interaction involving four identical leptons, the bounds on \(\Lambda\) reads: \(\Lambda \gtrsim 0.1(1.0)\) TeV for electron (muon) and \(\Lambda \gtrsim 7\) TeV for the AGS muon experiment for \((V^u_s V^l_s - A^u_s A^l_s) = 1\).

Bernabeu et al. \textsuperscript{[20]} evaluated the Standard Model contribution to the anomalous weak–magnetic moment and discuss the possibility of its measurement through the analysis of the angular asymmetry of the semileptonic \(\tau\)–lepton decay products. Assuming that the \(\tau\) direction is fully reconstructed, they obtain a sensitivity of the order of \(|a^\tau_Z(M^2_Z)| \lesssim 10^{-4}\). Present limits limits on the four–fermion interactions strongly reduces the possibility of observing its effect on the anomalous weak–magnetic moment of the \(\tau\) lepton at this level of sensitivity.

**C. Electric and Weak Dipole Moment**

A nonzero electric dipole moment for the leptons is forbidden by both \(T\) and \(P\) invariance. The best present bound on the electric dipole moment of the electron comes from its measurement using the atomic–beam magnetic resonance method with the \(^{205}\)Tl atom and reads \(|d_e| \leq 4.4 \times 10^{-27}\) e cm \textsuperscript{[21]}. For the muon, the present limit on electric dipole moment is \(|d_\mu| \leq 9.3 \times 10^{-19}\) e cm \textsuperscript{[22]}. For the \(\tau\) lepton the limits on the real and imaginary parts of the weak dipole moment were measured to be \textsuperscript{[23]} \(|\text{Re}(d^\tau_\mu)| \leq 4.8 \times 10^{-18}\) e cm, and \(|\text{Im}(d^\tau_\mu)| \leq 0.93 \times 10^{-17}\) e cm.

In Table \textsuperscript{[11]} we show the bound on the scale of the tensorial current interaction from the limits on the electron and muon electric dipole moment for \((A^e_T V^i_T + A^i_T V^e_T) = 1\). For the \(\tau\)–lepton, we can establish a limit on this interaction from the real part of the weak dipole
moment measured at the $Z$ from the reconstruction of $\tau^+\tau^-$ events given above. A bound of $\Lambda \gtrsim 260$ GeV is obtained when a top quark of $m_{\text{top}} = 175$ GeV is running in the loop.

For the scalar contact interaction of four equal leptons, we get $\Lambda \gtrsim 45$ TeV for electrons and just $\gtrsim 25$ GeV for muons, assuming that $(V^l_S A^u_S + V^u_S A^l_S) = 1$.

IV. CONCLUSIONS

In this paper we have evaluated the one-loop contribution to the leptonic $Z$ width, anomalous magnetic, weak-magnetic, electric and weak-dipole moments of leptons arising from the four-Fermi Lagrangian. Using the precise measurements of these parameters we extract bounds on the energy scale of these effective interactions.

Our results show that vector and axial vector interactions involving leptons in different combinations can be strongly constrained by the $Z$-width measurement. In particular, our bounds on four-Fermi interactions, for some current structures, are more restrictive than the ones from direct search at collider experiments. Scalar and tensor interactions can also be constrained from the measurement of the anomalous magnetic and weak-magnetic moments and from dipole and weak-dipole moments. Our results show that for interactions involving electrons the strongest bounds are derived from the precision measurement of the dipole electric moment of the electron, while for interactions involving muons the best bounds arise from their contributions to the anomalous magnetic moment of the muon.

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FIGURES

FIG. 1. $s$–channel diagram.

FIG. 2. $t$–channel diagram.
TABLES

TABLE I. 95 % CL bound on Λ, in TeV, from the leptonic width of Z for different chiralities of the vector couplings.

| Channel | Λ⁺ | LL | RR | LR | RL | VV | AA | LL+RR | LR+RL |
|---------|----|----|----|----|----|----|----|-------|-------|
| ee      | 1.1 | 0.56 | 0.7 | 0.7 | 1.4 | 2.2 | 1.8 | 1.1   |       |
|         | 1.2 | 0.65 | 0.6 | 0.6 | 1.6 | 2.5 | 2.0 | 1.0   |       |
| μμ      | 1.1 | 0.89 | 1.1 | 1.1 | —   | 2.3 | 1.5 | 1.7   |       |
|         | 1.2 | 1.0  | 1.0 | 1.0 | —   | 2.6 | 1.7 | 1.5   |       |
| ττ      | 1.1 | 0.89 | 1.1 | 1.1 | —   | 2.3 | 1.5 | 1.7   |       |
|         | 1.2 | 1.0  | 1.0 | 1.0 | —   | 2.6 | 1.7 | 1.5   |       |
| ℓℓ      | 2.5 | 1.6  | 1.9 | 1.9 | 1.4 | 4.3 | 3.1 | 2.9   |       |
|         | 2.8 | 1.8  | 1.7 | 1.7 | 1.6 | 4.8 | 3.5 | 2.6   |       |
| uu      | 2.7 | 1.6  | 2.2 | 1.5 | 0.5 | 4.9 | 3.3 | 2.9   |       |
|         | 2.4 | 1.4  | 2.5 | 1.7 | 0.5 | 4.3 | 2.9 | 3.2   |       |
| dd      | 2.7 | 0.9  | 2.8 | 1.1 | 0.7 | 4.3 | 3.0 | 3.2   |       |
|         | 3.0 | 1.0  | 2.5 | 1.0 | 0.8 | 4.9 | 3.4 | 2.8   |       |
| (uu + dd)| 1.0 | 1.0  | 1.0 | 1.0 | 0.4 | —   | 0.2 | 0.2   |       |
|         | 1.1 | 0.9  | 0.9 | 1.1 | 0.5 | —   | 0.3 | 0.3   |       |
| cc      | 2.7 | 1.6  | 2.2 | 1.5 | 0.5 | 4.9 | 3.3 | 2.9   |       |
|         | 2.4 | 1.4  | 2.5 | 1.7 | 0.5 | 4.3 | 2.9 | 3.2   |       |
| bb      | 2.7 | 0.9  | 2.8 | 1.1 | 0.7 | 4.3 | 3.0 | 3.1   |       |
|         | 3.1 | 1.0  | 2.5 | 0.9 | 0.8 | 4.8 | 3.3 | 2.8   |       |
| tt      | 11.5 | 10.7 | 11.8 | 13.0 | 0.5 | 23.9 | 16.3 | 18.2 |
|         | 12.7 | 12.0 | 10.5 | 11.6 | 0.5 | 26.7 | 18.2 | 16.3 |
| qq      | 3.3 | 1.0  | 3.4 | 1.0 | 1.1 | 4.3 | 3.0 | 3.0   |       |
|         | 3.7 | 0.9  | 3.0 | 1.1 | 1.2 | 4.8 | 3.4 | 2.7   |       |

a ℓ’ ℓ’ = ee + μμ + ττ.

b m_{top} = 175 GeV.

c qq = uu + dd + ss + cc + bb.
TABLE II. 95 % CL bound on the scale $\Lambda$ of the tensorial current interaction, in TeV, from the electron and muon anomalous magnetic moments.

| Channel | $\ell = \text{electron}$ | $\ell = \mu$ (present) | $\ell = \mu$ (AGS) |
|---------|--------------------------|------------------------|-------------------|
|         | $\eta = +1 / \eta = -1$ | $\eta = +1 / \eta = -1$ |                   |
| $\ell\ell\ell\ell$ | 0.40/0.31 | 3.2/4.0 | 26 |
| $ee\mu\mu$ | 7.3/5.6 | 0.22/0.28 | 1.8 |
| $ee\tau\tau$ | 31/24 | — | — |
| $\mu\mu\tau\tau$ | — | 16/20 | 130 |
| $\ell'\ell'\ell\ell$ | 32/25 | 17/21 | 133 |
| $uull$ | 1.7/2.1 | 1.4/1.1 | 8.7 |
| $dd\ell\ell$ | 2.1/1.7 | 1.1/1.4 | 8.7 |
| $s\ell\ell$ | 10.1/8.0 | 5.1/6.5 | 42 |
| $c\ell\ell$ | 32/41 | 27/21 | 169 |
| $b\ell\ell$ | 53/42 | 28/35 | 221 |
| $t\ell\ell$ | 367/468 | 317/251 | 1989 |
| $qq\ell\ell$ | 35/27 | 18/23 | 144 |

\[ a\ell'\ell' = ee + \mu\mu + \tau\tau. \]

\[ b\text{m}_{\text{top}} = 175 \text{ GeV}. \]

\[ cqq = uu + dd + ss + cc + bb. \]
TABLE III. 95% CL bound on scale $\Lambda$ of the tensorial current interaction from the electric dipolar moment. Note the different unities for electrons and muons

| Channel | $\ell = \text{electron (TeV)}$ | $\ell = \text{muon (GeV)}$ |
|---------|-------------------------------|-----------------------------|
| $\ell\ell\ell\ell$ | 132 | 77 |
| $ee\mu\mu$ | 2053 | 3.9 |
| $ee\tau\tau$ | 8670 | — |
| $\mu\mu\tau\tau$ | — | 348 |
| $\ell'\ell'\ell\ell$ | 8800 | 359 |
| $uul$ | 613 | 21 |
| $d\ell\ell$ | 613 | 21 |
| $s\ell\ell$ | 2842 | 108 |
| $c\ell\ell$ | 11340 | 460 |
| $b\ell\ell$ | 14719 | 604 |
| $t\ell\ell$ | 128573 | 5669 |
| $qq\ell\ell$ | 9750 | 390 |

\(\ell'\ell' = ee + \mu\mu + \tau\tau\).

\(m_{\text{top}} = 175\) GeV.

\(qq = uu + dd + ss + cc + bb\).