Z Physics Constraints on Vector Leptoquarks

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Abstract

We analyze the constraints on vector leptoquarks coming from radiative corrections to Z physics. We perform a global fitting to the LEP data including the oblique and non-universal contributions of the most general effective Lagrangian for vector leptoquarks, which exhibits the $SU(2)_L \times U(1)_Y$ gauge invariance. We show that the Z physics leads to stronger bounds on second and third generation vectors leptoquarks than the ones obtained from low energy and the current collider experiments.

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I. INTRODUCTION

A large number of extensions of the standard model (SM) predicts the existence of color triplet particles with spin 0 or 1, which carry simultaneously leptonic and baryonic number; the so-called leptoquarks. Leptoquarks are present in models that treat quarks and leptons on the same footing, and consequently allow quark-lepton transitions. This class of models includes composite models \cite{1}, grand unified theories \cite{2}, technicolour \cite{3}, and superstring-inspired \cite{4} models.

The impressive success of the SM \cite{5} poses strong limitations on the possible forms of new physics even when this one cannot be produced directly. In the present work we make use of this fact to obtain bounds on vector leptoquarks through their contributions to the radiative corrections to the $Z$ physics. We evaluate the one-loop contribution due to leptoquarks to all LEP observables, keeping only its non-analytical part. Then, the limits on the leptoquark masses and couplings are obtained through a global fitting to all available LEP data. Contrary to what happens to scalar leptoquarks \cite{6}, $Z$ physics sets bounds on first and second generation leptoquarks, in addition to the third generation ones. The bounds on leptoquarks coupling to the first generation are less restrictive than the ones derived from low energy experiments, except for very small couplings of the leptoquarks to the fermions. Notwithstanding, we obtain the strongest available limits on vector leptoquarks that couple to the second and third families.

Since the discovery of a leptoquark is an undeniable signal of new physics, there have been also many direct searches for leptoquarks in accelerators. The four LEP experiments, assuming that the $Z$ can decay into a pair of on-shell leptoquarks, established a lower bound $M_{lq} \gtrsim 44$ GeV for scalar leptoquarks \cite{7}, and a similar bound should hold for vector ones. The HERA collaborations \cite{8} obtained limits on the masses and couplings of first generation leptoquarks for masses up to 275 GeV, depending on the leptoquark type and couplings. The two Tevatron collider experiments, CDF and D0, searched for leptoquark pairs leading to charged dileptons plus one dijet. For leptoquarks decaying exclusively into charged lepton
and a jet, these collaborations constrained the scalar leptoquark masses to be larger than 180 (94) GeV for second and third generation leptoquarks, while similar limits exist for vector leptoquarks depending on their anomalous chromomagnetic moments [9]. There have also been some studies of the possibility of observing vector leptoquarks in the future \(pp\) [10] and \(e^+e^-\) [11] colliders.

Low energy experiments give rise to strong constraints on leptoquarks, unless their interactions are carefully chosen [12,13]. In order to evade the bounds from proton decay, leptoquarks are required not to couple to diquarks. Moreover, to avoid the appearance of leptoquark induced FCNC, leptoquarks are assumed to couple only to a single quark family and only one lepton generation. Nevertheless, there still exist low-energy limits on leptoquarks. Helicity suppressed meson decays restrict the couplings of leptoquarks to fermions to be chiral. Moreover, residual FCNC, atomic parity violation, and meson decay [14,15] constrain the first generation leptoquarks to be heavier than 0.5–1.5 TeV when the coupling constants are equal to the electromagnetic coupling \(e\).

II. EFFECTIVE INTERACTION AND ANALYTICAL EXPRESSIONS

Our starting point is the most general effective Lagrangian for vector leptoquarks invariant under the gauge symmetry \(SU(2)_L \times U(1)_Y\), and baryon \((B)\) and lepton \((L)\) number conserving [16]. This last condition is needed to comply with the strong bounds coming from the proton lifetime experiments;

\[
\mathcal{L} = \mathcal{L}^f_{|F|=2} + \mathcal{L}^f_{|F|=0} + \mathcal{L}^{\gamma,Z,W} + \mathcal{L}_{\text{dipole}},
\]

where the interactions with the fermions are described by

\[
\mathcal{L}^f_{|F|=2} = g_{2L} (V_{2\mu}^L)^T \bar{d}_R^c \gamma^\mu i \tau_2 l_L + g_{2R} \bar{q}_L^c \gamma^\mu i \tau_2 e_R V_{2\mu}^R \\
+ \tilde{g}_{2L} (\tilde{V}_{2\mu}^L)^T \bar{u}_R^c \gamma^\mu i \tau_2 l_L + \text{h.c.},
\]

\[
\mathcal{L}^f_{|F|=0} = h_{1L} \bar{q}_L^c \gamma^\mu l_L U_{1\mu}^L + h_{1R} \bar{d}_R^c \gamma^\mu e_R U_{1\mu}^R + \tilde{h}_{1L} \bar{u}_R^c \gamma^\mu e_R \tilde{U}_{1\mu}^R \\
+ h_{3L} \bar{q}_L \tilde{\tau}_c^\mu l_L \tilde{U}_{3\mu}^L + \text{h.c.},
\]
Here \( F = 3B + L \), \( q (\ell) \) stands for the left-handed quark (lepton) doublet, and \( u_R, d_R, \) and \( e_R \) are the singlet components of the fermions. We denote the charge conjugated fermion fields by \( \psi^c = C\bar{\psi}^T \) and we omitted in Eqs. (2) and (3) the flavour indices of the couplings to fermions and leptoquarks. The leptoquarks \( U_1^{L(R)} \) and \( \tilde{U}_1^R \) are singlets under \( SU(2)_L \), while \( V_2^{L(R)} \) and \( \tilde{V}_2^L \) are doublets, and \( U_3 \) is a triplet. Furthermore, we assumed in this work that the leptoquarks belonging to a given \( SU(2)_L \) multiplet are degenerate in mass, with their mass denoted by \( M_{lq} \). For the sake of simplicity, we also assumed that the leptoquarks couple to leptons and quarks of the same family.

It is convenient to summarize each term in the interaction lagrangians (2) and (3) as

\[
\sum_{q,j,\ell} M_{jq\ell}^j \bar{q}(c) \gamma_\mu P_X \ell \phi^j_{\mu} + \text{h.c.} ,
\]

where the sum is over all quarks, leptons, leptoquarks in the multiplets. \( P_X \), with \( X = L \) or \( R \), stands for the helicity projectors, while the matrices \( M_{jq\ell}^j \) can be easily obtained by comparing the above expression with Eqs. (2) and (3).

Local invariance under \( SU(2)_L \times U(1)_Y \) implies that leptoquarks also couple to the electroweak gauge bosons. To obtain the couplings to \( W^\pm, Z, \) and \( \gamma \), we substituted \( \partial_\mu \) by the electroweak covariant derivative in the leptoquark kinetic Lagrangian, resulting in \( \mathcal{L}_{\gamma,Z,W} \).

\[
\mathcal{L}_{\gamma,Z,W} = \sum_{lq} \left[ -\frac{1}{2} G_{\mu\nu} G^{\mu\nu} + M_{lq}^i \Phi^i \Phi^i \right] ,
\]

where \( \Phi^i \) stand for any vector leptoquark multiplet. The leptoquark field strength tensor is \( G_{\mu\nu} = D_\mu \Phi^i - D_\nu \Phi^i \), with the covariant derivative

\[
D_\mu = \partial_\mu - \frac{ie}{\sqrt{2} s_W} [W^+ I^+ + W^- I^-] - i e Q_Z Z_\mu + i e Q_\gamma A_\mu ,
\]

where \( Q_\gamma \) is the leptoquark electric charge in units of the positron charge, \( Q_Z = (I_3 - Q_\gamma s_W^2)/s_W c_W \), \( I^\pm = I_1 \pm i I_2 \), and the \( I_a \)'s are the generator of \( SU(2)_L \) for the leptoquark multiplet. \( s_W, c_W \) stands for the sine (cosine) of the weak mixing angle.

It is possible to write a further contribution to the vector leptoquark lagrangian that is also invariant under \( SU(2)_L \otimes U(1)_Y \).
\[
\mathcal{L}_{\text{dipole}} = -i \left[ \frac{\kappa}{2} \frac{e}{s_W} W^a_{\mu\nu} (I_a)_{bc} - \frac{\kappa'}{2} \frac{e}{c_W} \left( \frac{Y}{2} \right)_{bc} B_{\mu\nu} \right] \left( \Phi^{ib\mu} \Phi^{cv}_\nu - \Phi^{ib\nu} \Phi^{cv}_\mu \right). \quad (6)
\]

In this work we employed the on-shell-renormalization scheme, adopting the conventions of Ref. \[17\]. We used as inputs the fermion masses, \(G_F\), \(\alpha_{\text{em}}\), and the Z mass, hence, the electroweak mixing angle is a derived quantity defined through \(\sin^2 \theta_W = s^2_W \equiv 1 - M^2_W / M^2_Z\).

Close to the Z resonance, the physics can be summarized by the effective neutral current

\[
J^Z_\mu = (\sqrt{2} G_\mu M^2_Z \rho_f)^{1/2} \left[ (I^f_3 - 2 Q^f_s W_\mu) \gamma_\mu - I^f_3 \gamma_\mu \gamma_5 \right], \quad (7)
\]

where \(Q^f (I^f_3)\) is the fermion electric charge (third component of weak isospin). The form factors \(\rho_f\) and \(\kappa_f\) have universal contributions, i.e. independent of the fermion species, as well as non-universal parts:

\[
\rho_f = 1 + \Delta \rho_{\text{univ}} + \Delta \rho_{\text{non}}, \quad \kappa_f = 1 + \Delta \kappa_{\text{univ}} + \Delta \kappa_{\text{non}}. \quad (8)
\]

Leptoquarks modify the physics at the Z pole through their contributions to both universal \[18\] and non-universal corrections. The universal contributions, displayed in Fig. 1, can be expressed in terms of the unrenormalized vector boson self-energy (\(\Sigma\)) as

\[
\Delta \rho^\text{lq}_{\text{univ}}(s) = -\frac{\Sigma^Z_{\text{iq}}(s) - \Sigma^Z_{\text{iq}}(M^2_Z)}{s - M^2_Z} + \frac{\Sigma^Z_{\text{iq}}(M^2_Z)}{M^2_W} - \frac{\Sigma^W_{\text{iq}}(0)}{M^2_W} - \frac{2 s_W}{c_W} \frac{\Sigma^Z_{\text{iq}}(0)}{M^2_Z}, \quad (9)
\]

\[
\Delta \kappa^\text{lq}_{\text{univ}} = -c_W \frac{\Sigma^Z_{\text{iq}}(s)}{M^2_Z} - c_W \frac{\Sigma^Z_{\text{iq}}(M^2_Z)}{M^2_W} + \frac{c_W^2}{s_W} \frac{\Sigma^Z_{\text{iq}}(M^2_Z)}{M^2_Z} - \frac{\Sigma^W_{\text{iq}}(M^2_W)}{M^2_W}, \quad (10)
\]

where \(s\) is the square of the vector-boson four momentum.

Corrections to the vertex \(Z f \bar{f}\) give rise to non-universal contributions to \(\rho_f\) and \(\kappa_f\). Leptoquarks affect these couplings of the Z through the diagrams also given in Fig. 1 whose results we parametrize as

\[
i \frac{e}{2 s_W c_W} \left[ \gamma_\mu F^Z_{V\text{iq}} - \gamma_\mu \gamma_5 F^Z_{A\text{iq}} + I^f_3 \gamma_\mu (1 - \gamma_5) \frac{c_W}{s_W} \frac{\Sigma^Z_{\text{iq}}(0)}{M^2_Z} \right]. \quad (11)
\]

This leads to

\[
\Delta \rho^\text{lq}_{\text{non}} = 2 \frac{F^Z_{A\text{iq}}(M^2_Z)}{a_f}, \quad \Delta \kappa^\text{lq}_{\text{non}} = -\frac{1}{2 s_W^2 Q^f} \left[ F^Z_{V\text{iq}}(M^2_Z) - \frac{v_f}{a_f} F^Z_{A\text{iq}}(M^2_Z) \right]. \quad (12)
\]
where \( a_f = I^f_3 \) and \( v_f = I^f_3 - 2Q_f^2 s_W^2 \).

In order to evaluate the relevant Feynman diagrams we used dimensional regularization \[19\] and took the external fermion masses to be zero. Then, we retained only the leading non-analytical contributions from the loop diagrams – that is, the contributions that are relevant for our analysis were obtained by the substitution

\[
\frac{2}{4 - d} \rightarrow \log \frac{\Lambda^2}{M_Z^2},
\]

where \( \Lambda \) is the energy scale which characterizes the appearance of new physics, and we dropped all other terms.\(^2\)

The contribution of the vector leptoquarks to the vector-boson self-energies depends exclusively on their gauge couplings and it is given by

\[
\begin{align*}
\Sigma^W_{\text{iq}}(q^2) &= \frac{1}{s_W} \sum_j \left( I^j_3 \right)^2 q^2 I(q^2), \\
\Sigma^\gamma_{\text{iq}}(q^2) &= \sum_j \left( Q^j \gamma \right)^2 q^2 I(q^2), \\
\Sigma^{Z}_{\text{iq}}(q^2) &= \sum_j \left( Q^j Z \right)^2 q^2 I(q^2), \\
\Sigma^{\gamma Z}_{\text{iq}}(q^2) &= -\sum_j Q^j \gamma Q^j Z q^2 I(q^2),
\end{align*}
\]

with \( n_c = 3 \) being the number of colors. For simplicity we assumed that \( \kappa = \kappa' \).

The effect of the vector leptoquarks to the couplings of the \( Z \) to a lepton pair \( \ell \bar{\ell} \) is

\[
F_{V,\text{iq}}^\ell = \mp F_{A,\text{iq}}^\ell = \frac{g_{\text{iq},X}}{192\pi^2} s_{W}c_{W} N_c \sum_{j,q} M^j_{\text{iq}} M^j_{q\ell} Q^j Z q^2 \left[ \kappa \left( 3 \frac{m_q^2}{M^2_{\text{iq}}} - \frac{q^2}{M^2_{\text{iq}}} - 6 \right) - 10 \right] \ln \left( \frac{\Lambda^2}{M^2_{\text{iq}}} \right),
\]

for both \( |F| = 2 \) and \( F = 0 \) vector leptoquarks. \( n_c = 3, m_q \) is the mass of the quark running in the loop, and the \( + ( - ) \) corresponds to left- (right-) handed leptoquarks. For \( F = 0 \) leptoquarks, in order to obtain the \( Zq\bar{q} \) vertex correction we just have to change \( \ell \leftrightarrow q \) in the above expression and set \( n_c = 1 \). For \( |F| = 2 \) leptoquarks one also has to change \( g_{\text{iq},X} \leftrightarrow g_{\text{iq},-X} \) where we denote \( R = -L \).
In order to check the consistency of our calculations, we verified that the effect of leptoquarks to the $\gamma f \bar{f}$ vertex vanishes at zero momentum, which is used as one of the renormalization conditions in the on-shell scheme. This vertex function can be obtained from (16) by the substitutions $Q^j_Z \Rightarrow -Q^j_i$, $e/2s_Wc_W \Rightarrow -e$. As we can see from Eq. (16), the leading leptoquark contribution to the vertex function $\gamma f \bar{f}$ is proportional to $q^2$, and hence, the QED Ward identities [20] are satisfied, since the fermion electric charges at $q = 0$ are left unchanged.

Leptoquark corrections for the vertex $W \ell \nu_\ell$ ($\ell = e$ or $\mu$) at low energy contribute to $\Delta r$, see for instance the first reference in [3], and consequently to $\Delta \rho_{\text{univ}}$. However, the leading non-analytical correction is proportional to the mass of the quark running in the loop and therefore it vanishes since we assume that the leptoquark couples to the same generation of leptons and quarks.

III. RESULTS AND DISCUSSION

We performed a global fit to all LEP data including both universal and non-universal contributions. In Table I we show the most recent combined results of the four LEP experiments. These results are not statistically independent and the correlation matrix can be found in [3]. We expressed the theoretical predictions to these observables in terms of $\kappa^f$, $\rho^f$, and $\Delta r$, with the SM contributions being obtained from the program ZFITTER [21]. In order to perform the global fit we constructed the $\chi^2$ function and minimized it using the package MINUIT. In our fit we used five parameters, three from the SM ($m_{\text{top}}$, $M_H$, and $\alpha_s(M_Z^2)$) and two new ones: $M_{lq}$ and $g_{lq}$. We constrained the value of $m_{\text{top}}$ to lie in the range allowed by the Tevatron experiments [22].

We present in Fig. 2 the 90% CL allowed regions in the plane $M_{lq} - g_{lq}$ for third generation leptoquarks, assuming $\Lambda = 2$ TeV and $\kappa = \kappa' = 0$. Similar results hold for leptoquarks coupling to the other generations. As we can see from this figure, the bounds become more stringent as the leptoquark isospin grows. This happens because the leptoquark contribution
to the form factors $F_{V(A)}^f$ increases with the leptoquark isospin. It is interesting to notice that the bounds on right-handed and left-handed leptoquarks are basically the same since they lead to similar contributions to $F_{V(A)}^f$.

Low energy bounds on vector leptoquarks can be evaded provided the couplings leptoquark–quark–lepton are sufficiently weak, because they rely on the four fermion effective interactions generated by leptoquarks. On the other hand, the $Z$ physics can lead to bounds on leptoquarks, even if the coupling $g_{lq}$ is very small, due to their oblique contributions. In Table II we display the generation independent bounds (95 % CL) that can be obtained assuming $g_{lq} = 0$, which allow us to access the importance of their universal contributions. These bounds are weaker than the present experimental limits for first generation leptoquarks, however, they are stronger the available experimental limits for second and third generation leptoquarks.

We show in Table III the 95 % CL lower limits on the masses of second and third generation leptoquarks for several values of the couplings $g_{lq}$ and $\kappa = \kappa'$. Since the limits for leptoquarks coupling to the first generation are weaker than the ones drawn for the low energy experiments, we don’t exhibit them. In order to generate this table, we fixed $m_{\text{top}} = 175$ GeV and $\Lambda = 2$ TeV, and we varied $\alpha_s(M_Z)$ in the interval $0.121 \pm 0.005$ and $M_H$ in the range $60$–$1000$ GeV. Increasing the value of $\Lambda$ to $5$ TeV, leads to bounds that are 15 to 20% stronger, but exhibiting the same features. Comparing Tables II and III, we can witness that the limits on the leptoquarks get stronger when we consider their non-universal contributions. We can also see that the dependence on $m_{\text{top}}$ is rather weak since it is not the leading term in the $Z$ form factors, see Eq. (16).

In order to understand the importance of the parameters $\kappa$ $\kappa'$, we exhibit in Fig. 3 the limits on the mass of the leptoquark triplet $U_3$ as a function of $\kappa = \kappa'$ for several values of $g_{lq}$. As a general trend, we can see that the limits are more restrictive as $\kappa$ and $g_{lq}$ are increased. The position of the minimum, for a fixed $g_{lq}$, determined by the value of $\kappa$ that minimized the leptoquark contributions. In fact, for low values of $g_{lq}$ the minimum is close
to $\kappa = -0.32$, which is the value that leads to minimum oblique corrections. For large values of $g_{\ell q}$, the main leptoquark effect are arises from their contribution to the vertex functions, and those are minimum for $\kappa \simeq -10/6$.

Our conclusions are that the bounds on vector leptoquarks coming from $Z$ physics extend the limits obtained from low-energy data for second and third generation leptoquarks. In fact, the best limit for second generation leptoquarks come from their contribution to $(g-2)_\mu$ and it takes the form $m_{\ell q} > 183 \ g_{\ell q}$ GeV, which is weaker than the bounds presented in Table III. Therefore, we can conclude that our bounds exclude large regions of the parameter space where the new collider experiments could search for these particles, however, not all of it [10,11]. Nevertheless, we should keep in mind that nothing substitutes the direct observation.

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FIG. 1. Feynman diagrams leading to leptoquark contribution to vector-boson self-energies (left column) and to the vertex $Z-f-\bar{f}$ (right column).

FIG. 2. Allowed regions (90 % CL) in the plane $M_{lq}-g_{lq}$ for third generation vector leptoquarks, $\Lambda = 2$ TeV, and $\kappa = \kappa' = 0$. The values of all other parameters were allowed to vary. The solid (dashed) lines stand for left(right)-handed leptoquarks.
FIG. 3. Lower bounds (95 % CL) on the mass of the vector leptoquark $U_3^L$ as a function of $\kappa = \kappa'$ for $g_{hq} = 0, e/s_W, 1, (4\pi)^{1/2}$ (solid, dot-dashed, dashed and dotted lines respectively). We considered a third generation leptoquark with $\Lambda = 2 \text{ TeV}$ and varied all other parameters.
TABLES

| Quantity | Experimental value |
|----------|---------------------|
| $M_Z$[GeV] | 91.1863 ± 0.0020 |
| $\Gamma_Z$[GeV] | 2.4946 ± 0.0027 |
| $\sigma^0_{\text{had}}$[nb] | 41.508 ± 0.056 |
| $R_e = \frac{\Gamma(\text{had})}{\Gamma(e^+e^-)}$ | 20.754 ± 0.057 |
| $R_\mu = \frac{\Gamma(\text{had})}{\Gamma(\mu^+\mu^-)}$ | 20.796 ± 0.040 |
| $R_\tau = \frac{\Gamma(\text{had})}{\Gamma(\tau^+\tau^-)}$ | 20.814 ± 0.055 |
| $A^0_{FB}$ | 0.0160 ± 0.0024 |
| $A^0_{FB}$ | 0.0162 ± 0.0013 |
| $A^0_{FB}$ | 0.0201 ± 0.0018 |
| $A^0_\tau$ | 0.1401 ± 0.0067 |
| $A^0_c$ | 0.1382 ± 0.0076 |
| $R_b = \frac{\Gamma(b\bar{b})}{\Gamma(\text{had})}$ | 0.2179 ± 0.0012 |
| $R_c = \frac{\Gamma(c\bar{c})}{\Gamma(\text{had})}$ | 0.1715 ± 0.0056 |
| $A^0_{FB}$ | 0.0979 ± 0.0023 |
| $A^0_{FB}$ | 0.0733 ± 0.0048 |

TABLE I. LEP data

| $\kappa$ | $U_1^{L(R)}$ | $\bar{U}_1^{R}$ | $U_3^{L}$ | $V_2^{L(R)}$ | $\bar{V}_2^{L}$ |
|-----------|---------------|-----------------|------------|--------------|-----------------|
| 0         | 70 – 110      | 150 – 225       | 240 – 475  | 155 – 300    | 130 – 275       |
|           | 80 – 120      | 175 – 260       | 285 – 590  | 180 – 354    | 150 – 320       |
| 1         | 120 – 180     | 260 – 370       | 400 – 750  | 250 – 485    | 220 – 450       |
|           | 140 – 210     | 300 – 450       | 475 – 960  | 290 – 590    | 260 – 550       |

TABLE II. 95 % CL lower limits on vector leptoquarks from oblique corrections. Upper (lower) line is for $\Lambda = 2(5)$ TeV
| $\kappa$ | $g$ | $U_1^L$ | $U_1^R$ | $\tilde{U}_1^R$ | $U_3^L$ | $V_2^L$ | $V_2^R$ | $\tilde{V}_2^L$ |
|-------|----|-------|-------|-------------|-------|-------|-------|-------------|
| $\sqrt{4\pi}$ | 590−690 | 880−930 | 1040−1190 | 1490−1630 | 1040−1210 | 1160−1220 | 1180−1340 |
| | 660−840 | 720−790 | 970−1050 | 1410−1560 | 890−1060 | 950−1030 | 970−1180 |
| $1$ | 220−280 | 350−370 | 430−490 | 770−820 | 450−460 | 470−530 | 530−610 |
| | 250−350 | 260−310 | 360−440 | 700−740 | 330−370 | 310−450 | 410−470 |
| $e/s_W$ | 140−200 | 240−250 | 280−310 | 450−590 | 200−350 | 230−400 | 360−400 |
| | 160−240 | 160−210 | 200−310 | 380−550 | 150−290 | 180−350 | 260−360 |
| $\sqrt{4\pi}$ | 690−810 | 1010−1060 | 1270−1320 | 1600−1730 | 1180−1320 | 1300−1340 | 1310−1470 |
| | 770−970 | 840−920 | 1100−1180 | 1530−1670 | 1020−1180 | 1070−1170 | 1100−1310 |
| $1$ | 260−340 | 410−430 | 500−580 | 790−930 | 370−570 | 430−650 | 630−650 |
| | 290−410 | 300−370 | 360−520 | 680−860 | 280−480 | 310−570 | 460−500 |
| $e/s_W$ | 180−260 | 250−290 | 270−420 | 430−790 | 250−500 | 260−540 | 300−520 |
| | 200−300 | 170−260 | 250−400 | 400−760 | 240−470 | 250−510 | 230−430 |

TABLE III. 95 % CL lower limits for second (upper lines) and third (lower lines) generation vector leptoquarks for $\Lambda = 2$ TeV