Bounds on Scalar Leptoquarks from the LEP Data

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ABSTRACT

We obtain the constraints on scalar leptoquarks coming from radiative corrections to $Z$ physics. We perform a global fitting to the LEP data including the contributions of the most general effective Lagrangian for scalar leptoquarks, which exhibits the $SU(2)_L \times U(1)_Y$ gauge invariance. Our bounds on leptoquarks that couple to the top quark are much stronger than the ones obtained from low energy experiments.

1. Introduction

A large number of extensions of the SM predict the existence of color triplet particles carrying simultaneously leptonic and baryonic number, the so-called leptoquarks. Leptoquarks are present in models that treat quarks and leptons on the same footing, such as composite models,\textsuperscript{1} grand unified theories,\textsuperscript{2} technicolor models,\textsuperscript{3} and superstring-inspired models.\textsuperscript{4}

Since leptoquarks are an undeniable signal for physics beyond the SM, there have been several direct searches for them in accelerators. At the CERN Large Electron-Positron Collider (LEP), the experiments established a lower bound $M_{LQ} \gtrsim 45\,73 \text{ GeV}$ for scalar leptoquarks.\textsuperscript{5} On the other hand, the search for scalar leptoquarks decaying into an electron-jet pair in $p\bar{p}$ colliders constrained their masses to be $M_{LQ} \lesssim 113 \text{ GeV}$.\textsuperscript{6} Furthermore, the experiments at the DESY $ep$ collider HERA\textsuperscript{7} place limits on their masses and couplings, leading to $M_{LQ} \lesssim 92 \, 184 \text{ GeV}$ depending on the leptoquark type and couplings. There have also been many studies of the possibility of observing leptoquarks in the future $pp$,\textsuperscript{8} $ep$,\textsuperscript{9,10} $e^+e^-$,\textsuperscript{11} $e\gamma$,\textsuperscript{12} and $\gamma\gamma$\textsuperscript{13} colliders.

In this work we study the constraints on scalar leptoquarks that can be obtained from their contributions to the radiative corrections to the $Z$ physics. We evaluated the one-loop contribution due to leptoquarks to all LEP observables and made a global fit in order to extract the 95\% confidence level limits on the leptoquarks masses and couplings.\textsuperscript{14} The most stringent limits are for leptoquarks that couple to the top quark. Therefore, our results turn out to be complementary to the low energy bounds,\textsuperscript{15,16} since these constrain more strongly first and second generation leptoquarks.

The masses and couplings of leptoquarks are constrained by low-energy experiments, since the leptoquarks induce two-lepton–two-quark effective interactions, for

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energies much smaller than their masses.\textsuperscript{15,16} The processes that lead to strong limits are:

- Leptoquarks can give rise to flavor changing neutral current (FCNC) processes if they couple to more than one family of quarks or leptons.\textsuperscript{17,18} In order to avoid strong bounds from FCNC, we assumed that the leptoquarks couple to a single generation of quarks and a single one of leptons. However, due to mixing effects on the quark sector, there is still some amount of FCNC\textsuperscript{15} and, therefore, leptoquarks that couple to the first two generations of quarks must comply with some low-energy bounds.\textsuperscript{15}

- The analyses of the decays of pseudoscalar mesons, like the pions, put stringent bounds on leptoquarks unless their coupling is chiral – that is, it is either left-handed or right-handed.\textsuperscript{17}

- Leptoquarks that couple to the first family of quarks and leptons are strongly constrained by atomic parity violation.\textsuperscript{19} In this case, there is no choice of couplings that avoids the strong limits.

It is interesting to keep in mind that the low-energy data constrain the masses of the first generation leptoquarks to be bigger than 0.5–1 TeV when the coupling constants are equal to the electromagnetic coupling $e$.\textsuperscript{15}

The bounds on scalars leptoquarks coming from low-energy and $Z$ physics exclude large regions of the parameter space where the new collider experiments could search for these particles, however, not all of it.\textsuperscript{8,10–13} Notwithstanding, we should keep in mind that nothing substitutes the direct observation.

2. Effective Interactions and Analytical Expressions

A natural hypothesis for theories beyond the SM is that they exhibit the gauge symmetry $SU(2)_L \times U(1)_Y$ above the symmetry breaking scale $v$. Therefore, we imposed this symmetry on the leptoquark interactions. In order to avoid strong bounds coming from the proton lifetime experiments, we required baryon ($B$) and lepton ($L$) number conservation. The most general effective Lagrangian for leptoquarks satisfying the above requirements and electric charge and color conservation is\textsuperscript{14}

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{F=2} + \mathcal{L}_{F=0},$$

$$\mathcal{L}_{F=2} = (g_{1L} \bar{q}_L \tau_2 \ell_L + g_{1R} \bar{u}_R \epsilon_R) \, S_1 + \bar{g}_{1R} \bar{d}_R \epsilon_R \, \bar{S}_1 + g_{3L} \bar{q}_L \tau_2 \ell_L \cdot \bar{S}_3, \ (1)$$

$$\mathcal{L}_{F=0} = h_{2L} \, \bar{R}_2 \, \bar{u}_R \tau_2 \ell_L + h_{2R} \, \bar{q}_L \epsilon_R \, \bar{R}_2 + \bar{h}_{2L} \, \bar{R}_2 \, \bar{d}_R \tau_2 \ell_L,$$

where $F = 3B + L$, $q$ ($\ell$) 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 $\mathcal{L}$ the flavor indices of the couplings to fermions and leptoquarks. The leptoquarks $S_1$ and $\bar{S}_1$ are singlets under $SU(2)_L$ while $R_2$ and $\bar{R}_2$ are doublets, and $S_3$ 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 $M$.

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
∂μ by the electroweak covariant derivative \( (D_μ) \) in the leptoquark kinetic Lagrangian:

\[
D_μ Φ = \left[ \partial_μ - i \frac{e}{\sqrt{2} s_W} \left( W_μ^+ + W_μ^- \right) - ie Q_μ Z_μ + ie Q_μ A_μ \right] Φ ,
\]

where \( Φ \) stands for the leptoquarks fields, \( Q_μ \) is the electric charge matrix of the leptoquarks, \( s_W \) is the sine of the weak mixing angle, and the \( T^\prime s \) are the generators of \( SU(2)_L \) for the representation of the leptoquarks. The weak neutral charge is \( Q_Z = (T_3 - s_W^2 Q^\gamma) / s_W c_W \).

We employed the on-shell-renormalization scheme, adopting the conventions of Ref. [20]. We used as inputs the fermion masses, \( G_F, \alpha_{em}, \) and the \( Z \) mass, and the electroweak mixing angle being a derived quantity that is defined through \( \sin^2 \theta_W = 2 M_Z^2 / s_W M_W^2 \). We evaluated the loops integrals using dimensional regularization and we adopted the Feynman gauge to perform the calculations.

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

\[
J_μ = \left( \sqrt{2} G_μ M_Z^2 ρ_f \right)^{1/2} \left[ \left( I_3^f - 2 Q^f s_W^2 κ_f \right) γ_μ - I_3^f γ_μ γ_5^f \right] ,
\]

where \( Q^f \) (\( I_3^f \)) is the fermion electric charge (third component of weak isospin). The form factors \( ρ_f \) and \( κ_f \) have universal contributions, \( i.e. \) independent of the fermion species, as well as non-universal parts:

\[
ρ_f = 1 + \Delta ρ_{univ} + \Delta ρ_{non} , \quad κ_f = 1 + \Delta κ_{univ} + \Delta κ_{non} .
\]

Leptoquarks can affect the physics at the \( Z \) pole through their contributions to both universal and non-universal corrections. The universal contributions can be expressed in terms of the unrenormalized vector boson self-energy (\( Σ \)) as

\[
\Delta ρ_{univ}^{LQ} (s) = - \frac{Σ^Z_{LQ}(s) - Σ^Z_{LQ}(M_Z^2)}{s - M_Z^2} + \frac{Σ^Z_{LQ}(M_Z^2)}{M_Z^2} - \frac{Σ^W_{LQ}(0)}{c_W M_W^2} - 2 s_W Σ^Z_{LQ}(0) - \chi_e - \chi_{em},
\]

\[
\Delta κ_{univ}^{LQ} = - \frac{c_W Σ^Z_{LQ}(M_Z^2)}{s_W M_Z^2} - \frac{c_W Σ^Z_{LQ}(0)}{s_W M_Z^2} + \frac{c_W^2 s_W^2}{s_W^2} \left[ \frac{Σ^Z_{LQ}(M_Z^2)}{M_Z^2} - \frac{Σ^W_{LQ}(M_W^2)}{M_W^2} \right] ,
\]

where the factors \( χ_e \) are defined below. The leptoquark contributions to the self-energies can be easily evaluated, yielding

\[
Σ_{LQ}^V (k^2) = - \frac{α_{em}}{4π} N_c ∑_{j} ℱ_{j}^V \mathcal{H} \left( k^2, M^2 \right) ,
\]

where \( N_c = 3 \) is the number of colors and the sum is over all members of the leptoquark multiplet. The coefficient \( ℱ_{j}^V \) is given by \( (Q_j^V)^2, (Q_j^Z)^2, - Q_j^Z Q_j^Z, \) and \( (T_3^j)^2 / s_W^2 \) for \( V = γ, Z, γZ, \) and \( W \) respectively. The function \( \mathcal{H} \) is defined according to:

\[
\mathcal{H} (k^2, M^2) = - \frac{k^2}{3} Δ_M - \frac{2}{9} k^2 - \frac{4 M^2 - k^2}{3} ∫_0^1 dx \ln \left[ \frac{x^2 k^2 - x k^2 + M^2 - iε}{M^2} \right] ,
\]
with
\[ \Delta_M = \frac{2}{4 - d} - \gamma_E + \ln(4\pi) - \ln \left( \frac{M^2}{\mu^2} \right), \] (10)
and \( d \) being the number of dimensions.

The factors \( \chi_{\ell} (\ell = e, \mu) \) stem from corrections to the effective coupling between the \( W \) and fermions at low energy. Leptoquarks modify this coupling, inducing a contribution that we parametrize as
\[ i \frac{e}{\sqrt{2} s_W} \chi_{\ell} \gamma_{\mu} P_L, \] (11)
where \( P_L (P_R) \) is the left-handed (right-handed) projector and \( \ell \) stands for the lepton flavor. Since this correction modifies the muon decay, it contributes to \( \Delta r \), and consequently, to \( \Delta \rho_{\text{uniw}} \). Leptoquarks with right-handed couplings, as well as the \( F = 0 \) ones, do not contribute to \( \chi_{\ell} \). The analytical for \( \chi_{\ell} \) due to left-handed leptoquarks in the \( F = 2 \) sector can be found in Ref. [14].

Corrections to the vertex \( Z f \bar{f} \) give rise to non-universal contributions to \( \rho_f \) and \( \kappa_f \). We parametrize the effect of leptoquarks to these couplings by
\[ i \frac{e}{2 s_W c_W} \left[ \gamma_{\mu} F_{V LQ}^f - \gamma_{\mu} \gamma_5 F_{ALQ}^f + I_3^f \gamma_{\mu} (1 - \gamma_5) \frac{c_W}{s_W} \frac{\Sigma^{\gamma_Z}(0)}{M_Z^2} \right], \] (12)
where for leptons (\( \ell \)) and leptoquarks with \( F = 2 \)
\[ F_{V LQ}^f = \pm F_{ALQ}^f = \frac{g_{LQ X}^2}{32 \pi^2} N_c \sum_{j,q} M_{j \ell q}^j M_{q \ell}^j \]
\[ \left\{ \frac{g^q_X}{2} - s_W c_W Q_Z^j - \left( g^q_X + 2 s_W c_W Q_Z^j \right) \frac{M^2 - m_{l q}^2}{M_Z^2} \left[ -\frac{1}{2} \ln \left( \frac{M^2}{m_{l q}^2} \right) + \tilde{B}_0(0, m_{l q}^2, M^2) \right] \right\}, \] (13)
where the \( + (--) \) corresponds to left- (right-) handed leptoquarks and \( g^q_{L/R} = v^f \mp a_f \)
with the neutral current couplings being \( a_f = I_3^f \) and \( v_f = I_3^f - 2 Q_f s_W^2 \). \( M_{q \ell}^j \) summarizes the couplings between leptoquarks and fermions. The functions \( B_1, C_0, C_{00}, \) and \( C_{12} \) are the Passarino-Veltman functions. We used the convention \( X = L, R \) and \( -L = R \) \((-R = L)\). We also defined
\[ B_0(k^2, M^2, M'^2) \equiv \frac{1}{2} \Delta_M + \frac{1}{2} \Delta_{M'} + \tilde{B}_0(k^2, M^2, M'^2), \] (14)
\[ B_1(k^2, M^2, M'^2) \equiv - \frac{1}{2} \Delta_M + \tilde{B}_1(k^2, M^2, M'^2), \] (15)
with \( \Delta_M \) given by Eq. (10). From this last expression we can obtain the effect of \( F = 2 \) leptoquarks on the vertex \( Zq\bar{q} \) simply by the change \( \ell \leftrightarrow q \). Moreover, we can also employ the expression (13) to \( F = 0 \) leptoquarks provided we substitute \( g_{LQ,X} \Rightarrow h_{LQ,X} \) and \( g_{q\pm X} \Rightarrow -g_{q\pm X} \).

With all this we have

\[
\Delta \rho_{LQ,\text{non}} = \frac{F_{Zf}^{ALQ}}{a_f} (M_Z^2),
\]

\[
\Delta \kappa_{LQ,\text{non}} = -\frac{1}{2s_W Q_f^2} \left[ F_{V_f}^{ALQ}(M_Z^2) - \frac{v_f}{a_f} F_{Zf}^{V_f}(M_Z^2) \right].
\]

One very interesting property of the general leptoquark interactions that we are analyzing is that all the physical observables are rendered finite by using the same counter-terms as appear in the SM calculations. For instance, starting from the un-renormalized self-energies (8) and the mass and wave-function counter-terms we obtain finite expression for the two-point functions of vector bosons. Moreover, the contributions to the vertex functions \( Zf\bar{f} \) and \( Wf\bar{f}' \) are finite.

In order to check the consistency of our calculations, we analyzed the effect of leptoquarks to the \( \gamma f\bar{f} \) vertex at zero momentum. It turns out that the leptoquark contribution to this vertex function not only is finite but also vanishes at \( k^2 = 0 \) for all fermion species. Therefore, our expressions for the different leptoquark contributions satisfy the appropriate QED Ward identities, and leave the fermion electric charges unchanged. Moreover, we also verified explicitly that the leptoquarks decouple in the limit of large \( M \).

3. Results and Discussion

In our analyses, we assumed that the leptoquarks couple to leptons and quarks of the same family. In order to gain some insight on which corrections are the most relevant, let us begin our analyses by studying just the oblique corrections\(^2\) which we parametrized in terms of the variables \( \epsilon_1, \epsilon_2, \) and \( \epsilon_3 \). These variables depend only upon the interaction of leptoquarks with the gauge bosons and it is easy to see that leptoquarks contribute only to \( \epsilon_2 \). Imposing that this contribution must be within the limits allowed by the LEP data, we find out that the constraints coming from oblique corrections are less restrictive than the available experimental limits\(^5\)\(^-\)\(^7\).

We then performed a global fit to all LEP data including both universal and non-universal contributions. In Table 1 we show the the combined results of the four LEP experiments\(^2\) that were used in our analysis. In order to perform the global fit we constructed the \( \chi^2 \) function associated to these data and we minimized it using the package MINUIT. 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\(^2\). 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: \( M \), and the leptoquark coupling denoted by \( g_{LQ} \). Furthermore, we have also studied the dependence upon the SM inputs \( M_Z, \alpha_{\text{em}}, \) and \( G_F \).
Table 1. LEP data

| Quantity       | Experimental value |
|----------------|--------------------|
| $M_Z$ [GeV]    | 91.1888 ± 0.0044   |
| $\Gamma_Z$ [GeV] | 2.4974 ± 0.0038   |
| $\sigma^0_{\text{had}}$ [nb]     | 41.49 ± 0.12      |
| $R_e = \frac{\Gamma(\text{had})}{\Gamma(e^+e^-)}$ | 20.850 ± 0.067    |
| $R_\mu = \frac{\Gamma(\mu^+\mu^-)}{\Gamma(\text{had})}$ | 20.824 ± 0.059    |
| $R_\tau = \frac{\Gamma(\tau^+\tau^-)}{\Gamma(\text{had})}$ | 20.749 ± 0.070    |
| $A^0_{FB}$     | 0.0156 ± 0.0034    |
| $A^\mu_{FB}$   | 0.041 ± 0.0021     |
| $A^{0r}_{FB}$  | 0.0228 ± 0.0026    |
| $A^0_{FB}$     | 0.143 ± 0.010      |
| $A^0_e$        | 0.135 ± 0.011      |
| $R_b = \frac{\Gamma(\bar{b}b)}{\Gamma(\text{had})}$ | 0.2202 ± 0.0020    |
| $R_c = \frac{\Gamma(\bar{c}c)}{\Gamma(\text{had})}$ | 0.1583 ± 0.0098    |
| $A^{0b}_{FB}$  | 0.0967 ± 0.0038    |
| $A^{0c}_{FB}$  | 0.0760 ± 0.0091    |

The first part of our analysis consisted of the study of the constraints on the leptoquark masses and couplings. In order to determine the allowed region in the $M_{LQ}$–$g_{LQ}$ plane, shown in Fig. 1 for the different models, we obtained the minimum $\chi^2_{\text{min}}$ of the $\chi^2$ function with respect to the parameters above for each leptoquark model, and we then required that $\chi^2 \leq \chi^2_{\text{min}} + \Delta\chi^2(2, 90\%\text{CL})$, with $\Delta\chi^2(2, 90\%\text{CL}) = 4.61$. In this procedure, the parameters $m_{\text{top}}, M_H$, and $\alpha_s$, as well as the SM inputs $M_Z$, $\alpha_{\text{em}}$, and $G_F$ were varied so as to minimize $\chi^2$. We must comment here that the dependence on $\alpha_{\text{em}}$ and $G_F$ is negligible when they are allowed to vary in their 90% CL range. On the other hand, the variation of $M_Z$ in the interval $91.18 \leq M_Z \leq 91.196$ leads to a change on the allowed values of leptoquarks parameters of at most 1%.

The contour plots exhibited in Fig. 1 were obtained for third generation leptoquarks. From this figure we can see that the bounds are much more stringent for the leptoquarks that couple to the top quark, i.e. for $S_{1L(R)}, S_3$, and $R_{2L(R)}$, since their contributions are enhanced by powers of the top quark mass. Moreover, the limits are slightly better for left-handed leptoquarks than for right-handed ones, given a leptoquark type, and the curve is symmetric around $g_{LQ} = 0$ since the leptoquark contributions are quadratic functions of $g_{LQ}$.

The contributions from $\tilde{R}_2$ and $\tilde{S}_1$ are not enhanced by powers of the top quark mass since these leptoquarks do not couple directly to up-type quarks. Therefore, their limits are much weaker, depending on $m_{\text{top}}$ only through the SM contribution, and the
bounds for these leptoquarks are worse than the present discovery limits unless they are strongly coupled \(g_{LQ}^2 = 4\pi\). Moreover, the limits on first and second generation leptoquarks are also uninteresting for the same reason. Nevertheless, if we allow leptoquarks to mix the third generation of quarks with leptons of another generation the bounds obtained are basically the same as the ones discussed above\(^\dagger\), since the main contribution to the constraints comes from the \(Z\) widths.

We next present our results as 95\% CL lower limits in the leptoquark mass and study the dependence of these limits upon all other parameters. For this, we minimized the \(\chi^2\) function for fixed values of \(\alpha_s, M_H,\) and \(m_{top}\) and then required
\[
\chi^2(\alpha_s, M_H, m_{top}) \leq \chi^2_{\text{min}}(\alpha_s, M_H, m_{top}) + \Delta\chi^2(1, 90\%\text{CL}),
\]
with \(\Delta\chi^2(1, 90\%\text{CL}) = 2.71\). Our results are shown in Table 2 where we give the 95\% CL limits obtained for a third generation leptoquark for several values of the coupling constants \(g_{LQ} = \sqrt{4\pi}, 1,\) and \(e/s_W\). The values given correspond to \(m_{top} = 175\) GeV and variation of \(M_H = 60 - 1000\) GeV and \(\alpha_s(M_Z^2) = 0.126 \pm 0.005,\) which is the range associated to the best values obtained from a fit in the framework of the SM\(^2\). For a fixed value of \(m_{top}\) and leptoquark coupling constant, the dependence on \(\alpha_s(M_Z^2)\) and \(M_H\) is such that the limits are more stringent as \(\alpha_s(M_Z^2)\) increases and \(M_H\) decreases. The SM parameters \(M_Z, \alpha_{em},\) and \(G_F\) have been also varied in their allowed range. However, this did not affect the results in a noticeable way.

We would like to stress that the large apparent uncertainty associated with the value of \(\alpha_s\) and \(M_H\) can be considered somehow fictitious as the value of \(\chi^2_{\text{min}}\) grows very fast when we move from the central value \(\alpha_s = 0.126, M_H = 300\) GeV what means that the quality of the fit for the extreme values of these parameters is rather bad. For instance, \(\alpha_s = 0.117,\) results in a too high \(\chi^2,\) even in the context of the SM \((\chi^2_{\text{min}} > 26/12)\).

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\(^\dagger\)In the case of first generation leptons, we must also add a tree level \(t\)-channel leptoquark exchange to some observables.
References

1. See, for instance, W. Buchmuller, Acta Phys. Austriaca Suppl. XXVII (1985) 517.
2. See, for instance, P. Langacker, Phys. Rep. 72 (1981) 185.
3. See, for instance, E. Farhi and L. Susskind, Phys. Rep. 74 (1981) 277.
4. See, for instance, J. L. Hewett and T. G. Rizzo, Phys. Rep. 183 (1989) 193.
5. L3 Collaboration, B. Adeva et al., Phys. Lett. B261 (1992) 169; OPAL Collaboration, G. Alexander et al., Phys. Lett. B263 (1992) 123; DELPHI Collaboration, P. Abreu et al., Phys. Lett. B316 (1993) 620.
6. CDF Collaboration, F. Abe et al., Phys. Rev. D48 (1993) 3939; D0 Collaboration, Phys. Rev. Lett. 72 (1994) 965.
7. ZEUS Collaboration, M. Derrick et al., Phys. Lett. B306 (1993) 173; H1 Collaboration, I. Abt et al., Nucl. Phys. B396 (1993) 3.
8. O. J. P. Eboli and A. V. Olinto, Phys. Rev. D38 (1988) 3461; J. L. Hewett and S. Pakvasa, ibid. D37 (1988) 3165; J. Ohnemus et al., Phys. Lett. B334 (1994) 203.
9. W. Buchmuller, R. Ruckl, and D. Wyler, Phys. Lett. B191 (1987) 442.
10. J. Wudka, Phys. Lett. B167 (1986) 337; M. A. Doncheski and J. L. Hewett, Z. Phys. C56 (1992) 209; J. Blumlein, E. Boos, and A. Pukhov, Int. J. Mod. Phys. A9 (1994) 3007.
11. J. L. Hewett and T. G. Rizzo, Phys. Rev. D36 (1987) 3367; J. L. Hewett and S. Pakvasa, Phys. Lett. B227 (1987) 178; J. E. Ciez and O. J. P. Eboli, Phys. Rev. D47 (1993) 837; J. Blumlein and R. Ruckl, Phys. Lett. B304 (1993) 337; J. Blumlein and E. Boos, Nucl. Phys. B37 (Proc. Suppl.) (1994) 181.
12. O. J. P. Eboli et al., Phys. Lett. B311 (1993) 147; H. Nadeau and D. London, Phys. Rev. D47, (1993) 3742; M. A. Doncheski and S. Godfrey, Phys. Rev. D51 (1995) 1040.
13. G. Belanger, D. London, and H. Nadeau, Phys. Rev. D49 (1994) 3140.
14. J. K. Mizukoshi, O. J. P. Eboli, and M. C. Gonzalez-Garcia, Nucl. Phys. B444 (1995) 20; G. Bhattacharyya, J. Ellis, and K. Sridhar, Phys. Lett. B336 (1994) 100; (E) B338 (1994) 522.
15. M. Leurer, Phys. Rev. Lett. 71 (1993) 1324; Phys. Rev. D49 (1994) 333.
16. S. Davidson, D. Bailey, and A. Campbell, Z. Phys. C61 (1994) 613.
17. O. Shanker, Nucl. Phys. B204 (1982) 375.
18. W. Buchmuller and D. Wyler, Phys. Lett. B177 (1986) 377; J. C. Pati and A. Salam, Phys. Rev. D10 (1974) 275.
19. P. Langacker, M. Luo, and A. K. Mann, Rev. Mod. Phys. 64 (1992) 87.
20. See, for example, W. Hollik, in the Proceedings of the VII Swieca Summer School, editors O. J. P. Eboli and V. O. Rivelles (World Scientific, Singapore, 1994).
21. G. Passarino and M. Veltman, Nucl. Phys. B160 (1979) 151.
22. G. Altarelli, R. Barbieri, and F. Caravaglios, Nucl. Phys. B405 (1993) 3.
23. “Combined Preliminary data on Z0 Parameters from the LEP experiments and Constraints on the Standard Model”, The LEP Collaborations and The LEP Electroweak Working Group, report in preparation.
24. D. Bardin et al., Z. Phys. C44 (1989) 493; Comput. Phys. Commun. 59 (1990) 303; Nucl. Phys. B351 (1991) 1; Phys. Lett. B255 (1991) 290.
Fig. 1. Allowed regions (90% CL) in the plane $M_{LQ}-g_{LQ}$ for third generation leptoquarks. The values of all the other parameters ($m_{\text{top}}, M_H, \alpha_s, M_Z, \alpha_{em}$, and $G_F$) were allowed to vary. The solid lines stand for left-handed leptoquarks while the dashed ones are for right-handed leptoquarks. Notice the change of scale in the last window.