Production of Scalar and Vector Leptoquarks in e^+e^- Annihilation¹

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Abstract

A systematic study in a model-independent framework is presented for the production of scalar and vector leptoquarks in e^+e^- annihilation. We consider the most general couplings to the known fermions and gauge bosons which are dimensionless, baryon and lepton number conserving, family-diagonal, and $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant. Formal expressions are derived for production cross sections and differential distributions. Numerical predictions are discussed for LEP energies and beyond.

¹ This work was supported in parts by the Alexander von Humboldt-Foundation, the German Ministry for Research and Technology (BMFT) under contract number 055ZT91I-01, and by CED Science Project No. SCI-CT 91-0729.

1 Introduction

In the standard model the quark and lepton degrees of freedom are formally independent. On the other hand, they are rather similar with respect to the family and multiplet structure of the electroweak interactions. One important reason for the parallel assignment of quarks and leptons is the cancellation of triangle anomalies, necessary for the standard model to be a consistent quantum field theory. This interrelation might result from a more fundamental theory of quarks and leptons, which is then expected to contain bosonic fields mediating lepton–quark transitions. Examples for such theories are grand–unified models [1], the Pati–Salam $SU(4)$ model [2], and models of quark and lepton substructure [3].

In general, these new fields can give rise to lepton and baryon number non–conservation and flavour changing neutral current processes. In this case, there are strong experimental bounds, in particular, from proton lifetime measurements and rare processes [4]. However, bosons which exclusively induce lepton–quark transitions, usually called leptoquarks, are relatively weakly constrained provided the couplings are restricted to a single fermion family. They can still be light enough to be produced and observed at existing and projected colliders. While the production in pp collisions [5] mainly proceeds through the leptoquark–gluon couplings and in ep scattering [6, 7] dominantly through the leptoquark–fermion couplings, in e^+e^- annihilation [8–11] the leptoquark couplings to the electroweak gauge bosons *and* fermions play a rôle. In all cases, the signatures depend on the structure of the leptoquark–fermion couplings which determine the decay channels and branching fractions.

The interactions of leptoquarks with the known particles can be described by an effective Lagrangian, valid at sufficiently low energies. One can either take it from a concrete model, or make a model–independent ansatz based on few general assumptions. As a minimal requirement, it appears reasonable to demand the effective Lagrangian to respect the $SU(3)_c \times SU(2)_L \times U(1)_Y$ symmetry of the standard model [7]. Then, the possible representations of the leptoquarks with respect to the gauge groups and the couplings to the gauge bosons are completely determined. Only the strengths of the leptoquark–fermion couplings remain as free parameters.

In previous investigations of leptoquark production in e^+e^- annihilation the focus has been on particular species of scalar leptoquarks expected in E_6 models [8, 9]. In this paper, apart from experimental constraints, we only impose the above symmetry requirement but do not refer to specific models in order to keep the analysis as model–independent as possible. Furthermore, we perform a systematic study for scalar *and* vector leptoquarks. Starting from a general effective Lagrangian (section 2) we provide all necessary formal expressions for production cross sections and angular distributions (section 3). Numerical predictions are then presented and discussed for three interesting cms energies: $\sqrt{s} = M_Z, 190 \text{ GeV}$, and 1 TeV (section 4).

2 Effective Lagrangian

Our analysis is based on the most general effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{|F|=2}^f + \mathcal{L}_{F=0}^f + \mathcal{L}^{\gamma,Z} \quad (1)$$

which describes the interactions of scalar and vector leptoquarks with fermions ($\mathcal{L}^f$) and electroweak gauge bosons ($\mathcal{L}^{\gamma,Z}$), and satisfies the following requirements: (i) baryon (B) and lepton (L) number conservation, (ii) non-derivative and family-diagonal couplings to lepton-quark pairs, (iii) $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance. Adopting the notation of ref. [7], the leptoquark-fermion interactions are given by

$$\begin{aligned}\mathcal{L}_{|F|=2}^f &= (g_{1L}\bar{q}_L^c i\tau_2 l_L + g_{1R}\bar{u}_R^c e_R)S_1 \\ &+ \tilde{g}_{1R}\bar{d}_R^c e_R \tilde{S}_1 + g_{3L}\bar{q}_L^c i\tau_2 \vec{l}_L \vec{S}_3 \\ &+ (g_{2L}\bar{d}_R^c \gamma^\mu l_L + g_{2R}\bar{q}_L^c \gamma^\mu e_R)V_{2\mu} \\ &+ \tilde{g}_{2L}\bar{u}_R^c \gamma^\mu l_L \tilde{V}_{2\mu} + h.c.,\end{aligned}\tag{2}$$

$$\begin{aligned}\mathcal{L}_{F=0}^f &= (h_{2L}\bar{u}_R l_L + h_{2R}\bar{q}_L i\tau_2 e_R)R_2 + \tilde{h}_{2L}\bar{d}_R l_L \tilde{R}_2 \\ &+ (h_{1L}\bar{q}_L \gamma^\mu l_L + h_{1R}\bar{d}_R \gamma^\mu e_R)U_{1\mu} \\ &+ \tilde{h}_{1R}\bar{u}_R \gamma^\mu e_R \tilde{U}_{1\mu} + h_{3L}\bar{q}_L \vec{\tau} \gamma^\mu l_L \vec{U}_{3\mu} + h.c.\end{aligned}\tag{3}$$

where $F = 3B + L$, and q_L and l_L denote $SU(2)_L$ quark and lepton doublets, respectively, while u_R , d_R , and e_R are the corresponding singlet fields. Charge conjugated fields are denoted by $f^c = C\bar{f}^T$, and τ_i are the Pauli matrices. For simplicity, the color and family indices are suppressed. In most concrete models only few of the terms appearing in (2) and (3) are actually present. However, as shown recently [12], one can also construct models which lead to the whole set of leptoquark species listed above.

The interactions of leptoquarks with the photon and Z boson are generically described by

$$\mathcal{L}^{\gamma,Z} = \sum_{\text{scalars}} [(D^\mu \Phi)^\dagger (D_\mu \Phi) - M^2 \Phi^\dagger \Phi] + \sum_{\text{vectors}} \left[-\frac{1}{2} G_{\mu\nu}^\dagger G^{\mu\nu} + M^2 \Phi^{\mu\dagger} \Phi_\mu \right]\tag{4}$$

where the fields Φ and Φ^μ denote the scalar and vector leptoquarks $S_1, \tilde{S}_1, \vec{S}_3, R_2, \tilde{R}_2$, and $V_2^\mu, \tilde{V}_2^\mu, U_1^\mu, \tilde{U}_1^\mu, \vec{U}_3^\mu$, respectively. The field strength tensor $G_{\mu\nu}$ is defined by $G_{\mu\nu} = D_\mu \Phi_\nu - D_\nu \Phi_\mu$, and D_μ is the appropriate covariant derivative

$$D_\mu = \partial_\mu - ieQ^\gamma A_\mu - ieQ^Z Z_\mu\tag{5}$$

ensuring gauge invariance and implementing the minimal coupling of leptoquarks to the gauge bosons. Correspondingly, $Q^\gamma = Q_{em}$ is the electromagnetic charge of a given leptoquark and

$$Q^Z = \frac{T_3 - Q_{em} \sin^2 \theta_w}{\cos \theta_w \sin \theta_w},\tag{6}$$

with T_3 being the third component of the weak isospin and θ_w being the weak mixing angle. In table 1, we summarize the different leptoquark fields appearing in the Lagrangian (1), and list their quantum numbers.

The relevant Feynman rules follow from (2-4). In particular, for the vertex involving a vector leptoquark and a gauge boson one has

$$-ieQ^{\gamma(Z)}(\Phi) [(p+p')_\mu g_{\alpha\beta} - p'_\alpha g_{\beta\mu} - p_\beta g_{\alpha\mu}]\tag{7}$$

where p and p' are taken to be the ingoing and outgoing momenta, respectively. Note that (7) differs from a three-gauge-boson vertex¹. The couplings to Higgs bosons need not be specified here since contributions from Higgs-boson exchange to the processes under consideration are suppressed by the small electron mass. In fact, we set $m_e = m_{u,d} = 0$ throughout this paper.

3 Production cross sections

The lowest order Feynman diagrams for leptoquark production in e^+e^- annihilation² are shown in figure 1. Straightforward evaluation using the couplings given in section 2 yields the following angular distributions and cross sections for unpolarized beams.

3.1 Scalar Leptoquarks

For the angular distribution of scalar leptoquarks one finds

$$\frac{d\sigma_{\text{scalar}}}{d\cos\theta} = \frac{3\pi\alpha^2}{8s}\beta^3\sin^2\theta \sum_{a=L,R} \left\{ |\kappa_a(s)|^2 + \left(\frac{\lambda_a}{e}\right)^2 \frac{4\text{Re}[\kappa_a(s)]}{t(\beta, \cos\theta)} + \left(\frac{\lambda_a}{e}\right)^4 \frac{4}{t^2(\beta, \cos\theta)} \right\}. \quad (8)$$

This result applies to both $F = 0$ and $|F| = 2$ type leptoquarks. In the above,

$$\kappa_a(s) = \sum_{V=\gamma,Z} Q_a^V(e) \frac{s}{s - M_V^2 + iM_V\Gamma_V} Q^V(\Phi), \quad (9)$$

where $Q_{L,R}^\gamma(e) = -1$, $Q_L^Z(e) = (-1/2 + \sin^2\theta_w)/\cos\theta_w\sin\theta_w$, and $Q_R^Z(e) = \tan\theta_w$ are the relevant electroweak charges for the electron. The corresponding leptoquark charges can be found in section 2. M_V and Γ_V denote the mass and the width of the neutral current gauge bosons. Furthermore, the leptoquark-fermion couplings $\lambda_{L,R}$ can be inferred from table 1. Finally, $t(\beta, \cos\theta) = 1 + \beta^2 - 2\beta\cos\theta$ with $\beta = \sqrt{1 - 4M_\Phi^2/s}$. The photon-exchange contribution to (8) was derived already a long time ago in [14]. The full expression (8) agrees with the result obtained in [9].

The integrated cross section reads

$$\sigma_{\text{scalar}} = \frac{\pi\alpha^2\beta^3}{2s} \sum_{a=L,R} \left\{ |\kappa_a(s)|^2 + \left(\frac{\lambda_a}{e}\right)^2 \text{Re}[\kappa_a(s)] F_1(\beta) + \left(\frac{\lambda_a}{e}\right)^4 F_2(\beta) \right\} \quad (10)$$

where

$$F_1(\beta) = \frac{3}{2} \left(\frac{1+\beta^2}{\beta^2} - \frac{(1-\beta^2)^2}{2\beta^3} \ln \frac{1+\beta}{1-\beta} \right), \quad (11)$$

$$F_2(\beta) = 3 \left(-\frac{1}{\beta^2} + \frac{1+\beta^2}{2\beta^3} \ln \frac{1+\beta}{1-\beta} \right). \quad (12)$$

¹This contrasts with ref. [11] where gauge couplings are assumed for the vector leptoquarks appearing in the Abbott-Fahri model [13]. Since we consider it unlikely that light leptoquarks are gauge bosons, we do not make this restrictive assumption.

²Other interesting processes not considered here include single production and pair-production via boson-boson fusion.

For sufficiently large energies, $s \gg M_Z^2, M_\Phi^2$, the above formulae simplify to

$$\sigma_{\text{scalar}} \approx \frac{\pi \alpha^2}{2s} \sum_{a=L,R} \left\{ \kappa_a^2 + 3 \left(\frac{\lambda_a}{e} \right)^2 \kappa_a + 3 \left(\frac{\lambda_a}{e} \right)^4 \left[\ln \left(\frac{s}{M_\Phi^2} \right) - 1 \right] \right\} \quad (13)$$

with $\kappa_a = \sum_{V=\gamma,Z} Q_a^V(e) Q^V(\Phi)$.

3.2 Vector Leptoquarks

The angular distribution of vector leptoquarks is given by

$$\frac{d\sigma_{\text{vector}}}{d\cos\theta} = \frac{3\pi\alpha^2}{8M_\Phi^2} \beta \sum_{a=L,R} \left\{ |\kappa_a(s)|^2 \tilde{F}_1(\theta, \beta) + \left(\frac{\lambda_a}{e} \right)^2 \text{Re}[\kappa_a(s)] \tilde{F}_2(\theta, \beta) + \left(\frac{\lambda_a}{e} \right)^4 \tilde{F}_3(\theta, \beta) \right\} \quad (14)$$

with

$$\tilde{F}_1(\theta, \beta) = \beta^2 \left[1 + \frac{1}{4}(1 - 3\beta^2) \sin^2 \theta \right], \quad (15)$$

$$\tilde{F}_2(\theta, \beta) = 2 \left[1 - \frac{1 - \beta^2}{t(\beta, \cos \theta)} \right] (1 - \beta^2) + 4\beta^2 - \beta^2 \left[1 - 2 \frac{1 - \beta^2}{t(\beta, \cos \theta)} \right] \sin^2 \theta, \quad (16)$$

$$\tilde{F}_3(\theta, \beta) = 4 + \frac{\beta^2}{4} \left\{ (1 - \beta^2) \left[\frac{4}{t(\beta, \cos \theta)} \right]^2 + \frac{s}{M_\Phi^2} \right\} \sin^2 \theta. \quad (17)$$

Again, identical expressions are obtained for $F = 0$ and $|F| = 2$ leptoquarks.

From this one derives the following integrated cross section:

$$\sigma_{\text{vector}} = \frac{\pi \alpha^2 \beta}{2M_\Phi^2} \sum_{a=L,R} \left\{ |\kappa_a(s)|^2 \tilde{F}_1(\beta) + \left(\frac{\lambda_a}{e} \right)^2 \text{Re}[\kappa_a(s)] \tilde{F}_2(\beta) + \left(\frac{\lambda_a}{e} \right)^4 \tilde{F}_3(\beta) \right\} \quad (18)$$

where

$$\tilde{F}_1(\beta) = \beta^2 \left(\frac{7 - 3\beta^2}{4} \right), \quad (19)$$

$$\tilde{F}_2(\beta) = \frac{15}{4} + 2\beta^2 - \frac{3}{4}\beta^4 - \frac{3}{8\beta}(1 - \beta^2)^2(5 - \beta^2) \ln \frac{1 + \beta}{1 - \beta}, \quad (20)$$

$$\tilde{F}_3(\beta) = 3(1 + \beta^2) + \frac{\beta^2}{4} \frac{s}{M_\Phi^2} + \frac{3}{2\beta}(1 - \beta^4) \ln \frac{1 + \beta}{1 - \beta}. \quad (21)$$

Asymptotically, for $s \gg M_Z^2, M_\Phi^2$, the pure s-channel contribution and the interference of the s- and t-channel terms approach a finite value, whereas the pure t-channel contribution grows proportional to s . This behaviour is reminiscent of the t-channel contribution to $e^+e^- \rightarrow W^+W^-$. However, as is well-known, in the latter case the potentially dangerous term is cancelled by corresponding contributions from the s-channel graphs. This is due to the special structure of the three-gauge-boson couplings which differ from the coupling (7) used here. Yet, in the spirit of an effective theory, the behaviour of the cross section (18) is perfectly acceptable as long as the energy is kept sufficiently low. At high energies it is assumed that the effective description provided by the Lagrangian (1) is superceeded by a more fundamental theory in which the increase of the cross section with s is eventually damped and unitarity is preserved.

4 Numerical Results

For the purpose of numerical illustrations we consider three cases: production at the Z pole, at $\sqrt{s} = 190$ GeV (LEP 200) and at $\sqrt{s} = 1$ TeV (linear collider)³. We discuss the characteristics of the production mechanisms and the decay signatures. In particular, we compare the expectations for two rather different scenarios, one in which the couplings of the leptoquarks to the fermions are much weaker than the couplings to the gauge bosons, and one in which they are comparable.

The masses (M_Φ) and fermion couplings ($\lambda_{L,R}$) of leptoquarks are strongly constrained by experimental data on rare processes [4]. Most importantly, family-nondiagonal couplings involving the first and second family are bounded by $\lambda < M_\Phi/100$ TeV. This constraint is avoided in the family-diagonal scenario considered here. The next strongest bound applying to the leptoquarks S_1 and R_2 is given by $\sqrt{\lambda_L \lambda_R} < M_\Phi/10$ TeV. For these leptoquarks to be light enough for production at LEP or TeV linear colliders we must assume one or both of the couplings $\lambda_{L,R}$ to be very small: $\lambda \ll e$. Finally, lepton-quark universality puts a bound on the couplings to left-handed leptons: $\lambda_L < M_\Phi/1.7$ TeV. This bound has been derived specifically for S_1 , but probably applies to other leptoquarks with left-handed couplings as well. In the following we always take $\lambda \leq e \approx 0.3$.

Let us first concentrate on the individual production rates of the leptoquarks listed in table 1. For $\lambda/e \ll 1$, the cross sections are determined by the pure boson-exchange terms in (10) and (18). It is convenient to use S_1 and U_1 as reference cases and describe the expectations for the other leptoquark species relative to them. At the Z pole, using $M_Z = 91.16$ GeV, $\Gamma_Z = 2.534$ GeV, $\alpha = 1/128.8$ and $\sin^2 \theta_w = 0.230$, and assuming $M_\Phi = 40$ GeV, we find $\sigma(S_1) = 15.0 pb$ and $\sigma(U_1) = 0.49 nb$. In figure 2 the corresponding cross sections are shown for $\sqrt{s} = 190$ GeV and 1 TeV as functions of the leptoquark mass. Considering scalar and vector states separately, the relative cross sections at fixed values of $\sqrt{s}$ and M_Φ are simply given by $\sum_{a=L,R} |\kappa_a(s)|^2$. These factors include the electroweak charges Q^γ and Q^Z as specified in (9), and vary in value over about two orders of magnitude. Correspondingly large is the difference in the cross sections for the various states. Among the scalar leptoquarks, S_1 and $S_3^{1/3}$ have the smallest cross sections, while $S_3^{-2/3}$ has the largest one for $\sqrt{s} = M_Z$, and $S_3^{4/3}$ for $\sqrt{s} \geq 190$ GeV. Similarly, in the case of vector leptoquarks the minimal cross section is obtained for U_1 and $U_3^{2/3}$, while the maximal cross section is found at $\sqrt{s} = M_Z$ for $U_3^{-1/3}$ and at $\sqrt{s} \geq 190$ GeV for $U_3^{5/3}$. Here, the superscript identifies the members of the isospin triplets by their electromagnetic charge. The absolute cross section values for the above states can be read off from table 2.

If $\lambda/e = \mathcal{O}(1)$ the t -channel process displayed in figure 1 can have strong influence on the production cross sections. As pointed out above, this possibility is not excluded by existing data, at least for some couplings appearing in (2) and (3) and for restricted mass ranges. However, for family-diagonal couplings, t -channel exchange can obviously only take place in e^+e^- annihilation for leptoquarks which interact with the fermions of the first family. Leptoquarks associated with the second and third family are produced exclusively by the s -channel mechanisms.

In figure 3 we illustrate the t -channel effect using again S_1 and U_1 as examples. For the

³Illustrations for the case of a 500 GeV e^+e^- collider were given elsewhere [10].

fermion couplings we take $\lambda_L = 0$ and $\lambda_R/e = 0.3$ or 1 , a choice which safely circumvents the present bounds. It is interesting to note in this respect that the impact of t-channel exchange with left-handed couplings is very similar to the one for right-handed couplings. As can be clearly seen from figure 3, for $\lambda/e = 1$ the production cross sections are completely dominated by the t-channel process. However, for $\lambda/e = 0.3$ the influence is already quite moderate. In this case, the cross section for the scalar S_1 shrinks due to destructive s- and t-channel interference. The same is true for the vector U_1 , except close to the threshold and at large energies as compared to the mass. The qualitative behaviour is the same for $\sqrt{s} = 190 \text{ GeV}$ and $\sqrt{s} = 1 \text{ TeV}$ in the mass ranges considered. For completeness, we mention that at the Z pole for $M_\Phi = 40 \text{ GeV}$ the cross sections are affected by less than 1 % for fermion couplings $\lambda_R/e = 0.3$. If λ_R/e is of $\mathcal{O}(1)$ the effect may reach 10 to 20 %.

We have seen that the s-channel mechanism is characterized by strong variations in the size of the cross sections for different leptoquark species. This is a direct consequence of the differences in the $SU(2)_L \times U(1)_Y$ quantum numbers. In contrast, if t-channel exchange is the dominant process a priori no particular pattern is expected in the relative magnitudes of the cross sections. This is obvious from (10) and (18), and from table 1 where apart from Clebsch-Gordon coefficients in the case of $SU(2)_L$ triplets no other factors appear in the couplings $\lambda_{L,R}$. However, the possibility of t-channel dominance seems to exist only for particular types of leptoquarks. Firstly, the states $S_3^{-2/3}$, $\tilde{R}_2^{-1/3}$, $\tilde{V}_2^{-2/3}$, and $U_3^{-1/3}$ do not couple to electron-quark pairs at all. Secondly, the left-handed couplings λ_L are presumably rather weak as indicated by the universality bound. Therefore, it is only the cross sections for states with couplings to the right-handed electron, that is S_1 , $\tilde{S}_1$, R_2 , V_2 , U_1 , and $\tilde{U}_1$, which may differ substantially from the predictions for γ and Z exchange.

Let us now turn to the angular distributions. In figure 4, the normalized distributions for the scalar leptoquark S_1 and the vector leptoquark U_1 are plotted for $\sqrt{s} = 1 \text{ TeV}$ and $\beta = 0.6$. These distributions reflect the spin nature, but vary only slightly with the electroweak quantum numbers. Also the dependence on $\sqrt{s}$ is rather weak in the energy range from $\sqrt{s} = 190 \text{ GeV}$ to 1 TeV . For $\lambda_{L,R}/e \ll 1$ the angular distribution for scalars behaves like $\sin^2 \theta$, whereas the distribution for vector leptoquarks is essentially flat. In the presence of sizeable fermion couplings, the distributions are shifted in the forward direction. This is illustrated in figure 4. In the case of scalar leptoquarks a pronounced forward peak appears for $\lambda_R/e = 1$, while for $\lambda_L/e = 0.3$ the $\sin^2 \theta$ distribution is shifted slightly into the backward direction. For vector leptoquarks one observes a forward peak in both cases. However, the overall effect is much smaller than for scalars and $\lambda/e = 1$. In addition, there are slight differences for couplings to left- and right-handed leptons due to the interference with Z -boson exchange. If leptoquarks are discovered, the angular distribution may be used to determine their spin.

Leptoquarks decay to lepton-quark pairs as described by the Lagrangians (2) and (3). For $|F| = 2$ leptoquarks associated with the first family the following decay modes exist: $\bar{\Phi} \rightarrow \nu_e u$, $e^- u$, $\nu_e d$, $e^- d$, and the charge conjugated processes. Obviously, the first and fourth channel refer to states with charge $+2/3$ and $-4/3$, respectively, and the second and third to states with charge $-1/3$. For $F = 0$ leptoquarks one has to interchange quarks and antiquarks. Analogous decay modes with $l = \mu, \nu_\mu$ and $q = s, c$ are expected for second family leptoquarks. In the case of leptoquarks which couple to the third family, decays involving the top quark may be suppressed or forbidden by the heavy top mass. Consequently, at

LEP 200 the dominant channels are $\bar{\Phi} \rightarrow \tau^- b$ and $\nu_\tau b$ where instead of the bottom quark one may also have the corresponding antiquark.

The branching ratios for these decays can easily be inferred from table 1. For the majority of states they are uniquely determined and extremely simple as one either has only a single decay channel or a single (right- or left-handed) coupling, or both. Among all the states listed in table 1, only $S_1, V_2^{1/3}, U_1$, and $R_2^{2/3}$ have branching fractions which depend on the relative magnitude of λ_R and λ_L . For example, taking $\lambda_R = \lambda_L$ one predicts $B(\bar{S}_1 \rightarrow e^- u) = 2 B(\bar{S}_1 \rightarrow \nu_e d) = \frac{2}{3}$ and $B(\bar{V}_2^{-1/3} \rightarrow e^- u) = B(\bar{V}_2^{-1/3} \rightarrow \nu_e d) = \frac{1}{2}$. In contrast, $\lambda_L = 0$ yields $B(\bar{S}_1 \rightarrow e^- u) = B(\bar{V}_2^{-1/3} \rightarrow e^- u) = 1$, while $\lambda_R = 0$ gives $B(\bar{S}_1 \rightarrow e^- u) = B(\bar{S}_1 \rightarrow \nu_e d) = \frac{1}{2}$ and $B(\bar{V}_2^{-1/3} \rightarrow \nu_e d) = 1$. A similar pattern is predicted for $\bar{U}_1, \bar{R}_2^{-2/3} \rightarrow e^- \bar{d}, \nu_e \bar{u}$.

Pair-production and subsequent decays of leptoquarks lead to three different types of events: $e^+ e^- \rightarrow l^+ l^- + 2 \text{ jets}$, $l \nu + 2 \text{ jets}$, and $\nu \bar{\nu} + 2 \text{ jets}$. Since leptoquark initiated transitions between different fermion families must be highly suppressed, the leptons in a given event should carry identical flavours. In particular, it appears very unlikely that $e\mu$ events stem from leptoquarks with masses in and below the TeV range. The branching ratios for the allowed final states are summarized in table 3.

Finally, it is important to note that leptoquarks are relatively narrow states. The partial width for a single decay channel is given by

$$\Gamma = 0.4 \text{ GeV } f \left(\frac{\lambda}{e} \right)^2 \frac{M_\Phi}{200 \text{ GeV}} \quad (22)$$

where $f = 1$ for scalars and $f = 2/3$ for vectors. Since leptoquarks are coloured, they must fragment into hadrons within a distance of the order of 1 fm . In fact, the hadronization is expected to proceed similarly as in the case of heavy quarks.

5 Conclusions

Extensions of the standard model interrelating leptons and quarks by symmetry or substructure predict the existence of leptoquarks. For masses accessible at present and future colliders, low-energy experiments put stringent bounds on the couplings of leptoquarks to lepton-quark pairs. In $e^+ e^-$ annihilation the existence of leptoquarks can be probed irrespective of these constraints through their couplings to the photon and Z boson. Moreover, these tests can be performed simultaneously for a rather general class of leptoquarks without referring to a particular model.

In this paper, we set up a model-independent theoretical framework based on an effective Lagrangian. The latter is required to be $SU_c(3) \times SU_L(2) \times U_Y(1)$ invariant and to respect the low-energy bounds. We provide all necessary analytic expressions for cross sections and angular distributions. Furthermore, we explain and illustrate, by numerical examples, the characteristic features of the production and decay processes.

It is pointed out that the production cross sections for different leptoquark species can vary by as much as two orders of magnitude. This variation is a direct consequence of differences in the electroweak charges and thus a useful handle to determine the properties of leptoquarks in the event of a discovery. In addition, we show that the angular distributions

allow for a determination of the spin of leptoquarks and sensitive tests of the strength of their couplings to electron–(anti)quark pairs. Finally, we give the complete set of branching fractions for the channels $e^+e^- \rightarrow nl + m\nu + 2jets$ ($n + m = 2$) relevant for leptoquark searches.

From recent searches at LEP [15] one has derived mass bounds close to the kinematical limit, approximately, $M_\Phi > 41$ to 44 GeV. Although most of these analyses are performed explicitly for the scalar leptoquark S_1 , the above bound also applies to the other scalar as well as to the vector leptoquarks considered in this paper. This follows from the fact that S_1 has the smallest cross section of all and that all species lead with comparable branching fractions to the favourable signature, that is events containing two charged leptons and two jets.

Similar tests will be possible at LEP 200. Assuming an integrated luminosity of 200 pb^{-1} and requiring at least 10 events, one should be able to reach masses between 60 GeV (S_1) and 90 GeV ($\vec{S}_3$) for scalars, and around 90 GeV for vectors. A 1 TeV Linear Collider can be expected to push the limit of direct observability to $M_\Phi \approx 400$ GeV provided the integrated luminosity amounts to 10 fb^{-1} in the more difficult case of the S_1 , and to 1 fb^{-1} for the more favourable scalar and for all vector leptoquarks.

References

- [1] For reviews and references see e.g. P. Langacker, Phys. Rep. **72** (1981) 185;
J.A. Hewett and T.G. Rizzo, Phys. Rep. **183** (1989) 193.
- [2] J.C. Pati and A. Salam, Phys. Rev. **D10** (1974) 275.
- [3] B. Schrempp and F. Schrempp, DESY 84-055 (1984); Phys. Lett. **B153** (1985) 101;
W. Buchmüller, Acta Phys. Austr. Suppl. **XXVII** (1985) 517.
- [4] W. Buchmüller and D. Wyler, Phys. Lett. **B177** (1986) 377.
- [5] J. L. Hewett, Phys. Rev. **D37** (1988) 3165;
M. De Montigny and L. Marleau, Phys. Rev. **D40** (1989) 2869, 3616.
- [6] J. Wudka, Phys. Lett. **B167** (1986) 338.
- [7] W. Buchmüller, R. Rückl and D. Wyler, Phys. Lett. **B191** (1987) 442.
- [8] J. L. Hewett and T.G. Rizzo, Phys. Rev. **D36** (1987) 3367;
N.D.Tracas and S.D.P. Vlassopoulos, Phys. Lett. **B220** (1989) 285.
- [9] D. Schaile and P.M. Zerwas, in: Proc. of the Workshop on Physics at Future Accelerators, La Thuile and Geneva, 1987, ed. J.H. Mulvey, CERN 87-07, Vol. **II**, p. 251;
A.Djouadi, M. Spira and P.M. Zerwas, in: Proc. of the Workshop on e^+e^- Collisions at 500 GeV: The Physics Potential, Munich, Annecy, Hamburg, 1991, ed. P.M. Zerwas, DESY 92-123B, p. 561.
- [10] J. Blümlein and R. Rückl, in: Proc. of the Workshop on e^+e^- Collisions at 500 GeV: The Physics Potential, Munich, Annecy, Hamburg, 1991, ed. P.M. Zerwas, DESY 92-123B, p. 595.
- [11] J.E. Cieza Montalvo and O.J.P. Eboli, preprint IC/92/156.
- [12] P. H. Frampton, Mod. Phys. Lett. **A7** (1992) 559.
- [13] L. Abbott and E. Fahri, Phys. Lett. **B101** (1981) 69; Nucl. Phys. **B189** (1981) 547.
- [14] N. Cabibbo and R. Gatto, Phys. Rev. **124** (1961) 1577.
- [15] B. Adeva et al., L3 collaboration, Phys. Lett. **B261** (1991) 169;
G. Alexander et al., OPAL collaboration, Phys. Lett. **B263** (1991) 123;
P. Abreu et al., DELPHI collaboration, Phys. Lett. **B275** (1992) 222;
D. Decamp et al., ALEPH collaboration, Phys. Rep. **216** (1992) 253.

leptoquark (Φ)	spin	F	colour	T_3	Q_{em}	$\lambda_L(lq)$	$\lambda_R(lq)$	$\lambda_L(\nu q)$
S_1	0	-2	$\bar{3}$	0	1/3	g_{1L}	g_{1R}	$-g_{1L}$
$\tilde{S}_1$	0	-2	$\bar{3}$	0	4/3	0	$\tilde{g}_{1R}$	0
$\vec{S}_3$	0	-2	$\bar{3}$	+1	4/3	$-\sqrt{2}g_{3L}$	0	0
				0	1/3	$-g_{3L}$	0	$-g_{3L}$
				-1	-2/3	0	0	$\sqrt{2}g_{3L}$
R_2	0	0	3	1/2	5/3	h_{2L}	h_{2R}	0
				-1/2	2/3	0	$-h_{2R}$	h_{2L}
$\tilde{R}_2$	0	0	3	1/2	2/3	$\tilde{h}_{2L}$	0	0
				-1/2	-1/3	0	0	$\tilde{h}_{2L}$
$V_{2\mu}$	1	-2	$\bar{3}$	1/2	4/3	g_{2L}	g_{2R}	0
				-1/2	1/3	0	g_{2R}	g_{2L}
$\tilde{V}_{2\mu}$	1	-2	$\bar{3}$	1/2	1/3	$\tilde{g}_{2L}$	0	0
				-1/2	-2/3	0	0	$\tilde{g}_{2L}$
$U_{1\mu}$	1	0	3	0	2/3	h_{1L}	h_{1R}	h_{1L}
$\tilde{U}_{1\mu}$	1	0	3	0	5/3	0	$\tilde{h}_{1R}$	0
$\vec{U}_{3\mu}$	1	0	3	+1	5/3	$\sqrt{2}h_{3L}$	0	0
				0	2/3	$-h_{3L}$	0	h_{3L}
				-1	-1/3	0	0	$\sqrt{2}h_{3L}$

Table 1: Quantum numbers and couplings to lepton-(anti)quark pairs of the leptoquarks described by the Lagrangians (2) and (3). The particle-antiparticle convention is such that $\bar{\Phi}_{F=2} \rightarrow lq$ and $\bar{\Phi}_{F=0} \rightarrow l\bar{q}$.

	scalars		vectors	
	min	max	min	max
$\sqrt{s} = M_Z$	$S_1, S_3^{1/3}$	$S_3^{-2/3}$	$U_1, U_3^{2/3}$	$U_3^{-1/3}$
$M_\Phi = 40 \text{ GeV}$	15.02	1819	492	17721
$\sqrt{s} = 190 \text{ GeV}$	$S_1, S_3^{1/3}$	$S_3^{4/3}$	$U_1, U_3^{2/3}$	$U_3^{5/3}$
$M_\Phi = 80 \text{ GeV}$	0.040	1.18	1.366	12.08
$\sqrt{s} = 1 \text{ TeV}$	$S_1, S_3^{1/3}$	$S_3^{4/3}$	$U_1, U_3^{2/3}$	$U_3^{5/3}$
$M_\Phi = 430 \text{ GeV}$	0.001	0.029	0.060	0.368

Table 2: Maximum and minimum cross sections in pb assuming $\lambda_{L,R} = 0$. The cross sections for the remaining leptoquark states in table 1 ly in between these values. The masses correspond roughly to $\beta = 0.5$.

states	$l^+l^- + 2jets$	$l\nu + 2jets$	$\nu\bar{\nu} + 2jets$
$S_1 \quad U_1$	$\frac{4}{9} \quad 1 \quad \frac{1}{4}$	$\frac{4}{9} \quad 0 \quad \frac{1}{2}$	$\frac{1}{9} \quad 0 \quad \frac{1}{4}$
$R_2^{2/3} \quad V_2^{1/3}$	$\frac{1}{4} \quad 1 \quad 0$	$\frac{1}{2} \quad 0 \quad 0$	$\frac{1}{4} \quad 0 \quad 1$
$S_3^{1/3} \quad U_3^{2/3}$	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{4}$
$\tilde{S}_1 \quad S_3^{4/3} \quad R_2^{5/3} \quad \tilde{R}_2^{2/3}$ $V_2^{4/3} \quad \tilde{V}_2^{1/3} \quad \tilde{U}_1 \quad U_3^{5/3}$	1	0	0
$S_3^{-2/3} \quad \tilde{R}_2^{-1/3} \quad \tilde{V}_2^{-2/3} \quad U_3^{-1/3}$	0	0	1

Table 3: Branching ratios for final states arising from the decays of leptoquarks associated with the first ($l = e$) and second ($l = \mu$) family. The sequence of branching fractions given in the second and third row refers to the assumptions $\lambda_L = \lambda_R$, $\lambda_L = 0$, and $\lambda_R = 0$, respectively.

Figure 1: Feynman diagrams contributing to leptoquark pair-production in e^+e^- annihilation.

Figure 2: Mass dependence of the production cross sections at $\sqrt{s} = 190$ GeV (a) and 1 TeV (b) for the reference scalar (S_1) and vector (U_1) leptoquarks. The fermion couplings are assumed to be negligible ($\lambda_L = \lambda_R = 0$) in comparison to the electroweak couplings.

Figure 3: Effect of right-handed fermion couplings, $\lambda_R/e = 0.3$ (dashed) and 1 (solid), on the production cross sections for scalar (S_1) and vector (U_1) leptoquarks at $\sqrt{s} = 190$ GeV (a) and 1 TeV (b).

Figure 4: Angular distributions of the scalar leptoquark S_1 and the vector leptoquark U_1 at $\sqrt{s} = 1$ TeV and for $M_\Phi = 400$ GeV: $\lambda_L = \lambda_R = 0$ (solid); $\lambda_L/e = 0.3$, $\lambda_R = 0$ (dashed); $\lambda_R/e = 1$, $\lambda_L = 0$ (dotted).