Leptoquark/Squark Interpretation of HERA Events: Virtual Effects in $e^+e^-$ Annihilation to Hadrons

J. Kalinowski$^{1,2}$, R. Rückl$^3$,* H. Spiesberger$^4$,* and P.M. Zerwas$^1$

$^1$ Deutsches Elektronen-Synchrotron DESY, D-22607 Hamburg
$^2$ Institute of Theoretical Physics, Warsaw University, PL-00681 Warsaw
$^3$ Institut für Theoretische Physik, Universität Würzburg, D-97074 Würzburg
$^4$ Fakultät für Physik, Universität Bielefeld, D-33501 Bielefeld

ABSTRACT

In reference to the recently observed high $Q^2$, large $x$ events in deep-inelastic positron–proton scattering at HERA, various leptoquark and supersymmetric scenarios are discussed. We study the impact of virtual leptoquark or $R$-parity breaking squark exchange as well as generic contact interaction on the production of quark–antiquark pairs in $e^+e^-$ annihilation, in particular at LEP2.

* Supported by Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie, Bonn, Germany, Contracts 05 7BI92P (9) and 05 7WZ91P (0).
1 Introduction

The recent observation of events in deep-inelastic positron–proton scattering with very high $Q^2$ and large $x$ at HERA [1] has refuelled speculations on physics beyond the Standard Model, in particular on low-mass leptoquark-type particles. Such particles had been suggested a long time ago in a variety of physical scenarios: Pati–Salam SU(4) unification of quarks and leptons [2], grand unified theories such as SU(5) or $E_6$ [3], and composite models [4]. Moreover, in supersymmetric theories squarks couple to lepton–quark pairs if the $R$-symmetry is broken in the trilinear couplings of the superfields [5, 6]. Vector leptoquarks in grand unified theories with both lepton-quark and diquark couplings must be very heavy to suppress proton decay; certain scalar leptoquarks in GUT multiplets could nevertheless be relatively light [7] (disregarding the notorious hierarchy problem for the time being). Squarks in supersymmetric theories should naturally be expected in the mass range of a few hundred GeV.

A general classification of these novel states has been presented in Ref. [8]. In this analysis the couplings of leptoquarks to lepton–quark pairs are assumed to be baryon- and lepton-number conserving in order to avoid rapid proton decay, family diagonal to exclude FCNC processes beyond the CKM mixing, and chiral to preserve the helicity suppression in leptonic pion decay. Moreover, the couplings are taken dimensionless and all interactions are assumed to respect the $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry of the Standard Model. The allowed states can be classified according to spin, weak isospin and fermion number. We adopt the notation of Refs. [9] to conform with the notation generally employed in experimental papers: vector leptoquarks are denoted by $V_I$, scalar leptoquarks by $S_I$; isomultiplets with different hypercharges are distinguished by a tilde.

For convenience the nine possible states of scalar and vector leptoquarks are listed in Table 1. Leptoquarks in the upper (lower) part of Table 1 carry fermion number $F = 2$ ($F = 0$). The couplings are denoted generically by $g_R$ or $g_L$ with $R, L$ refering to the chirality of the lepton. Each state can couple with different strength; for simplicity, the additional indices are suppressed. In principle the two scalar states $S_0$ and $S_{1/2}$ and the two vector states $V_0$ and $V_{1/2}$ could have both chiral $g_R$ and $g_L$ couplings at the same time; however, since the product of the two couplings is constrained very strongly by rare decays [10, 11, 12, 13], we assume only one of the two couplings to be non-zero. The special type of leptoquark that does not induce proton decay (as a result of its quantum numbers) and is compatible with the renormalization of the electroweak mixing angle from the symmetry value 3/8 at the GUT scale down to $\sin^2 \Theta_W \approx 0.23$ at the electroweak scale [4], is marked by an asterisk. Only a small subset of all these states is realized in supersymmetric theories with $R$-parity breaking. Moreover, supersymmetry requires these states to have universal left-handed couplings to leptons.

If leptoquarks or squarks in $R$-parity breaking supersymmetric theories exist, a large

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1We shall generically denote leptoquarks and squarks in $R$-parity breaking scenarios by $LQ$. 

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| $LQ$ | $Q$ | Decay Mode | BR $e^\pm j$ | Coupling | Limits Ref. | HERA estimates | $e_i^-e^+ \to q_k\bar{q}$ |
|------|-----|------------|----------|----------|-------------|----------------|------------------------|
| $S_0$ | $\bar{d}_R$ | $-1/3$ | $\nu_Ld$ | $1/2$ | $g_L$ | $g_L < 0.06$ | 0.40 | $LL$ |
|      |       | $\nu_Ld$ | $1/2$ | $-g_L$ | $g_R < 0.1$ | 0.28 | $RR$ |
| $\tilde{S}_0$ | $-4/3$ | $e_Rd$ | 1 | $g_R$ | $g_R < 0.1$ | 0.30 | $RR$ |
| $S_1$ |       | $+2/3$ | $\nu_Lu$ | 0 | $\sqrt{2}g_L$ | $g_L < 0.09$ | 0.40 | $LL$ |
|      |       | $-1/3$ | $\nu_Ld$ | $1/2$ | $-g_L$ | $g_R < 0.05$ | 0.32 | $LR$ |
|      |       | $-4/3$ | $e_Ld$ | 1 | $-\sqrt{2}g_L$ |              | 0.21 | $LL$ |
| $V_{1/2}$ | $-1/3$ | $\nu_Ld$ | 0 | $g_L$ | $g_L < 0.09$ | 0.30 | $RL$ |
|      |       | $e_Rd$ | 1 | $g_R$ | $g_R < 0.09$ | 0.32 | $LR$ |
| $\tilde{V}_{1/2}$ | $+2/3$ | $\nu_Lu$ | 0 | $g_L$ | $g_L < 0.09$ | 0.32 | $LR$ |
|      |       | $-1/3$ | $\nu_Lu$ | 0 | $g_L$ | $g_L < 0.09$ | 0.32 | $LR$ |
| $S_{1/2}$ | $-2/3$ | $\nu_L\bar{u}$ | 0 | $g_L$ | $g_L < 0.1$ | 0.052 | $RL$ |
|      |       | $e_R\bar{d}$ | 1 | $g_R$ | $g_R < 0.09$ | 0.026 | $RL$ |
| $\tilde{S}_{1/2}$ | $+1/3$ | $\nu_L\bar{d}$ | 0 | $g_L$ | $g_L < 0.1$ | - | - |
|      | $\nu_L$ | $-2/3$ | $e_L\bar{d}$ | 1 | $g_L$ | $g_L < 0.09$ | 0.027 | $RR$ |
| $V_0$ | $-2/3$ | $\nu_L\bar{u}$ | $1/2$ | $g_L$ | $g_L < 0.05$ | 0.080 | $LL$ |
|      | $\nu_L\bar{u}$ | $-2/3$ | $e_R\bar{d}$ | 1 | $g_R$ | $g_R < 0.09$ | 0.056 | $RR$ |
| $\tilde{V}_0$ | $-5/3$ | $e_R\bar{u}$ | 1 | $g_R$ | $g_R < 0.09$ | 0.027 | $RR$ |
| $V_1$ | $+1/3$ | $\nu_L\bar{d}$ | 0 | $\sqrt{2}g_L$ | $g_L < 0.04$ | - | - |
|      | $\nu_L\bar{u}$ | $-2/3$ | $e_L\bar{d}$ | $1/2$ | $-g_L$ | $g_L < 0.09$ | 0.080 | $LL$ |
|      | $\nu_L\bar{u}$ | $-5/3$ | $e_L\bar{u}$ | 1 | $\sqrt{2}g_L$ |              | 0.019 | $LL$ |

Table 1: Scalar ($S$) and vector ($V$) leptoquarks/squarks with electric charges ($Q$), decay modes, branching ratios for charged lepton + jet channels with either $L$ or $R$ couplings, and the Yukawa couplings ($g_{R,L}$) with the most stringent limits from rare decays and estimates from the recent HERA data (see text). The helicity combinations $ik$ ($=L,R$) contributing to the process $e_i^-e^+\to q_k\bar{q}$ are given in the last column. Also shown are possible squark assignments of leptoquark-type states; the special leptoquark singled out in Ref. [11] is marked by an asterisk.

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variety of phenomena are expected to be observed experimentally. In electron/positron–proton collisions, these particles are produced as single resonances, with the rate determined by the strength of the $LQ-l-q$ Yukawa couplings [8, 14]. Pair production is an important production mechanism for leptoquarks in proton–(anti)proton [15], electron–positron [16] and photon–photon collisions [17]. In these reactions, the size of the cross section is determined (modulo anomalous couplings and form-factor effects) by the color, the electric and the electroweak charges of a given leptoquark (if the Yukawa couplings are small [18]). The predictions for the cross sections are therefore, to a first approximation, model-independent. Associated production of $LQ+l$ or $LQ+q$, again mediated by Yukawa interactions, can also be explored in these and other collision processes ($e\gamma$, for example [19]).

In addition to the direct production of leptoquarks/squarks, which is of course of central interest, indirect effects generated by the exchange of virtual $LQ$s, are also important experimental tools to provide cross checks, to explore the nature of these particles, and to have a glimpse at states which are too heavy to be produced directly. Virtual leptoquarks could strongly affect decay processes such as $\pi \rightarrow l\nu$ and $K \rightarrow \pi\nu\bar{\nu}$. These processes are suppressed for the $LQ$s considered here by the restrictions on the Yukawa couplings summarized above. Nevertheless, they still contribute to rare pion and kaon decays, $K^0 - \bar{K}^0$ and $D^0 - \bar{D}^0$ mixing, and atomic parity violation [10, 11, 12]. The strongest constraints can be deduced from atomic parity violation with two exceptions: the constraints on $g_L(S_0)$ and $g_L(V_0)$ which follow from the violation of universality in $\pi \rightarrow l\nu$ [11] or in $\mu$ and $\beta$ decays [12, 13]. The bounds, as derived in Refs. [11] and [12], are presented in Table 1 for the reference mass $m_{LQ} = 200$ GeV; the leptoquarks are taken mass degenerate within the isospin multiplets. In the few hundred GeV range the bounds on the couplings scale linearly with the leptoquark mass. Potential destructive interference effects between different states can lift these bounds considerably.

Additional indirect constraints can be derived from the $t/u$ channel exchange of leptoquarks/squarks in high energy processes, such as Drell–Yan production of lepton pairs in $pp$ and $p\bar{p}$ collisions [20], or $e^+e^-$ annihilation to hadrons [21]. The existing bounds can be improved significantly with the rise of the $e^+e^-$ energy to the LEP2 value close to $\sqrt{s} = 200$ GeV.

In the present analysis we study the production of $q\bar{q}$ pairs in $e^+e^-$ annihilation,

$$e^+e^- \rightarrow q\bar{q}$$  \hspace{1cm} (1)

which is mediated by $\gamma, Z$ exchanges in the $s$-channel (Fig. 1a), and leptoquark/squark exchanges in the $t/u$-channels (Fig. 1b and c). By definition, $t$-channel exchange is associated with $e^- \rightarrow q$ transitions ($F = 0$), while $u$-channel exchange involves $e^- \rightarrow \tilde{q}$ transitions ($F = 2$). We will consider both scalar and vector leptoquarks. Earlier analyses of Ref. [21] will be extended in several aspects: (i) We present a systematic analysis of the exchange of all types of leptoquarks. In particular, generalizing the helicity method of Ref. [22], a representation of the exchange amplitudes can be derived in which potential interference effects between different types of leptoquarks are made transparent. (ii) Simple expressions
Figure 1: Feynman diagrams for $e^+e^- \rightarrow q\bar{q}$ including leptoquarks and squarks in $R$-parity breaking supersymmetric theories.

for the integrated cross sections are presented. (iii) Special emphasis is given to squark exchange mechanisms in supersymmetric theories with $R$-parity breaking, complementing earlier discussions in Ref. [23].

2 Leptoquark/Squark Exchange in $e^+e^-$ Annihilation

After performing the standard Fierz transformations from $t/u$-channel leptoquark/squark exchange amplitudes in $e^+e^- \rightarrow q\bar{q}$ to standard $s$-channel amplitudes, only terms of the structure \((\text{lepton vector current}) \times (\text{quark vector current})\) are generated for leptoquarks carrying either left or right chiral couplings, but not both at the same time. This leads to a transparent representation of the matrix elements. Denoting the helicity amplitudes of the process $e^-_i e^+_j \rightarrow q_k \bar{q}_l$ with $i, j = R, L$ by $f_{ik}$ and the spin-density matrix elements, which depend on the polar angle $\theta$ between $e^-$ and $q$, by $\rho_{ik}$, the cross section for the process Eq. (1) can be written as

$$\frac{d\sigma}{d\cos\theta}(e^+e^- \rightarrow q\bar{q}) = \frac{N_c}{128\pi s} \sum_{i,k=L,R} \rho_{ik} |f_{ik}|^2$$

(2)

with the color factor $N_c = 3$. As a consequence of angular momentum conservation, the spin-density matrix elements are given by

$$\rho_{RR} = \rho_{LL} = s^2(1 + \cos\theta)^2$$

$$\rho_{RL} = \rho_{LR} = s^2(1 - \cos\theta)^2$$

(3)

(4)

The helicity amplitudes can be cast in the following form

$$f_{RR} = \frac{Q_{RR}^0}{s} + \delta_{qu} \left(\frac{g_R^2}{t - V_0} - \frac{g_R^2}{2(u - S_0)}\right) + \delta_{qd} \left(\frac{g_R^2}{t - V_0} - \frac{g_R^2}{2(u - S_0)}\right)$$

(5)
same helicity amplitude, interference terms between pairs of leptoquarks must be included; with the left/right 

$LQ$ mass squared, \( s \) production angle 

that the amplitudes for \( LQ \) \( \tau \) The ratio 

exchange amplitudes have been abbreviated by \( Q \) identifying the leptoquark type suppressed. The generalized charges in the standard \( \gamma, Z \) exchange amplitudes have been abbreviated by \( Q^{eq}_{ik} \) where 

\[
Q_{ik}^{eq} = e^2 Q_{e}Q_{q} + \frac{g_f^i g_f^k}{1 - m_Z^2/s}
\]  

(6)

with the left/right \( Z \) charges of the fermions defined as

\[
g_f^L = \frac{e}{s_W c_W} \left[ f_{3}^L - s_W^2 Q_f \right]
\]

\[
g_f^R = \frac{e}{s_W c_W} \left[ -s_W^2 Q_f \right]
\]

and \( s_W = \sin \Theta_W, c_W = \cos \Theta_W \). The Mandelstam variables \( t, u \) can be expressed by the production angle \( \theta \): \( t = -s(1 - \cos \theta)/2 \), \( u = -s(1 + \cos \theta)/2 \); they are both negative so that the amplitudes for \( LQ \) exchange do not change the sign when \( \theta \) is varied from the forward to the backward direction.

It is obvious from the expressions (5) that leptoquarks/squarks of a given fermion number \( F \) contribute with a fixed positive or negative sign to the helicity amplitude \( f_{ik} \), thus reinforcing their impact mutually. For a given \( F \), the sign of the interference with \( \gamma/Z \) exchange is determined by the sign of the generalized charges \( Q_{ik}^{eq} \), which, in the energy range considered here, are negative for \( u \)-quarks and positive for \( d \)-quarks, except \( Q_{RL}^{eq} \) which is negative. By contrast, leptoquarks with different fermion numbers interfere destructively with each other. Leptoquarks with integer isospin contribute to equal-helicity \( LL \) and \( RR \) amplitudes, while leptoquarks with \( I = 1/2 \) contribute to opposite-helicity amplitudes \( RL \) and \( LR \).

The angular integration can easily be performed to obtain the total cross section for 

\( e^+e^- \rightarrow q\bar{q} \) including the exchange of one leptoquark with either left or right coupling:

\[
\sigma(e^+e^- \rightarrow q\bar{q}) = \frac{N_c}{128\pi s} \left[ \frac{8}{3} \left( |Q_{RR}^{eq}|^2 + |Q_{LL}^{eq}|^2 + |Q_{RL}^{eq}|^2 + |Q_{LR}^{eq}|^2 \right) + \sum_{i=1}^{4} k_i C_i(\tau) \right]
\]  

(7)

The ratio \( \tau \) is defined as \( \tau = m_{LQ}^2/s \). If two or more leptoquarks contribute to the same helicity amplitude, interference terms between pairs of leptoquarks must be included;
they are collected in the Appendix. The interference terms between leptoquark and $\gamma$, $Z$ exchange amplitudes are described by two functions, depending on the mass ratio $\tau$,

$$C_1(\tau) = 12 + 8\tau - 8(1 + \tau)^2 \log \frac{1 + \tau}{\tau}$$  (8)

$$C_2(\tau) = 8\tau - 4 - 8\tau^2 \log \frac{1 + \tau}{\tau}$$  (9)

The couplings building up $k_1$ and $k_2$ are listed in Table 2. The squared leptoquark-exchange amplitudes are given by two additional functions,

$$C_3(\tau) = 16 + \frac{8}{\tau} - 16(1 + \tau) \log \frac{1 + \tau}{\tau}$$  (10)

$$C_4(\tau) = 16 - \frac{8}{1 + \tau} - 16\tau \log \frac{1 + \tau}{\tau}$$  (11)

with the coefficients $k_3$ and $k_4$ again listed in Table 2.
It is instructive to consider the helicity amplitudes explicitly in the large mass limit $m_{LQ} \gg \sqrt{s}$. In this limit they can be interpreted as lepton-quark contact terms:

$$
\begin{align*}
    f_{RR} &= \frac{Q_{RR}^{eq}}{s} - \delta_{qu} \left( \frac{g_R^2}{V_0} - \frac{g_R^2}{2S_0} \right) - \delta_{qd} \left( \frac{g_R^2}{V_0} - \frac{g_R^2}{2S_0} \right) \\
    f_{LL} &= \frac{Q_{LL}^{eq}}{s} - \delta_{qu} \left( \frac{2g_L^2}{V_1} - \frac{g_L^2}{2S_0} - \frac{g_L^2}{2S_1} \right) - \delta_{qd} \left( \frac{g_L^2}{V_0} + \frac{g_L^2}{V_1} - \frac{g_L^2}{S_1} \right) \\
    f_{RL} &= \frac{Q_{RL}^{eq}}{s} - \delta_{qu} \left( \frac{g_R^2}{2S_{1/2}} - \frac{g_R^2}{V_{1/2}} \right) - \delta_{qd} \left( \frac{g_R^2}{2S_{1/2}} - \frac{g_R^2}{V_{1/2}} \right) \\
    f_{LR} &= \frac{Q_{LR}^{eq}}{s} - \delta_{qu} \left( \frac{g_L^2}{2S_{1/2}} - \frac{g_L^2}{V_{1/2}} \right) - \delta_{qd} \left( \frac{g_L^2}{2S_{1/2}} - \frac{g_L^2}{V_{1/2}} \right)
\end{align*}
$$

As observed before, leptoquarks with integer isospin $I = 0$ and $I = 1$ build up equal-helicity $LL$ and $RR$ contact terms, while leptoquarks with $I = 1/2$ contribute to opposite-helicity $RL$ and $LR$ contact terms. These rules may also be cast into the standard form of the effective Lagrangian [24]

$$
\mathcal{L}_{eff} = \sum_{i,k=L,R} \frac{g_i^2}{m_{LQ}^2} \alpha^{ik} (\bar{e}_i \gamma^\mu e_i)(\bar{q}_k \gamma^\mu q_k)
$$

$$
:= \sum_{i,k=L,R} \eta_{ik} \frac{4\pi}{\Lambda_{ik}^2} (\bar{e}_i \gamma^\mu e_i)(\bar{q}_k \gamma^\mu q_k)
$$

with $e_i$, $q_k$ denoting left- and right-handed electron and quark fields. The coefficients $\alpha^{ik}$ for $u\bar{u}$ and $d\bar{d}$ final states are listed in Table [3]. Denoting the signs of $\alpha^{ik}$ by $\eta_{ik}$, the scales $\Lambda_{ik}^2$ of the contact interactions are related to the individual masses and couplings of the leptoquarks by $\Lambda_{ik}^2 = 4\pi m_{LQ}^2/g_i^2|\alpha^{ik}|$. In the total cross section $\sigma(e^+e^- \rightarrow q\bar{q})$ the interference terms and the squared contact terms approach the limits $C_1 = C_2 = -8s/3m_{LQ}^4$ and $C_3 = C_4 = 8s^2/3m_{LQ}^4$ for $m_{LQ} \gg \sqrt{s}$.

### 3 Phenomenological Evaluation

If the surplus of the HERA high $Q^2$, large $x$ events is interpreted as the production of scalar or vector leptoquarks, or of squarks, their Yukawa couplings can be estimated from the production rates. We present only qualitative estimates of these couplings which should illustrate the general expectations for possible effects in $e^+e^-$ annihilation but which should not anticipate a rigorous analysis to be performed by the experiments themselves. Nevertheless, averaging over the H1 and ZEUS data one finds the couplings listed in Table [3]. It is assumed in these estimates that only one type of leptoquark (i.e. a single member of an isomultiplet) has been generated with one specific chiral coupling ($L, R$) to one specific quark flavor ($u$, $d$) which gives rise to the branching ratios for the decays of leptoquarks into charged leptons shown in the same Table. The $F = 2$ leptoquarks (upper part
of the Table) are generated in positron sea-quark collisions, the $F = 0$ leptoquarks (lower part of the Table) in positron valence-quark collisions.

From the couplings shown in Table 1 we can draw interesting conclusions even at the present level of qualitative arguments:

(i) If the HERA events are interpreted as the signal of a leptoquark generated in positron valence-quark collisions, the Yukawa coupling is of the order $\sim e/10$, i.e. suppressed by a full order of magnitude compared with the electromagnetic coupling. The $t/u$-channel exchange of such a state affects the $e^+e^- \rightarrow u\bar{u}$ or $e^+e^- \rightarrow d\bar{d}$ parton cross sections generally only at the level of a percent (up to 10% for $V_0$ and $V_1$). If all parton channels are summed up, the impact on the total hadronic cross section is even smaller if the heavier flavors are not excited by the contact interactions.

(ii) The coupling for single leptoquark production out of the sea in positron scattering is large, of order $e$. However, for such couplings the cross section $\sigma(e^-p \rightarrow LQ)$ would be two orders of magnitude larger than $\sigma(e^+p \rightarrow LQ)$ and it seems unlikely that the large number of events with $m_{LQ} \sim 200$ GeV could have been missed in the earlier electron-proton runs at HERA\textsuperscript{2}. Nevertheless, Yukawa couplings of the order $g_{L,R} \sim e/3$ do not seem to be ruled out yet completely \cite{25}. In such a scenario several types of leptoquarks

\begin{table}[h]
\centering
\begin{tabular}{|c|cccc|cccc|}
\hline
\multirow{2}{*}{$\alpha^{ik}$} & \multicolumn{4}{c|}{$u\bar{u}$ final state} & \multicolumn{4}{c|}{$d\bar{d}$ final state} \\
\cline{2-9}
 & RR & LL & RL & LR & RR & LL & RL & LR \\
\hline
$S_0$ & $\frac{1}{2}$ & $\frac{1}{2}$ & & & & & & \\
$\tilde{S}_0$ & & & $\frac{1}{2}$ & & & & & \\
$S_1$ & & & & 1 & & & & \\
$V_{1/2}$ & & & & 1 & & & 1 & 1 \\
$\tilde{V}_{1/2}$ & & & & 1 & & & & \\
$S_{1/2}$ & & $-\frac{1}{2}$ & $-\frac{1}{2}$ & $-\frac{1}{2}$ & & & & \\
$\tilde{S}_{1/2}$ & & & & $-\frac{1}{2}$ & & & & \\
$V_0$ & & & & & $-1$ & $-1$ & & \\
$\tilde{V}_0$ & & & & & $-1$ & & & \\
$V_1$ & & & $-2$ & & & & $-1$ & \\
\hline
\end{tabular}
\caption{The coefficients $\alpha^{ik}$ in the Lagrangian of the contact interactions.}
\end{table}

\textsuperscript{2}Moreover, the low energy bounds restrict the couplings to $g_{L,R} \lesssim 0.1$, see Table\[1\].
could be responsible for the observed events at HERA. The $F = 2$ leptoquarks may lead to observable effects in hadron production in $e^+e^-$ annihilation at LEP2, or at least more stringent bounds on the Yukawa couplings can be established.

(iii) If the HERA events are interpreted as the signal of leptoquark resonance production, they must originate from valence quarks, that is from $e^+u$ or $e^+d$ fusion to $F = 0$ states, and they must couple chirally to an extremely good approximation in order to be consistent with the existing bounds. Because of charge conservation, there is only one possible process which can give rise to new events in charged–current reactions, $e^+d \rightarrow \bar{\nu}u$, and only in the presence of left-handed couplings. This implies that an excess of events in the $CC$ channel, in addition to the $NC$ channel, will single out just two states: the vector LQs $V_0$ and $V_1$ carrying charge $\frac{2}{3}$. Thus, even without switching from an $e^+$ to an $e^-$ beam, the $NC$ and $CC$ searches combined are very selective in the $LQ$ quantum numbers.

However, recalling that no symmetry principles are known which give rise to relations among Yukawa scalar-fermion couplings – even within isomultiplets they differ by nearly two orders of magnitude in the Higgs sector – there could be additional leptoquarks at higher masses and with larger couplings that cannot be observed as resonance states in the HERA experiments. We have therefore studied the sensitivity of the total hadronic $e^+e^-$ cross section to the entire ensemble of scalar and vector leptoquarks listed in Table 1. The result is illustrated in Figs. 2 and 3 for the parameter set $(g_L, g_R) = (0.1, 0)$ or $(0, 0.1)$ at $\sqrt{s} = 192$ GeV as a function of the $LQ$ mass. Since the couplings are arbitrary parameters, only the relative size of the curves is relevant. For small enough couplings and large enough masses the curves scale in $g_{L,R}^2/m_{LQ}^2$. We observe both constructive and destructive interference effects, depending on the type of quarks in the final state. The impact of $I = 0, 1$ leptoquarks on the hadronic cross section is larger than the impact of $I = 1/2$ leptoquarks.

For large masses, the exchange of leptoquarks can be described by contact interactions. Depending on the type of leptoquark, different helicity combinations of lepton and quark currents are affected in either $u\bar{u}$ or $d\bar{d}$ final states. The sign of the contact interaction depends on the fermion number as shown in the previous section. Potentially large effects can be expected for $e^+e^-$ annihilation to hadrons. This is exemplified for a series of $\Lambda$ values in Table 4. The symbols $LL$ etc. denote the helicity of the lepton current followed by the helicity of the quark current. The effect of the contact interaction ($CI$) is shown for the total $e^+e^-$ hadronic cross section at LEP192 if only one of the $u$-type or $d$-type quarks is involved in the contact interactions. Present analyses of hadron production at LEP set limits to $\Lambda$ already at the level of about 1.5 to 2.5 TeV [27].

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3Numerical cross checks have been performed with the help of CompHEP [26] adapted to leptoquark processes.
$\Delta = \frac{\sigma(SM \oplus LQ)}{\sigma(SM)} - 1$

Figure 2: Effect of $t/u$-channel exchange of scalar leptoquarks on the total hadronic cross section as a function of $m_{LQ}$ for $\sqrt{s} = 192$ GeV. The couplings have been fixed arbitrarily to $(g_L, g_R) = (0.1, 0)$ or $(0, 0.1)$ indicated by $LQ^{L,R}$, respectively.
\[ \Delta = \frac{\sigma_{\text{SM} \oplus \text{LQ}}}{\sigma_{\text{SM}}} - 1 \]

\[ \sigma_{\text{SM} \oplus \text{LQ}} \sum q\bar{q} \]

\[ LQ = \text{vector} \]

Figure 3: Effect of $t/u$-channel exchange of vector leptoquarks on the total hadronic cross section as a function of $m_{LQ}$ for $\sqrt{s} = 192$ GeV. The couplings have been fixed arbitrarily to $(g_L, g_R) = (0.1, 0)$ or $(0, 0.1)$ indicated by $LQ^L, R$, respectively.
Table 4: The effect of contact interactions with different helicities on the cross section for hadron production in $e^+e^-$ annihilation: $\Delta = \sigma(SM \oplus CI)/\sigma(SM) - 1$.

### 4 Squarks in $R$-parity Breaking SUSY Models

In the minimal supersymmetric extension of the Standard Model, the only renormalizable, gauge invariant operator that couples squarks to quarks and leptons is given by

$$W_R = \lambda_{ijk} L_i L_i Q_j L_i$$

in the superpotential [6]. The indices $ijk$ are generation indices in the left-handed doublets of leptons ($L$) and quarks ($Q$), and right-handed singlets of down-type quarks ($D$). This interaction term violates global invariance of $R$-parity, defined as $R = (-1)^{3B+L+2S}$ which is $+1$ for particles and $-1$ for superpartners. This interaction has also been considered in the context of the Aleph 4-jet events in Ref. [29].

Expanding the superfields in terms of matter fields, the interaction Lagrangian can be written as

$$\mathcal{L}_R = \lambda_{ijk} \left[ \bar{u}^i_L \bar{d}^k_R e^i_L + \bar{d}_R (\bar{e}^i_L)^c u^j_L + \bar{e}_L \bar{d}^k_R \bar{u}^j_L - \bar{\nu}^i_L \bar{u}^k_R d^j_L - \bar{d}^i_L \bar{d}^k_R \nu^j_L - d^i_R (\bar{\nu}_L^i)^c d^j_L \right] + h.c.$$ (15)

where $u^j$ and $d^k$ stand for $u$- and $d$-type quarks, respectively, and the superscript $( )^c$ denotes charge conjugate spinors. The first two terms with $i = 1$ are of particular interest since they allow for resonant squark production in $e^+p$ scattering at HERA via the subprocesses

$$e^+ + d^k_R \rightarrow \bar{u}^j_L \quad (\bar{u}^j = \bar{u}, \bar{c}, \bar{t})$$

$$e^+ + \bar{u}^j_L \rightarrow \bar{d}^k_R \quad (\bar{d}^k = \bar{d}, \bar{s}, \bar{b})$$
If more than one of the couplings $\lambda'_{1jk}$ is non-vanishing, strong limits on their product are imposed by the absence of FCNC reactions [28]. Since $\lambda'_{111} \lesssim 10^{-3}$ (for a mass $m = 200$ GeV of supersymmetric partners mediating neutrinoless double beta decay [13]), second or third generation fermions must be coupled to electrons in order to account for the rate at HERA. Below we will consider the two possible scenarios, shown in Fig. 4, in which a) quarks, b) antiquarks from the proton participate in the production process. In particular we will discuss two cases for $\lambda'_{1j1} \neq 0$ or $\lambda'_{11k} \neq 0$ and their implications for $e^+e^-$ annihilation to hadrons.

a) $\lambda'_{1j1} \neq 0$, $j = 2, 3$

In this case, down quarks are involved via (16) in the production of left-handed charm ($j = 2$) or top ($j = 3$) squarks at HERA, Fig. 4a. The other process (17) is irrelevant since another possibility is to consider $\lambda'_{132} \neq 0$ which would involve strange quarks from the sea in the production of top squarks (Fig. 4a). The qualitative analysis below applies to this case as well: $s\bar{s}$ production via $t_L$ (see Fig. 4a and Fig. 4).

Figure 4: Squarks production mechanisms in $e^+p$ collisions.

Figure 5: The scenario with $\lambda'_{1j1} \neq 0$: $\tilde{c}$ for $j = 2$, $\tilde{t}$ for $j = 3$. 

In this case, down quarks are involved via (16) in the production of left-handed charm ($j = 2$) or top ($j = 3$) squarks at HERA, Fig. 4a. The other process (17) is irrelevant since another possibility is to consider $\lambda'_{132} \neq 0$ which would involve strange quarks from the sea in the production of top squarks (Fig. 4a). The qualitative analysis below applies to this case as well: $s\bar{s}$ production via $t_L$ (see Fig. 4a and Fig. 4).
it would require charm or top sea antiquarks in the proton. To account for the observed number of events at HERA, \( \lambda_{1j1} \) must exceed 0.052 which is still within the limits derived from atomic parity violation for a sufficiently heavy \( \tilde{d}_R \) [11, 28]. Notice that since \( \tilde{u} \) does not couple to neutrinos, the surplus of events in CC reactions at HERA is not expected. In \( e^+e^- \to q\bar{q} \) the coupling \( \lambda'_{1j1} \) leads to two additional hadron channels, as shown in Fig. 3: \( e^+e^- \to d\bar{d} \) via charm or top squark exchange in the \( t \)-channel, and \( e^+e^- \to c\bar{c} \) via down squark exchange in the \( u \)-channel. Since the left-handed up-type squarks couple in the same way as the \( \tilde{S}_{1/2} \) leptoquark, and the right-handed down squark like the \( S_0 \) leptoquark with left-handed coupling \( g_L \), their contributions can easily be obtained from the formulae given in the previous section. The impact of these exchange mechanisms on the total hadronic \( e^+e^- \) cross section is shown in Fig. 4. The impact of squark exchange on the single parton cross section \( e^+e^- \to c\bar{c} \) is larger; the experimental analysis of this process however requires the tagging of charm quarks in the final state.

b) \( \lambda'_{1ik} \neq 0, \, k = 2, 3 \)

In this case, up antiquarks of the sea are involved in the process (17) so that strange \( (k = 3) \) or bottom \( (k = 3) \) antisquarks would be produced at HERA, Fig. 4b). The \( \tilde{d} \) couples also to neutrinos, therefore similar events in CC reactions could be expected. The coupling \( \lambda'_{1ik} \) would introduce two additional mechanisms in the \( e^+e^- \to q\bar{q} \) process, Fig. 5: \( e^+e^- \to s\bar{s} \) or \( e^+e^- \to b\bar{b} \) via up squark exchange in the \( t \)-channel, and \( e^+e^- \to u\bar{u} \) via strange or bottom squark exchange in the \( u \)-channel. Since the parton densities of sea quarks are much smaller than the densities of valence quarks, this scenario would require a large coupling, \( \lambda'_{1ik} > 0.3 \). Such a large value of \( \lambda'_{1ik} \) is however in conflict with the limit \( \lambda'_{1ik} < 0.06 \) derived from charged current universality [30] or from earlier \( e^-p \) data [25]. This mechanism therefore cannot explain the surplus of HERA data.

In contrast to genuine leptoquarks which decay solely to leptons and quarks, squarks can decay not only via \( R \)-parity violating couplings but in general also via a large number of \( R \)-parity conserving modes: \( \tilde{q} \to q\chi \) with \( \chi \) being either a neutralino or a chargino state, cascading in a chain reaction down to ordinary particles. The lower limits for the couplings \( \lambda' \) inferred from the HERA events were based on branching ratios of 100\% for the \( R \)-parity violating decay modes to lepton plus quark jet. If the branching ratios for \( \tilde{q} \to q\chi \) decays are non-negligible, the couplings \( \lambda' \) would have to be larger correspondingly. This would increase the impact on \( e^+e^- \) collisions. At the same time, new types of events at HERA would be expected with multiple jet topologies and leptons from the \( R \)-parity breaking \( \chi \) decays.
Figure 6: Effect of t/u-channel exchange of squarks in the supersymmetry scenario (a) on the total hadronic cross section, $\Delta = \frac{\sigma(SM \oplus \tilde{q})}{\sigma(SM)} - 1$, as a function of $m_{\tilde{q}}$ for $\lambda'_{ij1} = 0.1, j = 2$ or 3 (or $\lambda'_{132} = 0.1$ for $\tilde{s}\tilde{s}$) and $\sqrt{s} = 192$ GeV.
5 Summary

The conclusions of our analysis can be summarized in four points.

(i) If the high $Q^2$, large $x$ events observed at HERA in deep-inelastic positron-proton scattering are interpreted as the direct production of a narrow leptoquark state, two cases must be distinguished. For leptoquarks generated in collisions with valence quarks, the Yukawa couplings are so small, $\sim e/10$, that the contribution of the $t/u$-channel exchange of these leptoquarks affects the production of hadrons in high-energy $e^+e^-$ annihilation only at the level of less than one percent. For leptoquarks generated from antiquarks in the sea, the Yukawa couplings can still be larger. However, the couplings presumably do not exceed the value $e/3$ since the leptoquark states would have been observed otherwise in the earlier electron-proton runs at HERA. In this second case, the effects of leptoquark exchange may be accessible in $e^+e^-$ annihilation at LEP2.

(ii) For masses above the range covered directly by HERA, the impact of the leptoquark exchange on hadron production in $e^+e^-$ annihilation can be significant for a wide range of Yukawa couplings. The interactions are effectively described by contact terms, similar to contact interactions at HERA. The cross sections have been presented for all standard leptoquark states.

(iii) In $R$-parity breaking supersymmetric models, the HERA events could be interpreted as the production of either left-handed charm or top squarks. The observed number of events requires $\lambda'_{ij1} > 0.065$, the lower limit corresponding to a branching ratio of $\sim 100\%$ for the $R$-parity violating decays to lepton and hadron jets. If the coupling is close to the lower limit, the impact on the hadronic cross section in $e^+e^-$ annihilation is small, $\sim 1\%$. If the coupling is stronger, the impact on $e^+e^-$ annihilation will be more pronounced. In this case, interesting multi-jet and lepton signatures due to the $R$-parity conserving decays $\tilde{q} \to q\chi$, followed by $R$-parity breaking $\chi$ decays, could occur at HERA.

(iv) If the HERA events are not interpreted as the production of narrow leptoquark reso-
nances but are described globally by contact interactions, the effective scale $\Lambda$ is predicted to be in a range which is easily accessible at LEP2. However, if deviations from the prediction of the Standard Model for the cross section of $e^+e^-$ annihilation to hadrons are not observed, contact interactions with scales of order 2 TeV cannot account for the HERA events. This would restrict the interpretation of the events to the direct production of narrow leptoquark-type resonances.

**Appendix**

If more than one leptoquark contributes to the same helicity amplitude, the expression in Eq. (7) has to be supplemented by the interference terms between pairs of leptoquarks. For the $u\bar{u}$ final states we find

$$\frac{N_c}{128\pi s} \left[ + \frac{1}{2} g_{1L}^2 g_{3L}^2 C_6(\tau_1, \tau_3) - g_{1R}^2 g_{6R}^2 C_7(\tau_9, \tau_1) - 2g_{10L}^2 g_{1L}^2 C_7(\tau_{10}, \tau_1) \right]$$

$$-2g_{10L}^2 g_{2L}^2 C_7(\tau_{10}, \tau_3) - g_{6R}^2 g_{1R}^2 C_7(\tau_4, \tau_6) - g_{6L}^2 g_{8L}^2 C_7(\tau_5, \tau_6)$$

(18)

and for $d\bar{d}$ final states

$$\frac{N_c}{128\pi s} \left[ +2g_{6L}^2 g_{10L}^2 C_5(\tau_{10}, \tau_8) - g_{2R}^2 g_{8R}^2 C_7(\tau_8, \tau_2) - 2g_{6L}^2 g_{3L}^2 C_7(\tau_8, \tau_3) \right]$$

$$-2g_{10L}^2 g_{2L}^2 C_7(\tau_{10}, \tau_3) - g_{6R}^2 g_{4R}^2 C_7(\tau_4, \tau_6) - g_{7L}^2 g_{4L}^2 C_7(\tau_4, \tau_7)$$

(19)

The numbering of the leptoquark states and their couplings ($g_{iL}$ or $g_{iR}$) and masses ($\tau_i = m_i^2/s$) follows the listing in Table 1 with $i = 1, \ldots, 10$. For example $g_{6R}$ and $\tau_6$ refer to the right-handed coupling and mass of the $S_{1/2}$ state. The functions $C_5$, $C_6$ and $C_7$ can be expressed in terms of $C_1$ and $C_2$ as follows:

$$C_5(x, y) = \frac{C_1(x) - C_1(y)}{2y - 2x}$$

$$C_6(x, y) = \frac{C_2(x) - C_2(y)}{2y - 2x}$$

$$C_7(x, y) = \frac{C_1(x) + C_2(y)}{2 + 2x + 2y}$$

(22)

**Acknowledgments:**

We have benefitted from discussions with E. Boos, W. Buchmüller, P. Mättig and U. Martyn.

NOTE: When finalizing the present paper we received copies of Refs. [31, 32]. The main conclusions are in mutual agreement.
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