Abstract

We calculate the cross section for the production of pairs of scalar leptoquarks (sleptoquarks) in a supersymmetric $E_6$ model, at hadron colliders. We estimate higher order corrections by including $\pi^2$ terms induced by soft-gluon corrections. Discovery bounds on the sleptoquark mass are estimated at collider energies of 1.8, 2, and 4 TeV (Tevatron), and 16 TeV (LHC).

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A natural explanation for the proliferation of fermions, and their pattern of masses and mixing angles, is to assume that the current elementary particles are composite. In various “preonic” models \cite{1}, quarks and leptons have some common constituents. Among the particles contained in these models, leptoquarks are exotic particles which have both a nonzero leptonic and baryonic number. They also appear in many extensions of the Standard Model \cite{2}. They can decay directly into a quark-lepton pair, which is a new feature, since there are no quark-lepton-boson interactions in the Standard Model. Here we are concerned with the leptoquarks that come from a supersymmetric grand unified $E_6$ theory (the low energy limit of an $E_8 \otimes E_8$ heterotic string theory \cite{3}), where they — together with their supersymmetric scalar partners, sleptoquarks — are fractionally charged color triplets. For constraints on the parameters of these superstring-inspired models, see, for example, Ref. \cite{4} or for a more extensive review, Ref. \cite{5}.

In principle, the best place to look for a leptoquark signal would be at $ep$ colliders \cite{6} since they can be produced directly via the lepton-quark-sleptoquark coupling (called from now on the Yukawa coupling). However, for small couplings (or large leptoquark masses), hadron colliders seem more appropriate since leptoquarks can still be pair produced through their strong interactions for arbitrarily low Yukawa couplings. Experiments at LEP have already imposed a lower bound of 45 GeV on the leptoquark mass \cite{7}. Results from HERA have ruled out masses below 180 GeV \cite{8} for a Yukawa coupling of electromagnetic strength, whereas searches at $p\bar{p}$ colliders have set these bounds to 113 GeV (for a branching ratio $BR= 1$), or 80 GeV ($BR= 0.5$) \cite{9}. More recently, experiments both at HERA and the Tevatron have strengthened these bounds reaching with a 95% confidence level, 240 GeV for HERA \cite{10} and respectively 133 GeV and 120 GeV at the Tevatron \cite{11}. Note that HERA bounds depends on the value of the Yukawa coupling whereas the hadron collider results are somewhat insensitive to this parameter.

Low energy data (e.g. atomic parity violation, . . . ) also impose very strict bounds on leptoquark masses. Leurer has updated a previous analysis by Buchmüller and Wyler, and obtained bounds that restrict the leptoquarks (with Yukawa coupling equal to the electromagnetic strength) to have masses larger than 600 GeV or 630 GeV for leptoquarks that couple to RH quarks, and above 1040 GeV, 440 GeV, and 750 GeV for the $SU(2)_W$ scalar, doublet and triplet leptoquarks, respectively, that couple to LH quarks \cite{12}. These are “unavoidable” bounds, in the sense that they are independent of the following three assumptions, which are used to circumvent other constraints: (1) leptoquarks do not also couple to diquarks, (2) leptoquarks couple chirally (i.e. to one quark chirality at a time), and (3) leptoquarks couple diagonally (i.e. to a single fermion generation at a time), but they remain heavily dependent on the strength of the Yukawa coupling. Finally, some model-independent bounds are also discussed by Davidson et al. in Ref. \cite{12}. Hence, it is quite possible that leptoquarks could escape detection at $ep$ colliders but could still be detectable at hadron colliders. Also, in practice, the energy available in hadron colliders is greater than that in $ep$ colliders, which would in principle extend the search to larger values of the leptoquark mass.

The purpose of this brief report is to reanalyze the production of pairs of sleptoquarks in hadron colliders \cite{13,14} in view of the most recent data and experimental situation. In previous work, we calculated the total cross section at center-of-mass energies of 2, 16, and 40 TeV (corresponding to the Fermilab Tevatron, the CERN LHC, and the late SSC,
respectively), for sleptoquark masses up to 400 GeV. We extend here our calculation of the cross section to sleptoquark masses of up to 2600 GeV, and we add the results for the (current and newly proposed) Tevatron energies $\sqrt{s} = 1.8$ TeV and 4 TeV. (We keep the SSC energies in order to compare with our previous results.) The soft-gluon $\pi^2$ term corrections are included. We also have taken special care to reduce uncertainties in the numerical calculations by performing a more reliable numerical integration (using VEGAS [15]), and by taking a more recent set of distribution functions.

Let us briefly review the model and our calculations. (More details are given in Refs. [14], and references therein). In the supersymmetric $E_6$ model, the leptoquark $D$ is an exotic colored particle which lies in the $27$ fermionic multiplet, and the sleptoquark that we consider is its scalar superpartner. If we restrict our study to the first generation of fermions, then the Yukawa interactions take the form:

$$\mathcal{L}_Y = \lambda_L \bar{D}^c (e_L u_L + \nu_L d_L) + \lambda_R \bar{D}e_L u_L + \text{h.c.} \quad (1)$$

where $c$ denotes the charge conjugate state, and $\bar{D}$ is the scalar superpartner of $D$. We assume the $\lambda$’s to be independent and arbitrary. We analyze the pair production of sleptoquarks which arise from two subprocesses: (1) quark-antiquark annihilation ($u_R + u^c_L \rightarrow \bar{D} + \bar{D}^*$ and $u_L + u^c_R \rightarrow \bar{D}^c + \bar{D}^c$), and (2) gluon fusion ($g + g \rightarrow \bar{D} + \bar{D}^*$ and $g + g \rightarrow \bar{D}^c + \bar{D}^c$). The subprocess (1) occurs in $s$-channel (through the exchange of a virtual gluon) and in $t$-channel (virtual electron). The subprocess (2) arises via color gauge interactions from the trilinear term $gDD$ in the $s$-channel (through the exchange of a gluon) and in the $t$- and $u$-channels (exchange of virtual sleptoquarks), and from the quartic term $ggDD$ in which two gluons annihilate to produce directly a pair of sleptoquarks. Note that, to lowest order, the gluon fusion process does not depend on the Yukawa interactions. The details of the calculation of the amplitudes and the cross sections are given in Refs. [14].

We also estimate $\pi^2$ terms, which are the soft-gluon corrections that arise from the regularization of either collinear or infrared singularities, when a timelike momentum transfer is involved in the process [16]. The first-order corrections to a subprocess involving massless particles contain an infrared singularity of the form

$$\text{Re} \left[ \frac{1}{\epsilon^2} \left( -\frac{q^2}{\mu^2} \right)^{-\epsilon} \right] = \frac{1}{\epsilon^2} - \frac{1}{\epsilon} \text{Re} \left[ \ln \left( -\frac{q^2}{\mu^2} \right) \right] + \frac{1}{2} \text{Re} \left[ \ln^2 \left( -\frac{q^2}{\mu^2} \right) \right] + \cdots \quad (2)$$

where $\mu^2$ is the renormalization point. The $\pi^2$ term is generated by the last term,

$$\text{Re} \left[ \ln^2 \left( -\frac{q^2}{\mu^2} \right) \right] = \ln^2 \left( \frac{q^2}{\mu^2} \right) - \pi^2. \quad (3)$$

Note that $\pi^2$ terms arise only when $q^2$ is timelike. Unless there is a suppression of the $\pi^2$ terms, their contribution is large and cannot be neglected. It is usually expressed by means of the so-called $K$-factor. In general, we expect $\pi^2$ terms to appear to all orders in $\alpha_S$. Low-order results in many QCD processes indicate that the summation of the ensuing large corrections into an exponential could take place, as is the case for electromagnetic interactions. It is important to remark that not all of the first-order correction diagrams lead to a $\pi^2$ term. (The detailed investigation of the soft-gluon corrections leading to a $K$-factor through $\pi^2$ term is described in Ref. [14], for $q\bar{q}$ and $gg$ subprocesses. The analogous study for other leptoquark processes is given in Ref. [16].)
We now display the contributions to the total cross section for each of the two subprocesses mentioned previously, including the $K$-factors coming from soft-gluon corrections. For the Born term only, one just has to set $K = 1$. The contribution from the $q\bar{q}$ annihilation is:

$$
\sigma_{AB} = \int_{x_{\text{min}}/x}^{1} dy \int_{x_{\text{min}}}^{1} dx K_{AB} \alpha_A \alpha_B \tilde{\sigma}_{AB} \left[ G_{u/p}(x, Q^2)G_{\pi/\overline{p}}(y, Q^2) + (1 \leftrightarrow 2, p \leftrightarrow \overline{p}) \right],
$$

with $x_{\text{min}} = 4(M_D^2 + p_T^2)/s$ (we take $p_T = 10$ GeV), and $Q^2 = \hat{s}/2$ ($\hat{s} = yxs$). Here $AB$ stands for $SS$, $YY$, or $SY$ (i.e. purely strong, purely Yukawa, and mixed subprocesses, respectively) where $\alpha_S$ and $\alpha_Y$ are the QCD and Yukawa couplings, respectively. We set $\alpha_Y = \alpha_{\text{em}}$ in the numerical calculations. Finally, $G_{a/h}(x, Q^2)$ stands for the distribution function associated to the parton $a$ in the hadron $h$, with scaling variable $x$ and momentum scale $Q^2$. We use the parametrization set B2 of Morfin and Tung [17], which is based on more recent nucleon data than the parametrization we used in our previous work. Defining $\chi = M_D^2/\hat{s}$ and $\eta = \sqrt{1 - 4M_D^2/\hat{s}}$, the purely strong, mixed, and purely Yukawa contributions are, respectively,

$$
\tilde{\sigma}_{SS} = \frac{2\pi}{27\hat{s}} \eta^3,
$$

$$
\tilde{\sigma}_{SY} = \frac{2\pi}{36\hat{s}} \left[ \eta(1 - 2\chi) + 2\chi^2 \ln \left( \frac{1 - \eta - 2\chi}{1 + \eta - 2\chi} \right) \right],
$$

$$
\tilde{\sigma}_{YY} = \frac{\pi}{8\hat{s}} \left[ -2\eta + (2\chi - 1) \ln \left( \frac{1 - \eta - 2\chi}{1 + \eta - 2\chi} \right) \right].
$$

The $K$-factors are found to be

$$
K_{SS} = K_{SY} = 1 + \pi\alpha_S \left( C_F - \frac{1}{2} C_A \right) = 1 - \frac{1}{6}\pi\alpha_S, \quad \text{and} \quad K_{YY} = 1.
$$

Here $C_F = \frac{4}{3}$ and $C_A = 3$ are the Casimir operators for the $SU(3)$ fundamental and adjoint representations, respectively. (Later on, $K_{SS}$ and $K_{SY}$ will be denoted generically as $K_{qq}$.)

For the gluon fusion subprocess, the integrated cross section is

$$
\sigma_{gg} = \int_{x_{\text{min}}/x}^{1} dy \int_{x_{\text{min}}}^{1} dx K_{gg} \alpha_s^2 \tilde{\sigma}_{gg} G_{g/p}(x, Q^2)G_{g/\overline{p}}(y, Q^2),
$$

with

$$
\tilde{\sigma}_{gg} = \frac{\pi}{6\hat{s}} \left[ \left( \frac{5}{8} + \frac{31}{4}\chi \right) \eta + (4 + \chi) \chi \ln \left( \frac{1 - \eta}{1 + \eta} \right) \right].
$$

The values for $x_{\text{min}}$, $p_T$, $Q^2$ are the same as in (4). Here, the $K$-factor induces a much larger correction to the Born term,

$$
K_{gg} = 1 + \frac{1}{2}\pi\alpha_s C_F + \cdots = 1 + \frac{2}{3}\pi\alpha_S + \cdots
$$
The cross sections (5-7) and (10) are similar to those in [18] (for \( q \bar{q} \rightarrow \bar{q}q, gg \rightarrow \bar{q}q \)), except for a factor. For the Born term, one just replaces \( K \) by 1 in (8) and (11). Fig. 1 displays the total cross section, that is, the sum of \( gg \) fusion and \( q\bar{q} \) contributions, with and without corrections.

Higher order effects (only the \( \pi^2 \) terms are included here) are easy to estimate. From (8) the \( \pi^2 \) corrections for the quark-antiquark annihilation are small and negative (i.e. they slightly suppress the cross section). For sleptoquark masses in the range 100 GeV < \( M_D \) < 2600 GeV, the strong coupling constant \( \alpha_S \) lies between 0.13 and 0.09, which corresponds to \( K_{qq} = 0.932 \) and 0.953, respectively. Here the cross section is suppressed by 7 to 4\%, depending on the relative importance of the different channels. For the gluon fusion process (11), the cross section is significantly increased with \( K_{gg} = 1.272 \) and 1.189 for \( \alpha_S = 0.13 \) and 0.09, respectively. From Fig. 1, we see that the \( \pi^2 \) term leads to a slight increase of the cross section for the small values of the leptoquark mass, and that the signal is suppressed for large values. This is due to the fact that, at high energies, the gluon fusion subprocess–which undergoes bigger corrections–dominates in the region of low leptoquark mass. The value of the mass for which the two curves (Born and corrected) intersect increases with the center-of-mass energy. These corrections may be crucial if the values of \( \alpha_Y \) and \( M_D \) are such that we are close to the detection threshold. It should be noted that the \( K \)-factors found here are only part of the first order corrections. However, whereas one expects \( K_{qq} \) to be of the same order of magnitude as the rest of the first order corrections, it appears that \( K_{gg} \) is the dominant part of the gluon fusion corrections.

We expect the final leptoquarks to decay into a quark and a lepton. The most interesting signature for \( \bar{D} \bar{D}^* \) pair is the production of 2 jets +\( l^+l^- \). The standard background would come from \( pp \rightarrow Q\bar{Q} \), where \( Q \) is a heavy quark which decays semileptonically into 2 jets +\( l^+l^-+\nu\bar{\nu} \), and will in general involve some missing \( p_T \). It is easy to see that the subprocesses involved in \( Q\bar{Q} \) production get similar \( \pi^2 \) corrections (i.e. a factor \( K_{qq} \) for \( q\bar{q} \rightarrow Q\bar{Q} \) and a factor \( K_{gg} \) for \( gg \rightarrow Q\bar{Q} \)). This could slightly modify the signal-to-background ratio in a manner which depends on parameters such as the masses of sleptoquarks and heavy quarks and the relative importance of each subprocess. For example, if gluon fusion is the dominant process in both sleptoquark and heavy quark pair production, the signal-to-background ratio will not be affected by the soft-gluon corrections, but the total cross section will be appreciably enhanced.

Finally, we discuss the detection possibilities, taking into account the expected luminosities at the various colliders considered in this work. In all cases, we assume that the discovery limit is 20 events, and we base our estimates on the corrected cross sections (i.e. including \( K \)-factors). We have obtained the results of Fig. 1 by putting \( \alpha_Y = \alpha_{em} \). For the sake of comparison we give also an estimate for the case of a very small Yukawa coupling as well, by setting \( \alpha_Y = 0 \). Experiments at Fermilab expect to gather about 100 pb\(^{-1} \) during the current Tevatron run (for which \( \sqrt{s} = 1.8 \) TeV), which should last until the middle of 1995. With the discovery limit mentioned above, the mass reach would be 184 GeV (if \( \alpha_Y = 0 \) rather than \( \alpha_{em} \), then it is 181 GeV). If we assume a luminosity equal to 500 pb\(^{-1} \) at \( \sqrt{s} = 2 \) TeV, then this number would increase by an appreciable amount: up to 251 GeV (247 GeV for \( \alpha_Y = 0 \)). The design luminosity at LHC is expected to be \( 10^{34} \) cm\(^{-2} \) s\(^{-1} \). A run of one year would then give a luminosity of 100 fb\(^{-1} \), providing a search limit of 2110 GeV (or 2070 GeV for \( \alpha_Y = 0 \)). Fermilab has recently started discussing an upgrade of
the center-of-mass energy to 4 TeV, and the numbers used by different people as expected luminosities are 1 fb$^{-1}$ and 10 fb$^{-1}$. The discovery of 20 events would be reached for masses not exceeding 434 (428) GeV and 597 (590) GeV, respectively (numbers in parentheses are for $\alpha_Y = 0$). At the SSC, with a hypothetical luminosity of 10 fb$^{-1}$, the same discovery limit would lead to a mass reach of 2565 GeV for $\alpha_Y = \alpha_{em}$, and 2525 GeV for $\alpha_Y = 0$. Actually, changing from $\alpha_Y = \alpha_{em}$ to $\alpha_Y = 0$ has an overall effect of only a few percent on the discovery limits. This means that the strong processes dominate even at high energies where the ratio $\alpha_{em}(Q^2)/\alpha_S(Q^2)$ is not that small.

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FIGURES

FIG. 1. The total cross section for pair production of scalar leptoquarks at $p\bar{p}$ colliders with a center-of-mass energy of 1.8, 2, 4, 16 and 40 TeV versus the mass of the leptoquark. The Yukawa coupling is taken to be $\alpha_Y = \alpha_{em}$. Solid (broken) lines represent the Born ($\pi^2$-corrected) cross sections. The bottom-left axis are valid for 1.8 and 2 TeV, and the top-right axis, for 4, 16 and 40 TeV.
This figure "fig1-1.png" is available in "png" format from:

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