Leptoquark production at the Tevatron

Michael Krämer

Rutherford Appleton Laboratory, Chilton, OX11 0QX, UK

Abstract. I discuss the production of leptoquarks in $p\bar{p}$ collisions at the Fermilab Tevatron. Evaluated on the basis of a recent next-to-leading order calculation, the combined D0 and CDF leptoquark searches lead to a parameter-free lower mass bound of about $m_S \sim 240$ GeV for scalar leptoquarks or squarks decaying solely to a first generation charged lepton plus quark. These results provide very stringent constraints on any explanation of the recently observed HERA excess events in terms of new particle production.

1. Introduction

The recent observation of an excess of events in deep-inelastic positron-proton scattering at HERA \cite{1} has aroused new interest in physics beyond the Standard Model. Theoretical speculations have focussed on two different scenarios to explain the experimental results: contact interactions at an effective scale $\Lambda_{eq} \gtrsim 1.5$ TeV, and narrow resonance formation at a mass scale $M \sim 200$ GeV. The resonance interpretation is based in particular on the H1 data in \cite{1} which appear to cluster in a narrow range at invariant $(eq)$ masses of about 200 GeV. Such resonances can be identified with scalar squarks in supersymmetric theories with $R$-parity breaking or leptoquarks in general \cite{2}. If low-mass leptoquark-type states exist, they are produced at significant rates via QCD interactions in $p\bar{p}$ collisions at the Fermilab Tevatron. Evaluated on the basis of a recent next-to-leading

\footnote{1 Talk presented at “Beyond the Desert 97” – Accelerator and Non-Accelerator Approaches, Castle Ringberg, Tegernsee, Germany, 8-14 June 1997, to appear in the proceedings}

\footnote{2 E-mail: Michael.Kraemer@rl.ac.uk}
order calculation, the D0 and CDF leptoquark searches lead to a parameter-free lower mass bound of about $m_S \gtrsim 240$ GeV for scalar leptoquark-type states decaying solely to a first generation charged lepton plus quark. The corresponding mass bound on vector leptoquarks appears significantly higher, even if the unknown anomalous couplings of vector leptoquarks to gluons are chosen such as to minimize the cross section. These results rule out the standard leptoquark interpretation of the HERA data as discussed in Section 2 and provide very stringent constraints on any explanation of the excess events in terms of new particle production.

The article is organized as follows: In Section 2, I briefly review the leptoquark interpretation of the HERA data. Single and pair production of scalar and vector leptoquarks in $p\bar{p}$ collisions at the Fermilab Tevatron are discussed in Section 3. The next-to-leading order (NLO) QCD corrections to scalar-leptoquark pair production in $p\bar{p}$ collisions have been evaluated recently. As shown in Section 4, including the higher-order contributions stabilizes the theoretical prediction and increases the size of the cross section for renormalization/factorization scales close to the mass of the leptoquarks. The leptoquark searches at the Fermilab Tevatron and the resulting mass bounds for leptoquarks and scalar squarks in supersymmetric theories with $R$-parity breaking are described in Section 5. I conclude in Section 6.

2. Leptoquarks: basic set-up

The interactions of leptoquarks with lepton-quark pairs can be described by an effective low-energy lagrangian including the most general dimensionless and SU(3) × SU(2) × U(1) invariant couplings. The allowed states are classified according to their spin ($S = 0, 1$), weak isospin and fermion number ($F = 0, -2$). The leptoquark-fermion couplings of low-mass leptoquark states are severely constrained by low-energy experiments. The couplings are assumed to be baryon- and lepton number conserving in order to avoid rapid proton decay and family diagonal to exclude FCNC beyond CKM mixing. Moreover, the leptoquark-fermion couplings have to be essentially chiral to preserve the helicity suppression in leptonic pion decays.

Additional constraints on the leptoquark-fermion couplings from the HERA ($e^-p$) data and atomic parity violation measurements only allow certain fermion number zero scalar and vector leptoquarks as a possible source of the ($e^+p$) excess. Within the standard scheme discussed above, i.e. imposing chiral and family diagonal couplings to evade the low-energy bounds, and assuming the fermionic content of the Standard Model, all leptoquark candidates consistent with the HERA data decay with 100% branching fraction to a first generation charged lepton plus quark.
3. Leptoquark production at the Fermilab Tevatron

The most stringent mass limits on leptoquark-type states arise from direct searches in $p\bar{p}$ collisions at the Fermilab Tevatron. The leptoquark cross section is dominated by pair production

$$p + \bar{p} \rightarrow \text{LQ} + \bar{\text{LQ}} + X \quad (1)$$

which proceeds through quark-antiquark annihilation and gluon-gluon fusion. The interactions of scalar leptoquarks with gluons are completely determined by the non-abelian SU(3)$_C$ gauge symmetry of scalar QCD so that the theoretical predictions for the pair production of scalar leptoquarks are parameter-free. Vector leptoquarks can have additional anomalous couplings ($\kappa_V, \lambda_V$) to gluons which violate unitarity in the production cross section. These couplings vanish in any theory wherein vector leptoquarks appear as fundamental gauge bosons of an extended gauge group, in the absence of a definite model however the general case $\kappa_V, \lambda_V \neq 0$ should be considered.

The partonic cross sections that contribute to leptoquark pair production (1) are given by

$$\hat{\sigma}_{\text{LO}}[q\bar{q} \rightarrow S\bar{S}] = \frac{\alpha_s^2 \pi}{27\hat{s}} 2\beta^3$$

$$\hat{\sigma}_{\text{LO}}[gg \rightarrow S\bar{S}] = \frac{\alpha_s^2 \pi}{96\hat{s}} \left[ \beta (41 - 31\beta^2) + (18\beta^2 - \beta^4 - 17) \ln \frac{1 + \beta}{1 - \beta} \right]$$

for scalar leptoquarks [8] and

$$\hat{\sigma}_{\text{LO}}[q\bar{q} \rightarrow V\bar{V}] = \frac{\alpha_s^2 \pi}{27\hat{s}} \frac{\beta^3}{1 - \beta^2} \left[ 23 - 3\beta^2 + \frac{4}{1 - \beta^2} \right]$$

$$\hat{\sigma}_{\text{LO}}[gg \rightarrow V\bar{V}] = \frac{\alpha_s^2 \pi}{24\hat{s}} \frac{1}{(1 - \beta^2)} \left[ \beta \left( \frac{523}{4} - 90\beta^2 + \frac{93}{4}\beta^4 \right) - \frac{3}{4} \left( 65 - 83\beta^2 + 19\beta^4 - \beta^6 \right) \ln \frac{1 + \beta}{1 - \beta} \right]$$

for vector leptoquarks with vanishing anomalous couplings $\kappa_V, \lambda_V = 0$ [8]. The invariant energy of the subprocess is denoted by $\sqrt{\hat{s}}$ and $\beta = (1 - 4m_{\text{LQ}}^2/\hat{s})^{1/2}$ is the velocity of the produced leptoquarks in their centre-of-mass system. Results for the general case of vector leptoquark pair production with $\kappa_V, \lambda_V \neq 0$ are given in [9]. Contributions to the quark-antiquark annihilation cross sections from lepton exchange in the $t$-channel involve the leptoquark-fermion coupling and can be neglected compared to the $\mathcal{O}(\alpha_s^2)$ processes listed above.

The $p\bar{p}$ cross section is found by folding the parton cross sections (2,3) with the gluon and light-quark luminosities in $p\bar{p}$ collisions. Due to the
dominating $qq$ luminosity for large parton momenta, the total cross section is built up primarily by quark-antiquark initial states for leptoquark masses $m_{LQ} \gtrsim 100$ GeV. From Figure 1 one can infer that the leading order (LO) cross sections for $m_{LQ} \sim 200$ GeV scalar and vector leptoquarks are $\sigma(p\bar{p} \to S\bar{S}) \sim 0.2$ pb and $\sigma(p\bar{p} \to V\bar{V}) \sim 10$ pb respectively, assuming vanishing anomalous couplings of vector leptoquarks to gluons. Even if the anomalous couplings are chosen such as to minimize the cross section, the total rate for vector leptoquark pair production is still a factor of two larger than that for scalar leptoquarks [6].

![Figure 1. The leading-order cross sections for single and pair production of scalar and vector leptoquarks ($\kappa_V, \lambda_V = 0$) in $p\bar{p}$ collisions at the Tevatron as a function of the leptoquark mass $m_{LQ}$. The CTEQ4L parton densities have been adopted and the renormalization/factorization scale has been set to $\mu = m_{LQ}$. ‘Su’ denotes the contribution to single scalar leptoquark production from scattering off $u$ and $\bar{u}$ quarks in the proton, taking $\lambda = e/10$.]

Another source of leptoquarks at the Tevatron is associated production $p\bar{p} \to LQ + l + X$. The cross section for this process depends quadratically on the leptoquark-fermion coupling and is thus significantly smaller than for leptoquark pair production. Taking $\lambda = e/10 \approx 1/30$ for illustration, one finds $\sigma(p\bar{p} \to Sl) \sim 4 \times 10^{-3}$ pb for a $m_S = 200$ GeV scalar leptoquark with couplings to $u$ and $\bar{u}$ quarks (see Figure 1), i.e. too small to be experimentally accessible at the moment.

The LO cross sections for scalar leptoquark pair production coincide
with the LO cross sections for squark-pair production in the infinite gluino mass limit \(m_{\tilde{g}} \to \infty\) [12]. For finite values \(m_{\tilde{g}} \lesssim 1\) TeV, \(t\)-channel gluino exchange significantly contributes to the partonic squark cross section: taking \(m_{\tilde{g}} = m_{\tilde{q}} = 200\) GeV, \(\tilde{u}/\tilde{d}\) pair production at the Tevatron is enhanced by almost an order of magnitude as compared to scalar leptoquark pair production. However, the squark solutions of the HERA excess events discussed in the literature belong to the second and third generation [12]. The corresponding pair production cross sections at the Tevatron are virtually independent of the gluino mass since the \(t\)-channel gluino exchange contributions are convoluted with the strongly suppressed heavy \(c, b, t\) parton distributions in the proton. The \(\tilde{c}, \tilde{b}, \tilde{t}\) cross sections are thus completely dominated by light \(u, d\)-quark fusion and coincide numerically with those for scalar leptoquarks, for any value of the gluino mass.

4. QCD corrections to scalar leptoquark pair production

Given the potentially large vector leptoquark cross section of \(\mathcal{O}(1-10\) pb) and the absence of a leptoquark signal at the Tevatron, vector leptoquarks are at best considered as only a marginal consistent explanation of the HERA data. Moreover, the excess over the Standard Model expectation at HERA is prominent at large values of the DIS variable \(y\), while vector leptoquark production would lead to a \(y\) distribution \(\propto (1-y)^2\). The most powerful competitor in this scenario is thus pair production of scalar leptoquarks. The leading order prediction based on the partonic cross sections (2) exhibits a steep and monotonic dependence on spurious parameters, i.e. the renormalization and factorization scales: Changing the scales from \(\mu = 2m_S\) to \(\mu = m_S/2\), the LO cross section varies by \(\sim 100\%\). A refinement of the theoretical analysis by inclusion of higher-order QCD corrections is thus mandatory to extract reliable mass limits from the Tevatron data.

The complete calculation of the next-to-leading QCD corrections has been performed recently in [3]. The scale dependence of the theoretical prediction is reduced significantly when higher order QCD corrections are included. This is demonstrated in Figure 2 where I compare the renormalization/factorization scale dependence of the total cross section at leading and next-to-leading order. For a consistent comparison of the LO and NLO results, all quantities [i.e. \(\alpha_s(\mu^2)\), the parton densities, and the partonic cross sections] have been calculated in leading and next-to-leading order, respectively. The NLO cross section runs through a broad maximum near \(\mu \sim m_S/2\), which supports the stable behavior in \(\mu\).

\[\begin{align*}
\text{Soft gluon corrections to the production of leptoquark pairs have been discussed in [14] (based, though, on erroneous Born calculations).}
\end{align*}\]
The QCD radiative corrections enhance the cross section for the production of scalar leptoquarks above the central value \( \mu \sim m_S \). If the LO cross section is calculated at large scales \( \mu \sim \sqrt{s} \), the enhancement in NLO is as large as \( \sim 70\% \), nearly independent of the leptoquark mass, see Figure 3. The convergence of the perturbative approach should however be judged by examining a properly defined \( K \)-factor, \( K = \sigma_{\text{NLO}}/\sigma_{\text{LO}} \), with all quantities in the numerator and denominator calculated consistently in NLO and LO, and evaluated at the central scale \( \mu = m_S \). In the interesting mass range between 150 \( \leq m_S \leq 250 \) GeV, these \( K \)-factors vary only between 1.20 and 1.08 \( \uparrow \). They are small enough to ensure a reliable perturbative expansion. Since the cross section for \( m_{LQ} \gtrsim 150 \) GeV is built up mainly by the quark–antiquark channels, thus based on well-measured parton densities, the variation between different parton parametrizations is less than 5%.

\[ \text{(4)} \]

It is not legitimate to use \( \mu = \sqrt{s} \) beyond LO since this choice of scale results in an error of order \( \alpha_s \), no matter how accurately the hard-scattering cross section is calculated \( \uparrow \).
Figure 3. The cross section for the production of scalar leptoquark pairs, \( p + \bar{p} \rightarrow S + \bar{S} + X \), at the Tevatron energy \( \sqrt{s} = 1.8 \) TeV as a function of the leptoquark mass \( m_S \). The NLO result is compared with LO calculations. The variation of the NLO cross section with the value of the renormalization/factorization scale is indicated by the shaded band. The CTEQ4 parton densities have been adopted.

5. Experimental searches and mass bounds

Leptoquark searches have been performed by the D0 and CDF collaborations at the Fermilab Tevatron. No leptoquark signal has been found in the full Run I data sample, resulting in upper cross section limits for scalar leptoquark pair production. Figure 4 shows the most recent D0 [4] and CDF [5] 95% confidence level limits on the production cross section times \( \beta^2 \), where \( \beta \) is the branching fraction of the leptoquark to a charged first generation lepton plus quark. Comparing the experimental limits with the NLO theoretical cross section prediction one obtains a lower bound on the leptoquark mass as a function of the branching fraction \( \beta \). Assuming \( \beta = 1 \) one finds:

\[
m_S \geq \begin{cases} 
210 \text{ GeV} & \text{[CDF]} \\
225 \text{ GeV} & \text{[D0]}
\end{cases} \quad \text{for} \quad \beta = 1 \quad (95\% \text{ C.L.}) \quad (4)
\]
The 95% confidence level upper cross section limits on scalar leptoquark pair production ($\beta = 1$) [4,5] compared to the NLO theoretical prediction (see Figure 3) as a function of the leptoquark mass $m_S$. Also shown is an estimate for a combined D0 and CDF exclusion limit.

Not taking into account (the small) correlated uncertainties, one can derive an estimate for a combined D0 and CDF exclusion limit⁵, resulting in

$$m_S \gtrsim 240 \text{ GeV} \quad \text{[CDF+D0]} \quad \text{for} \quad \beta = 1 \quad (95\% \text{ C.L.}) \quad (5)$$

The limit (5) can be translated into an upper limit on the branching fraction $\beta$ of a scalar leptoquark with mass $m_S = 200$ GeV:

$$\beta \lesssim 0.5 \quad \text{[CDF+D0]} \quad \text{for} \quad m_S = 200 \text{ GeV} \quad (6)$$

The corresponding limits on the masses and branching fractions of first generation squarks in supersymmetric theories with $R$-parity breaking are in general significantly stronger, depending in detail on the value of the gluino mass (see Section 3). Taking $m_\tilde{g} = m_\tilde{u}/\tilde{d} = 200$ GeV for illustration, one finds

$$\beta \lesssim 0.2 \quad \text{[CDF+D0]} \quad \text{for} \quad m_\tilde{u}/\tilde{d} = 200 \text{ GeV} \quad (7)$$

However, the squark solutions of the HERA excess events discussed in the literature belong to the second and third generation [2,13]. As discussed⁵, to extend the CDF results beyond 240 GeV, I assume the experimental cross section limit to be mass independent in that region.
in Section 3, the pair production cross sections and mass bounds for \( \tilde{c}, \tilde{b}, \) and \( \tilde{t} \) squarks are virtually independent of the gluino mass and coincide numerically with those for scalar leptoquarks.

It is worth pointing out that the limits on the branching fraction \( \beta \) are conservative in the sense that no assumptions have been made about the nature of possible additional decay modes. For leptoquarks/squarks decaying into electron-neutrino plus quark, additional experimental information can be used to further strengthen the exclusion bounds.

6. Conclusions

The leptoquark searches at the Fermilab Tevatron lead to a lower mass bound of about

\[
m_S \gtrsim 240 \text{ GeV} \quad \text{[CDF+D0]} \quad \text{for} \quad \beta = 1 \quad (95\% \text{ C.L.})
\]

for a leptoquark-type scalar particle decaying solely to a first generation charged lepton plus quark. These results exclude the interpretation of the excess events found at HERA as being due to the production of a leptoquark state with chiral and family-diagonal couplings to fermions. The Tevatron bounds are weakened by suppressing the branching fraction \( \beta \) into \((e\bar{q})\) final states. Branching fractions \( \beta < 1 \) are expected for squarks in supersymmetric theories with R-parity breaking. The limits on the masses and branching fractions of first generation squarks are in general significantly stronger than those for scalar leptoquarks, depending on the value of the gluino mass, as discussed in Section 5. The cross sections and mass bounds for the second and third generation squarks \( \tilde{c}, \tilde{b}, \tilde{t} \) are however not sensitive to gluino exchange contributions and identical to those for scalar leptoquarks.

Acknowledgments

It is a pleasure to thank Herbi Dreiner, Tilman Plehn, Michael Spira and Peter Zerwas for their collaboration and comments on the manuscript. I have benefitted from discussions and communications with Carla Grosso-Pilcher, John Hobbs and Greg Landsberg.

References

[1] C. Adloff et al., H1 Collaboration, Z. Phys. C74 (1997) 191; J. Breitweg et al., Zeus Collaboration, Z. Phys. C74 (1997) 207; Y. Sirois, these proceedings

\(^6\) Note however that the limits are not completely model-independent – they have been derived assuming the particle content of the Standard Model plus one additional scalar leptoquark-type state.
[2] H. Dreiner, these proceedings; T.G. Rizzo, these proceedings; R. Rückl, these proceedings, and references therein

[3] M. Krämer, T. Plehn, M. Spira, and P.M. Zerwas, Phys. Rev. Lett. 79 (1997) 341

[4] B. Abbott et al., D0 Collaboration, Fermilab-Pub-97/252-E [hep-ex/9707033]; S. Eno, these proceedings

[5] F. Abe et al., CDF Collaboration, Fermilab-Pub-97/280-E [hep-ex/9708017]; J. Conway, these proceedings

[6] J. Blümlein, E. Boos, and A. Kryukov, DESY 96-174 [hep-ph/9610408], Z. Phys. C in press; J. Blümlein, Z. Phys. C74 (1997) 605

[7] W. Buchmüller, R. Rückl, and D. Wyler, Phys. Lett. B191 (1987) 442; QCD corrections to the leptoquark production cross section have been calculated in: Z. Kunszt and W.J. Stirling, DTP/97/16 [hep-ph/9703427]; T. Plehn, H. Spiesberger, M. Spira, and P.M. Zerwas, Z. Phys. C74 (1997) 611; C. Friberg, E. Norrbin, and T. Sjöstrand, LU-TP-97-04 [hep-ph/9704214]

[8] J.A. Grifols and A. Méndez, Phys. Rev. D26 (1982) 324; I. Antoniadis, L. Baulieu, and F. Delduc, Z. Phys. C23 (1984) 119; E. Eichten, I. Hinchliffe, K.D. Kane, and C. Quigg, Rev. Mod. Phys. C56 (1984) 579; G. Altarelli and R. Rückl, Phys. Lett. B144 (1984) 126; S. Dawson, E. Eichten, and C. Quigg, Phys. Rev. D31 (1985) 1581; J. Blümlein, E. Boos, and A. Kryukov, in [6]

[9] P. Arnold and C. Wendt, Phys. Rev. D33 (1986) 1873; G.V. Borisov, Y.F. Pirogov, and K.R. Rudakov, Z. Phys. C36 (1987) 217; J.L. Hewett, T.G. Rizzo, S. Pakvasa, H.E. Haber, and A. Pomarol, Argonne Accel. Phys. 1993:539-546; J. Blümlein, E. Boos, and A. Kryukov, in [6]

[10] H.L. Lai, et al., Phys. Rev. D55 (1997) 1280

[11] J.L. Hewett and S. Pakvasa, Phys. Rev. D37 (1988) 3165; O.J.P. Eboli and A.V. Olinto, Phys. Rev. D38 (1988) 3461; A. Dobado, M.J. Herrero, and C. Munoz, Phys. Lett. B207 (1988) 97; V. Barger, K. Hagiwara, T. Han, and D. Zeppenfeld, Phys. Lett. B220 (1989) 464; M. de Montigny and L. Marleau, Phys. Rev. D40 (1989) 2869; J.L. Hewett and T.G. Rizzo, SLAC-PUB-7430 [hep-ph/9703337]

[12] G.L. Kane and J.P. Leveille, Phys. Lett. B112 (1982) 227; P.R. Harrison and C.H. Llewellyn-Smith, Nucl. Phys. B213 (1983) 223 [Err. Nucl. Phys. B223 (1983) 542]; E. Reya and D.P. Roy, Phys. Rev. D32 (1985) 645; S. Dawson, E. Eichten, and C. Quigg, in [6]; H. Baer and X. Tata, Phys. Lett. B160 (1985) 159; W. Beenakker, R. Höpker, M. Spira, and P.M. Zerwas, Phys. Rev. Lett. 74 (1995) 2905, and Nucl. Phys. B492 (1997) 51

[13] H. Dreiner, M. Krämer, and P. Morawitz, RAL preprint to be published.

[14] M. de Montigny and L. Marleau, Phys. Rev. D41 (1990) 3523

[15] J. Collins, D.E. Soper, and G. Sterman, in Perturbative Quantum Chromodynamics (ed. A.H. Mueller), World Scientific, Singapore (1989)