DESY 94–086
UCD–94–17
UMN–TH–1258/94
May 1994

SINGLE LEPTOQUARK PRODUCTION AT HADRON COLLIDERS

J. Ohnemus[1], S. Rudaz[2],
T.F. Walsh[2] and P.M. Zerwas[3]

[1] Physics Department, University of California, Davis CA 95616, USA
[2] School of Physics and Astronomy, University of Minnesota, Minneapolis MN 55455, USA
[3] Deutsches Elektronensynchrotron DESY, D-22603 Hamburg, FRG

Abstract

Leptoquarks can be produced in pairs by gluon–gluon fusion and quark–antiquark annihilation at hadron colliders. While HERA is the proper machine for single production of (eu) and (ed) type leptoquarks, the flavor species of (μu), (μd) and (τu), (τd) type leptoquarks can be produced at hadron colliders very efficiently. Besides exploiting gluon-quark collisions, leptoquarks can also be produced singly by colliding the quarks in one proton beam with leptons e, μ, τ generated by splitting photons which are radiated off the quarks in the other proton beam. For Yukawa couplings of the size α leptoquark masses up to about 300 GeV can be generated at the Tevatron while the LHC can produce leptoquarks with masses up to about 3 TeV. [Leptoquarks involving heavy quarks can be produced singly at a lower rate, determined by the heavy flavor flux in the proton beam.]

HEP-PH-9406235

Leptoquarks of any type (lq) where $l = e^\pm, \mu^\pm, \tau^\pm$ and $q = \overset{(-)}{u}, \overset{(-)}{d}, \ldots$, can be produced in pairs by gluon–gluon fusion and quark–antiquark annihilation at hadron colliders. Since the coupling strength to gluons is determined by the color charges of the particles, the production rates can be predicted in a model–independent way as long as form factor effects do not play a significant role [1].

In addition, leptoquarks can be generated singly at hadron colliders in association with leptons by exploiting gluon-quark collisions [1, 2]. At the electron–proton collider HERA, on the other hand, leptoquarks of the type (eu) and (ed) can be produced singly in a very efficient way by colliding electrons/positrons with u/d valence quarks [3]. The production rates in these cases are determined by the *a priori* unknown Yukawa couplings between leptons, quarks and leptoquarks. We will follow the general strategy of choosing the leptoquark coupling $\alpha_{LQ} = g_{LQ}^2/4\pi$ to be equal to the electromagnetic coupling α as a reference value for illustration.

In this framework, lower bounds for masses of scalar leptoquarks[1] have been set so far to ~ 170 GeV at HERA [5] and ~ 120 GeV at the Tevatron [6].

Powerful constraints can also be derived from high precision low–energy experiments [7, 9]. However, leptoquarks of all charge assignments are constrained stringently only in the electron sector [8, 9] by atomic parity violation, leptonic π decays and the absence/suppression of FCNC processes *etc.* The masses of leptoquarks involving electrons are bound to be larger than about 600 to 700 GeV if the coupling is of electromagnetic strength. Constraints on (μq) type leptoquarks are much weaker. Almost none of the (τq) type leptoquarks are significantly constraint by low energy data.

It is therefore an interesting problem to search for processes in which leptoquarks involving μ and τ leptons can be generated.[2] This is possible at hadron colliders where pairs of leptoquarks can be produced. Phase space suppression, however, sets stringent limits on the masses of the leptoquarks that can be reached by this method, in particular at the LHC where these particles are produced by gluon–gluon fusion. The problem is less severe at the Tevatron where valence quarks and antiquarks are engaged in the production process. We might therefore exploit also the single production of leptoquarks at hadron colliders even though the prediction of the production rate depends on the unknown Yukawa coupling constant in this case. Besides the Compton process, leptoquarks can be produced singly in these machines by splitting photons emitted from the (anti)proton beam into lepton pairs. One of the leptons can then collide with a quark from the other (anti)proton beam and thereby produce a leptoquark:

$$p\overset{(-)}{p} \to l + q \to LQ \, .$$

This mechanism, which is sketched in Fig. 1, is the topic of this letter.

Lepton (e, μ, τ) beams of sufficient intensity are generated automatically by splitting Weizsäcker–Williams photons $\gamma \to l^+l^-$ radiated either off protons which do not break

[1] We do not discuss vector particles in this letter [4].

[2] We restrict ourselves to leptoquarks $LQ = (lq)$ with unique l, q family assignments.

up, or off the quarks if the protons fragment. The second mechanism provides the more intense flux of photons [10, 11] and leptons, and it will be adopted in the following analyses. Since the leptons and quarks in leptoquark decays have large transverse momenta, the presence of proton fragments travelling along the beam direction with small to moderate transverse momenta is not disturbing in the present context. Folding the charge weighted flux of quarks $\Sigma e_q^2 q(x) = F_2(x)/x$ with the Weizsäcker–Williams spectrum we obtain for the γ flux in the proton beam

$$f_{\gamma/p}(z) = \frac{\alpha}{2\pi} \log\left(\frac{Q^2}{m_q^2}\right) \frac{1}{z} \int_z^1 \frac{dx}{x} \left[1 + (1 - z/x)^2\right] F_2(x, Q^2) \,, \tag{1}$$

where $z = E_\gamma/E_p$ denotes the fraction of the energy transferred from the proton to the photon. m_q is the effective light quark mass at the confinement scale which we will choose as ~ 300 MeV; since we restrict ourselves to leading logarithmic accuracy, a precise definition of this quantity is not needed. For Q^2 we will choose the mass of the leptoquarks M_{LQ}^2; again since we are interested in the kinematic range where M_{LQ} is *not much less* than the $p\overline{p}/pp$ c.m. energy, this choice is precise enough in leading logarithmic order. The γ splitting rate to lepton pairs of mass m_l is well–known to be [12]

$$f_{l/\gamma}(y) = \frac{\alpha}{2\pi} \left[y^2 + (1-y)^2\right] \log\left(\frac{Q^2}{m_l^2}\right) \,. \tag{2}$$

Combining the spectra from Eqs. (1) and (2) we obtain the lepton flux in the proton beam

$$f_{l/p}(x_l) = \int_{x_l}^1 \frac{dz}{z} f_{l/\gamma}(x_l/z)\; f_{\gamma/p}(z) \,. \tag{3}$$

The (lq) luminosity $d\mathcal{L}^{lq}/d\tau$ in $p\overline{p}$ and pp collisions follows from these spectra immediately,

$$p\overline{p}: \quad \frac{d\mathcal{L}^{lq}}{d\tau} = \int_\tau^1 \frac{dx_l}{x_l} f_{l/p}(x_l) \left[q(\tau/x_l) + \overline{q}(\tau/x_l)\right] , \tag{4}$$

$$pp: \quad \frac{d\mathcal{L}^{lq}}{d\tau} = 2\int_\tau^1 \frac{dx_l}{x_l} f_{l/p}(x_l)\; q(\tau/x_l) \,. \tag{5}$$

These expressions are valid for one specific lepton of fixed charge and one specific quark flavor described by the parton density $q(x, Q^2)$. The Drell-Yan variable is defined as $\tau = M_{lq}^2/s$ with M_{lq} being the invariant (lq) mass and $\sqrt{s}$ the $p\overline{p}/pp$ c.m. energy.

For τ sufficiently small we may estimate the luminosities by approximating the proton structure function [10] crudely as $F_2 \sim |c| \log(1/x)$ with $|c| = 0.16$ in the x range above 10^{-3}, resulting in

$$\tau \frac{d\mathcal{L}^{lq}}{d\tau} \sim \frac{\alpha^2 |c|^2}{48\pi^2} \log\left(\frac{Q^2}{m_l^2}\right) \log\left(\frac{Q^2}{m_q^2}\right) \log^4(1/\tau) \,, \tag{6}$$

for both $p\overline{p}$ and pp colliding beams. This expression works surprisingly well for order of magnitude estimates if compared with accurate numerical evaluations of the particle fluxes.

If we define, as usual, the coupling of the (lq) type scalar leptoquark to the quark q and the lepton l of given (but opposite) helicities [13] by e.g. $\mathcal{L} = g_{LQ}\, \overline{l}_L q_R \cdot LQ + h.c.$, the cross section for the production of the leptoquark in lq collisions can easily be derived in the narrow width approximation,

$$\hat{\sigma}\,(l + q \to LQ) = \alpha_{LQ}\, \pi^2\, \delta_1(\hat{s} - M_{LQ}^2) \tag{7}$$

with $\alpha_{LQ} = g_{LQ}^2/4\pi$. From Eq. (7) we obtain the $p\overline{p}/pp$ cross section for single leptoquark production,

$$\sigma\,(p\overline{p}/pp \to LQ) = \frac{\alpha_{LQ}\, \pi^2}{M_{LQ}^2}\, \tau\, \frac{d\mathcal{L}^{lq}}{d\tau} \tag{8}$$

where $\tau = M_{LQ}^2/s$. A rough estimate of the cross section is provided by

$$\sigma(p\overline{p}/pp \to LQ) \sim \frac{\alpha^2\, \alpha_{LQ}}{M_{LQ}^2}\, \frac{|c|^2}{48}\, \log\left(\frac{M_{LQ}^2}{m_l^2}\right)\, \log\left(\frac{M_{LQ}^2}{m_q^2}\right)\, \log^4\left(\frac{s}{M_{LQ}^2}\right)\,, \tag{9}$$

which reproduces the cross section to leading logarithmic order for leptoquark masses $M_{LQ} \lesssim \sqrt{s}/5$.

In Figs. 2a) and b) we present numerical examples for the production cross sections of single leptoquarks at the Tevatron [$p\overline{p}\ at\ \sqrt{s} = 1.8\, TeV$] and the LHC [$pp\ at\ \sqrt{s} = 14\, TeV$] to estimate the respective discovery potentials. The numerical results were obtained using the MRS set D'_- parton distribution functions [14]. We restrict ourselves to (eu), (μu) and (τu) type scalar leptoquarks since the cross sections are maximal for u quarks. The curves are the same for both lepton charges $l^\pm$. At the Tevatron the cross sections also remain the same if the u quark is replaced by the $\bar{u}$ anti–quark. This exchange leads to a big suppression of course at the LHC for large LQ masses. For d type leptoquarks the cross sections drop by about a factor 2, *cum grano salis*, compared with the u type cross sections [in the parton sea range for small masses a little less]. The Yukawa couplings of the left/right–handed quarks and leptons to the scalar leptoquarks have been fixed, in both figures, at the representative electroweak value $\alpha_{LQ} = 1/137$. The cross sections scale linearly with α_{LQ}.

Leptoquarks decay either into a charged lepton plus quark jet or into a neutrino plus quark jet, depending on the electric and isospin charge assignments. If the two channels are open at the same time, the branching ratio is close to 1/2 in the scenario of charge assignments we have assumed here. The widths of the states are small, $\mathcal{O}(1\ GeV)$, if the Yukawa coupling α_{LQ} is $\mathcal{O}(\alpha)$. This obviously produces a very clean signature, since we expect that the parent leptoquark will have small transverse momentum compared to its decay products. The situation is similar to that for W or Z production in low energy colliders, with a Jacobian peak for the high transverse momentum lepton, smeared by the parent transverse momentum distribution.

(i) For the parameters given above leptoquark masses of about 300 GeV can be reached at the Tevatron with an integrated luminosity of 1 fb^{-1}. These limits are a little smaller but still in the same ballpark as the discovery limits for the pair production of leptoquarks and the single production of leptoquarks in gluon-quark collisions. However, the final state, a lepton plus a jet, both at large transverse momenta $p_T \sim M_{LQ}/2$ and balanced, has a simple topology and it may be easy to analyze experimentally. The main background is due to $W+$ jet final states with the W decaying leptonically. Since the transverse momenta of the charged lepton and the jet are not balanced in the background events, the background can be suppressed very efficiently. The neutrino decay channel of the leptoquarks can be exploited if the background $Z(\rightarrow \nu\overline{\nu})$ + jet can be controlled properly. Though the cross section is smaller, the rejection of this background involves the difficult task of reconstructing the invariant mass $M(\nu\overline{\nu}) \sim M_Z$ from missing momentum and energy. HERA can produce, under the same assumptions, leptoquarks of the (eu) type up to the kinematical limit of a little less than 300 GeV. Single leptoquark production at the Tevatron in the (μq) and (τq) type sectors therefore opens interesting complementary production channels involving the heavy leptons μ and τ.

(ii) The real potential of the method discussed above, however, becomes apparent at the LHC. Pair production of leptoquarks at this machine is limited to masses not exceeding a value between 1.5 to 2 TeV [15]. This is a result of the softness of the gluon and antiquark spectra in proton beams. For single leptoquark production, on the other hand, the phase space suppression is less severe. From Fig. 2b) we conclude that leptoquarks of the (eq), (μq) and (τq) type [q = light quarks u, d] with masses of about 3 TeV could be discovered in this machine through the production channel discussed in this note. [Background events can be rejected in the same way as discussed above.] This limit is only a little smaller than the limit reached in gluon-quark collisions, but it is significantly larger than the masses one can reach at colliding $ee, e\gamma$ and $\gamma\gamma$ beam facilities [16] in the foreseeable future. The method exploited here is also more powerful than colliding the LHC with LEP; such a hybrid would only be capable of generating leptoquarks with masses of less than ~ 1.5 TeV [17].

Theoretical arguments have been discussed, based on technicolor models for instance, which would favor the coupling of the heavy leptons and quarks to leptoquarks [18], preferably (τb) and (τt). These particles will obviously be produced in pairs through gluon fusion and quark–antiquark annihilation at the Tevatron and LHC with the model–independent standard scalar cross section. Of course, single leptoquark production mechanisms are less competitive compared to leptoquark pair production when considering these (τb) and (τt) states [and (μs), (μc)] since the relevant quark flux in the proton beam must be generated by splitting gluons or involves sea quarks. Nevertheless, there may be somewhat of a compensating advantage even here because of the relatively clean signature from single leptoquark production at small and moderate transverse momenta.

Acknowledgements

We thank J. Blümlein, W. Buchmüller and F. Schrempp for discussions. Special thanks go to P. Jenni for providing us with material on the production of pairs of leptoquarks at the LHC. This work has been supported in part by Department of Energy grants # DE-FG03-91ER40674 and # DE-FG02-94ER40823 and by Texas National Research Laboratory grant # RGFY93-330.

References

[1] J. L. Hewett and S. Pakvasa, Phys. Rev. D37 (1988) 3165; J. L. Hewett and T. G. Rizzo, Phys. Rep. C183 (1989) 193.

[2] M. de Montigny and L. Marleau, Phys. Rev. D40 (1989) 2869.

[3] Reports in the Proceedings "Physics at HERA", DESY Hamburg 1992; J. Blümlein, E. Boos and A. Pukhov, DESY 94–072.

[4] J. L. Hewett et al., Proceedings "Workshop on Physics at Current Accelerators and Supercolliders", Argonne 1993.

[5] M. Derrick et al. [ZEUS Coll.], Phys. Lett. B306 (1993) 173; I. Abt et al. [H1 Coll.], Nucl. Phys. B396 (1993) 3.

[6] F. Abe et al. [CDF Coll.], Phys. Rev. D48 (1993) 3939; S. Abachi et al. [D0 Coll.], Phys. Rev. Lett. 72 (1994) 965.

[7] O. Shanker, Nucl. Phys. B204 (1982) 375; I. Bigi, G. Köpp and P.M. Zerwas, Phys. Lett. B166 (1986) 238; W. Buchmüller and D. Wyler, Phys. Lett. B177 (1986) 377; J. L. Hewett and T. G. Rizzo, Phys. Rev. D36 (1987) 3367; B. Schrempp, Proceedings "Physics at HERA", DESY Hamburg 1992.

[8] M. Leurer, Phys. Rev. D49 (1994) 333.

[9] S. Davidson, D. Bailey and B. A. Campbell, Z. Phys. C61 (1994) 613.

[10] J. Ohnemus, T. F. Walsh and P. M. Zerwas, DESY 93–173 / UCD–93–39 [Phys. Lett. B, in print].

[11] M. Drees, R. M. Godbole, M. Nowakowski and S. D. Rindani, MAD/PH/824 (1994) [Phys. Rev. D, in print].

[12] P. Kessler, Nuovo Cim. 16 (1960) 809; V. Baier, V. Fadin and V. A. Khoze, Nucl. Phys. B65 (1973) 381; M. Chen and P. M. Zerwas, Phys. Rev. D12 (1975) 187; G. Altarelli and G. Parisi, Nucl. Phys. B126 (1977) 298.

[13] W. Buchmüller, R. Rückl and D. Wyler, Phys. Lett. B191 (1987) 442.

[14] A. D. Martin, R. G. Roberts and W. J. Stirling, Phys. Lett. B 306 (1993) 145.

[15] For a summary see P. Jenni, Proceedings La Thuile Workshop, La Thuile 1994, based on E. Tsesmelis, ATLAS Internal Notes PHYS–NO–021 and 029, and A. d'Avella, *ibid.* 026.

[16] D. Schaile and P. M. Zerwas, Proceedings "Physics at Future Colliders", La Thuile 1987, CERN 87–07 (II); J. Blümlein, Proceedings "e^+e^- Collisions at 500 GeV: The Physics Potential", DESY 92–123A+B and 93–123C; J. E. Cieza Montalvo and O. J. P. Eboli, Phys. Rev. D47 (1993) 837; J. Blümlein and P. Frampton, Proceedings "Physics and Experiments with e^+e^- Linear Colliders", Waikoloa, Hawaii 1993; O. J. Eboli et al., Phys. Lett. B311 (1993) 147; H. Nadeau and D. London, Phys. Rev. D47 (1993) 3742; G. Bélanger, D. London and H. Nadeau, Phys. Rev. D49 (1994) 3140; M. A. Doncheski and S. Godfrey, Ottawa preprint OCIP–C–93–15.

[17] N. Harnew, Proceedings "Large Hadron Collider", Aachen 1990, CERN 90–10.

[18] S. Rudaz and J. Vermaseren, CERN-TH.2961; A. Djouadi, T. Köhler, M. Spira and J. Tutas, Z. Phys. C46 (1990) 679.

FIGURES

1. Schematic representation of the mechanism for producing single leptoquarks in proton–(anti)proton collisions.

2. Cross sections for single scalar leptoquark production as a function of the leptoquark mass M_{LQ}. Parts a) and b) are for the Tevatron [$p\bar{p}$ at $\sqrt{s} = 1.8$ TeV] and the LHC [pp at $\sqrt{s} = 14$ TeV], respectively. Cross sections are shown for (eu), (μu), and (τu) type leptoquarks. The Yukawa coulping is fixed to $\alpha_{LQ} = 1/137$. The left-hand-sides of the figures are labeled with the cross section in femtobarns, while the right-hand-sides are labeled with the number of events corresponding to integrated luminosities of 1 fb^{-1} and 200 fb^{-1} for the Tevatron and LHC, respectively.