Searches for Scalar and Vector Leptoquarks at Future Hadron Colliders *

Thomas G. Rizzo
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA

ABSTRACT

The search reaches for both scalar(S) and vector(V) leptoquarks at future hadron colliders are summarized. In particular we evaluate the production cross sections of both leptoquark types at TeV33 and LHC as well as the proposed 60 and 200 TeV colliders through both quark-antiquark annihilation and gluon-gluon fusion: $q\bar{q}, gg \to SS, VV$. Experiments at these machines should easily discover such particles if their masses are not in excess of the few TeV range.

I. INTRODUCTION

Many extensions of the standard model(SM) which place quarks and leptons on a symmetric footing predict the existence of leptoquarks, which are spin-0 or 1, color-triplet objects that couple to a $q\ell$ or $\bar{q}\ell$ pair[1]. While these particles may be sought indirectly through their influence on low energy processes[2], the most promising approach is via direct production at colliders. In particular, searches for leptoquarks at LEP[3], HERA[4], and the Tevatron[5] have already been performed, in most cases concentrating on the specific scenario of scalar leptoquarks. Based on both the direct and indirect searches we might expect that if leptoquarks exist their masses must be above a few hundred GeV, and possibly up in the TeV range. In this paper we will examine the search reach for both scalar and vector leptoquarks at future hadron colliders. The production rates for leptoquarks at such colliders will be shown to be sufficiently large so that particles of this type in the TeV mass range and above become accessible. In addition, we will see that the size of the production cross section alone is sufficient to distinguish scalar from vector leptoquark types.

II. LEPTOQUARK PAIR PRODUCTION

Leptoquarks can be produced either singly or in pairs in hadronic collisions. The cross section for single production, however, relies on the size of the *a priori* unknown Yukawa couplings of the leptoquark and is therefore model dependent. Pair production, on the otherhand, proceeds through QCD interactions and thus depends *only* on the leptoquark spin and the fact that it is a color triplet field. It has been shown in Ref.[6] that this mechanism will be dominant unless the Yukawa couplings, which are governed by the electroweak interactions, are rather large, *i.e.*, of order electromagnetic strength or greater. This is an important result in that the production of both scalar and vector leptoquarks at hadron colliders is not dependent upon the electroweak properties of these particles. Of course, the converse is also true, *i.e.*, the production properties cannot be used to probe the detailed nature of the leptoquark type.

The production cross section for pairs of scalar leptoquarks(S) in either gg or $q\bar{q}$ collisions is easily calculated and has been available for some time; we use the results of Hewett *et al.* in Ref.[6] in what follows. Given the mass of S there are no real ambiguities in this calculation except for the possible inclusion of a $K-$factor (which we omit) to account for higher order QCD corrections and leads to a slight enhancement in the rate.

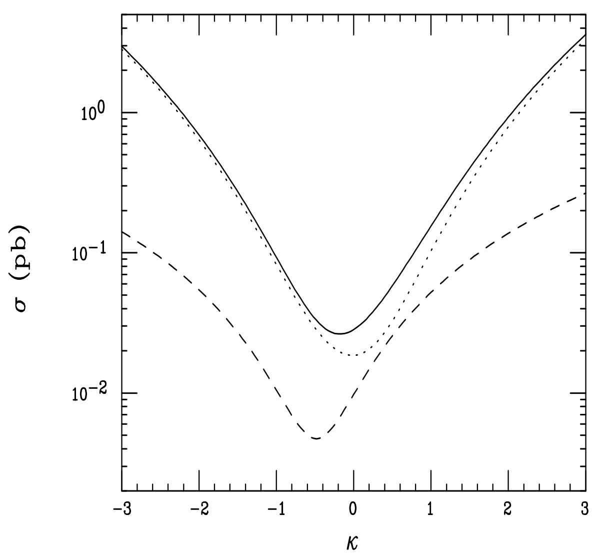

Figure 1: Production cross section for a pair of 1 TeV vector leptoquarks at the LHC as a function of κ. The dotted(dashed) curve corresponds to the $gg(q\bar{q})$ production subprocess whereas the solid curve is their sum.

The vector leptoquark(V) case is not as straightforward. In order to calculate the $gg \to VV$ cross section we need to determine both the trilinear gVV and quartic $ggVV$ couplings, which may naively at first glance appear to be unknown. (For the $q\bar{q}$ subprocess, only the gVV coupling is required.) However, in any realistic model wherein vector leptoquarks appear and are *fundamental* objects, they will be the gauge bosons of an extended gauge group like $SU(5)$. In this case the gVV and $ggVV$ couplings are *completely* fixed by extended gauge invariance. These particular couplings will also insure that the subprocess cross sections obey tree-level unitarity, as is the hallmark of all gauge theories. Of course, it might be that the appearance of vector leptoquarks is simply some low energy

*Work supported by the Department of Energy, contract DE–AC03–76SF00515.

manifestation of a more fundamental theory at a higher scale and that these particles may even be composite. In this case so-called `anomalous' couplings in both the $gVV$ and $ggVV$ vertices can appear. One possible coupling of this type is an `anomalous chromomagnetic moment', usually described in the literature by the parameter κ, which takes the value of unity in the more realistic gauge theory case. Among these `anomalous couplings', the term which induces κ is quite special in that it is the only one that conserves CP and is of dimension 4.

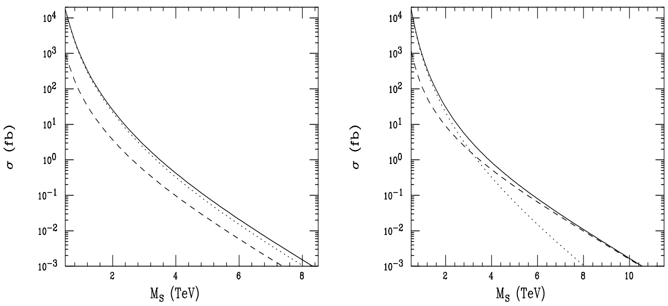

Figure 2: Scalar leptoquark pair production cross section as a function of mass at a 60 TeV pp(left) or $p\bar{p}$(right) LSGNA collider. The dotted(dashed) curve corresponds to the $gg(q\bar{q})$ production subprocess whereas the solid curve is their sum. MRSA′ parton densities are employed.

The Feynman rules for the vector leptoquark-gluon interactions can then be derived from the following effective Lagrangian which includes the most general set of $SU(3)_c$ gauge invariant, CP-conserving operators of dimension 4 (or less)

$$\mathcal{L}_V = -\frac{1}{2}F^{\dagger}_{\mu\nu}F^{\mu\nu} + M_V^2 V^{\dagger}_{\mu}V^{\mu} - ig_s\kappa V^{\dagger}_{\mu}G^{\mu\nu}V_{\nu}\,. \quad (1)$$

Here, $G_{\mu\nu}$ is the usual gluon field strength tensor, V_μ is the vector leptoquark field and $F_{\mu\nu} = D_\mu V_\nu - D_\nu V_\mu$, where $D_\mu = \partial_\mu + ig_s T^a G^a_\mu$ is the gauge covariant derivative (with respect to $SU(3)$ color), G^a_μ is the gluon field and the $SU(3)$ generator T^a is taken in the triplet representation. In most of the numerical results that follow we will assume $\kappa = 1$, *i.e.*, we will assume that V is indeed a gauge boson and use the results of Hewett *et al.* in Ref.[7] for the evaluation of production rates. The cross sections for other nearby values of κ are generally qualitatively comparable as is demonstrated by the results shown in Fig. 1 for the case of the pair production of 1 TeV vector leptoquarks at the LHC. If the vector leptoquark is *not* a gauge boson then we might, *e.g.*, expect it to be minimally coupled to the gluon field, as discussed by Blümlein and Rückl[7]. In this case we have instead that $\kappa = 0$. The cross section in this case, as can be seen from the figure, is somewhat smaller than in the situation where V is a vector boson with $\kappa = 1$. We remind the reader that changes in κ will also lead to modifications in the distributions associated with vector leptoquark pair production but these are subjects are beyond the scope of the present analysis and will be discussed elsewhere.

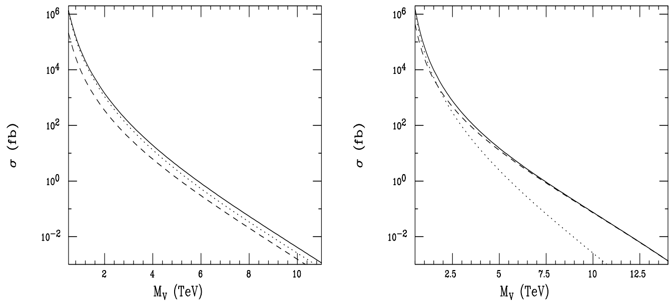

Figure 3: Same as the previous figure but now for a spin-1 vector leptoquark with $\kappa = 1$.

III. RESULTS

We now turn to some numerical results. We will consider the production of only a single type of leptoquark at a time and ignore the possibility of a degenerate multiplet of leptoquarks being produced simultaneously. Here we concentrate on cross sections for S and V pair production at the $\sqrt{s}$=60 (LSGNA) and 200 (PIPETRON) TeV machines, which are displayed in Figures 2, 3, 4 and 5, since the corresponding results for the Tevatron and LHC can be found in, *e.g.*, Ref.[8]. In these figures, the contributions of the two distinct subprocesses $gg \to SS, VV$ and $q\bar{q} \to SS, VV$ are separately displayed together with their sum. From Figures 2 and 3 several conclusions are immediately obvious for leptoquark production at the $\sqrt{s} = 60$ TeV collider: (i) The vector leptoquark cross section is substantially larger than that for scalars in both pp and $p\bar{p}$ collisions since the rates for both $gg \to VV$ and $q\bar{q} \to VV$ are larger than their scalar counterparts. (ii) Due to the contribution of the $q\bar{q}$ production mode, $p\bar{p}$ colliders have larger leptoquark cross sections than do pp colliders. For example, the ratio of $p\bar{p}$ to pp cross sections for a 4(6) TeV scalar(vector) leptoquark is approximately 2(6) at $\sqrt{s} = 60$ TeV. At pp machines, for both vector and scalar leptoquarks, the cross sections are dominated by the gg process out to the machine's anticipated mass reach. In the $\sqrt{s} = 60$ TeV $p\bar{p}$ case, the $q\bar{q}$ process dominates over gg for masses greater than about 3.0(1.8) TeV for scalar(vector) leptoquarks. The mass reaches for the 60 TeV machine can be found in Table I.

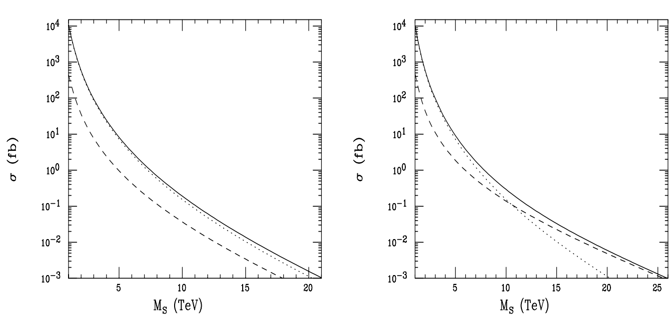

Figure 4: Same as Fig. 2 but now at the 200 TeV PIPETRON collider.

At $\sqrt{s}$=200 TeV, the patterns observed at 60 TeV are repeated. For example, the ratio of $p\bar{p}$ to pp cross sections for a 10(15) TeV scalar(vector) leptoquark is approximately 1.5(3.5). In the $p\bar{p}$ collider mode, the $q\bar{q}$ process dominates over gg for masses greater than about 10(6) TeV for scalar(vector) leptoquarks.

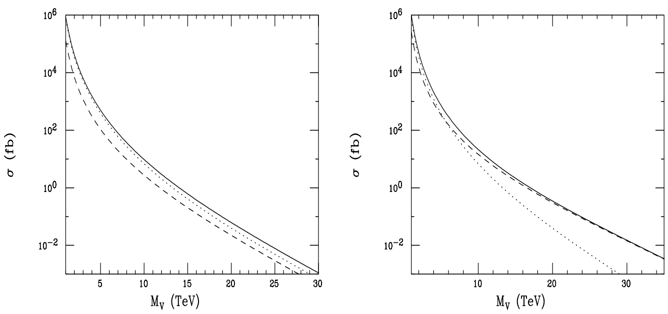

Figure 5: Same as Fig. 3 but now for the 200 TeV PIPETRON collider.

Table I summarizes and compares the search reaches for both scalar and vector leptoquarks at the Tevatron and LHC as well as the hypothetical 60 and 200 TeV pp and $p\bar{p}$ colliders. Our results for the Tevatron confirm the expectations of the TeV2000 Study Group [9], who also assume the 10 event discovery limit, while those obtained for the LHC are somewhat smaller[10] than that given by a fast CMS detector simulation. As discussed above, the larger cross sections for vector leptoquarks results in higher search reaches at all machines. Similarly, the larger $q\bar{q}$ subprocess contribution to the total cross section at $p\bar{p}$ machines leads to a greater reach for both scalar and vector leptoquarks in this collision mode.

It is clear from this table that future hadron colliders will be able to significantly extend the present search reaches for scalar and vector leptoquarks.

Table I: Search reaches in TeV for scalar(S) and vector(V) leptoquarks at future hadron colliders assuming a branching fraction into a charged lepton plus a jet of unity($1/2$). For vector leptoquarks, $\kappa = 1$ has been assumed and in both cases the MRSA$'$ parton densities have been employed. These results are based on the assumption of 10 signal events.

Machine	$\mathcal{L}(fb^{-1})$	S	V
LHC	100	1.34(1.27)	2.1(2.0)
60 TeV(pp)	100	4.9(4.4)	7.6(7.0)
60 TeV($p\bar{p}$)	100	5.7(5.2)	9.6(9.0)
200 TeV(pp)	1000	15.4(14.1)	24.2(23.3)
200 TeV($p\bar{p}$)	1000	18.1(16.2)	31.1(29.0)
TeV33	30	$\simeq 0.35$	$\simeq 0.58$

IV. ACKNOWLEDGEMENTS

The author would like to thanks S. Godfrey, J. Hewett, G. Wrochna and W. Merritt for discussions related to this work.

V. REFERENCES

[1] W. Buchmüller, R. Rückl, and D. Wyler, Phys. Lett. **B191**, 442 (1987); J.L. Hewett and T.G. Rizzo, Phys. Rep. **183**, 193 (1989); H. Georgi and S.L. Glashow, Phys. Rev. Lett. **32**, 438 (1974); J.C. Pati and A. Salam, Phys. Rev. **D10**, 275 (1974); H. Murayama and T. Yanagida, Mod. Phys. Lett. **A7**, 147 (1992); L.F. Abbott and E. Farhi, Phys. Lett. **B101**, 69 (1981).

[2] S. Davidson, D. Bailey, and B.A. Campbell, Z. Phys. **C61**, 613 (1994); M. Leurer, Phys. Rev. **D49**, 333 (1994) and Phys. Rev. **D50**, 536 (1994); W. Buchmüller, and D. Wyler, Phys. Lett. **B177**, 377 (1986).

[3] P. Maettig, OPAL Collaboration, talk given at the *28th International Conference on High Energy Physics*, Warsaw, Poland, 25-31 July 1996.

[4] S. Aid *et al.*, H1 Collaboration, Phys. Lett. **B369**, 173 (1996); D. Krakauer, ZEUS Collaboration, these proceedings.

[5] S. Abachi *et al.*, D0 Collaboration, Phys. Rev. Lett. **75**, 3618 (1995) and Phys. Rev. Lett. **72**, 965 (1994); F. Abe *et al.*, CDF Collaboration, Phys. Rev. Lett. **75**, 1012 (1995) and Phys. Rev. **D48**, 3939 (1993); H. Wenzel, CDF Collaboration, talk given at the *XI Topical Workshop on $p\bar{p}$ Collider Physics*, Padova, Italy, 27 May-1 June, 1996.

[6] J.L. Hewett and S. Pakvasa, Phys. Rev. **D37**, 3165 (1988).

[7] J.E. Cieza Montalvo and O. Eboli, Phys. Rev. **D47**, 837 (1993); J. Blümlein and R. Rückl, Phys. Lett. **B304**, 337 (1993); J.L. Hewett, T.G. Rizzo, S. Pakvasa, A. Pomarol, and H.E. Haber, in the *Proceedings of the Workshop on Physics at Current Accelerators and Supercolliders*, edited by J. Hewett, A. White and D. Zeppenfeld, Argonne National Laboratory, 2-5 June, 1993.

[8] A. Djouadi, J. Ng and T.G. Rizzo, SLAC-PUB-95-6772, 1995, a part of the DPF long-range planning study to be published in *Electroweak Symmetry Breaking and Physics Beyond the Standard Model*, eds. T. Barklow, S. Dawson, H. Haber, and J. Seigrist (World Scientific 1996).

[9] See the discussion in *Future ElectroWeak Physics at the Fermilab Tevatron: Report of the tev_{2000} Study Group*, eds. D. Amidei and R. Brock, D0 Note 2589 and CDF Note 3177, 1996.

[10] G. Wronchna, CMS Collaboration, these proceedings.