VECTOR LEPTOQUARK PRODUCTION AT HADRON COLLIDERS

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ABSTRACT

We explore the production of vector leptoquarks(V) at the Tevatron, LHC, and SSC through both quark-antiquark and gluon fusion: $q\bar{q}, gg \to VV$. The cross sections are found to be somewhat larger than for scalar leptoquarks of the same mass implying enhanced search capabilities.

Many extensions of the standard model (SM) which place quarks and leptons on an equal footing predict the existence of leptoquarks, which are spin-0 or 1 objects that couple to a $q\ell$ or $\bar{q}\ell$ pair[1]. While these objects 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. While the current LEP bounds ($M_{LQ} \gtrsim M_Z/2$) are insensitive to the leptoquark spin, the HERA limits display a sizeable sensitivity to the choice of spin-0 or spin-1. The HERA bounds also depend directly on the unknown $q\ell$-leptoquark coupling; taking this coupling to be electroweak strength, the leptoquark mass is restricted to be $M_{LQ} > 98 - 192\,\mathrm{GeV}$, for various choices of the spin, electric charge, and helicity of the leptoquark. The Tevatron places a bound of $M_{LQ} > 116\,\mathrm{GeV}$ (assuming a 100% branching ratio into electrons) on scalar leptoquarks. The sensitivity of the Tevatron limits to the spin of the leptoquark has not yet been addressed in the literature. The cross section for the $q\bar{q} \to VV$ subprocess, with V denoting a vector leptoquark, is readily obtainable from existing results, while the parton level cross section for $gg \to VV$ remains to be calculated. In this work we calculate these cross sections at the Tevatron, the LHC, and the SSC, and compare our results to those previously obtained for scalar leptoquarks[6]. We will show that the cross section in the spin-1 case may be substantially larger than that for spin-0, implying stronger search limits from existing data and an extended search range in the future. We also find that while the gg subprocess is generally dominant at both the LHC and SSC, the

$q\bar{q}$ subprocess at the Tevatron is extremely important particularly for larger values of the V mass. We note that vector leptoquark production at high energy linear e^+e^- colliders has been considered elsewhere in the literature[7].

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 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. In this case the gVV and $ggVV$ couplings are completely fixed by gauge invariance. These particular couplings will also insure that the subprocess cross section obeys 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 manifestation of a more fundamental theory at a higher scale and that these particles may even be composite, in which case so-called 'anomalous' couplings in both the gVV and $ggVV$ vertices can appear. One such possible coupling is an 'anomalous magnetic moment', usually described in the literature by the parameter κ (Ref. 8), which takes the value of unity in the gauge theory case. Among these 'anomalous couplings', the term which induces κ is special in that it is the only one that conserves CP and is of dimension 4.

The Feynman rules for the leptoquark-gluon inteactions are derived from the following effective Lagrangian which includes the most general set of CP-conserving operators of dimension 4 (or less)

$$\mathcal{L}_V = -\frac{1}{2}F^\dagger_{\mu\nu}F^{\mu\nu} + M_V^2 V^\dagger_\mu V^\mu - ig_s\kappa V^\dagger_\mu G^{\mu\nu}V_\nu\,. \tag{1}$$

Here, $G_{\mu\nu}$ is the usual gluon field strength tensor, V_μ is the 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. As values of κ differing from one have been entertained in the literature when discussing vector leptoquarks[7], we will generally assume $\kappa = 1$ or 0, with the latter value corresponding to 'minimal' coupling, in order to probe the sensitivity of our results to the assumed gauge nature of V. We will also describe the results in the more general case where κ is arbitrary.

The calculation of the parton-level differential cross section, $d\hat{\sigma}/d\hat{t}$, for the gg subprocess for arbitrary values of κ is now straightforward but algebraically cumbersome. The details of the calculation will be presented elsewhere[9]. The matrix element receives contributions from $\hat{s}$-, $\hat{t}$-, and $\hat{u}$-channel graphs as well as the $ggVV$ four-point seagull graph, as depicted in Fig. 1. All of these diagrams appear in the corresponding scalar leptoquark case albeit with a different tensor structure. Once the result for this parton level cross section is obtained we can fold it together with the gluon distributions from the initial state hadrons and impose either rapidity and/or p_t cuts. To this, the $q\bar{q}$ contribution must be added to obtain the total cross section. The $q\bar{q}$ subprocess cross section can be easily obtained from the process $e^+e^- \to W^+W^-$ via a virtual photon, by the replacement $\alpha \to \alpha_s$ and the incorporation of the appropriate color factors. We remind the reader that this cross section also depends on the choice of κ. In addition to an $\hat{s}$-channel gluon exchange, shown in Fig. 2a, this subprocess can also receive contributions from $\hat{t}$- or $\hat{u}$-channel diagrams as displayed in Fig. 2b. These additional diagrams involve lepton exchange and are proportional to the square of the unknown $q\ell$-leptoquark Yukawa couplings. If these couplings are assumed to be of electromagnetic strength or smaller, we find that these diagrams do not make a significant contribution and are hence neglected in our analysis. (A similar situation, of course, arises[6] in the case of scalar leptoquarks.)

The two individual subprocess result in the total cross sections displayed in Figs. 3, 4 and 5 at the Tevatron, SSC, and LHC, respectively, and should be compared with the existing calculations for the scalar case in Ref. 6. In obtaining these results we have made use of the NLO parton distributions of Ref. 10. As we see from the figures, the production rate for spin-1 leptoquarks can be substantially larger than in the spin-0 case. The current Tevatron limit of 116 GeV (Ref. 5) on the mass of a hypothetical scalar leptoquark which couples to only the first generation fermions, can be translated easily to the vector case if identical assumptions about the leptoquark branching fractions are made. We find, taking the branching fraction of V to the $\ell^{\pm}+j$ final state to be 1(0.5), that the vector leptoquark mass must be $\gtrsim 230(200)$ GeV at 95% CL assuming $\kappa=1$. A slightly smaller bound is obtained in the case of $\kappa=0$, with $M_V \gtrsim 180(150)$ GeV, showing that the constraints on the mass of vector leptoquarks from hadron colliders are somewhat sensitive to the assumption that these particles are fundamental gauge bosons from an extended gauge model. We anticipate that these limits will increase to near 270(250) GeV for the $\kappa=1$ case after the data from the 1992-93 Tevatron run 1a have been fully analyzed. As we can see from these calculations, the Tevatron may eventually be able to push the lower bound on the mass of V beyond the kinematic reach of HERA, at least for the case of a large $\ell^{\pm}+j$ branching fraction and $\kappa=1$. These figures also show that at the Tevatron the gg subprocess is overcome by the $q\bar{q}$ subprocess for V masses above 50 GeV. We also learn that the gg contribution has a minimum very close to $\kappa=0$ and the corresponding minimum for the $q\bar{q}$ subprocess is also not far from zero (but is somewhat dependent upon the average $\hat{s}$ and the vector leptoquark mass). This implies that the $\kappa=0$ result essentially yields the smallest vector leptoquark pair cross section at the Tevatron and can be used to place a model-independent bound.

At the SSC/LHC, the accessible mass range for vector leptoquarks is also seen to be significantly larger than in the scalar case. Since the contribution from the $q\bar{q}$ subprocess is insignificant here, the total cross section will have a minimum near $\kappa=0$ so that this cross section can again be used to set a model-independent limit on V pair production. Assuming an integrated luminosity of $10 fb^{-1}$ at the SSC, and a 10 event discovery limit, the mass reach for vector (scalar) leptoquarks is 3.6 (2.2) TeV assuming $\kappa=1$. A somewhat smaller search limit of 3.0 TeV is obtained for $\kappa=0$, which again demonstrates the sensitivity to the assumptions about the fundamental nature of these particles. At the LHC (taking $\sqrt{s}=14$ TeV), we obtain the corresponding search limits for vector leptoquarks of 2.2(1.8) for $\kappa=1(0)$ assuming a factor of ten increase in the integrated luminosity is available in comparison to the SSC. For scalar leptoquarks a limit of 1.4 TeV is achievable at the LHC.

If leptoquark type events are discovered, it will be important to determine the underlying nature of these events. Observing a mass peak in the jet-lepton invariant mass would rule out Standard Model backgrounds such as W+jet production. It will then be crucial to measure the spin and color of the leptoquark (to distinguish it from other possible exotic objects such as a leptogluon). This will clearly require a substantially larger data sample than the 10 events referred to above. In a future publication, we intend to study in detail the nature of the leptoquark signals and ascertain the requirements for a full determination of the leptoquark quantum numbers. Clearly, the discovery of such a particle would have a profound effect on the development of theories beyond the Standard Model.

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Fig. 1: The Feynman diagrams responsible for the parton level process $gg \to VV$.

Fig. 2: Feynman diagrams for VV production in $q\bar{q}$ scattering.

Fig. 3: Production cross section for a pair of vector leptoquarks at the Tevatron as a function of the leptoquark mass assuming (a)$\kappa = 1$ or (b)$\kappa = 0$. The dotted(dashed, solid)curve corresponds to the $q\bar{q}$(gg, total) contribution respectively for the CTEQ1MS parton distributions. Our results can vary by about 10 % if other distributions are used instead. (c)κ dependence of the $q\bar{q}$ (dots), gg(dashes), and total(solid) V pair production cross sections at the Tevatron for a vector leptoquark mass of 200 GeV assuming the CTEQ1MS distributions. No cuts have been applied in this figure.

Fig. 4: Same as Fig. 3, but for the SSC. In (c), a vector leptoquark mass of 1 TeV is assumed.

Fig. 5: Same as Fig. 4, but for the LHC.