

Leptoquarks decaying to a top quark and a charged lepton at hadron colliders

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(Received 15 March 2011; published 17 June 2011)

We study the sensitivity of the Tevatron and the 7 TeV LHC to a leptoquark S coupling to a top quark and a charged lepton L ($= e, \mu$, or τ). For the Tevatron, we focus on the case $m_S < m_t$, where the leptoquark pair production cross section is large, and the decay is three-body: $S \rightarrow WbL^\pm$. We argue that existing Tevatron observations could exclude $m_S \lesssim 160$ GeV. For $m_S > m_t$, we show that the LHC experiments with low integrated luminosity could be sensitive to such leptoquarks decaying to $tl^\pm$ with $l = \mu$ or τ .

DOI: 10.1103/PhysRevD.83.115016

PACS numbers: 14.80.Sv

I. INTRODUCTION AND REVIEW

Leptoquarks [1] are bosons which couple to a lepton and a quark. Although they are not known to address current issues in particle physics (such as the identity of dark matter or the hierarchy problem), they can be motivated in several ways. Most pragmatically, they are strongly interacting and their decay products include leptons, so they are interesting search candidates for hadron colliders. The Tevatron sets bounds on leptoquarks which decay to first and second generation fermions, and to b 's; in this paper, we consider leptoquarks which couple to the top quark and any charged lepton $L^\pm$ ($L \in \{e, \mu, \tau\}$). We discuss the bounds that could be set with 4.3 fb^{-1} of Tevatron data, and the prospects for the 7 TeV LHC with 1 fb^{-1} .

Leptoquarks can arise in several extensions of the standard model, such as grand unified theories [2], technicolor [3], and R -parity violating supersymmetry [4]. We focus on scalar leptoquarks called S , with baryon and lepton number conserving interactions, and a mass $m_S \lesssim 1 \text{ TeV}$. Several recent models [5–7] include such leptoquarks. The Lagrangian describing their renormalizable interactions with standard model fermions and singlet neutrinos n is [8]

$$\begin{aligned} \mathcal{L} = & S_0(\lambda_{LS_0} \bar{\ell} i \tau_2 q^c + \lambda_{RS_0} \bar{e} u^c) + \tilde{S}_0 \tilde{\lambda}_{RS_0} \bar{e} d^c \\ & + (\lambda_{LS_2} \bar{\ell} u + \lambda_{RS_2} \bar{e} q[i\tau_2]) S_2 + \tilde{\lambda}_{LS_2} \bar{\ell} d \tilde{S}_2 \\ & + \bar{\ell}[i\tau_2] \tilde{\tau} q^c \cdot \tilde{S}_3 + \text{H.c.} + S'_0 \lambda'_{RS_0} \bar{n} u^c \\ & + \tilde{S}'_0 \tilde{\lambda}'_{RS_0} \bar{n} d^c + \lambda'_{RS_2} \bar{n} q[i\tau_2] S_2 + \text{H.c.}, \end{aligned} \quad (1)$$

where the leptoquark subscript is its SU(2) representation, the λ 's are 3×3 matrices in the lepton and quark flavor spaces and are labeled by the SU(2) representation of the leptons (L = doublet, R = singlet) and the leptoquark name, τ_2 is a Pauli matrix [so $i\tau_2$ provides the antisymmetric SU(2) contraction], the standard model SU(2) singlets are e, u, d , and ν , and in this equation, q and ℓ are the

doublets. For most of the rest of the paper, L and ℓ label physical particles

$$\ell \in \{e, \mu\}, \quad L \in \{e, \mu, \tau\}.$$

In Eq. (1), we included for completeness, leptoquarks which couple to singlet neutrinos n . If the neutrino masses are Dirac, these interactions could allow $S \rightarrow t\nu$ without $S \rightarrow b\nu$. However, we do not analyze such decays. Notice that we neglect, or set to zero, the (renormalizable) interactions of the leptoquark with the Higgs, which naturally should be present, and can contribute via loops to precision electroweak parameters [9] and neutrino masses [10].

To look for leptoquarks, some theoretical expectations about the structure and hierarchy of their interactions would be helpful. Various theoretical arguments can suggest that the largest leptoquark couplings should be to the third generation, at least in the quark sector. This arises, for instance, in the Cheng-Sher ansatz [11] for flavored couplings

$$\lambda^{LQ} \propto \sqrt{\frac{m_L m_Q}{v^2}}, \quad (2)$$

where $v = 174 \text{ GeV}$ is the Higgs vacuum expectation value and Q and L are generation indices. This would give the largest leptoquark coupling to t and τ , and can arise Randall-Sundrum type extra dimensional models, or in composite models as recently discussed in [6]. The expectations of this ansatz are compared to current low energy constraints in [12]; improving the sensitivity of $K \rightarrow \pi\nu\bar{\nu}$ could probe this pattern for leptoquarks that couple to neutrinos.

A phenomenological “bottom-up” approach to the couplings of new particles, motivated by the success of the minimal flavor violation hypothesis [13,14], is to construct them by multiplying the known mass and mixing matrices of leptons and quarks. Some possibilities for leptoquarks were studied in [15]. In this approach, Nikolidakis and Smith [16] noted that a new physics coupling with a single lepton index L can be proportional to

$$\varepsilon^{LJK} [Y_e Y_e^\dagger m_\nu]_{JK}, \quad (3)$$

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where Y_e is the charged lepton Yukawa matrix (index order doublet-singlet), and m_ν is the majorana neutrino mass matrix. This idea was studied for leptoquarks in [15]. Since m_ν is fairly democratic, the $Y_e Y_e^\dagger$ hierarchy selects the τ index. The totally antisymmetric SU(2) tensor is ϵ , so this construction favors couplings to the e and μ . It is therefore interesting to study leptoquarks which decay to t and any charged lepton: $L = \tau, \mu, \text{ or } e$. The μ and e are particularly attractive final state particles for hadron colliders: if one of the W 's from the t 's decays to the $\ell = e$ or μ , as occurs $\sim 29\%$ of the time, the final state would be jets $+ E_T + \ell^\pm \ell^\pm \ell^\mp$ (see Fig. 1.)

There are various experimental constraints on leptoquarks. At hadron colliders, they can be produced via their strong interactions. The Tevatron [17] has searched for leptoquarks decaying to any lepton and a quark other than the top, with a coupling $\lambda \gtrsim 10^{-8}$. The restriction on λ ensures that the leptoquark decays at the collision point. The bounds depend on the final state; a recent review [18] gives $m_S \gtrsim 210[\tau b], 214[\nu q], 247[\nu b], 299[eq, eb], 316[\mu q, \mu b]$ GeV, where $q \in \{u, d, s, c\}$. Leptoquarks have also been searched for at the HERA ep collider, which allows us to exclude a s -channel resonance with $\lambda \gtrsim 0.1$ and $m_S \lesssim 250\text{--}300$ GeV [19]. Finally, there are bounds on two quark, two lepton contact interactions from several (mostly accelerator) experiments [20], which give interesting constraints (see, e.g., [12,21]) on leptoquarks interacting with lower generation fermions. The prospects of discovering leptoquarks above the various backgrounds at the early LHC have been discussed in [22].

There are numerous precision/rare decay bounds on leptoquarks, which usually apply to products of different λ 's, and depend on the SU(2) representation of the leptoquark. Some recent compilations are [23] (bounds from meson antimeson mixing, allowing for complex couplings) and [12] (mostly tree processes). In general, it is clear that these bounds exclude flavor-democratic $\lambda^{LQ} \sim \mathcal{O}(1)$ for $m_S < \text{TeV}$. Certain processes, such as $K \rightarrow \pi \nu \bar{\nu}$ or $K_L \rightarrow \mu^\pm e^\mp$ provide much more stringent bounds.

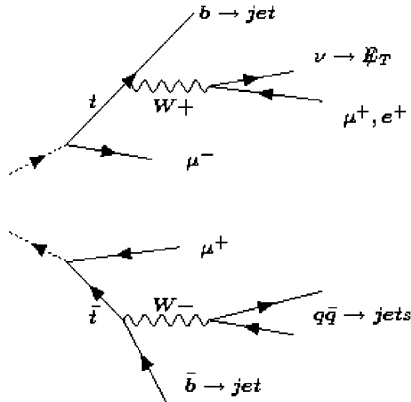


FIG. 1. Possible decay chain for a pair of scalar leptoquarks interacting with tops and muons.

Bounds and prospects for a “third generation” leptoquark interacting with a top have been discussed by several people, in particular, Eboli and collaborators. The constraints from the loop contribution to leptonic Z decay [24] are satisfied if $\lambda \lesssim e$ for $m_S \sim 300$ GeV [for both the leptoquarks of Eq. (1) which couple to t_R]. To extrapolate this bound for leptoquarks in the range $300 \text{ GeV} \rightarrow m_W$, we assume that the bound can be scaled as $\lambda/m_S \lesssim e/(300 \text{ GeV})$, see Eq. (4). The LHC prospects of a leptoquark decaying to $t\tau$ or $b\tau$ were discussed in [25], which emphasized the interesting one, two, and three lepton final states which could be detected above backgrounds. Gripaios *et al.* recently implemented the various leptoquarks of Eq. (1) in HERWIG [26], and discussed kinematic reconstruction techniques for leptoquarks decaying to third generation fermions at the 7 TeV LHC.

In this paper, we study leptoquarks which couple to tops, but not to b 's or lower generation quarks, because leptoquarks with an $\mathcal{O}(1)$ branching ratio to $b\nu$, or jet $+ e$ or μ , are already excluded by the Tevatron up to $m_S \lesssim 200\text{--}300$ GeV [17,18]. We are therefore interested in leptoquarks which couple to singlet up-type quarks, that is, the SU(2) singlet leptoquark S_0 with coupling λ_{RS_0} (and $\lambda_{LS_0} = 0$), or the doublet leptoquark S_2 with couplings $\lambda_{LS_2} \neq 0$ and $\lambda_{RS_2} = 0$. (Neither of these leptoquarks arise in R -parity violating supersymmetry, where the LQD^c interaction couples doublet t quarks—never singlets—to leptons and squarks.) We then restrict the coupling to third generation quarks, and assume, for the body of the paper, a branching ratio of 1 to the final state of the top plus the charged lepton $L^\pm$ of our choice.

Leptoquarks can be singly or pair produced via their strong interactions at hadron colliders (see Fig. 2). As discussed in [27], single production can lead to the same final state as pair production. However, since we are interested in leptoquarks that couple to the top quark, we can neglect single production, because the top density in the proton is negligible. The cross section, for pair production from gg or $q\bar{q}$, has been computed at next to leading order

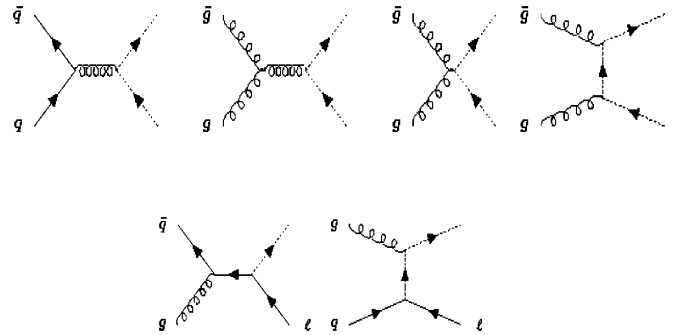


FIG. 2. Lowest order diagrams for leptoquark single and pair production; single production can be neglected for a leptoquark which couples only to t quarks because the t content of the proton is small.

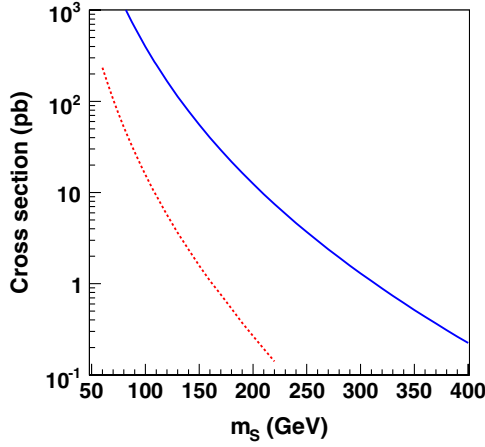


FIG. 3 (color online). Pair production cross section for SU(2) singlet leptoquarks at the Tevatron (dotted line) and the 7 TeV LHC (solid line). Standard model $t\bar{t}$ production, with $\sigma_{pp \rightarrow t\bar{t}}(\sqrt{s} = 7 \text{ TeV}) \approx 165 \text{ pb}$ and $\sigma_{pp \rightarrow t\bar{t}}(\sqrt{s} = 1.96 \text{ TeV}) \approx 7.8 \text{ pb}$, could be a significant background to the leptoquark signal, in particular, in the $m_S \sim m_t \pm 15 \text{ GeV}$ region, where the leptons from leptoquark decays would be soft.

(NLO) [28], and included in the PROSPINO program, which we used to produce Fig. 3. The NLO cross section for leptoquark pair production [28], via the strong interaction, is plotted in Fig. 3. This shows that the Tevatron with 5 fb^{-1} of data could produce $\gtrsim \mathcal{O}(5000)$ pairs of leptoquarks with $m_S \lesssim 150 \text{ GeV}$, whereas the 7 TeV LHC with 1 fb^{-1} could produce a thousand pairs of 300 GeV leptoquarks. Section II outlines a simple counting experiment that compares current Tevatron data to leptoquarks with $m_S < m_t$, decaying via an off-shell top to bW and a charged lepton. It suggests that the Tevatron could exclude such leptoquarks for leptoquark masses sufficiently below m_t . In Sec. III, we briefly mention perspectives with 1 fb^{-1} of data from the 7 TeV LHC.

II. LEPTOQUARKS WITH $m_S < m_t$ AT THE TEVATRON

In this section, we consider leptoquarks S interacting only with the top (and any L) with masses in the range $m_W + m_b < m_S < 2m_W < m_t$. They would be copiously pair produced via their strong interactions at the Tevatron. There are two reasons for this limited mass range, despite that Fig. 3 suggests several hundred leptoquark pairs could be produced at the Tevatron up to masses $m_S \sim 250 \text{ GeV}$. First, in the range $m_S \approx m_t \pm 15 \text{ GeV}$, the lepton produced with the almost-on-shell top is unlikely to pass the $p_T > 15\text{--}20 \text{ GeV}$ cuts that we impose. Second, it is convenient to analyze separately the $m_S < m_t$ and $m_S > m_t$ cases; so we study the former at the Tevatron and the latter at the LHC.

Leptoquarks with $m_S < m_t$ could also be singly produced in top decay; however, we neglect this process

because $\text{BR}(t \rightarrow SL) \leq 2|\lambda|^2/|y_t|^2$ is suppressed by the leptoquark coupling λ (y_t is the top quark Yukawa coupling). We consider the range

$$10^{-(6 \div 3)} < \lambda \ll e \frac{m_S}{300 \text{ GeV}}, \quad (4)$$

where the upper bound is approximately the constraint from leptoquark loop contributions to the $Z\bar{L}L$ vertex [24]. It implies that $\text{BR}(t \rightarrow SL)$ is negligible, when it is kinematically allowed. The lower bound ensures that λ is sufficiently large that the leptoquarks decay at the collision point (no displaced vertex); see the discussion after Eq. (12). We also assume that S interacts only with a top and a charged lepton $L^\pm$, so $\text{BR}(S \rightarrow bWL) = 1$, where L is a e, μ , or τ .

Since the leptoquark decays to a singlet t_R , its decay rate to bWL , via an off-shell t , has a simple analytic form, which we obtain in Sec. II A. This allows us to implement the three-body decay in PYTHIA, as the product of the two-body decays $\Gamma(S \rightarrow t^*L)\Gamma(t^* \rightarrow bW)$ with variable m_t and leptoquark coupling λ . This is discussed at the end of Sec. II A.

Section II B contains preliminary estimates of the contribution of such leptoquarks to the jets + $E_T + \ell^\pm$ [29] and jets + $E_T + \ell_i^\pm \ell_j^\mp$ [30] data sets used by D0 to measure the $t\bar{t}$ production cross section (ℓ here means e or μ). We consider separately the cases $S \rightarrow t\tau^\pm$ and $S \rightarrow t\mu^\pm$; we assume that the bounds which could be obtained on $S \rightarrow te^\pm$ are similar to those on $S \rightarrow t\mu^\pm$.

A. The decay rate $S \rightarrow bWL^\pm$ for $m_S < m_t$

If the masses of the b and $L \in \{e, \mu, \tau\}$ are neglected, then the invariant mass of the bW system (or equivalently, the magnitude of the four-momentum carried by the off-shell top in the decay $S \rightarrow bWL$), is

$$t^2 = m_{bW}^2 = (p_b + p_W)^2 = 2p_b \cdot p_W + m_W^2. \quad (5)$$

The differential three-body decay rate can be written [31]

$$\frac{d\Gamma}{dt} = \frac{1}{(2\pi)^5} \frac{1}{16m_S^2} \int |\mathcal{M}|^2 |\vec{p}_b^*| |\vec{p}_L| d\Omega_b^* d\Omega_L, \quad (6)$$

where the L parameters are in the S rest frame, and the starred b parameters in the bW rest frame.

The matrix element for $S \rightarrow bWL$ is

$$\mathcal{M} = \frac{\lambda g}{\sqrt{2}} \bar{u}_L P_R \frac{\not{p}_t + m_t}{t^2 - m_t^2 + im_t \Gamma_t} \gamma^\mu P_L u_b \varepsilon_\mu \quad (7)$$

(where u_L is the spinor field for L), and is simple in squared form because the top must flip chirality on the internal line:

$$|\mathcal{M}|^2 = \frac{-m_t^2 \lambda^2 g^2}{(t^2 - m_t^2)^2 + m_t^2 \Gamma_t^2} \times \left(p_L \cdot p_b + 2 \frac{p_L \cdot p_W p_b \cdot p_W}{m_W^2} \right). \quad (8)$$

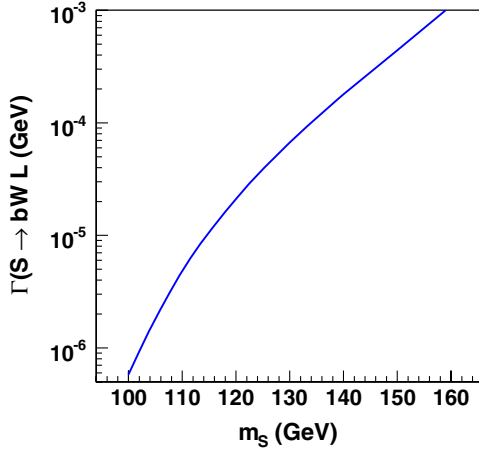


FIG. 4 (color online). The total decay rate $\Gamma(S \rightarrow bWL)$, for $\lambda = 1$, as a function of the leptoquark mass m_S , where L is a charged lepton e , μ , or τ .

To evaluate the angular integrations of Eq. (6) with $|\mathcal{M}|^2$ from Eq. (8), requires the Lorentz transformation of the b 4-momentum in the S frame (p_b), to the t frame (p_b^*). Writing

$$E_b = \gamma E_b^* (1 + \beta \cos \theta^*) \quad (9)$$

with $\gamma = E_t/m_t$, $\beta = |\vec{p}_t|/m_t$, and using

$$|\vec{p}_b^*| = \frac{t}{2} \left(1 - \frac{m_W^2}{t^2}\right), \quad |\vec{p}_L| = \frac{m_S}{2} \left(1 - \frac{t^2}{m_S^2}\right), \quad (10)$$

gives

$$\begin{aligned} & \int \left(p_L \cdot p_b + 2 \frac{p_L \cdot p_W p_b \cdot p_W}{m_W^2} \right) d\Omega_b^* d\Omega_L \\ &= 4\pi^2 m_S^2 \left(1 - \frac{t^2}{m_S^2}\right) \frac{t^2}{m_W^2} \left(1 - \frac{m_W^2}{t^2}\right) \left(1 + 2 \frac{m_W^2}{t^2}\right). \end{aligned}$$

So one obtains

$$\frac{d\Gamma}{dt} = \frac{\Gamma(S \rightarrow t^* L)}{2m_t} \frac{\Gamma(t^* \rightarrow Wb)}{\pi m_t} \frac{m_t^4}{(t^2 - m_t^2)^2 + m_t^2 \Gamma_t^2}, \quad (11)$$

where the two-body decay rates of the leptoquark S and the top quark t are the rest-frame formulas, with m_t replaced by t :

$$\begin{aligned} \Gamma(t^* \rightarrow Wb) &= \frac{g^2 t}{64\pi} \frac{t^2}{m_W^2} \left(1 + 2 \frac{m_W^2}{t^2}\right) \left(1 - \frac{m_W^2}{t^2}\right)^2, \\ \Gamma(S \rightarrow t^* L) &= \frac{\lambda^2 m_S}{16\pi} \left(1 - \frac{t^2}{m_S^2}\right)^2. \end{aligned}$$

A check that can be performed on Eq. (11) is to take the limit $t^2 \rightarrow m_t^2$. Using the identity:

$$\frac{1}{\pi} \frac{\epsilon}{x^2 + \epsilon^2} \rightarrow \delta(x) \quad (12)$$

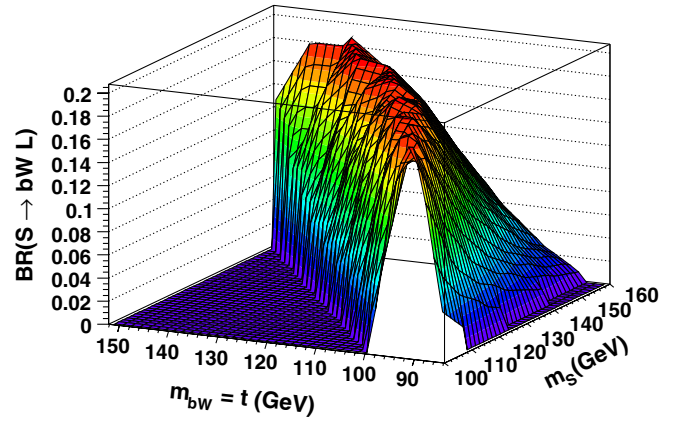


FIG. 5 (color online). The fraction of decays to a bW of invariant mass t for a leptoquark masses m_S .

with $x = t^2 - m_t^2$, the dt integration can be performed, and one obtains the two-body leptoquark decay rate $\Gamma(S \rightarrow tL)$, as expected. We are interested in the case $t^2 - m_t^2 \gg \Gamma_t m_t$, so we drop the Γ_t term in the denominator of Eq. (11). The total decay rate $\Gamma(S \rightarrow bWL)$ can also be obtained analytically, but is not illuminating. It is plotted in Fig. 4 for $\lambda = 1$. The leptoquark will decay in less than a centimeter for $\lambda \gtrsim 10^{-3}$ at $m_S \simeq 100$ GeV, and for $\lambda \gtrsim \text{few} \times 10^{-6}$ at $m_S \simeq 160$ GeV.

Equation (11) implies that the decay $S \rightarrow bWL$ can be computed as the two-body decay $S \rightarrow t^* L$, where t^* is a top quark of mass t , followed by the decay $t^* \rightarrow bW$, provided the whole process has a t -dependent coupling constant $\propto 1/(t^2 - m_t^2)^2$. We implement the $m_S < m_t$ leptoquarks in PYTHIA from this perspective: for each event, the top mass is randomly selected, distributed between $m_W + m_b$ and m_S according to Eq. (11). The two-body leptoquark decay is then performed by PYTHIA followed by a two-body top decay. We checked that the resulting bW invariant mass distribution (see Fig. 5) reproduces Eq. (11).

B. Potential bounds from the Tevatron

In this section we estimate the number of events from $m_S < m_t$ leptoquarks that could appear in two recent D0 data samples used to measure the $t\bar{t}$ production cross section: $\ell^\pm + E_T + \text{jets}$ [29], for leptoquarks decaying to $t\tau^\pm$, and $\ell_i^\pm \ell_j^\mp + E_T + \text{jets}$ [30] for leptoquarks decaying to $t\mu^\pm$. These two analyses are not optimal to select these leptoquark signals because they require exactly one and two leptons, respectively, in the final state. However, due to the important leptoquark pair production cross section when $m_S < m_t$, we will show that a significant number of leptoquark events would nevertheless enter in these data samples.

We obtain the leptoquark events using PYTHIA 6.4 [32] with TAUOLA [33] to decay τ 's [34], and reconstruct jets using the anti- k_t algorithm of the FASTJET package [35]. All final state particles except neutrinos and charged leptons are used to construct the jets. We do not include a detector

simulation. We only impose the preselection cuts of the experimental analyses on our leptoquark events, and count the number of remaining events. D0 uses multivariate techniques to further discriminate the $t\bar{t}$ signal from $W + \text{jets}$ or $Z + \text{jets}$, which we do not consider.

In PYTHIA, leptoquarks can decay to t and L^+ , but not [36] to t and L^- . The first is appropriate to the $SU(2)$ doublet leptoquark S_2 , whereas the second would correspond to the singlet leptoquark S_0 . In the $S \rightarrow t\mu$ case, the events corresponding to $t\mu^-$ or $t\mu^+$ should be equally detectable, so we let PYTHIA decay the leptoquarks to $t\mu^+$, and apply the resulting bounds to both S_2 and S_0 .

The case of $S \rightarrow t\tau^\pm$ is more delicate because the angular and energy distribution of the tau decay products depends on the charge and polarization of the τ . We therefore ask TAUOLA to flip the sign of τ 's produced in S_0 decays. In the case of leptonic τ decays, energetic ℓ^- are emitted preferentially anti-parallel to the direction of motion of a relativistic τ_R (see, e.g., the e distribution from μ decay in [31]). So for the singlet leptoquark S_0 , which decays to $t_R(\tau_R)^-$, the neutrinos from the leptonic tau decays frequently carry most of the p_T of the τ . Since the τ 's are already not very energetic, this means the charged leptons from their decay may not pass p_T cuts, so hadronic τ decays are more useful. We assume that the bounds we obtain on the singlet leptoquark S_0 can be applied to the doublet leptoquark S_2 , which decays $S_2 \rightarrow t(\tau_L)^+$, because our bounds will mostly come from events with hadronic τ decays [37].

1. $S \rightarrow t\tau^\pm$

Consider first the production of a leptoquark anti-leptoquark pair, followed by leptoquark decay to a t and a τ^- or τ^+ . This could contribute to the $\ell^\pm + E_T + \text{jets}$ signal from which D0 extracted the standard model top pair production cross section $\sigma_{t\bar{t}}$ in [29]; since the leptoquark process should have more jets than $t\bar{t}$ production, we focus on the $\ell^\pm$ and at least 4 jet sample.

In our simulated sample of leptoquark events, we require that a $W^\pm$ from the t or $\bar{t}$ decays to ν and $e^\pm$ or $\mu^\pm$, which reduces the cross section by a factor $\text{BR}(\ell^\pm + E_T + \text{jets}) = 0.22(W^+ \rightarrow \ell^+ \nu) \times 0.66(W^- \rightarrow \text{had}) \times 2(W^+ \leftrightarrow W^-) \simeq 0.29$. Then we impose the following cuts, patterned on the preselection of the D0 analysis. We require

- (1) $E_T > 25$ GeV,
- (2) a lepton with $p_T > 20$ GeV and $|\eta| \leq 1.1(e)$, $2.0(\mu)$ and no second lepton with $p_T > 15$ GeV,
- (3) at least 4 jets with $p_T > 20$ GeV, and $|\eta| < 2.5$.

With ε_{sim} the fraction of simulated events which pass these cuts, the inclusive leptoquark signal efficiency is simply $\varepsilon(E_T, 1\ell, 4j) = \varepsilon_{\text{sim}} \times \text{BR}(\ell^\pm + E_T + \text{jets})$. This efficiency is given in column 3 of Table I. We then estimate the number of leptoquark-induced events in the 4.3 fb^{-1} of data used in [29] to be the last column of Table I.

TABLE I. The second column is the leptoquark pair production cross section at the Tevatron for various masses. The leptoquarks decay to $t\tau^\pm$. The third column estimates the fraction of events remaining after the cuts given in Sec. II B 1. The last column is the expected number of leptoquark-induced events in the D0 lepton+ ≥ 4 jets sample [29] based on 4.3 fb^{-1} .

m_S (GeV)	σ (pb)	$\varepsilon(E_T, 1\ell, 4j)$	$N(S)$
160	1	0.0823	367
140	2.4	0.0618	658
120	6	0.0389	1035
100	16	0.0149	1060

The total number of observed (expected) $\ell^\pm + E_T + \geq 4$ jets events in [29] is 1795 [1796 ± 158]. Using the modified frequentist CL_s method,[38] the number of signal events excluded at 95% C.L. is 388. By interpolating our results, we find that leptoquarks with mass

$$m_S < 158 \text{ GeV} \quad \text{for } \text{BR}(S \rightarrow t\tau^\pm) = 1$$

are excluded at 95% C.L.

2. $S \rightarrow t\mu^\pm$

Consider now a pair of leptoquarks which decay to a t and a $\mu^\pm$, which could contribute to the $\ell_i^+ \ell_j^- + E_T + \text{jets}$ data sample from which D0 extracts $\sigma_{t\bar{t}}$ [30]. In this analysis [30], $\ell_i^+ \ell_j^-$ can be $e^+ e^-$, $e^\pm \mu^\mp$, or $\mu^+ \mu^-$. The leptoquarks we study would contribute mostly to $e^\pm \mu^\mp$ or $\mu^+ \mu^-$. However, to be conservative, we compare our expectations to the observed number of $\ell_i^+ \ell_j^- + \text{jets}$ events, including $e^+ e^-$.

We simulate leptoquark pair production, followed by leptoquark decays $S \rightarrow W^+ b \mu^+$, and require that one W decay to a charged lepton e , μ , or τ , which should represent a fraction

$$0.34(W^+ \rightarrow \ell^+ \nu) \times 0.66(W^- \rightarrow \text{had}) \times 2(W^+ \leftrightarrow W^-) \simeq 0.45 \quad (13)$$

of the events. We require a leptonic W to ensure missing transverse energy in the event, but include also the $W \rightarrow \tau \nu$ decays, because a lepton from the W is unnecessary; two charged leptons are already coming directly from the leptoquark decay. Since the D0 analysis requires exactly two leptons, one of our three leptons must fail the p_T cuts.

Our cuts to select two charged leptons are patterned on the D0 analysis [30]. We therefore require exactly two opposite sign leptons of $p_T > 15$ GeV with $|\eta| \leq 1.1(e)$, $2.0(\mu)$. Then, D0 uses a multivariate technique (Bayesian decision tree or BDT) to further discriminate top pair events from $Z/\gamma^* + \text{jets}$ events which we can not take into account. But since the topology of our leptoquark signal is very close to that of top pair production, we believe that leptoquark events will nevertheless pass the selection cut applied on this BDT output with an efficiency

TABLE II. The second column is the leptoquark pair production cross section for various masses. The leptoquarks decay to $t\mu^\pm$. The third column estimates the fraction of events remaining after the cuts given in Sec. II B 1. The last column is the expected number of leptoquark-induced events in the D0 $\ell^+\ell^- + \geq 3$ jets sample [30] of 4.3 fb^{-1} .

m_S (GeV)	σ (pb)	$\varepsilon(E_T, 2OS\ell, 3j)$	$N(S)$
160	1	0.0900	387
140	2.4	0.0752	776
120	6	0.0500	1288
100	16	0.0090	960

very close to the one from top pair events. In the following, we will not take into account the efficiency of the BDT, and simply replace it by a cut $E_T > 25 \text{ GeV}$. Then, we count the number of jets satisfying $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$ and require at least 3 jets.

In the third and fourth columns of Table II, we give the estimated fraction of leptoquark events which would pass the above cuts [obtained by multiplying Eq. (13), and the fraction of simulated events which pass cuts] and the expected number of leptoquark-induced events in 4.3 fb^{-1} . These numbers can be compared to the $\sim 51[65 \pm 15]$ observed (expected) events, [39] bearing in mind that we have not simulated detector effects and that we did not take into account the efficiency of the selection cut on the BDT output rejecting Drell-Yan events, which is around 70%. From those events, we computed that the number of signal events excluded at 95% C.L. is 39. We therefore see that the expected number of leptoquarks events is much larger than this number: this leptoquark signal would significantly contribute to the number of events observed in the D0 analysis, and we can conclude that leptoquarks with mass

$$m_S < 160 \text{ GeV} \quad \text{for } \text{BR}(S \rightarrow t\mu^\pm) = 1$$

are excluded at 95% C.L.

III. AT THE 7 TEV LHC

Leptoquarks decaying to a top and an e or μ are attractive search candidates for the early LHC because the final state contains leptons and many jets. If a $W^\pm$ from the t or $\bar{t}$ decays leptonically, various combinations of same sign and opposite sign leptons of a different flavor can be obtained (see Fig. 1).

Since the events contain many jets, the leptoquark pair production and decay should be calculated at NLO, so that the Monte Carlo simulation matches as well as possible to the real events. In addition, a detailed study of backgrounds would be required to identify suitable cuts to select leptoquark events and identify the leptoquark mass. We leave this analysis to the experimental collaborations, and here, we merely estimate the number of leptoquark events which could be expected in recent LHC $t\bar{t}$ samples [40,41].

We consider leptoquarks that decay with a branching ratio of one to either $t\tau^-$, or $t\mu^+$, with a mass in the range 200–400 GeV (so they decay to an on-shell top). The production and decay are calculated by PYTHIA 6.4 [32]. Jets are reconstructed with the anti- k_t algorithm of the FASTJET package [35], with $R = 0.5$. To estimate a total number of surviving events, we assume 1 fb^{-1} of data.

A. Counting events: $S \rightarrow t\mu^+$

Consider first the decay $S \rightarrow t\mu^+$. If one W decays leptonically, this could be searched for in events with $\ell^+\ell^- + E_T$ + jets. CMS recently determined the $t\bar{t}$ production cross section [40] (with two leptonic W 's) from such events, and our cuts are patterned on this analysis. We expect more leptons and jets in $S\bar{S}$ production than in $t\bar{t}$ production, so we impose:

- (1) $E_T > 30 \text{ GeV}$
- (2) Exactly two opposite sign charged leptons ($e^\pm, \mu^\pm$), with $p_T > 20$, $|\eta| < 2.5$.
Or alternatively, two OS leptons, with at least one other lepton.
- (3) At least four jets of $p_T > 30 \text{ GeV}$, and $|\eta| < 2.5$

The CMS analysis has an isolation cut for the leptons; we instead require that the simulated leptons who pass p_T cuts be produced in W or S decays (to avoid high p_T leptons from meson decays). We allow all decays to our W 's in PYTHIA [42]. The fraction of events that survive cuts 1, 3 and either of the versions of 2, are, respectively, defined as $\varepsilon(= 2OS\ell)$ and $\varepsilon(>2OS\ell)$, and are given in columns three and five of Table III. The number of events at the 7 TeV LHC with $\mathcal{L} = 1 \text{ fb}^{-1}$ of integrated luminosity is estimated in the fourth and sixth columns.

We can compare to the CMS determination [40] of the $t\bar{t}$ production cross section based on 3.1 pb^{-1} of data from the 7 TeV LHC. In the $2OS\ell$ and ≥ 4 jet bin, CMS observes one event, where $\simeq 0.75 \rightarrow 1.5$ signal events are expected. From [43], it appears that the background is $\leq 1/3$ of the signal. We anticipate that a 200 GeV leptoquark would contribute ~ 2 events in the $\geq 4j$ and exactly 2 OS lepton bin.

The integrated luminosity available now (winter 2011) is of order 35 pb^{-1} , or 10 times that used in the CMS analysis [40]. This suggests that $\sigma_{t\bar{t}}$ measurements at the LHC are already sensitive to leptoquarks S with $\text{BR}(S \rightarrow t\mu^\pm) = 1$ and $m_S \gtrsim 200 \text{ GeV}$. Furthermore, searching for $\geq 3\ell$ and ≥ 4 jets would be more sensitive to such leptoquarks.

B. Counting events: $S \rightarrow t\tau^-$

Consider now the decay $S \rightarrow t\tau^-$ with $\text{BR}(S \rightarrow t\tau^-) = 1$. This decay would be more challenging to reconstruct, because the neutrinos from both τ 's and a leptonic W can contribute to E_T . We decay $S \rightarrow t\tau^+$ in PYTHIA, and tell TAUOLA to flip the sign of the τ 's from the leptoquarks: $\tau^\pm \rightarrow \tau^\mp$, with helicity assigned as if it were chiral singlet

TABLE III. The second column is the leptoquark pair production cross section at the 7 TeV LHC. The leptoquarks decay to $t\mu^\pm$. The third column is the fraction of events which pass the cuts of Sec. III A (which always require four jets and missing transverse energy) with exactly one pair of opposite sign leptons, and the fourth column is the estimated number of events in 1 fb^{-1} of data. Columns five and six are the same for the events which pass the cuts of Sec. III A with three or more leptons.

m_S	$\sigma_{\text{prod}}/\text{pb}$	$\varepsilon(=2OS\ell)$	$N_=(S)$	$\varepsilon(>2OS\ell)$	$N_>(S)$
200	12.5	0.055	683	0.035	438
250	3.69	0.095	352	0.094	346
300	1.3	0.104	136	0.116	151
350	0.515	0.109	56	0.12	62
400	0.224	0.121	27	0.129	29

(τ_R). Similar to the discussion of $S \rightarrow t\tau$ at the Tevatron (see Sec. II B 1), we attempt to constrain these leptoquarks at the LHC from lepton + jets + E_T events. However, in our simulation of $S \rightarrow t\tau$ at the LHC, unlike that of Sec. II B 1, we allow all decays to the W 's from the tops. This is because, at the LHC, leptons produced in τ decay can be energetic enough to pass p_T cuts.

We then impose the following cuts, patterned on an ATLAS [41] analysis which extracts the $t\bar{t}$ production cross section from lepton + jets + E_T events:

- (1) $E_T > 25 \text{ GeV}$, where all the neutrinos are summed into E_T ,
- (2) at least four jets with $p_T > 25 \text{ GeV}$, $|\eta| < 2.5$.
- (3) We require at least one $e^\pm$, $\mu^\pm$ with $p_T > 20 \text{ GeV}$, $|\eta| < 2.5$. To mimic an isolation cut on our simulated leptons, we then check that the e^+ , e^- , μ^+ , and μ^- with highest p_T 's are separated from the jets which pass cuts, by $\Delta R = \sqrt{(\eta_j - \eta_\ell)^2 + (\phi_j - \phi_\ell)^2} \geq 0.3$. The leptons failing this check are rejected. Then, we may, in addition, require either exactly one lepton (as in the ATLAS analysis) or at least 7 jets and/or $e^\pm$ and/or $\mu^\pm$ which pass these cuts.

To take into account both hadronic and leptonic τ decays, the requirement of ≥ 7 jets and/or leptons is applied.

TABLE IV. The second column is the leptoquark pair production cross section at the 7 TeV LHC. The leptoquark decays to $t\tau^\pm$. The third, fifth, and seventh columns are the fraction of events which survive the cuts of Sec. III B; the three ε 's correspond to the three different lepton cuts. Then the fourth, sixth, and eighth columns are the estimated number of events passing cuts in 1 fb^{-1} of data for $\text{BR}(S \rightarrow t\tau^-) = 1$.

m_S	σ/pb	$\varepsilon(\geq 1\ell)$	$N(\geq 1\ell)$	$\varepsilon(1\ell)$	$N(1\ell)$	$\varepsilon(\geq 7j, \ell)$	$N(\geq 7j, \ell)$
200	12.5	0.160	2000	0.143	1788	0.039	488
250	3.69	0.297	1096	0.241	889	0.126	465
300	1.30	0.374	486	0.285	370	0.199	259
350	0.515	0.428	220	0.322	166	0.234	121
400	0.224	0.451	101	0.328	74	0.264	59

Our estimates of the fraction of leptoquark events that would pass these cuts (for the three possible lepton cuts), and the number of events in 1 fb^{-1} of data, are in Table IV. Notice that the efficiencies, for finding an $S \rightarrow t\tau^\pm$ leptoquark in such single lepton events, are higher than the efficiencies to find $S \rightarrow t\mu^\pm$ leptoquarks in the dilepton events, given in Table III. This is because there is always E_T (ν_τ 's) in the $S \rightarrow t\tau^\pm$ final state, and there is an $e^\pm$ or $\mu^\pm$ approximately 2/3 of the time. Whereas requiring E_T in the $S \rightarrow t\mu^\pm$ decays imposes a leptonic W , which occurs $\sim 29\%$ of the time.

It is less straightforward to anticipate LHC sensitivity in this channel. ATLAS [41] measured the $t\bar{t}$ production cross section in the single lepton + jets + E_T channel, with 2.8 pb^{-1} of data. In the bin containing ≥ 4 jets of which two are tagged as b 's, they observe 37 events, expected 30 from $t\bar{t}$, and estimate the background as 12.2 ± 3.9 . The ATLAS b tagging efficiency varies (40%–60% for E_j : $25 \rightarrow 85 \text{ GeV}$); if we assume that $\sim 50\%$ of the b 's from leptoquarks are tagged, one can guess from Table IV that a $m_S = 200 \text{ GeV}$ leptoquark, with $\text{BR}(S \rightarrow t\tau^-) = 1$, could contribute $\sim 1 - 2$ events to this bin. Explicitly counting events with extra jets (beyond the four expected from $t\bar{t}$), or events with extra leptons (ATLAS required one and only one), could improve the sensitivity to leptoquarks decaying to $t\tau^-$.

IV. SUMMARY

Like the Higgs, a scalar leptoquark is a boson that couples to two fermions. Since the quark Yukawa couplings to the Higgs are hierarchical, and flavor physics in the quark sector follows standard model expectations, one can anticipate that leptoquarks, like the Higgs, interact preferentially with third generation quarks. This also arises in several models. However, expectations for leptoquark couplings to leptons are less straightforward to extract from lepton mass matrices. The charged leptons are hierarchical, so one could imagine that leptoquarks should preferentially decay to $t\tau^\pm$. On the other hand, the neutrino sector is comparatively democratic, suggesting that leptoquarks could decay to t and any lepton. The $te^\pm$ and $t\mu^\pm$ final states could be interesting search channels for the early LHC.

This paper studied possible bounds on leptoquarks S , with a mass in the range $100 \text{ GeV} < m_S < 400 \text{ GeV}$, which are pair-produced via their strong interactions, and decay to a top quark (and only the top; no $b, c \dots$), and a charged lepton $L = e, \mu$ or τ . We expect the Tevatron, with its high luminosity, to be sensitive to the range $m_S < m_t$, where the leptoquarks decay to the three-body final state $bW^\pm L^\mp$. Leptoquarks with $m_S > m_t$ could be found at the LHC. The range $m_S \approx m_t \pm 15 \text{ GeV}$ appears difficult: the soft leptons in the final state may not pass p_T cuts, so the $S\bar{S}$ final state becomes difficult to distinguish from $t\bar{t}$. Recall that at $m_S \sim m_t$, the $S\bar{S}$ production cross section is $\sim 1/10$ of the $t\bar{t}$ production cross section [44].

We estimated the number of leptoquark-induced events containing lepton(s) plus jets, using PYTHIA 6.4, TAUOLA, and the anti- k_t jet algorithm of FASTJET. We include no detector simulation. We consider separately the sensitivities to leptoquarks which decay to $t\tau^\pm$, or $t\mu^\pm$, assuming a branching ratio of 1 in each case. We further assume that our estimates for the $t\mu^\pm$ final state could apply to leptoquarks decaying to $te^\pm$.

Our results suggest that current determinations of the $t\bar{t}$ production cross section, both from the Tevatron and the LHC, could constrain a leptoquark with $\text{BR}(S \rightarrow t\mu^\pm) = 1$, and a mass of order $100 \rightarrow 250 \text{ GeV}$. At the Tevatron, D0 determines the $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ from the final state $\ell_i^\pm \ell_j^\mp + E_T + \geq 3$ jets, using 4.3 fb^{-1} of data. We estimate that these results could exclude

$$m_S \lesssim 160 \text{ GeV} \quad \text{for } \text{BR}(S \rightarrow t\ell^\pm) = 1, \quad \ell \in \{e\mu\}.$$

At the LHC, CMS recently obtained $\sigma_{t\bar{t}}$ from events containing $\ell_i^\pm \ell_j^\mp + E_T + \geq 2$ jets (with 3.1 pb^{-1} of data). It is possible that leptoquarks with $m_S \gtrsim 200 \text{ GeV}$, could have

contributed a few events to their scantily populated (1 event) ≥ 4 jet bin.

Leptoquarks with $\text{BR}(S \rightarrow t\tau^\pm)$ would contribute to the final state $\ell + E_T + \geq 4$ jets (which are used to determine $\sigma_{t\bar{t}}$), if at least one of the W 's or τ 's decay leptonically. A significant fraction of the leptoquark events should have more than four jets, but the available data sets present a single ≥ 4 jet bin, so we cannot profit from this property. We estimate that a D0 analysis could exclude

$$m_S \lesssim 160 \text{ GeV} \quad \text{for } \text{BR}(S \rightarrow t\tau^\pm) = 1.$$

ATLAS also obtained $\sigma_{t\bar{t}}$ from events with $\ell + E_T + \geq 4$ jets (using 2.8 pb^{-1} of data), but leptoquarks with $m_S \sim 200 \text{ GeV}$ would be consistent with the backgrounds. Searching for events with more than four jets, or with additional leptons, would be more sensitive to the leptoquarks discussed here.

The current integrated luminosity of the LHC is significantly larger than the few pb^{-1} of the analyses we compared to [40,41]. In the $S \rightarrow t\mu^\pm$ channel, the determination of $\sigma_{t\bar{t}}$ with 1 fb^{-1} of data would give an expected limit $m_S > 300 \text{ GeV}$. However, we reiterate that $S\bar{S}$ production followed by $S \rightarrow tL^\pm$ should usually give a final state with more leptons and/or jets than $t\bar{t}$ production. Simple estimates suggest that dedicated searches counting additional leptons and/or jets, using 1 fb^{-1} of data, could be sensitive to $m_S \lesssim 400 \text{ GeV}$ for $\text{BR}(S \rightarrow tL^\pm)$, $L \in \{e, \mu, \tau\}$.

ACKNOWLEDGMENTS

We thank A. Aparici, C. Biscarat, G. Grenier, S. Perries, and V. Sanz for useful discussions.

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