

Signals for vector leptoquarks in hadronic collisions

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We analyze systematically the signatures of vector leptoquarks in hadronic collisions. We examine their single and pair productions, as well as their effects on the production of lepton pairs. Our results indicate that a machine like the CERN Large Hadron Collider (LHC) will be able to unravel the existence of vector leptoquarks with masses up to the range of 2–3 TeV.

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I. INTRODUCTION

Many extensions of the standard model predict the existence of leptoquarks, which are color triplet particles carrying simultaneously leptonic and baryonic number and can have spin 0 or 1. For instance, some composite models postulate a preonic substructure where quarks and leptons have some common constituents [1,2]. These models exhibit a very rich spectrum which includes excited states of the known particles, as well as new particles possessing unusual quantum numbers, such as leptoquarks and dileptons. Leptoquarks are also present in extensions of the standard model that treat quarks and leptons in the same basis and, consequently, allow the existence of new particles mediating quark-lepton transitions. This class of models includes grand unified theories [3], technicolor models [4], and superstring-inspired models [5].

The production and signals of scalar leptoquarks have already been analyzed in the literature for ep [6,7], hadronic [8], e^+e^- [9], and $e\gamma$ [10] colliders. However, previous studies of vector leptoquarks (V) considered only e^+e^- [11,12] and ep colliders [7]. In this paper we study the capability of hadron colliders to unravel the existence of vector leptoquarks. We analyze their pair production via gluon-gluon and quark-antiquark fusion [$g(q) + g(\bar{q}) \rightarrow V + \bar{V}$], single production in association with a lepton [$g + q \rightarrow V + \ell$, $\ell = e^\pm, \mu^\pm, \nu$], and their effects in the production of lepton pairs ($q + \bar{q} \rightarrow \ell^+ + \ell^-$). Our results show that a machine like the CERN Large Hadron Collider (LHC) can expand considerably the range of leptoquark masses and couplings that can be explored.

It is interesting to notice that pair production of vector leptoquarks is essentially model independent since it is related to the strong interactions. On the other hand, single production and indirect effects are to a great extent model dependent because they are due to unknown

interactions. Moreover, these three signals for vector leptoquarks are complementary since they allow us not only to reveal their existence but also to determine their properties such as mass, spin, and couplings to quarks and leptons.

There have been several direct searches for leptoquarks in accelerators. Analyzing the decay of the Z into a pair of on-shell leptoquarks, the CERN Large Electron-Positron Collider (LEP) experiments established a lower bound $M_{lq} \gtrsim 44$ GeV for scalar leptoquarks [13,14], and a similar bound should hold for vector ones. This limit can be improved by looking for Z decays into an on-shell and an off-shell leptoquark, resulting in $M_{lq} \gtrsim 65$ –73 GeV [14]. The search for scalar leptoquarks decaying into an electron-jet pair in $p\bar{p}$ colliders constrained their masses to be $M_{lq} \gtrsim 113$ GeV [15]. Furthermore, the experiments at the DESY ep collider HERA [16] placed limits on their masses and couplings, leading to $M_{lq} \gtrsim 92$ –184 GeV depending on the leptoquark type and couplings.

Leptoquarks are also tightly constrained by low energy experiments [17,18], such as the proton lifetime measurements and the study of rare decays associated with flavor-changing neutral currents. In order to avoid the strong low energy bounds we assumed that the leptoquark interactions conserve lepton and baryon number in addition to electric charge and color, and that their couplings are chiral [17]. Furthermore, leptoquarks that couple to more than one fermion generation are constrained to be very heavy; therefore, we shall study vector leptoquarks that couple only to one family. However, there are further bounds on first generation vector leptoquarks satisfying the above assumptions since the chirality of the couplings implies that processes involving leptoquarks violate parity and diagonal couplings to only one generation induce deviations from universality [19]. In what follows, we demonstrate that the direct search for vector leptoquarks leads to stronger bounds on these particles than the low energy experiments do.

For the sake of definiteness, we shall consider the vector leptoquarks inspired by the Abbott-Farhi model [2], which is a confining version of the standard model and is described by a Lagrangian which has the same general structure of the standard model one. Nevertheless, the choice of parameters is such that no spontaneous symmetry breaking occurs and the $SU(2)_L$ gauge interac-

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tion is confining. In this model, the physical left-handed fermions are bound states of a preonic scalar and a preonic left-handed fermion, while the vector bosons are P -wave bound states of the scalar preons. The vector leptokuarks predicted by this model are color triplets with electric charge $Q_V = -2/3$ and weak isospin 0.

This model cannot be analyzed perturbatively since it is strongly interacting in the energy scale of interest. Therefore, we shall parametrize the interaction between vector leptokuarks (V_μ^{ab}) and physical left-handed fermions by an effective Lagrangian [6] given by

$$\mathcal{L}_{\text{int}} = -F \frac{e}{2\sqrt{2}\sin\theta_W} \left(V_\mu^{ab\dagger} \bar{L}^a \gamma^\mu L^b + \text{H.c.} \right), \quad (1)$$

where L^a are physical left-handed doublets, a (b) is a flavor index, θ_W is the weak mixing angle, and the parameter F is a measure of the strength of this interaction compared to the $Wq\bar{q}'$ vertex. The above Lagrangian is a prototype of a wide class of models [7] presenting the interaction of color triplet, charged vectors with B and L numbers. According to (1), vector leptokuarks couple to both upper or lower components of the lepton and quark doublets with the same strength.

We can estimate the size of the coupling F imposing that unitarity be respected at the tree level [20]. For instance, the process $e^+e^- \rightarrow V\bar{V}$ violates unitarity at high energies for arbitrary values of the couplings. However, this can be avoided by choosing $F = \sqrt{|Q_V|} = \sqrt{\frac{2}{3}}$ [11].

Since the vector leptokuarks are color triplets, it is natural to assume that they interact with gluons. To obtain their couplings to gluons we substituted ∂_μ by the covariant derivative $D_\mu = \partial_\mu + ig_s \lambda_{jk}^a G_\mu^a/2$ in the vector leptokuark kinetic Lagrangian and introduced an anomalous color magnetic moment κ . For $\kappa \neq 1$, unitarity is not respected at the tree level by this model. Therefore, we must either impose $\kappa = 1$ or introduce a new cutoff mass scale Λ . In this work, we assumed that $\kappa = 1$.

The main decay modes of vector leptokuarks are into pairs ℓq and $\nu q'$; thus, their signal is a charged lepton plus a jet or a jet plus missing energy. Using the cou-

plings given above we obtain that the width of a vector leptokuark is

$$\Gamma_V = \frac{\alpha F^2}{4\sin^2\theta_W} M_V, \quad (2)$$

where we neglected all fermion masses and summed over all possible decay channels.

The outline of this paper is the following. Section II contains the study of the production of vector leptokuark pairs via quark-antiquark and gluon-gluon fusion, which leads to conservative estimates of the discover potential of vector leptokuarks in the next generation of hadronic colliders. In Sec. III we analyze the single production of vector leptokuarks through quark-gluon fusion, exhibiting our results for first and second generation vector leptokuarks. The analysis of the indirect signals for leptokuarks is contained in Sec. IV: One way to look for vector leptokuarks is through their effects on the production of lepton pairs at high energies, since they can be exchanged in the t channel. Our conclusions are drawn in Sec. V.

II. PAIR PRODUCTION OF VECTOR LEPTOKUARKS

Pair production of new particles is, to a good approximation, a model-independent process since it usually proceeds through well-known strong and electroweak interactions. Consequently, this process leads to more reliable estimates of the possibility of discovering new physics. In a hadronic collider there are two main mechanisms for the production of vector leptokuark pairs: gluon-gluon fusion ($g + g \rightarrow V + \bar{V}$) and quark-antiquark fusion ($q + \bar{q} \rightarrow V + \bar{V}$).

In lowest order, the Feynman diagrams contributing to the production of vector leptokuark pairs via gluon-gluon fusion are the exchange of gluons in the s channel, vector leptokuarks in the t and u channels, and a contact interaction ($ggVV$), its cross section for $\kappa = 1$ being given by [21]

$$\frac{d\hat{\sigma}_{gg}}{d\cos\theta} = \frac{\pi\alpha_s^2\beta}{16\hat{s}} \left(\frac{4}{3} - 3\frac{t_M u_M}{\hat{s}^2} \right) \left[3 + 2\frac{\hat{s}^2}{t_M u_M} \left(\frac{\hat{s}^2}{t_M u_M} - 2 \right) + 6\frac{\hat{s}M_V^2}{t_M u_M} \left(\frac{\hat{s}M_V^2}{t_M u_M} - 1 \right) \right], \quad (3)$$

where $\sqrt{\hat{s}}$ is the invariant mass of the subprocess, $t_M = -\hat{s}(1 - \beta\cos\theta)/2$, $u_M = -\hat{s}(1 + \beta\cos\theta)/2$, θ is the angle between the vector leptokuark and the incident gluon in the subprocess center-of-mass frame, and $\beta = \sqrt{1 - 4M_V^2/\hat{s}}$ is the leptokuark velocity in this frame. This cross section has a good high energy behavior and, for large values of $\hat{s}$, it approaches a constant value proportional to $1/M_V^2$ due to the exchange of a vector particle in the t channel.

The quark-antiquark fusion production of vector leptokuark pairs takes place by the exchange of a gluon in the s channel and a lepton in the t channel. However, this last contribution is expected to be much smaller than the gluon exchange since the leptokuark couplings to quarks and leptons are expected to have a weak interaction strength—that is, it is natural to have F of the order of the unit. Therefore, we restrict ourselves to the s -channel production only [22], and the elementary cross section for this process is [21]

$$\frac{d\hat{\sigma}_{q\bar{q}}}{d\cos\theta} = \frac{9\pi\alpha_s^2\beta}{2\hat{s}} \left\{ \frac{1}{4} (1 + \beta^2)^2 \frac{\hat{s}}{M_V^2} - 1 + \beta^2 + \frac{1}{4} \left(\frac{t_M u_M}{\hat{s}^2} - \frac{M_V^2}{\hat{s}} \right) \left[8 + \frac{1}{4} (1 + \beta^2)^2 \frac{\hat{s}^2}{M_V^4} \right] \right\}. \quad (4)$$

In order to obtain the inclusive total cross section for the production of pairs of vector leptoquarks ($pp \rightarrow V\bar{V}X$) we must fold the proton structure functions with the elementary cross sections above:

$$\sigma_{\text{pair}} = \int dx_1 dx_2 \left[g(x_1, Q^2)g(x_2, Q^2)\hat{\sigma}_{gg}(\hat{s}) + [q(x_1, Q^2)\bar{q}(x_2, Q^2) + q(x_2, Q^2)\bar{q}(x_1, Q^2)]\hat{\sigma}_{q\bar{q}}(\hat{s}) \right], \quad (5)$$

where g and q are the relevant gluon and quark structure functions, and $\hat{s} = x_1 x_2 s$ with $\sqrt{s}$ being the machine center-of-mass energy. Figure 1 exhibits our results for the total cross section for the production of vector leptoquark pairs as a function of its mass at the LHC (taking $\sqrt{s} = 15.4$ TeV), where we imposed a rapidity cut $|y_{V(\bar{V})}| < 2.5$ and used the set I of structure functions given in Ref. [23] evaluated at the scale $Q^2 = \hat{s}$. As expected, the gluon-gluon fusion contribution dominates over the quark-antiquark-fusion one at such high energies due to the large gluon-gluon luminosity. Notice that the above results hold true for any kind of vector leptoquark since we used only their strong interaction properties in the calculations. Moreover, it has been recently shown [24] that the total cross section for this process has a minimum for κ close to zero and that it is reduced (increased) by a factor of 5 if we assume $\kappa = 0$ (2).

The signal for leptoquark pair production is either $jj\ell^+\ell^-$ ($j = \text{jet}$), $jj\ell^\pm p_T$, or jjp_T , where $\ell^\pm = e^\pm$ or $\mu^\pm$. Certainly the last signal will be immersed in a QCD background and will be very hard to extract. The other two, mainly the first, have a very good chance to be observed since they have the striking feature of producing charged lepton-jet pairs with a given invariant mass; however, a careful study of the QCD and electroweak backgrounds is needed to know whether these kinds of events can be seen or not [25]. Nevertheless, in order to have a rough estimate of the potential of the LHC to unravel the existence of vector leptoquarks via their pair production,

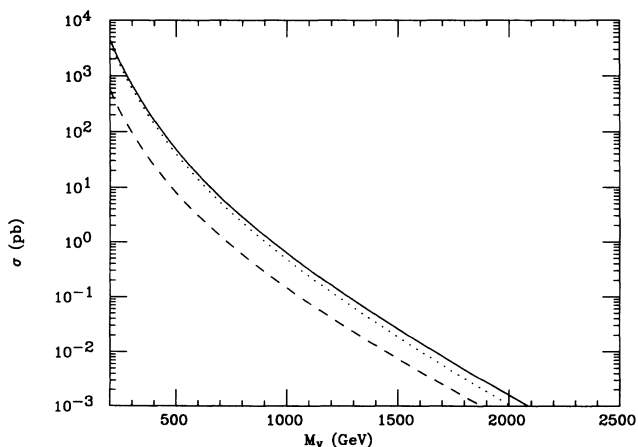


FIG. 1. Cross section for the production of vector leptoquarks pairs as a function of M_V at the LHC: the dashed, dotted, and solid lines stand for $q\bar{q}$, gg and total contributions. We imposed the rapidity cut $|y_V| < 2.5$.

we required the production of 100 of such pairs per year. Taking into account the expected integrated luminosity for the LHC ($10^5 \text{ pb}^{-1}/\text{yr}$), we obtain that this machine will be able to discover first and second generation vector leptoquarks with masses up to 2.1 TeV. Since this number of events (100) is rather arbitrary, it is interesting to know how the discovery limit changes when the number of events required for establishing the signal is varied. If we require 10 (1000) events, the discovery limit changes to 2.5 (1.6) TeV.

III. SINGLE PRODUCTION OF VECTOR LEPTOQUARKS

The production of a single leptoquark in a hadronic collider must be associated with a lepton due to lepton number conservation. The subprocess $q + g \rightarrow V + \ell$ proceeds through the exchange of a leptoquark in the t channel and a quark in the s channel. This is a model-dependent reaction since it involves unknown leptoquark-quark-lepton interactions. Using the model described in the Introduction, it is easy to obtain that the elementary cross section for this process is

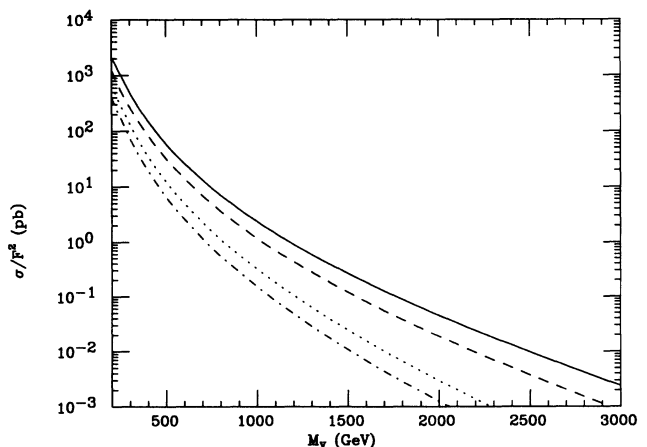


FIG. 2. Total cross section for the associated production of vector leptoquarks and leptons ($e^\pm$, $\mu^\pm$, ν_e , and ν_μ) as a function of M_V at the LHC. The dashed and solid (dotted and dot-dashed) stand for the production of a first (second) generation leptoquark in association with $e^\pm$ and ν_e ($\mu^\pm$ and ν_μ), respectively. We imposed the rapidity cut $|y_{V\ell^\pm}| < 2.5$.

$$\frac{d\hat{\sigma}_{\text{single}}}{d\hat{t}} = \frac{\pi\alpha_s F^2}{12\sin^2\theta_W M_V^2} \frac{1}{\hat{s}^2(\hat{s} + \hat{t})^2} \times \{2\beta^2 \hat{s}^3(3 - 2\beta) + \hat{s}^2 \hat{t}(-6 + 15\beta - 2\beta^2 - 2\beta^3) + \hat{s} \hat{t}^2(-1 + 8\beta - 2\beta^2) + \hat{t}^3(1 + \beta)\}, \quad (6)$$

where $\hat{t} = M_V^2 - (\hat{s} + M_V^2)(1 - \beta \cos \theta)/2$, θ is the angle between the vector leptoquark and the incident quark in the subprocess center-of-mass frame, and $\beta = 1 - M_V^2/\hat{s}$ is the leptoquark velocity in this frame.

In order to obtain the total cross section for the inclusive process $pp \rightarrow V\ell X$ we must evaluate

$$\sigma_{\text{single}} = \int dx_1 dx_2 [g(x_1; Q^2)q(x_2, Q^2) + g(x_2; Q^2)q(x_1; Q^2)] \hat{\sigma}_{\text{single}}(x_1 x_2 s), \quad (7)$$

where g is the gluon structure function and q is the density of down (up) quarks for $\ell = e^\pm$ ($\ell = \nu_e$) assuming a first generation leptoquark. In the case of a second generation leptoquark, q is the strange (charm) structure function for $\ell = \mu^\pm$ ($\ell = \nu_\mu$). Figure 2 summarizes our results for the total cross section for the production of a vector leptoquark in association with charged leptons and neutrinos, where we imposed a rapidity cut on the charged particles $|y_{V(\ell^\pm)}| < 2.5$ and considered first and second generation vector leptoquarks. As expected, the cross section for producing pairs $V\nu_e$ is approximately a factor of 2 larger than the one for the production of $Ve^\pm$ since they are associated to the up and down structure functions, respectively. Since the strange content of the proton is larger than the charm one, the cross section for production of pairs $V\mu^\pm$ is larger than the one for pairs $V\nu_\mu$.

Taking into account that the decay of the leptoquark can give rise to an electron-jet pair or a jet plus missing energy, three different signals are possible for its single production: $j\ell^+\ell^-$, $j\ell^\pm p_T$, and $j\cancel{p}_T$, where $\ell^\pm = e^\pm$ or $\mu^\pm$. This last signal has an incisive feature since it is a monojet event. However, it is going to be buried in the background produced by standard-model processes, such as the production of $Z (\rightarrow \nu\bar{\nu})$ associated with a jet, which are expected to have a much higher cross sections [26]. On the other hand, the other two possible signals are very striking since they exhibit $\ell^\pm j$ pairs with (approximately) the same invariant mass. *A priori*, it is hard to estimate the background for these signals since it is due to the QCD production of heavy quarks, or W and Z in association with jets, thus requiring further Monte

Carlo work to determine their size [25].

In order to have an approximate idea of the potential of the LHC to discover vector leptoquarks via their single production, we required 100 events per year exhibiting a leptoquark decaying into a $\ell^\pm j$ pair. Using the expected luminosity for the LHC and that the branching ratio of vector leptoquarks to $\ell^\pm j$ pairs is 1/2, we obtain that the LHC will be able to probe first (second) generation vector leptoquark masses up to 2.7, 3.0, and 3.5 (1.9, 2.1, and 2.4) for couplings $F = 0.5$, $\sqrt{2/3}$, and 1.5, respectively. However, if we demand 10 (1000) events, the maximum masses of a first generation leptoquark that can be seen are 3.5, 3.9, and 4.2 (1.9, 2.2, and 2.7) TeV for the above couplings F , respectively, while the discovery limits for a second generation leptoquark are 2.4, 2.8, and 3.1 (1.3, 1.6, and 1.8) TeV. It is interesting to notice that the above bounds for first generation vector leptoquarks are stronger than the ones derived from universality and parity violation [27].

IV. INDIRECT SIGNALS FOR VECTOR LEPTOQUARKS

The existence of leptoquarks can also be investigated through their effects as an intermediate state in the inclusive dilepton production ($pp \rightarrow \ell^+\ell^- X$), where they lead to a new t channel contribution in addition to the usual exchange of γ and Z in the s channel. The color-averaged cross section for the subprocess $q\bar{q} \rightarrow \ell^+\ell^-$ is, in the center of mass of the subprocess,

$$\begin{aligned} \frac{d\hat{\sigma}}{d\Omega}(\hat{s}) = & \frac{\alpha^2}{12\hat{s}} \left\{ Q^2(1 + \cos^2\theta) + \frac{1}{16\sin^4\theta_W \cos^4\theta_W} \frac{\hat{s}^2}{(\hat{s} - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \right. \\ & \times \left[(C_V^e)^2 + (C_A^e)^2 \right] (C_V^q)^2 + (C_A^q)^2 (1 + \cos^2\theta) + 8C_V^e C_A^e C_V^q C_A^q \cos\theta \Big] \\ & - \frac{Q}{2\sin^2\theta_W \cos^2\theta_W} \frac{\hat{s}(\hat{s} - M_Z^2)}{(\hat{s} - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} [C_V^e C_V^q (1 + \cos^2\theta) + 2C_A^e C_A^q \cos\theta] \\ & + \frac{F^2}{\sin^2\theta_W} \frac{(1 + \cos\theta)^2}{\cos\theta - \eta} \left[\frac{F^2}{4\sin^2\theta_W} \frac{1}{\cos\theta - \eta} + \frac{Q}{2} \right. \\ & \left. \left. - \frac{1}{8\sin^2\theta_W \cos^2\theta_W} (C_V^q + C_A^q)(C_V^e + C_A^e) \frac{\hat{s}(\hat{s} - M_Z^2)}{(\hat{s} - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \right] \right\}, \quad (8) \end{aligned}$$

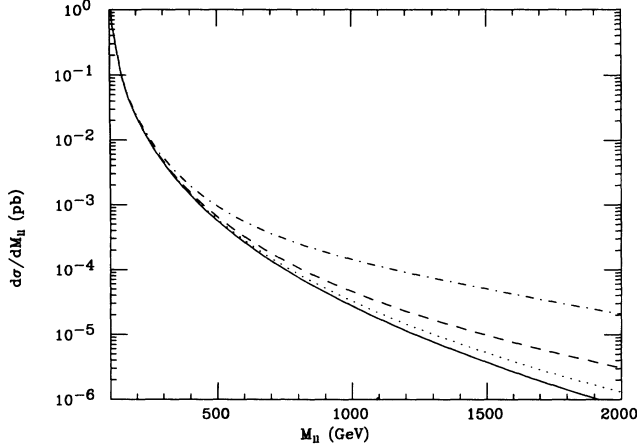


FIG. 3. Invariant mass distribution for e^+e^- pairs at the LHC: the solid, dotted, dashed, and dot-dashed lines stand for $F = 0$ (standard model), 0.5, $\sqrt{2/3}$, and 1.5, respectively. We assumed a first generation leptoquark of mass $M_V = 1$ TeV and imposed that $|y_{e\pm}| < 2.5$.

where M_Z is the mass of the Z boson and $\eta = 1 + 2M_V^2/s$. According to our conventions the charge of a quark is Q_e ($e > 0$), $C_V = I_z - 2Q \sin^2 \theta_W$, and $C_A = I_z$.

The exchange of a vector particle in the t channel modifies the high energy behavior of this subprocess: Within the scope of the standard model this elementary cross section decreases as the center-of-mass energy increases; however, the new contribution alters this behavior, yielding a constant cross section at high energies,

$$\sigma_{\text{limit}}(q\bar{q} \rightarrow \ell^+\ell^-) \simeq \frac{\pi\alpha\alpha_s F^4}{12 \sin^4 \theta_W M_V^2}. \quad (9)$$

The effect of this modification to the process $pp \rightarrow e^+e^-X$ due to a first generation vector leptoquark can be seen in Fig. 3, which displays the invariant mass distribution of dilepton pairs at the LHC for a vector leptoquark of mass $M_V = 1$ TeV and several values of the coupling F . From this figure we can see that the presence of the

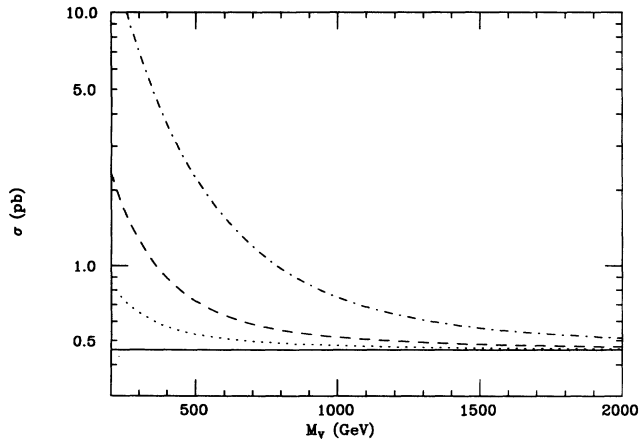


FIG. 4. Total cross section for the production of e^+e^- pairs as a function of M_V at the LHC, satisfying $M_{e^+e^-} > 300$ GeV and $|y_{e\pm}| < 2.5$. Conventions are the same as in Fig. 3

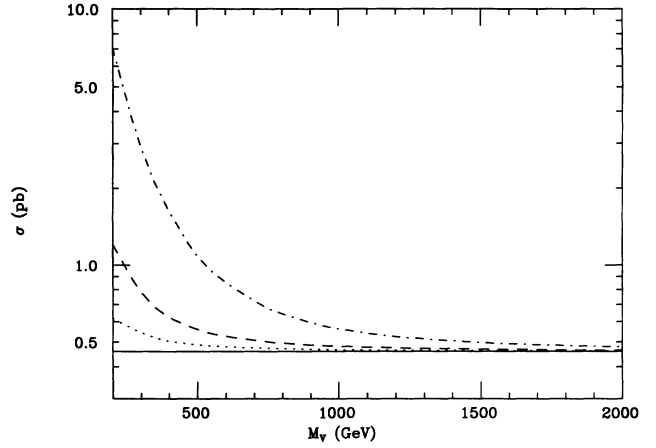


FIG. 5. Same as in Fig. 4 but for $\mu^+\mu^-$ pairs.

leptoquark leads to a dramatic increase of the production of dilepton pairs at high invariant masses.

In order to estimate the capability of the LHC to search for vector leptoquarks, we evaluated the total cross section for the production of dileptons with an invariant mass greater than 300 GeV, exhibiting our results for first and second generation vector leptoquarks in Figs. 4 and 5, respectively. Demanding that the anomalous production of high invariant mass dileptons have a statistical significance of 5σ , we obtain that the largest first (second) generation vector leptoquark mass accessible at the LHC is 1.3, 2.1, and 4.0 (0.8, 1.4, and 2.6) TeV assuming that $F = 0.5$, $\sqrt{2/3}$, and 1.5, respectively. As in the case of single production, the bounds derived from the searches at the LHC are stronger than the indirect low energy ones [28].

V. CONCLUSIONS

The discovery of leptoquarks is without any doubt a striking signal for the existence of life beyond the standard model. In this work we analyzed the potential of hadronic colliders, such as the LHC, to unravel the existence of vector leptoquarks. Our typical results for the discovery limits at the LHC are summarized in Table I, from where we see that such a machine can extend considerably the range of leptoquark masses and couplings that can be probed when compared to the low energy ones [19,27].

It is interesting to notice that the three signals for vec-

TABLE I. Maximum first and second generation vector leptoquark masses that can be probed at the LHC for pair ($V\bar{V}$), single ($V\ell$), and dilepton ($\ell^+\ell^-$) production, assuming an integrated luminosity of $10^5 \text{ pb}^{-1} / \text{yr}$.

F	$V\bar{V}$	$V\ell$	$\ell^+\ell^-$
0.5	2.1/2.1	2.7/1.9	1.3/0.8
$\sqrt{2/3}$	2.1/2.1	3.0/2.1	2.1/1.4
1.5	2.1/2.1	3.5/2.4	4.0/2.6

tor leptoquarks that we studied are complementary; i.e., their analysis allow us to shed some light on the leptoquark type and its couplings to quarks and leptons. For instance, the pair production, since it is basically model independent, can be used to establish their existence. On the other hand, the single production rates, together with the knowledge of the charged lepton observed from their decays, can be used to determine to which quarks the leptoquarks couple. Moreover, the production of high invariant mass lepton pairs can further confirm the signal and help to pinpoint the value of the couplings between leptoquarks, quarks, and leptons.

Note added. During the time that we were writing this work we became aware of Ref. [24], which analyzes the

vector leptoquark pair production in hadronic colliders. We verified that our results for this process agree.

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