PHYSICAL REVIEW D, VOLUME 59, 035002

Multilepton signatures for leptoquarks

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(Received 11 August 1998; published 22 December 1998)

The production of third generation leptoquarks can give rise to multilepton events accompanied by jets and missing E_T. In this work we study the signals of these leptoquarks at the CERN Large Hadron Collider and compare them with the ones expected in supersymmetric models. [S0556-2821(99)07201-X]

PACS number(s): 12.60.−i, 13.85.Rm, 14.80.−j

I. INTRODUCTION

Many theories, such as composite models [1,2], technicolor [3], and grand unified theories [4], predict the existence of new particles, called leptoquarks, which mediate quark-lepton transitions. In this work we focus our attention on scalar leptoquarks (S) that couple to t-τ or b-τ pairs. At the CERN Large Hadron Collider (LHC), leptoquarks can be pair produced by gluon-gluon and quark-quark fusion, as well as singly produced in association with a lepton in gluon-quark reactions. Therefore, the production of third generation leptoquarks can lead to multilepton signals accompanied by jets and missing $E_T(\not{E}_T)$ since the heavy quark decay can give rise to further leptons and jets. This means that third generation leptoquarks can, in principle, mimic multilepton supersymmetry (SUSY) signals [5]. For this reason, we investigated the importance of the multilepton signatures for such leptoquarks at the LHC.

In our analyses we considered the following multilepton topologies: one lepton topology (1L) which exhibits one lepton ($e^{\pm}$ or $\mu^{\pm}$) in association with jets and $\not{E}_T$, opposite-sign dilepton events (OS) which contain a pair of leptons of opposite charge in addition to jets and $\not{E}_T$, same-sign dilepton topology (SS) which presents a pair of leptons with the same charge, jets and $\not{E}_T$, and trilepton events (3L) which possess three charged leptons, jets, and $\not{E}_T$.

Moreover, we employed the cuts of Ref. [5], which studied the multilepton signals for supersymmetry in the framework of the minimal supergravity model (MSUGRA). The use of these cuts not only reduces the standard model (SM) backgrounds, but also allows us to compare the leptoquark signals with the MSUGRA ones.

In principle, leptoquark events possess the striking signature of a peak in the invariant mass of a charged lepton and a jet, which could be used to further reduce backgrounds and to establish that an observed signal is due to leptoquarks. This is an important feature of the signals for first generation leptoquarks [6]. Notwithstanding, third generation leptoquarks exhibit cascade decays containing heavy quarks and $\tau^{\pm}$, which give rise to neutrinos, and consequently wash out the lepton-jet invariant mass peak.

Since leptoquarks are an undeniable signal of physics beyond the SM, there have been several direct searches for them in accelerators. At the Fermilab Tevatron collider it was established that leptoquarks coupling to b-τ pairs should be heavier than 99 GeV [7]. Moreover, low-energy experiments lead to indirect bounds on the couplings and masses of third generation leptoquarks. Leptoquarks may give rise to flavor-changing neutral current processes if they couple to more than one family of quarks or leptons [8,9]. In order to avoid these bounds, we assumed that the leptoquarks couple only to one quark family and one lepton generation. The effects of third generation leptoquarks on the Z physics through radiative corrections lead to strict limits on leptoquarks that couple to top quarks and loose bounds on leptoquarks coupling to the b quark [10]. As a rule of a thumb, the Z-pole data constrain the masses of leptoquarks to be larger than 200–500 GeV when their Yukawa coupling to top quarks is equal to the electromagnetic coupling e and larger than about 100 GeV when the Yukawa coupling to bottom quarks is 10 times the electromagnetic coupling [10–12].

II. ANALYSES

A natural hypothesis for theories beyond the SM is that they exhibit the gauge symmetry $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ above the electroweak symmetry-breaking scale v; therefore, we imposed this symmetry on the leptoquark interactions. In order to evade strong bounds coming from the proton lifetime experiments, we required baryon (B) and lepton (L) number conservation. The most general effective Lagrangian for leptoquarks satisfying the above requirements and electric charge and color conservation is given by [13]

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0556-2821/98/59(3)/035002(6)/$15.00

$$\mathcal{L}_{eff}=\mathcal{L}_{F=2}+\mathcal{L}_{F=0}, \tag{1}$$

$$\mathcal{L}_{F=2}=g_{1L}\overline{q^c_L}i\tau_2 l_L S_{1L}+g_{1R}\overline{u^c_R}e_R S_{1R}+\tilde{g}_{1R}\overline{d^c_R}e_R\tilde{S}_1 +g_{3L}\overline{q^c_L}i\tau_2\vec{\tau}l_L\cdot\vec{S}_3,$$

$$\mathcal{L}_{F=0}=h_{2L}R^T_{2L}\overline{u_R}i\tau_2 l_L+h_{2R}\overline{q_L}e_R R_{2R}+\tilde{h}_{2L}\tilde{R}^T_2\overline{d_R}i\tau_2 l_L,$$

where $F=3B+L$, $q(l)$ stands for the left-handed quark (lepton) doublet, and we omitted the flavor indices of the leptoquark couplings to fermions. The leptoquarks $S_{1R(L)}$ and $\tilde{S}_1$ are singlets under $\mathrm{SU}(2)_L$, while $R_{2R(L)}$ and $\tilde{R}_2$ are doublets, and S_3 is a triplet.

The multilepton samples due to leptoquarks were obtained using the Monte Carlo event generator PYTHIA [14]. We assumed in our analyses that the leptoquarks decay exclusively into a single quark-lepton pair. The general case can be easily obtained by multiplying the signal cross section by an appropriate branching ratio, which can be read from the Lagrangian (1).

The cross sections for leptoquark (S_{lq}) pair production via $q+\bar{q}\to S_{lq}+\overline{S_{lq}}$ or $g+g\to S_{lq}+\overline{S_{lq}}$ are model independent because the leptoquark-gluon interaction is entirely determined by the $\mathrm{SU}(3)_C$ gauge invariance. On the other hand, the single production through $q+g\to S_{lq}+l$ is model dependent once it involves the unknown Yukawa coupling of leptoquarks to a lepton-quark pair. However, this last process is important only for third generation leptoquarks coupling to b quarks since the top quark content of the proton is negligible at the LHC energy.

In this work we focused our attention on leptoquarks decaying into b-τ or t-τ. For both types we considered the two possible mechanisms of pair production, quark and gluon fusion, and for the leptoquark decaying into a b quark we also considered single production with the value of the Yukawa coupling taken to be equal to the electromagnetic one. We assumed three values for the masses: 300 GeV, 500 GeV, and 1 TeV (this last one only for leptoquarks decaying into a t quark). Samples containing 10 000 events were generated for each of the cases.

In our analyses, we applied the following cuts, which were used in Ref. [5] for the study of the MSUGRA multilepton signals and backgrounds: clusters with $E_T>100$ GeV and $|\eta(\mathrm{jet})|<3$ are labeled as jets; however, for jet-veto only, clusters with $E_T>25$ GeV and $|\eta(\mathrm{jet})|<3$ are regarded as jets; muons and electrons are classified as isolated if they have $p_T>10$ GeV, $|\eta(l)|<2.5$ and the visible activity within a cone of $R=\sqrt{\Delta\eta^2+\Delta\Phi^2}=0.3$ about the lepton direction is less then $E_T(\mathrm{cone})=5$ GeV; jet multiplicity, $n_{\mathrm{jet}}\geqslant 2$, with $E_T(\mathrm{jet})>100$ GeV; transverse sphericity $S_T>0.2$; $E_T(j_1)$, $E_T(j_2)>E^c_T$, and $\not{E}_T>E^c_T$, where E^c_T is a parameter that one can vary (see the figures below); we required the leptons to have $p_T(l)>20$ GeV and $M_T(l,\not{E}_T)>100$ GeV for the one lepton signal and $p_T(l_{1(2)})>20$ GeV for $n=2,3$ lepton signals.

In our analyses, we simulated a simple calorimeter using the subroutine LUCELL, which is part of the JETSET-PYTHIA package, adopting the same parameters employed in Ref. [5]. We should also point out that the effects of cracks, edges, and other detector inefficiencies have not been taken into account here. The SM backgrounds and the MSUGRA signals used in the present work were taken from Ref. [5].

III. RESULTS

In the following figures we present our results for the leptoquark cross sections after the above cuts as a function of the parameter E^c_T. For the sake of comparison, we also exhibit in our figures the SM backgrounds (BG's) and MSUGRA cross sections for two sets of parameters chosen in Ref. [5], which correspond to the extreme cases analyzed in this work. In case 1, it is assumed that $m_0=m_{1/2}=100$ GeV, $m_{\tilde{g}}=290$ GeV, and $m_{\tilde{q}}=270$ GeV, while, in case 6, $m_0=4m_{1/2}=2000$ GeV, $m_{\tilde{g}}=1300$ GeV, and $m_{\tilde{q}}=2200$ GeV. Both scenarios employ $A_0=0, \tan\beta=2$, and $m_t=170$ GeV.

We show in Fig. 1(a) the leptoquark production cross sections into the 1L topology as a function of E^c_T for scalar leptoquarks decaying into b-τ with masses of 300 and 500 GeV for a Yukawa coupling equal to the electromagnetic one (e). We also present in this figure the gq contribution to the production cross section of 300 GeV leptoquarks for this value of the Yukawa coupling. The gg contribution dominates the total cross section as long as the Yukawa coupling is not much larger than e since the single production cross section scales with the Yukawa coupling squared. We can also see from this figure that the b-τ signal is well above the background for all values of the parameter E^c_T. Furthermore, the b-τ leptoquarks lead to cross sections with values between the two MSUGRA cases for $E^c_T\lesssim 350$ GeV. In Fig. 1(b) we present the results for the 1L topology in the case of t-τ leptoquarks with masses of 300, 500, and 1000 GeV. In this case, except for the leptoquark with mass of 1 TeV, the signals are always above the background and are also between the two MSUGRA cases.

In Fig. 2(a) we exhibit our results for the OS topology in the case of scalar b-τ leptoquarks with masses of 300 and 500 GeV. Here, again, we display the gq contribution to the cross section for 300 GeV leptoquark production considering the strength of the Yukawa coupling to be equal to e. In this topology this contribution is also very much smaller than the total cross section, which is dominated by gg fusion too. The b-τ leptoquark signals are above the background for $E^c_T\gtrsim 200$ GeV and these leptoquarks lead to cross sections with values between the two MSUGRA cases independently of the E^c_T cut applied. In Fig. 2(b) the results for the OS topology but for t-τ leptoquarks with masses of 300, 500, and 1000 GeV are shown. For $E^c_T\lesssim 200$ GeV the two lower mass signals are above the expected BG and their cross section values are between the two MSUGRA extreme cases even if one imposes a large E^c_T cut. For $E^c_T\gtrsim 300$ GeV the 1000 GeV mass signal is also above the BG.

The production cross sections for third generation lepto-

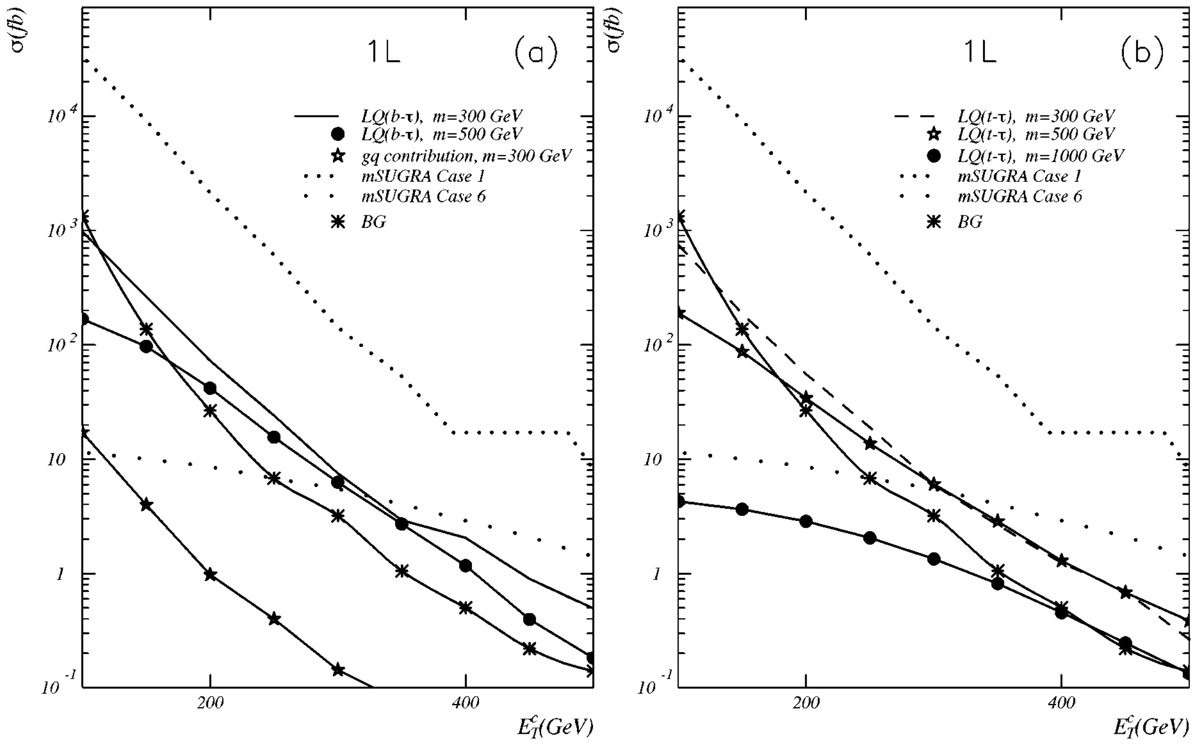

FIG. 1. Production cross sections of 1L events as a function of E_T^c for the SM backgrounds and two sets of MSUGRA parameters (case 1 and case 6). In (a) we also exhibit the results for b-τ leptoquarks with masses of 300 and 500 GeV, as well as the gq contribution for 300 GeV leptoquarks; see text for further details. In (b) we present the results for t-τ leptoquarks with masses of 300, 500, and 1000 GeV.

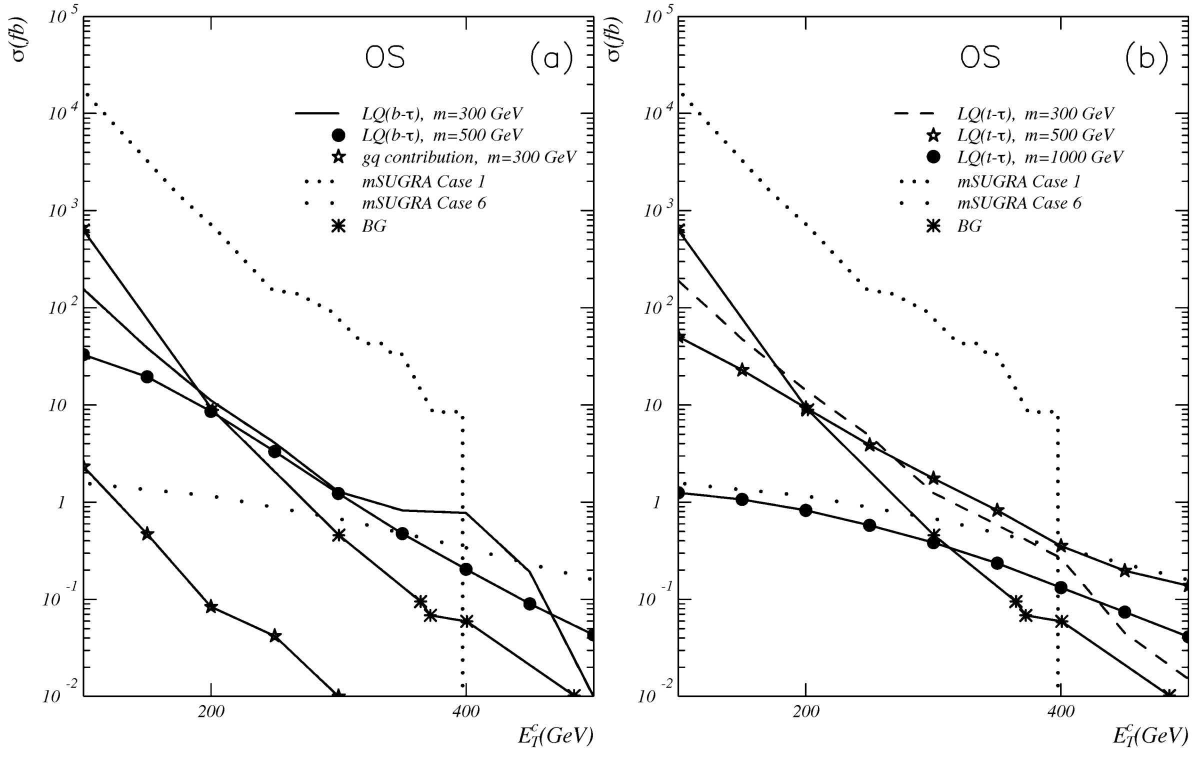

FIG. 2. Same as Fig. 1 for OS events.

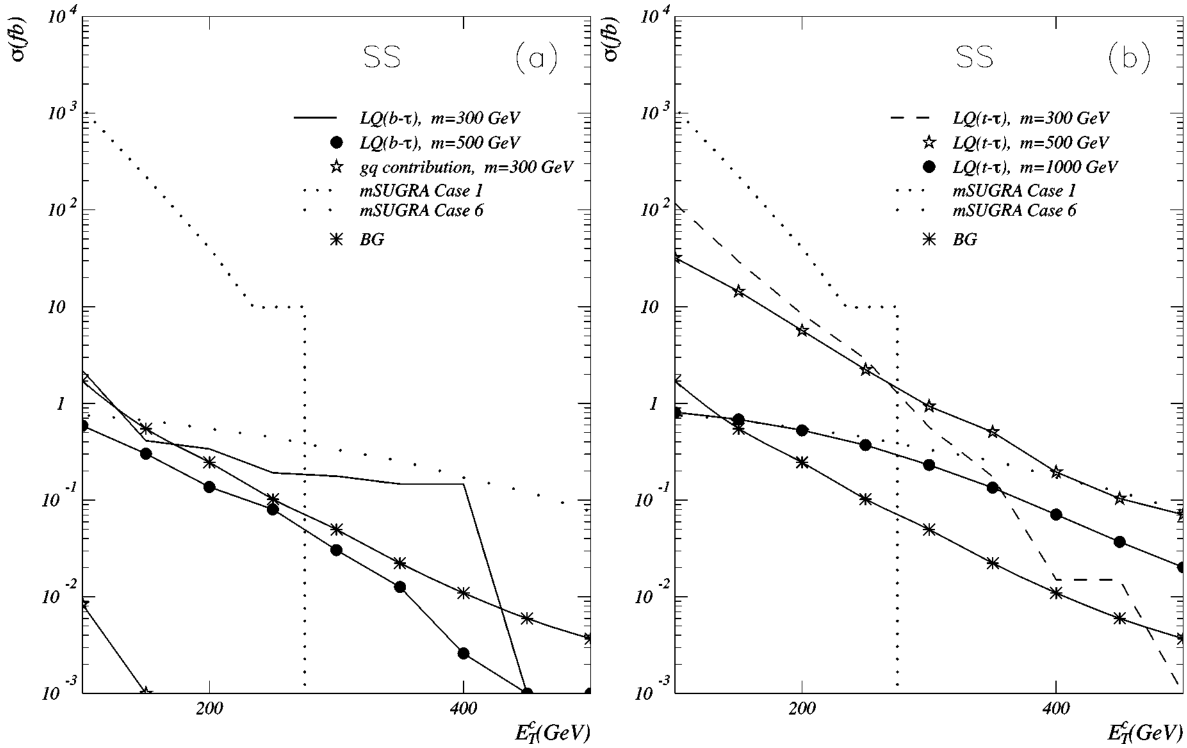

FIG. 3. Same as Fig. 1 for SS events.

quarks into the SS topology as a function of E_T^c are shown in Fig. 3. Analogously to the previous topologies, the gq contribution to the production cross section is well below the total cross section for Yukawa couplings equal to e. In Fig. 3(a) we can see that the signal of 300 GeV b-τ leptoquarks is above the backgrounds for 200 GeV$\lesssim E_T^c \lesssim$430 GeV while the 500 GeV leptoquark signal is immersed in the SM backgrounds. Furthermore, the b-τ leptoquark of 300 GeV can probably only be distinguished from the MSUGRA case 6 if one demands $E_T^c > 400$ GeV. We also show in Fig. 3(b) that

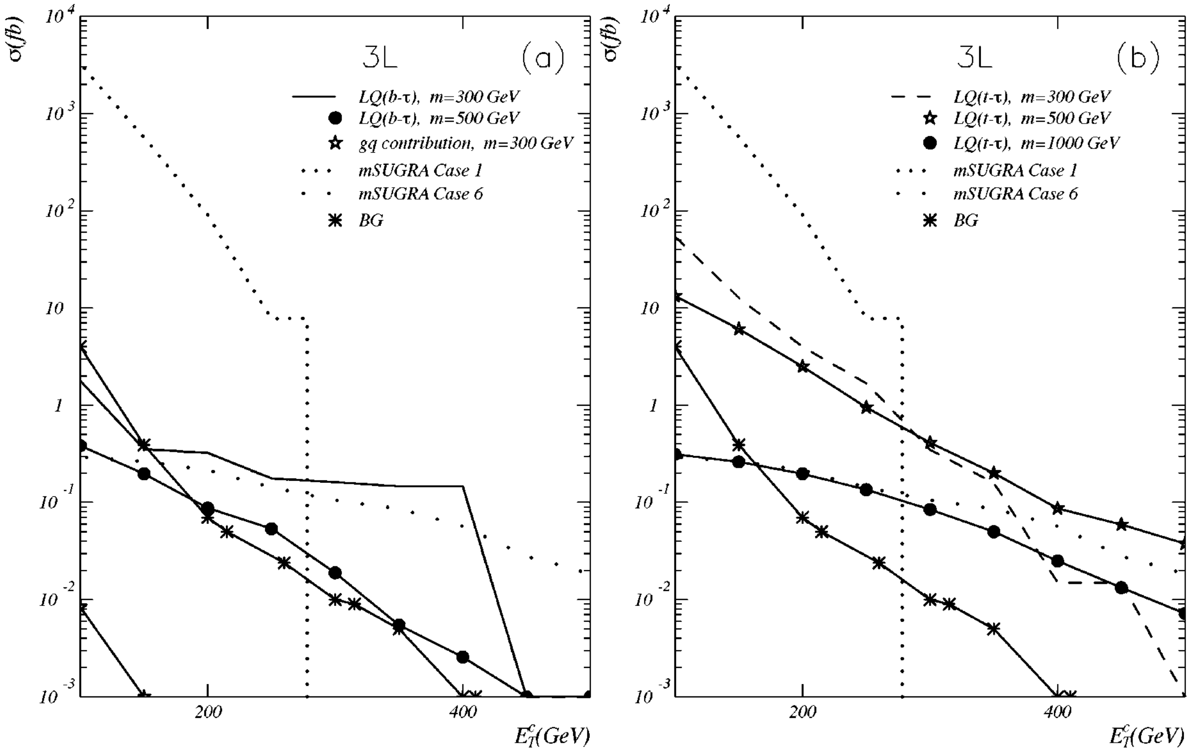

FIG. 4. Same as Fig. 1 for 3L events.

the SS signal of t-τ leptoquarks is well above the backgrounds and lay between the MSUGRA cases for masses of 300, 500, and 1000 GeV.

Finally in Fig. 4 the behavior of the cross sections for the 3L topology as a function of E_T^c is presented for the scalar leptoquarks as well as for the MSUGRA cases and SM backgrounds. The cross sections for b-τ leptoquarks of 300 and 500 GeV shown in Fig. 4(a) are above the background for $E_T^c \lesssim 100$ GeV and $E_T^c \lesssim 200$ GeV, respectively. The production cross section of b-τ leptoquarks of 300 GeV presents a flat plateau in the region where $100 \text{ GeV} \lesssim E_T^c \lesssim 400$ GeV. In Fig. 4(b) we see again that t-τ leptoquarks of 300, 500, and 1000 GeV are above the background and between the MSUGRA extreme cases.

In the above analyses we observe that third generation leptoquark cross sections are generally above the SM background in all multilepton topologies we have investigated. Moreover, the leptoquark signals are of the same magnitude as MSUGRA cross sections, making it rather difficult to distinguish SUSY events from leptoquark ones. It is clear that one has to investigate more carefully the possibility of mistaken third generation leptoquarks for SUSY in the multilepton channels. Observation of the signal in several multilepton channels is crucial to try to identify the source of new physics but this may turn out to be a great challenge.

Besides the results presented above, we considered some other situations, which deserve to be mentioned, although they were not included in this work. First of all, we analyzed the signals for leptoquarks heavier than the ones considered here; however, their signals are very small compared to background even before the cuts are applied. In addition we have studied third generation leptoquarks decaying into neutrinos and b or t quarks, but their cross sections after cuts are, in general, smaller than the background one, due to the lack of hard leptons. The only exception is the 1L topology for which the cross sections after cuts are of the same magnitude of the one for the leptoquark decaying into t-τ.

We also analyzed the signals of leptoquarks decaying into t-l and b-l, with $l=e,\mu$. In principle these leptoquarks are still allowed by the available experimental data provided they couple to a single quark generation and a single lepton family [12]. In fact the strongest bounds on these leptoquarks comes from the Z-pole physics, which require them to be heavier than 200–300 GeV for Yukawa couplings of the order of e. Our analyses of these leptoquarks show that their signals are slightly smaller than the ones for t-τ and b-τ leptoquarks.

IV. CONCLUSION

In this work, we analyzed the multilepton signals for third generation leptoquarks. We showed that the analyses designed to discover gluinos and squarks via multilepton events are also rather good to select third generation leptoquarks. We concluded that for third generation leptoquarks with masses of several hundred GeV, the leptoquark signal is not only above the standard model backgrounds, but also of the same order of the expected MSUGRA cross sections. Therefore, the observation of an excess of multilepton events accompanied by jets and missing E_T can be due to leptoquarks or supersymmetric particles. Since the leptoquark mass reconstruction is usually not efficient, due to the presence of neutrinos in many decays, there is no clear indication of leptoquarks in this class of events. Therefore, the origin of the multilepton events can only be established looking at other topologies, for instance, multilepton events without the presence of jets, which are characteristic of $\chi_0^2 - \chi^\pm$ production in some regions of the MSUGRA parameter space [15]. It seems that unless nature is extremely kind to us, exhibiting signals of new physics in many different channels, an observed signal in any of the four discussed channels at the LHC cannot be uniquely interpreted as due to the production of SUSY particles. Even if observation is accomplished in all four channels analyzed in this work, it may still not be possible to distinguish between leptoquarks and supersymmetric particles.

ACKNOWLEDGMENTS

We would like to thank X. Tata for useful discussions. This work was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), and by Programa de Apoio a Núcleos de Excelência (PRONEX).

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