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Multilepton Signatures for Leptoquarks

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Abstract

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.

I. INTRODUCTION

Many theories, like composite models [1,2], technicolor [3], and grand unified theories [4], predict the existence of new particles, called leptoquarks, that mediate quark-lepton transitions. In this work we focus our attention to scalar leptoquarks (S) that couple to pairs t–ℓ or b–ℓ with $\ell = e$, μ or τ. At the CERN Large Hadron Collider (LHC), leptoquarks can be pair produced by gluon–gluon and quark–quark fusions, 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 the multilepton 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 $\not{E}_T$;

• trilepton events (3L) which possess 3 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 allow 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/or $\tau^{\pm}$, 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 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 limits on leptoquarks that couple to top quarks [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 is equal to the electromagnetic coupling e [10,11].

II. ANALYSES

A natural hypothesis for theories beyond the SM is that they exhibit the gauge symmetry $SU(2)_L \otimes U(1)_Y$ 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 [12]

$$\begin{aligned}
\mathcal{L}_{eff} &= \mathcal{L}_{F=2} + \mathcal{L}_{F=0} , \qquad (1)\\
\mathcal{L}_{F=2} &= g_{1L}\, \bar{q}^c_L\, i\tau_2\, \ell_L\, S_{1L} + g_{1R}\, \bar{u}^c_R\, e_R\, S_{1R} + \tilde{g}_{1R}\, \bar{d}^c_R\, e_R\, \tilde{S}_1 \\
&\quad + g_{3L}\, \bar{q}^c_L\, i\tau_2\, \vec{\tau}\, \ell_L \cdot \vec{S}_3 , \\
\mathcal{L}_{F=0} &= h_{2L}\, R^T_{2L}\, \bar{u}_R\, i\tau_2\, \ell_L + h_{2R}\, \bar{q}_L\, e_R\, R_{2R} + \tilde{h}_{2L}\, \tilde{R}^T_2\, \bar{d}_R\, i\tau_2\, \ell_L
\end{aligned}$$

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 $SU(2)_L$, 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 [13]. 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 $q + \bar{q} \to S_{lq} + \bar{S}_{lq}$ or $g + g \to S_{lq} + \bar{S}_{lq}$ are model independent because the leptoquark–gluon interaction is entirely determined by the $SU(3)_C$ gauge invariance. On the other hand, the single production through $q + g \to S_{lq} + \ell$ 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–ℓ or t–ℓ pairs, with $\ell = e$, μ, τ. We generated samples containing 10 000 events for each leptoquark type and production mechanism, assuming two values for the masses: 300 and 500 GeV. Since the b content of the proton is rather small, we assumed that the leptoquark Yukawa coupling to be 10 times de electron electric charge for the single production of b–τ, b–μ, or b–e leptoquarks.

In this work, we applied the following cuts used in Ref. [5]:

- clusters with $E_T > 100$ GeV and $|\eta(\text{jet})| < 3$ are labeled as jets; however, for jet-veto only, clusters with $E_T > 25$ GeV and $|\eta(\text{jet})| < 3$ 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 $E_T(\text{cone}) = 5$ GeV;
- jet multiplicity, $n_{\text{jet}} \geq 2$, with $E_T(\text{jet}) > 100$ GeV;

- transverse sphericity $S_T > 0.2$,
- $E_T(j_1)$, $E_T(j_2) > E_T^c$ and $\not{E}_T > E_T^c$, where E_T^c is a parameter that one can vary, see the figures below;
- we require the leptons to have $p_T(l) > 20$ GeV and $M_T(l,\not{E}_T) > 100$ GeV for the one lepton signal and $p_T(l_1)$,$p_T(l_2) > 20$ GeV for $n = 2, 3$ lepton signals.

In our analyses, we simulated a simple calorimeter using the subroutine LUCELL , which is part of JETSET/PYTHIA package, adopting the same parameters employed in 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_T^c. For the sake of comparison, we also exhibit in our figures the SM background (BG) 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 $m_0 = m_{\frac{1}{2}} = 100$ GeV, $m_{\tilde{g}} = 290$ GeV, and $m_{\tilde{q}} = 270$ GeV, while, in case 6, $m_0 = 4m_{\frac{1}{2}} = 2000$ 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. 1a the leptoquark production cross section into the 1L topology as a function of E_T^c for scalar leptoquarks decaying into b–e and b–τ with a mass of 300 GeV. The production of b–μ leptoquarks possesses the same cross section than the case b–e. As we can see, the b–e signal is immersed in the SM backgrounds since the E_T cuts affects strongly the signal. On the other hand, the b–τ signal is well above the background for all values of the parameter E_T^c. Furthermore, the b–τ leptoquarks lead to cross sections with values between the two mSUGRA cases for $E_T^c \lesssim 350$ GeV. In Fig. 1b we present the results for the $1L$ topology in the case of t–e and t–τ leptoquarks with masses of 500 GeV. In this case, the signals are always above the backgrounds and are also between the two mSUGRA cases.

In Fig. 2 we present our results for scalar leptoquarks type (b, e) and (b, τ) with mass=300 GeV and type (t, τ) and (t, e) with mass=500 GeV for the OS+jets+$\not{E}_T$ channel. Here all the shown leptoquark cross sections are above BG for $E_T^c > 200$ GeV or so and can be of at same level of SUSY cross sections even if one imposes a large E_T^c cut.

In Fig. 3 we present our results for scalar leptoquarks type (b, e) and (b, τ) with mass=300 GeV and type (t, τ) and (t, e) with mass=500 GeV for the SS+jets+$\not{E}_T$ channel. In this channel leptoquark cross section is almost always several times higher than BG and can produce signals of the same magnitude of SUSY depending on the E_T^c imposed.

Finally in Fig. 4 we present our results for scalar leptoquarks type (b, e) and (b, τ) with mass=300 GeV and type (t, τ) and (t, e) with mass=500 GeV for the 3l+jets+$\not{E}_T$ channel. In this analysis we also note that leptoquark cross sections are in general above BG and can be of the same order of SUSY cross sections making it rather difficult to distinguish SUSY events from this type of leptoquark signal.

We should also point out that the effect of cracks, edges and other detector inefficiencies that have not been taken into account here may play an important hole in the possibility to separate SUSY signal from leptoquark signal.

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 as the SUSY framework is not unique this may turn out to be a great challenger.

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 mSUGRA cross section. 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 footprint of leptoquarks in this class of events. Therefore, the origin of the multilepton events can only the establish looking at other topologies, for instance, multilepton events without the presence of jets, which are characteristic of χ_0^2–$\chi^\pm$ production in some regions of the mSUGRA parameter space [14]. It seems that unless nature is extremely kind to us an observed signal of new physics 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 it may still not be possible to distinguish between leptoquark production and SUSY production with some choice of parameters in a particular SUSY framework.

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FIGURES

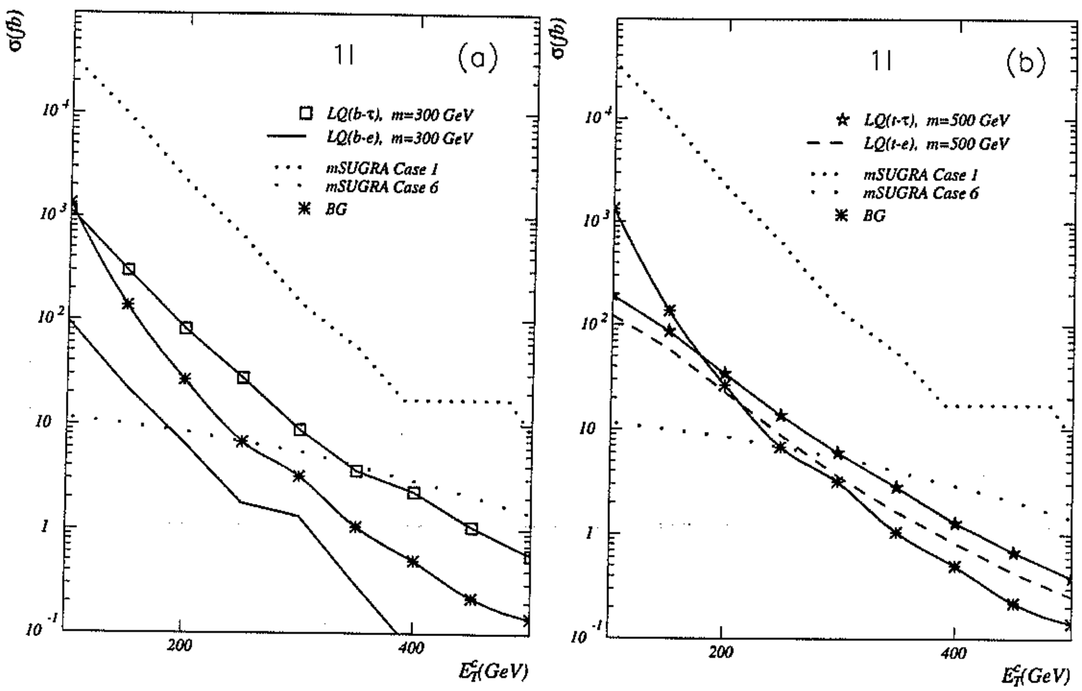

FIG. 1. Cross section for SM background, two sets of mSUGRA parameters (case 1 and case 6) and (b, e), (b, τ) leptoquarks with mass=300 GeV (a); (t, e), (t, τ) leptoquarks with mass=500 GeV (b) for the 1l+jets analysis.

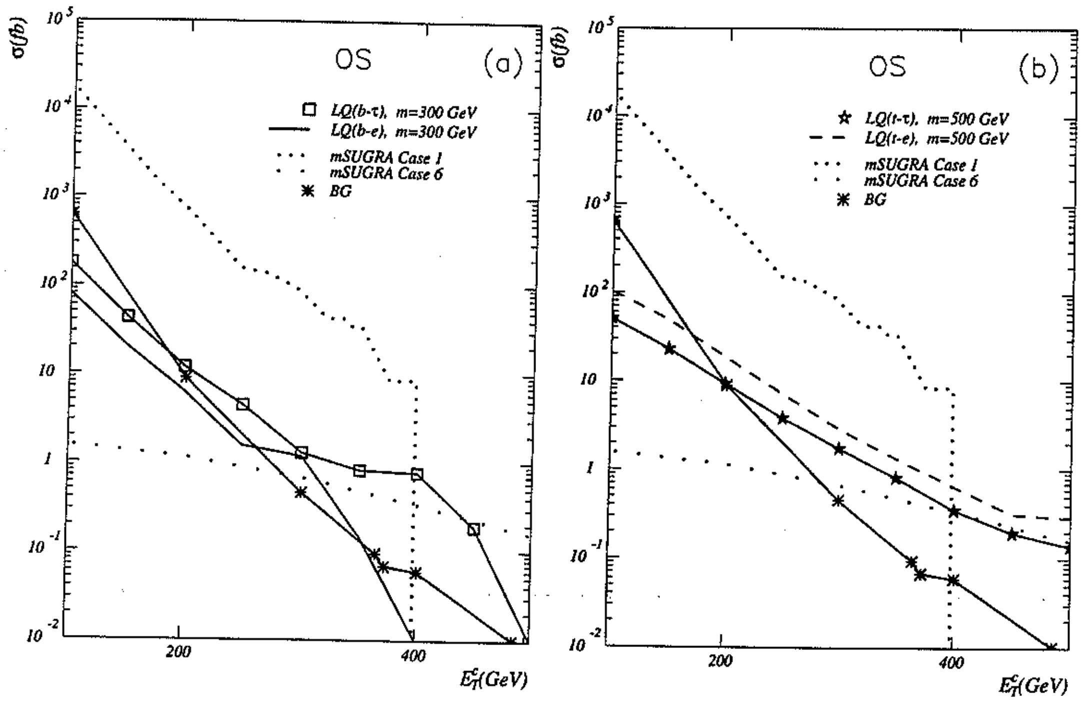

FIG. 2. Cross sections for SM background, two sets of mSUGRA parameters (case 1 and case 6) and (b, e), (b, τ) leptoquarks with mass=300 GeV (a); (t, τ), (t, e) leptoquarks with mass=500 GeV (b) for the OS+jets analysis.

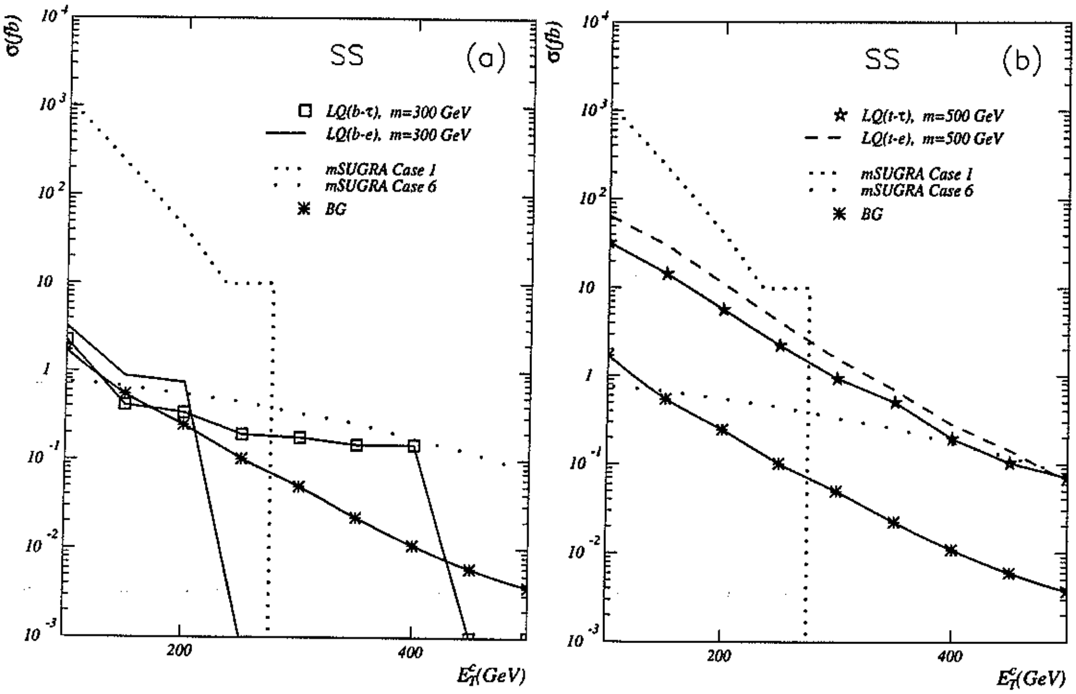

FIG. 3. Cross sections for SM background, two sets of mSUGRA parameters (case 1 and case 6) and (b,e), (b,τ) leptoquarks with mass=300 GeV (a); (t,τ), (t,e) leptoquarks with mass=500 GeV (b) for the SS+jets analysis.

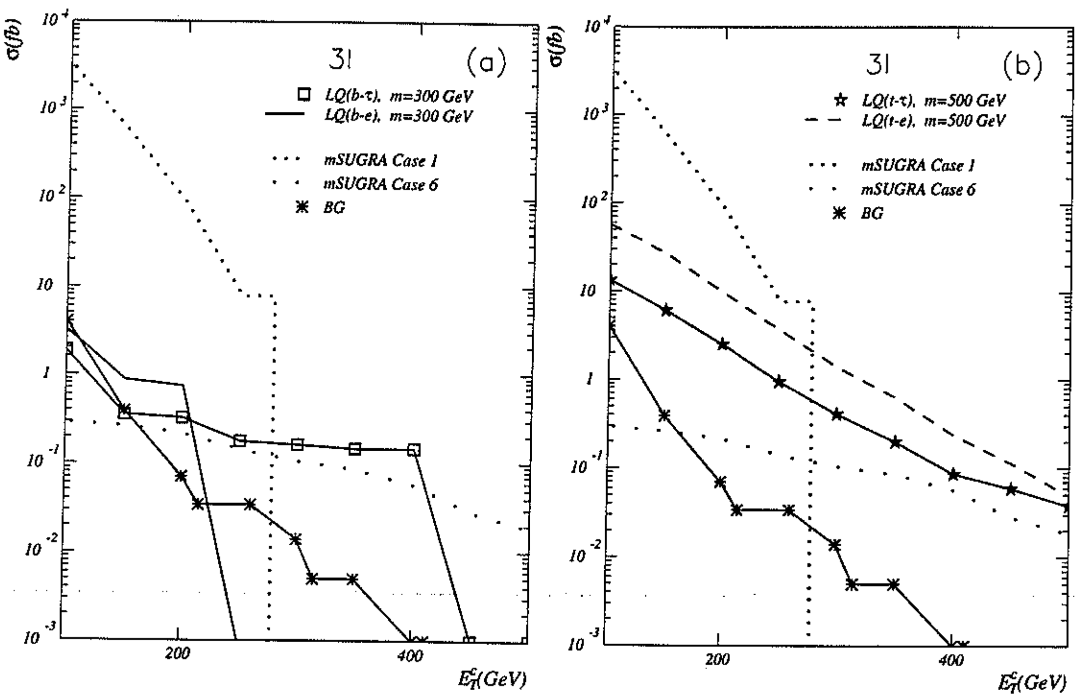

FIG. 4. Cross sections for SM background, two sets of mSUGRA parameters (case 1 and case 6) and (b, e), (b, τ) leptoquarks with mass=300 GeV (a); (t, τ), (t, e) leptoquarks with mass=500 GeV (b) for the 3l+jets analysis.