PHYSICAL REVIEW D **88,** 035016 (2013)

Vector-bilepton contribution to four lepton production at the LHC

E. Ramirez Barreto*

Centro de Ciências Naturais e Humanas, UFABC, Santo André 09210-170, São Paulo, Brazil

Y. A. Coutinho†,‡

Instituto de Física - Universidade Federal do Rio de Janeiro, Avenida Athos da Silveira Ramos, 149 Rio de Janeiro, Rio de Janeiro 21941-972, Brazil

J. Sá Borges§

Instituto de Física - Universidade do Estado do Rio de Janeiro, Rua São Francisco Xavier, 524 Rio de Janeiro, Rio de Janeiro 20550-013, Brazil

(Received 1 March 2013; published 19 August 2013)

Some extensions of the standard model predict the existence of particles having two units of leptonic charge, known as bileptons. One such model is based on the $SU(3)_c \times SU(3)_L \times U(1)_X$ symmetry group (3-3-1 model, for short). Our search uses the minimal version of the 3-3-1 model, which has exotic charges for the quarks and new gauge bosons. This model predicts the existence of bileptons as vector particles having one ($V^\pm$) and two ($Y^{\pm\pm}$) units of electric charge. We study the signatures for the production of four leptons by considering the contribution of a pair of bileptons in pp collisions for three energy and luminosity regimes at the Large Hadron Collider (LHC). We present invariant mass and transverse momentum distributions, the total cross section, and we determine the expected number of events for each bilepton type. Finally, we analyze the LHC potential for discovering single and double charged vector bileptons at 95% C.L. We conclude that the LHC collider can show a clear signature for the existence of bileptons as a signal of new physics.

DOI: 10.1103/PhysRevD.88.035016 PACS numbers: 14.70.Pw, 12.15.Ji

I. INTRODUCTION

A peculiar feature of the Standard Model (SM) is that none of the gauge bosons carry baryon or lepton number. Many extensions of the SM predicted the existence of exotic particles that carry global quantum numbers, among them leptoquarks and bileptons. The bileptons are defined as bosons carrying two units of lepton number and are present in $SU(15)$ grand unification theory and in the 3-3-1 model, for example.

In particular, the 3-3-1 model in its minimal version [1,2] includes single ($V^\pm$) and double charged ($Y^{\pm\pm}$) bileptons, whereas neutral and single-charged bileptons are present in the model version with right-handed neutrinos [3]. In addition to these new gauge bosons, there are new quarks, called leptoquarks, that carry two units of lepton number.

It is interesting to study the prospects for the detection of bileptons at linear and hadron colliders because its existence leads to a unique experimental signature. One expects that the LHC will spoil new physics and reveal the existence of new particles. We guess that bileptons are among the new discoveries and we intend, in this work, to extend our analysis about the production of bileptons at the LHC.

*elmer@if.ufrj.br
†Present address: CERN, Switzerland.
‡yara.amaral.coutinho@cern.ch
§jsaborges@uerj.br

It is known that LHC experiments have made efforts to search for a new charged gauge boson. ATLAS and CMS established model dependent bounds for the W' mass by analyzing lepton-antineutrino production from a sequential W' particle having the same coupling to fermions as the ordinary SM gauge boson [4]. In the present work we explore lepton-neutrino production from a single charged bilepton with peculiar properties and couplings for which the experimental mass limits do not apply. We also include the production of a pair of same-sign leptons related to double charged bilepton contribution. There is no background for these processes; however, we consider the production of leptons from SM contribution that can be misidentified with the signal and we show that they can be easily eliminated by convenient cuts.

There are some previous works about the production of charged bileptons in the literature. Some authors established model independent bounds for mass and couplings from low energy data and linear collider experiments. Using two versions of the 3-3-1 model, H. N. Long *et al.* [5] studied the bilepton production in an e^+e^- collider. The contribution of double charged bileptons to four lepton production at a linear collider was considered in [6]. For a detailed review about bileptons from an independent model approach, see [7].

From the same model, B. Dion *et al.* [8] obtained the total cross section for the production of a pair of bileptons in hadron colliders, whereas in Ref. [9] the authors studied the production of just one bilepton associated with an exotic quark. More recently, we considered two versions of this model to analyze single and double charged bilepton pair production for LHC energies [10–12]. It is shown that the total cross section for vector bilepton production is 3 orders of magnitude larger than for scalar pair production for $\sqrt{s} = 7$ and 14 TeV. For that reason we do not include the scalar bilepton contribution in the present paper.

A recent result was obtained by one of us for the decay of a 3-3-1 Higgs candidate into two photons where the vector bilepton plays an important role [13,14]. Their analysis shows that a bilepton doublet with mass $\simeq 213$ GeV and an $\mathcal{O}(10\%)$ branching ratio of the Higgs boson into invisible states can reasonably fit the available data. It was also shown that bileptons are associated with leptoquark production [15].

Here we analyze the contribution of bileptons to lepton production. We consider an unexplored bilepton mass domain accessible by the LHC (from 200 to 700 GeV) by respecting peculiar relations between the gauge boson masses.

We consider the elementary process $q + \bar{q}$ where, apart from the Standard Model particles, the exotic quarks and the extra neutral gauge boson Z' contributions are taken into account. In Sec. II we give a brief review of the 3-3-1 model, Sec. III is devoted to our results for the total cross section and final lepton distributions, and Sec. IV is devoted to our conclusion.

II. THE 3-3-1 MODEL

The electric charge operator is defined as

$$Q = T_3 + \beta T_8 + XI, \tag{1}$$

where T_3 and T_8 are two of the eight generators satisfying the $SU(3)$ algebra, I is the unit matrix, and X denotes the $U(1)$ charge. Besides the ordinary Standard Model gauge bosons, the model predicts the existence of a neutral Z', double charged $Y^{\pm\pm}$, and single charged $V^{\pm}$ gauge bosons. The charge operator determines how the fields are arranged in each representation and depends on the β parameter. Among the possible choices, $\beta = -\sqrt{3}$ [1,2] corresponds to the minimal version of the model, whereas $\beta = 1/\sqrt{3}$ leads to a model with right-handed neutrinos and no exotic charged fields [3].

In the minimal version of the model, the left- and right-handed lepton components of each generation belong to the triplet representation of $SU(3)$. The procedure to cancel model anomalies imposes that quark families be assigned to different $SU(3)$ representations [16]. Here we elect the left component of the first quark family to be accommodated in $SU(3)$ triplet and the second and third families ($m = 2, 3$) to belong to the antitriplet representation, as follows:

$$\begin{aligned} Q_{1L} &= \begin{pmatrix} u_1 & d_1 & J_1 \end{pmatrix}_L^T \sim (\mathbf{3}, 2/3) \\ Q_{mL} &= \begin{pmatrix} d_m & u_m & j_m \end{pmatrix}_L^T \sim (\mathbf{3}^*, -1/3). \end{aligned} \tag{2}$$

The corresponding right-handed components are

$$\begin{aligned} u_{aR} &\sim (\mathbf{1}, 2/3), & d_{aR} &\sim (\mathbf{1}, -1/3) \\ J_{1R} &\sim (\mathbf{1}, 5/3), & j_{mR} &\sim (\mathbf{1}, -4/3), \end{aligned}$$

where $a = 1, 2, 3$, $m = 2, 3$ and J_1, j_2, and j_3 are exotic quarks with, respectively, $5/3$, $-4/3$, and $-4/3$ units of the positron charge (e). The numbers inside the parentheses are the $SU(3)$ representation dimension and the X charge of each quark.

The Higgs structure that is necessary for symmetry breaking and that gives acceptable masses to quarks includes three triplets (η, ρ, and χ) and a scalar (σ_2) in the sextet representation that generates the correct lepton mass spectrum [17]. The neutral field of each scalar multiplet develops nonzero vacuum expectation value (v_χ, v_ρ, v_η, and v_{σ_2}), and the consistency of the model with the SM phenomenology is imposed by fixing a large scale for v_χ, which is responsible for giving mass to the exotic particles ($v_\chi \gg v_\rho,\ v_\eta,\ v_{\sigma_2}$), with $v_\rho^2 + v_\eta^2 + v_{\sigma_2}^2 = v_W^2 = (246)^2$ GeV^2.

We call attention to the relation between Z', $V^{\pm}$, and $Y^{\pm\pm}$ masses [8,18]:

$$\frac{M_V}{M_{Z'}} = \frac{M_Y}{M_{Z'}} = \frac{\sqrt{3 - 12\sin^2\theta_W}}{2\cos\theta_W}. \tag{3}$$

This constraint respects the experimental bounds, and it is equivalent to the W to Z masses relation in the SM. This ratio is $\simeq 0.3$ for $\sin^2\theta_W = 0.23$ [19], and so, Z' can decay into a bilepton pair.

The charged current interaction of leptons (ℓ) with vector-bileptons is given by

$$\mathcal{L}^{CC} = -\frac{g}{\sqrt{2}}\sum_\ell [\bar{\ell}^c \gamma^\mu \gamma^5 \ell Y_\mu^{++} + \bar{\ell}^c \gamma^\mu (1 - \gamma^5)\nu_\ell V_\mu^+] + \text{H.c.} \tag{4}$$

In the neutral gauge sector, the interactions of fermions Ψ_f and bosons are described by the Lagrangian:

$$\begin{aligned} \mathcal{L}_{NC} = \sum_f & e q_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu \\ & - \frac{g}{2\cos\theta_W}[\bar{\Psi}_f \gamma^\mu (g_{V_f} - g_{A_f}\gamma^5)\Psi_f Z_\mu \\ & + \bar{\Psi}_f \gamma^\mu (g'_{V_f} - g'_{A_i}\gamma^5)\Psi_f Z'_\mu], \end{aligned} \tag{5}$$

where eq_f is the fermion electric charge and g_{V_f}, g_{A_f}, g'_{V_f}, and g'_{A_f} are the fermion vector and axial-vector couplings with Z and Z', respectively, displayed in Table I. The trilinear couplings from the self-interactions of gauge fields are shown in Table II.

Finally, the couplings of ordinary to exotic quarks are driven by charged bileptons as follows:

TABLE I. The Z and Z' vector and axial-vector couplings to quarks ($u_1 = u$, $u_2 = c$, $u_3 = t$, and $d_1 = d$, $d_2 = s$, $d_3 = b$), $\mathcal{U}_{ii}$ and $\mathcal{V}_{jj}$ are $\mathcal{U}$ and $\mathcal{V}$ diagonal mixing matrix elements, with $s_W = \sin\theta_W$, $c_W = \cos\theta_W$, and $r = \sqrt{1-4s_W^2}$.

	Vector couplings	Axial-vector couplings
$Z\bar{u}_i u_i$	$\frac{1}{2} - \frac{4s_W^2}{3}$	$\frac{1}{2}$
$Z\bar{d}_j d_j$	$-\frac{1}{2} + \frac{2s_W^2}{3}$	$-\frac{1}{2}$
$Z'\bar{u}_i u_i$	$\frac{1-6s_W^2-\mathcal{U}^*_{ii}\mathcal{U}_{ii}c_W^2}{2\sqrt{3}r}$	$\frac{1+2s_W^2+\mathcal{U}^*_{ii}\mathcal{U}_{ii}c_W^2}{2\sqrt{3}r}$
$Z'\bar{d}_j d_j$	$\frac{1-\mathcal{V}^*_{jj}\mathcal{V}_{jj}c_W^2}{2\sqrt{3}r}$	$\frac{r^2+\mathcal{V}^*_{jj}\mathcal{V}_{jj}c_W^2}{2\sqrt{3}r}$

TABLE II. Couplings of neutral gauge bosons with vector-bilepton $Y^{\pm\pm}$, with $s_W = \sin\theta_W$, $c_W = \cos\theta_W$, and $r = \sqrt{1-4s_W^2}$.

Vertex	$\gamma Y^{++}Y^{--}$	$ZY^{++}Y^{--}$	$Z'Y^{++}Y^{--}$
Coupling	$2e$	$\frac{r^2}{2s_W c_W}$	$\frac{\sqrt{3}}{2s_W c_W}\frac{r}{\sqrt{1-2s_W^2}}$

$$\begin{aligned}\mathcal{L}^{CC} = &-\frac{g}{2\sqrt{2}}[\bar{u}\gamma^\mu(1-\gamma^5)(\mathcal{U}_{21}\ j_2 + \mathcal{U}_{31}\ j_3) \\ &+ \bar{J}_1\gamma^\mu(1-\gamma^5)\mathcal{V}_{11}d]Y^{++}_\mu + [\bar{d}\gamma^\mu(1-\gamma^5) \\ &\times(\mathcal{V}_{21}\ j_2 + \mathcal{V}_{31}\ j_3) \\ &+ \bar{J}_1\gamma^\mu(1-\gamma^5)\mathcal{U}_{11}u]V^+_\mu + \text{H.c.} \qquad (6)\end{aligned}$$

where $\mathcal{V}_{ij}$, $\mathcal{U}_{ij}$ are mixing matrix elements.

From this expression, and considering the leptonic number conservation, we conclude that the exotic quarks carry two units of leptonic quantum number and so they are a class of leptoquarks.

III. RESULTS

Let us first consider the experimental bounds on bilepton masses. As it was explained in the introduction, the experimental limits for the W' mass established by the ATLAS and CMS collaborations do not apply to the bilepton $V^\pm$ mass [20], because this bilepton couples with exotic quarks in addition to the ordinary quarks. On the other hand, a bound on the double charged bilepton mass of 510 GeV was obtained from LEP data when including exotic contributions to $\mu^+\mu^-$ and $\tau^+\tau^-$ production; this bound increases to 740 GeV when lepton-flavor violating charged lepton decay data are included [21]. A model independent and more recent analysis shows that a bilepton mass value around 500 GeV is at the limit of the exclusion region from LEP data for a specific range of double charged bilepton-lepton coupling [22]. The relation between bileptons to Z' masses gives the Z' mass values used in the present work ($\simeq$1.1, 1.8, and 2.6 TeV), not excluded by the experimental bounds that are model dependent [23].

From the theoretical point of view, a small bilepton mass (around 500 GeV) is convenient for respecting the constraint on the three measurable quantities, called S, T, and U, that parametrize potential new physics contributions to electroweak radiative corrections. Another important issue related to the gauge boson mass in the 3-3-1 model is a Landau pole that appears when the ratio of $SU(3)_L$ to $U(1)_X$ coupling constants becomes infinite at a finite energy scale. To avoid this critical situation, the Z' must be kept below 4 TeV [24]. From these remarks, we adopt three values for the single charged bilepton mass, namely, 300, 500, and 700 GeV, corresponding to $M_{Z'} = 1.0$, 1.7, and 2.3 TeV, respectively.

Next we consider bilepton contribution for lepton-neutrino production. For the three values of bilepton mass, the corresponding widths are 0.8, 1.4, and 2.0 GeV. We make an important choice in order to avoid $V^\pm$ decaying into exotic quarks by fixing, in our calculation, the exotic quark mass equal to 1 TeV. This way, $V^\pm$ decays only into the three lepton flavors with the same branching ratios.

In our procedure we consider the production of two pairs of lepton-neutrino in proton-proton collision from the process below:

$$q + \bar{q} \to \gamma, \qquad Z, Z' \to V^- + V^+ \to \{\ell + \nu_\ell\} + \{\bar{\ell}' + \bar{\nu}_{\ell'}\},$$

where ℓ and ℓ' stands for electron or muon and the braces indicate the particles corresponding to the decay of each charged gauge boson.

We calculate the total cross section and we generate the final state events by using the CompHep package [25]. On the set of events previously generated, we apply convenient cuts for the detector acceptance, and kinematic cuts for final leptons:

$$|\eta| \le 3.0, \qquad p_T > 20\ \text{GeV} \quad \text{and} \quad \not{E}_T > 20\ \text{GeV}.$$

From the selected events and using MadGraph/MadAnalysis [26] we obtain some distributions which allow us to compare the signal from the SM process

$$q + \bar{q} \to \gamma, \qquad Z \to W^- + W^+ \to \{\ell + \bar{\nu}_\ell\} + \{\bar{\ell}' + \nu_{\ell'}\},$$

and

$$\begin{aligned} q + \bar{q} &\to t + \bar{t} \to W^+ + j + W^- + j \\ &\to \{\ell \mp \nu_\ell\} + \{\bar{\ell}' + \nu_{\ell'}\} + j + j,\end{aligned}$$

where ℓ and ℓ' stands for electron or muon, the braces indicate the particles corresponding to the decay of each charged gauge boson, and j is a hadronic jet.

In Fig. 1, we present our results for the lepton-neutrino invariant mass distribution (upper) and lepton transverse momentum distribution (lower) at $\sqrt{s} = 7$ TeV. In the invariant mass distribution plot, we are including the signal from the bilepton production plus the SM background. From this figure one observes that W^+W^- contribution is smaller than the three considered bilepton contributions for

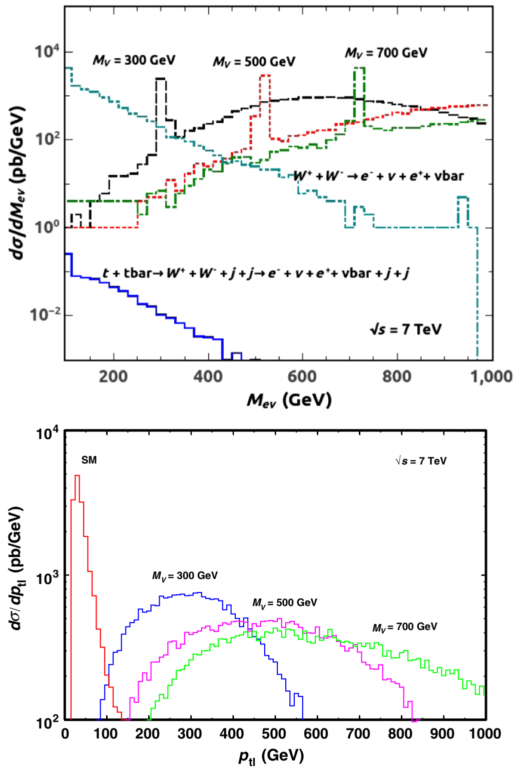

FIG. 1 (color online). Lepton-neutrino and lepton-antineutrino (SM backgrounds) invariant mass distributions (upper), and 3-3-1 and SM lepton transverse momentum distributions (lower), for three values of the single charged bilepton mass at $\sqrt{s} = 7$ TeV.

a lepton invariant mass from 600 GeV. On the other hand, the $t\,\bar{t}$ channel contributes less than bileptons for a 200 GeV dilepton invariant mass and its contribution becomes even less important for larger dilepton masses. One also observes that when the final lepton comes from a bilepton, its transverse momentum distribution is smeared in a wide range of p_T in contrast with the SM final lepton p_T distribution. These plots clearly show that it is possible to completely isolate the SM contributions by applying a convenient cut on the lepton-antineutrino final state invariant mass and on the charged lepton transverse momentum.

Finally, from the calculated cross section and considering 5 fb^{-1} integrated luminosity, one expects 3500, 125, and 8 events per year for $M_V = 300$, 500, and 700 GeV, respectively.

In the following we consider the contribution of the double charged bilepton for the production of two pairs of equal-sign leptons:

$$q + \bar{q} \to \gamma, \quad Z, Z' \to Y^{--} + Y^{++} \to \{\ell + \ell\} + \{\bar{\ell}' + \bar{\ell}'\},$$

where ℓ and ℓ' stand for electron or muon and the braces indicate the particles corresponding to the decay of each charged gauge boson.

This is an interesting process because it can encode a nonconservation of lepton number. This violation is much more clear in this case than for a single charged induced process, where it can also occur.

In the present analysis we respect the relation between gauge boson masses that characterizes the minimal version of the 3-3-1 model [Eq. (3)], by selecting three values for the bilepton mass (300, 500, and 700 GeV) corresponding, respectively, to $M_{Z'} \simeq 1.1$, 1.8, and 2.6 TeV.

In our calculation, exotic quark t-channel exchange is taken into account to guarantee that the elementary processes cross section does respect unitarity. On the other hand, we fix exotic quark masses equal to 1 TeV to avoid a large jet production from bileptons decaying into exotic plus ordinary quarks. This way we get equal branching fractions for bileptons ($M_Y = 300$, 500 and 700 GeV) decaying into same-sign leptons with widths $\Gamma_Y = 2.5$, 4.2, and 5.9 GeV.

We follow the same procedure as before by adopting the kinematic cuts for final leptons:

$$|\eta| \leq 3.0, \qquad p_T > 20\ \text{GeV}, \qquad m_{\ell\ell}\ \text{and}\ m_{\ell'\ell'} > 50\ \text{GeV},$$

to obtain 765, 41, and 2 events per year for the select masses at $\sqrt{s} = 7$ TeV and 5 fb^{-1} integrated luminosity.

Figure 2 shows the results for equal-sign lepton invariant mass (upper) and lepton transverse momentum distributions (lower). One observes the peak related to the resonance

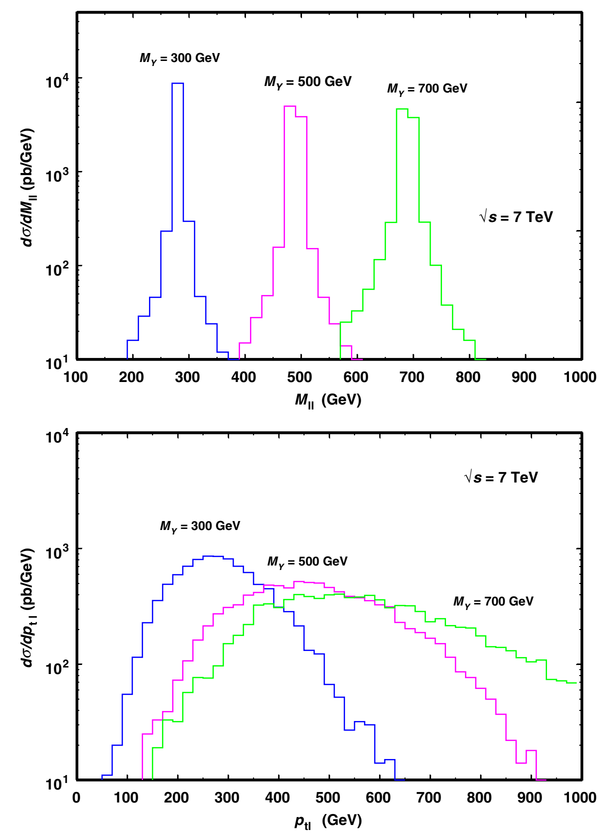

FIG. 2 (color online). Same-sign lepton invariant mass distribution (upper) and lepton transverse momentum distribution (lower) for three values of the double charged bilepton mass at $\sqrt{s} = 7$ TeV.

corresponding to three bilepton masses and their very narrow widths. Also, lepton transverse momentum distribution is similar to the case where it is produced from a single charged bilepton.

We have analyzed the LHC potential for discovering single and double charged vector bileptons at 95% C.L. and 66% for electron channel efficiency ϵ, defined as $\mathcal{L}_{\text{int}} = 5/[\epsilon(m_V)\sigma_{\text{tot}}(m_V)]$.

Our results in Fig. 3 show the calculated values of integrated luminosity as a function of bilepton mass. First it is shown in Fig. 3 (upper) that $\mathcal{L} \simeq 5\ \text{fb}^{-1}$ is sufficient for discovering a single charged bilepton with M_V up to 700 GeV at $\sqrt{s} = 7$ TeV. For the same bilepton mass and higher energies ($\sqrt{s} = 8$, 14 TeV) the integrated luminosities of 1 and 0.1 fb^{-1} are required.

The LHC potential for discovering a double charged bilepton is represented in Fig. 3 (lower), where one realizes that these bileptons can be found for the same luminosity referred to before with $M_Y \simeq M_V - 100$ GeV. We extended our analysis below 300 GeV in order to consider the bilepton mass used in [14].

The potential for discovering double charged vector bileptons at $\sqrt{s} = 7$ and 14 TeV was also obtained in [27]. In that paper, the authors clearly violate the constraint expressed in Eq. (3) by combining four bilepton mass values with a fixed Z' mass equal to 1 TeV. Another issue that deserves a comment is the choice made by the authors exploring low exotic quark masses (< 1 TeV) that gives an uncontrolled jet production rate.

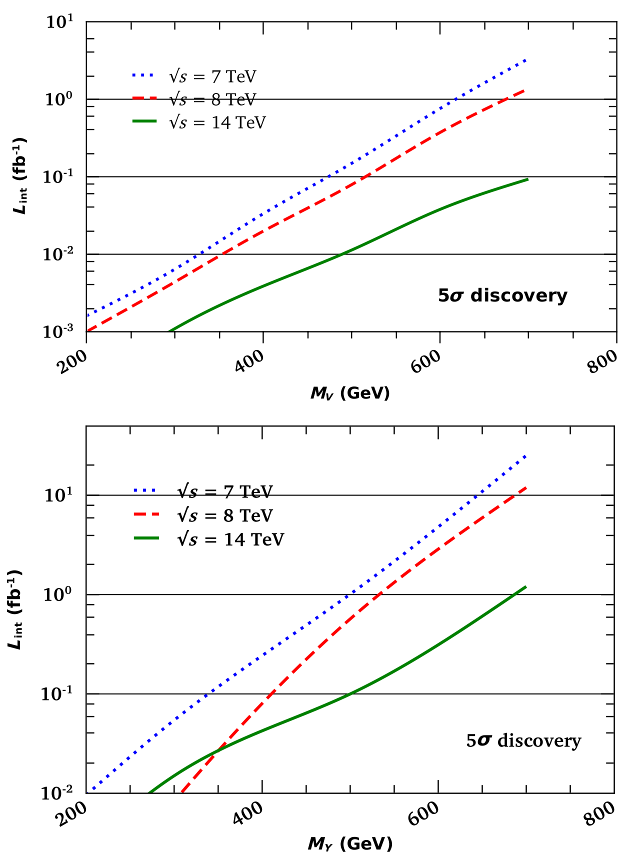

FIG. 3 (color online). Minimal integrated luminosity needed for a 5σ single charged (upper) and double charged (lower) bilepton discovery at the LHC.

IV. CONCLUSION

The LHC at CERN opened the possibility to explore an energy regime where the Standard Model of electroweak interactions have not yet been tested. At these energies, one expects that new resonances, associated with the existence of extra gauge bosons like W' and/or Z', can be produced. These particles are predicted in some SM extensions or alternative models such as the 3-3-1 model studied in the present paper.

The particle content of the minimal version of this model includes scalars and gauge bosons carrying two units of leptonic charge (L), called bileptons, and new quarks (leptoquarks) with exotic electric charges ($4/3e$, $5/3e$) leading to rich phenomenological consequences. In particular, this paper focuses on lepton number violation in the production of one lepton pair ($L = +2$) and an antilepton pair ($L = -2$) induced by bileptons.

An important characteristic of this model keeps some similarity with the SM one. We are referring to the relation between charged and neutral gauge boson masses that in the SM is $M_W = \cos\theta_W \times M_Z$. Our calculation takes into account the constraint expressed in Eq. (3) in contrast with [27], where the authors combined different charged bilepton masses with only one extra neutral gauge boson mass.

We perform the total cross section calculation using the CompHep and MadGraph packages to generate events that for $\mathcal{L} = 5\ \text{fb}^{-1}$ annual integrated luminosity result in a considerable number of leptons.

The observation of a transverse lepton momentum distribution smeared and located at large p_T values is in contrast with the shape corresponding to the misidentified leptons from the SM resonance. Moreover, the invariant mass distribution is shifted to large values, in contrast with the SM distribution, allowing us to select the signal by a convenient cut.

We analyzed the LHC discovery potential as a function of bilepton mass, showing that an integrated luminosity of order of 5 fb^{-1} is enough for discovering a bilepton with $M_V \simeq 700$ GeV, which implies that such a signal can be observed for the LHC at 7 or 8 TeV, whereas for the LHC running at 14 TeV one needs lower luminosity.

From our study in this specific model, we conclude that the LHC is capable of revealing signals for the existence of new particles related to new phenomena, including lepton number violation.

ACKNOWLEDGMENTS

E. R. B., Y. A. C., and J. S. thank Fapesp, Faperj and CNPq for financial support, respectively.

[1] F. Pisano and V. Pleitez, Phys. Rev. D **46**, 410 (1992).
[2] P. H. Frampton, Phys. Rev. Lett. **69**, 2889 (1992).
[3] J. C. Montero, F. Pisano, and V. Pleitez, Phys. Rev. D **47**, 2918 (1993); R. Foot, H. N. Long, and T. A. Tran, Phys. Rev. D **50**, R34 (1994); H. N. Long, Phys. Rev. D **53**, 437 (1996); **54**, 4691 (1996); V. Pleitez, Phys. Rev. D **53**, 514 (1996).
[4] S. Chatrchyan *et al.* (CMS Collaboration), J. High Energy Phys. 08 (2012) 023.
[5] H. N. Long and D. V. Soa, Nucl. Phys. **B601**, 361 (2001).
[6] E. R. Barreto, Y. A. Coutinho, and J. Sá Borges, Phys. Lett. B **632**, 675 (2006).
[7] F. Cuypers and S. Davidson, Eur. Phys. J. C **2**, 503 (1998).
[8] B. Dion, T. Gregoire, D. London, L. Marleau, and H. Nadeau, Phys. Rev. D **59**, 075006 (1999).
[9] B. Dutta and S. Nandi, Phys. Lett. B **340**, 86 (1994).
[10] E. R. Barreto, Y. A. Coutinho, and J. Sá Borges, Phys. Rev. D **83**, 075001 (2011).
[11] E. R. Barreto, Y. A. Coutinho, and J. Sá Borges, Nucl. Phys. **B810**, 210 (2009).
[12] E. R. Barreto, Y. A. Coutinho, and J. Sá Borges, Braz. J. Phys. **38**, 495 (2008).
[13] A. Alves, E. R. Barreto, A. G. Dias, C. A. Pires, F. S. Queiroz, and P. S. R. da Silva, Phys. Rev. D **84**, 115004 (2011).
[14] A. Alves, A. G. Dias, E. R. Barreto, C. A. de S. Pires, F. S. Queiroz, and P. S. Rodrigues da Silva, Eur. Phys. J. C **73**, 2288 (2013).
[15] A. Alves, E. R. Barreto, and A. G. Dias, Phys. Rev. D **86**, 055025 (2012).
[16] A. E. C. Hernandez, R. Martinez, and F. Ochoa, Phys. Rev. D **73**, 035007 (2006).
[17] R. Foot, O. F. Hernandez, F. Pisano, and V. Pleitez, Phys. Rev. D **47**, 4158 (1993).
[18] D. Ng, Phys. Rev. D **49**, 4805 (1994).
[19] J. Beringer *et al.* (Particle Data Group Collaboration), Phys. Rev. D **86**, 010001 (2012).
[20] ATLAS Collaboration, Report No. ATLAS-CONF-2012-007.
[21] M. B. Tully and G. C. Joshi, Phys. Lett. B **466**, 333 (1999).
[22] E. M. Gregores, A. Gusso, and S. F. Novaes, Phys. Rev. D **64**, 015004 (2001).
[23] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Lett. B **714**, 158 (2012); Report No. CMS-EXO-11-019; Report No. CERN-PH-EP-2012-157.
[24] A. G. Dias, R. Martinez, and V. Pleitez, Eur. Phys. J. C **39**, 101 (2005).
[25] E. Boos, V. Bunichev, M. Dubinin, L. Dudko, V. Edneral, V. Ilyin, A. Kryukov, V. Savrin, A. Semenov, and A. Sherstnev (CompHEP Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **534**, 250 (2004).
[26] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, J. High Energy Phys. 06 (2011) 128.
[27] B. Meirose and A. A. Nepomuceno, Phys. Rev. D **84**, 055002 (2011).