Some extensions of the standard model predict the existence of particles having two units of leptonic charge, known as bileptons. One of such models 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, having 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 singly and doubly 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.

PACS numbers:

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

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

It is known the effort of LHC experiments to search for new charged gauge boson. ATLAS and CMS established model dependent bounds for $W'$ mass, by analyzing lepton-antineutrino production from a sequential $W'$ particle, having the same coupling to fermions as the ordinary SM gauge boson. In the present work we explore lepton-neutrino production from a singly 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 lepton related to doubly charged bilepton contribution. There are 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. studied the bilepton production in $e^+e^-$ collider. The contribution of doubly charged bileptons to four lepton production at 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 bilepton in hadron colliders, whereas in Ref. [9] the authors studied the production of just one bilepton associated with an exotic quark. More recently, we consider two versions of this model to analyze singly and doubly charged bilepton pair production for LHC energies [10–12]. It is shown that the total cross section for vector bilepton production is three orders of magnitude larger than for scalar pair production for $\sqrt{s} = 7$ TeV 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 play an important role [13, 14]. Their analysis show 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 the section II we give a brief review of the 3-3-1 model, section III is devoted to our results for the total cross section and final lepton distributions, and section IV is devoted to our conclusion.

II. THE 3-3-1 MODEL

The electric charge operator is defined as:

$$Q = T_3 + \beta T_8 + XI$$

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 $\beta$ parameter. Among the possible choices, $\beta = -\sqrt{3}$ 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 triplet representation of $SU(3)$. The procedure to cancel model anomalies imposes that quark families be assigned to different $SU(3)$ representation [10]. 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 anti-triplet representation as follows:

$$Q_{1L} = (u_1 d_1)^T_L \sim (3, 2/3)$$
$$Q_{mL} = (d_m u_m)^T_L \sim (3^*, -1/3),$$

the corresponding right handed component are:

$$u_{aR} \sim (1, 2/3), d_{aR} \sim (1, -1/3)$$
$$J_{1R} \sim (1, 5/3), J_{2R} \sim (1, -4/3),$$

where $a = 1, 2, 3$ 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 necessary for symmetry breaking and that gives to quarks acceptable masses includes three triplets ($\eta, \rho$ and $\chi$) and a scalar ($\sigma_2$) in the sextet representation that generates the correct lepton mass spectrum [17]. The neutral field of each scalar multiplet develops non-zero vacuum expectation value ($\nu_x, v_\rho, v_\eta, v_\sigma_2$) and the consistency of the model with the SM phenomenology is imposed by fixing a large scale for $\nu_x$, responsible to give mass to the exotic particles ($v_x \gg v_\rho, v_\eta, v_\sigma_2$), 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]:

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

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 ($\ell$) with vector-bilepton are given by:

$$\mathcal{L}^{CC} = -\frac{g}{\sqrt{2}} \sum_\ell \left[ \bar{\ell}^\mu \gamma^\mu \gamma^5 \ell^\mu + \bar{\ell}^\mu \gamma^\mu (1 - \gamma^5) \nu_\ell \gamma^\mu \nu_\mu \right] + h.c.$$
In the neutral gauge sector, the interactions of fermions $\Psi_f$ and bosons are described by the Lagrangian:

$$\mathcal{L}_{\text{NC}} = \sum_f e q_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu - \frac{g}{2 \cos \theta_W} \left[ \bar{\Psi}_f \gamma^\mu (g_{V_f} - g_{A_f} \gamma^5) \Psi_f Z_\mu + \bar{\Psi}_f \gamma^\mu (g_{V_f} - g'_{A_f} \gamma^5) \Psi_f Z'_\mu \right]$$

(5)

where $e q_f$ 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 bilepton as follows:

$$\mathcal{L}^{\text{CC}} = -\frac{g}{2\sqrt{2}} \left[ \bar{\Psi} \gamma^\mu \left(1 - \gamma^5\right) \left(U_{21} j_2 + U_{31} j_3\right) + \bar{J}_1 \gamma^\mu \left(1 - \gamma^5\right) V_{11} \nu \right] Y_{\mu}^{++}$$

$$+ \left[ \bar{d} \gamma^\mu \left(1 - \gamma^5\right) \left(V_{21} j_2 + V_{31} j_3\right) + \bar{J}_1 \gamma^\mu \left(1 - \gamma^5\right) U_{11} u \right] V_{\mu}^+ + h.c.$$  

(6)

where $V_{ij}$, $U_{ij}$ are mixing matrices elements.

From this expression, and considering the leptonic number conservation, we conclude that the exotic quarks carries 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 $W'$ mass established by ATLAS and CMS collaborations do not apply to the bilepton $V^\pm$ mass because this bilepton couples with exotic quarks in addition to the ordinary quarks. On the other hand, a bound on the doubly charged bilepton mass of 510 GeV was obtained from LEP data when including exotic contributions to $\mu^\pm \mu^-$ and $\tau^+ \tau^-$ production; this bound increases to 740 GeV when lepton-flavour violating charged lepton decay data are included. A model independent and more recent analysis shows that a bilepton mass values around 500 GeV is at the limit of the exclusion region from LEP data for a specific range of double charged bilepton-lepton coupling. The relation between bileptons to $Z'$ masses gives $Z'$ 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.

On 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 parameterize 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. From these remarks, we adopt three values for the singly charged bilepton mass namely: 300, 500 and 700 GeV, corresponding $M_{Z'} = 1.0, 1.7$ 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 do 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:

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

where $\ell$ and $\ell'$ 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. On the set of events previously generated, we apply convenient cuts for the detector acceptance, and kinematic cuts for final leptons:

$$|\eta| \leq 3.0, \ p_T > 20 \text{ GeV and } E_T > 20 \text{ GeV}.$$  

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

$q + \bar{q} \rightarrow \gamma, Z \rightarrow W^- + W^+ \rightarrow \{\ell + \nu_\ell\} + \{\bar{\ell}' + \nu_{\ell}'\},$

and

$q + \bar{q} \rightarrow t + \bar{t} \rightarrow W^+ + j + W^- + j \rightarrow \{\ell + \nu_\ell\} + \{\bar{\ell}' + \nu_{\ell}'\} + j + j,$

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

In the Figure 1, we presents our results for the lepton-neutrino invariant mass distribution (up) and lepton transverse momentum distribution (down) at $\sqrt{s} = 7$ TeV.
the SM background. From this figure one observes that $W^+ W^-$ contribution is smaller than the three considered bilepton contributions for lepton invariant mass from 600 GeV. On the other hand the $t \bar{t}$ channel contributes less than bileptons for 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 expect 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 doubly charged bilepton for the production of two pairs of equal sign leptons:

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

where $\ell$ and $\ell'$ stands 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 non conservation of lepton number. This violation is much more clear in this case than for for singly 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 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 bilepton decaying into exotic plus ordinary quark. This way we get equal branching fraction for bilepton ($M_V = 300, 500$ 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:

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

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 leptons invariant mass (up) and lepton transverse momentum distributions (down). One observes the peak related to the resonance corresponding to three bilepton masses and their very narrow widths. Besides, 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 singly and doubly charged vector bileptons at 95% C.L. and 66% for electron channel efficiency $\epsilon$, defined as $\mathcal{L}_{\text{int}} = 5/\left[\epsilon(M_V) \times \sigma_{\text{tot}}(M_V)\right]$.

Our results in the Figure 4 show the calculated values of integrated luminosity as a function of bilepton mass. First it is shown in Figure 4 (up) that $\mathcal{L} \simeq 5 \text{ fb}^{-1}$ is sufficient for discovering a singly charged bilepton with $M_V$ up to 700 GeV at $\sqrt{s} = 7$ TeV. For the same bilepton mass and higher energies ($\sqrt{s} = 8, 14 \text{ TeV}$) the integrated luminosities of 1 and 0.1 fb$^{-1}$ are required.

The LHC potential for discovering a doubly charged bilepton is represented in the Figure 4 (down) where one realize that these bileptons can be found for the same luminosity referred before with $M_V \simeq M_V - 100 \text{ GeV}$. We extended our analysis below 300 GeV in order to consider the bilepton mass used in [14].

The potential for discovering doubly charged vector bileptons at $\sqrt{s} = 7$ and 14 TeV was also obtained in [27]. In that paper, the authors clearly violates the constraint expressed in Eq. [3] by combining four bilepton

FIG. 1: Lepton-neutrino and lepton-antineutrino (SM backgrounds) invariant mass distributions (up), and 3-3-1 and SM lepton transverse momentum distributions (down), for three values of the singly charged bilepton mass at $\sqrt{s} = 7$ TeV.
FIG. 2: Same sign lepton invariant mass distribution (up) and lepton transverse momentum distribution (down) for three values of the doubly charged bilepton mass at $\sqrt{s} = 7$ TeV.

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.

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 expect 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.
FIG. 3: Minimal integrated luminosity needed for a 5σ singly charged (up) and doubly charged (down) bilepton discovery at the LHC.

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Vector Couplings | Axial-Vector Couplings
---|---
$Zu_1 u_i$ | $\frac{1}{2} - \frac{4 s^2_W}{3}$ | $\frac{1}{2}$
$Zd_j d_j$ | $-\frac{1}{2} + \frac{2 s^2_W}{3}$ | $\frac{1}{2}$
$Z' u_1 u_i$ | $\frac{1 - 6 s^2_W - U_{i1}^* U_{i4} c^2_W}{2 \sqrt{3} r}$ | $\frac{1 + 2 s^2_W + U_{i1}^* U_{i4} c^2_W}{2 \sqrt{3} r}$
$Z'd_j d_j$ | $\frac{1 - V_{jj}^* V_{jj} c^2_W}{2 \sqrt{3} r}$ | $\frac{r^2 + V_{jj}^* V_{jj} c^2_W}{2 \sqrt{3} r}$

TABLE I: The $Z$ and $Z'$ vector and axial-vector couplings to quarks ($u_1 = u, u_2 = c, u_3 = t$, and $d_1 = d, d_2 = s, d_3 = b$), $U_{i1}$ and $V_{jj}$ are $\mathcal{U}$ and $\mathcal{V}$ diagonal mixing matrix elements, with $s_W = \sin \theta_W$, $c_W = \cos \theta_W$ and $r = \sqrt{1 - 4 s^2_W}$.

| Vertex | $\gamma Y^{++} Y^{--}$ | $Z Y^{++} Y^{--}$ | $Z' Y^{++} Y^{--}$ |
|---|---|---|---|
| Coupling | 2e | $\frac{r^2}{2 s_W c_W}$ | $\sqrt{3} \frac{r}{2 s_W c_W} \frac{r}{\sqrt{1 - 4 s^2_W}}$ |

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 $r = \sqrt{1 - 4 s^2_W}$.

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