Fractional charged leptons in a 331 Model

D Romero Abad and E Ramirez Barreto

Grupo de Investigación en Física, Universidad San Ignacio de Loyola, Av. La Fontana 550, La Molina, Lima, Perú

E-mail: davidromeroabad@gmail.com

Abstract. The extensions of the Standard Model based on $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ gauge group are known as 331 Models. Different properties, as the fermion assignment and the electric charges of the exotic spectrum, that defines a particular version of the model, are fixed by a parameter β. In this work, we explore a 331 version, set by the condition $\beta = 1/\left(3\sqrt{3}\right)$, where new particles arise with peculiar signatures as heavy fractionally charged leptons and electrical neutral quarks, among others. We examine different sectors of the model with emphasis in the Yukawa lagrangian of the new leptons, in order to study their branching fraction for scalar particles.

1. Introduction

The possibility of having fermions with exotic charges within non-supersymmetric constructions beyond the SM has been the object of several studies [1, 2]. For example, in models based on the local gauge group $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$ called hereafter 331 models for short. In this context, considering the definition of electric charge operator ($\mathcal{Q}$), as a linear combination of the $SU(3)_L$ group generators (T_3, T_8) and the X charge of $U(1)_X$, we have

$$\mathcal{Q} = T_3 + \beta\, T_8 + X I \tag{1}$$

where β fixes the matter content of the model. We can find 331 versions containing quarks with exotic electric charges ($-4/5\, e$ and $+5/3\, e$) for $\beta = \pm\sqrt{3}$ [3, 4, 5, 6]. On the other hand, a new version, for $\beta = 0$ has been proposed, containing leptons and quarks with charge $\pm 1/2\, e$ and $\pm 1/6\, e$ respectively. Also, in this version, appears new gauge and scalar bosons with charges $\pm 1/2\, e$ [7]. In a similar way, we study in this work an unfamiliar 331 model set by the condition $\beta = 1/\left(3\sqrt{3}\right)$. In this framework, emerge new leptons with charge $-2/3\, e$, extra quarks with charges $+1/3\, e$, 0, and exotic gauge and scalar bosons with charges $\pm 1/3\, e$ and $\pm 2/3\, e$, in addition to a new neutral boson Z'. Specifically, associated with the electric charge, this new 331 version differs from the previous case ($\beta = 0$) in that all the extra particles in the model acquire electric charge values compatible with $\mathcal{Q} = \pm 1/3\, e$, that happens in grand unified theories (GUTs) for example [8]. Thus, the paper is organized as follows: in Sec. II we present the model involving the Standard Model and exotic particles at all sectors: fermions, gauge bosons, scalar bosons, and the charged and neutral currents for leptons and quarks. In Sec. III, we study the decay and production of the exotic lepton within the current and future energy regimes for hadron colliders and finally, in Sec. IV we present our conclusions and perspectives.

2. The model

As already mentioned, the 331 models are constructions with $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ gauge symmetry, where the electric charge operator through the β parameter, fixes the content of matter defining a distinct version of such models. Thus, from the charge operator expression in Eq.(1) and with the particular choice $\beta = 1/\left(3\sqrt{3}\right)$, we have the leptons assigned in $SU(3)_L$ triplets:

$$\begin{aligned} \psi_{iL} &= \left(\nu_i, e_i^-, E_i^{-2/3}\right)_L^T \sim (\mathbf{1}, \mathbf{3}, -5/9)\,, \quad i = 1, 2, 3. \\ e_{i_R}^- &\sim (\mathbf{1}, \mathbf{1}, -1)\,, \quad E_{i_R}^{-2/3} \sim (\mathbf{1}, \mathbf{1}, -2/3)\,, \end{aligned} \tag{2}$$

where the new lepton have exotic electric charge $-2/3\,e$. The numbers in parentheses indicate the field transformation properties under $SU(3)_C$, $SU(3)_L$, and $U(1)_X$, respectively. The two first quark families form $SU(3)_L$ anti-triplets

$$\begin{aligned} Q_{aL} &= (d_a, -u_a, D_a^c)_L^T \sim (\mathbf{3}, \mathbf{3}^*, 2/9)\,, \quad u_{a_R} \sim (\mathbf{3}, \mathbf{1}, 2/3) \\ d_{a_R} &\sim (\mathbf{3}, \mathbf{1}, -1/3)\,, \quad D_{a_R}^c \sim (\mathbf{3}, \mathbf{1}, 1/3)\,, \quad a = 1, 2 \end{aligned} \tag{3}$$

and the third family is assigned to $SU(3)_L$ triplet:

$$\begin{aligned} Q_{3L} &= \left(t, b, T^0\right)_L^T \sim (\mathbf{3}, \mathbf{3}, 1/9)\,, \quad t_R \sim (\mathbf{3}, \mathbf{1}, 2/3)\,, \\ b_R &\sim (\mathbf{3}, \mathbf{1}, -1/3)\,, \quad T_R^0 \sim (\mathbf{3}, \mathbf{1}, 0) \end{aligned} \tag{4}$$

where the new exotic quarks D_a and T acquire the electric charge $+e/3$ and 0, respectively. We call attention to the fact that in order to cancel anomalies associated with $SU(3)_L$ gauge group, the leptons, and the third quark family are assigned in triplets, while the first two quark families are $SU(3)_L$ anti-triplets. In order to generate mass to the particles in this model, we introduce the following scalar sector [9]

$$\begin{aligned} \eta &= \begin{pmatrix} \eta^0 \\ \eta_2^- \\ \eta_3^{-2/3} \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, -5/9)\,, \; \rho = \begin{pmatrix} \rho_1^+ \\ \rho^0 \\ \rho_3^{+1/3} \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, 4/9)\,, \\ \chi &= \begin{pmatrix} \chi_1^{2/3} \\ \chi_2^{-1/3} \\ \chi^0 \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, 1/9) \end{aligned} \tag{5}$$

where the charges were assigned using the charge operator matrix, Eq.(1) with $\beta = 1/\left(3\sqrt{3}\right)$. These three Higgs multiplets will be necessary to generate mass for fermions and gauge bosons in the model. In addition, those fields develop vacuum expectation values (VEVs) as

$$\begin{aligned} \langle \eta^0 \rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} v_\eta \\ 0 \\ 0 \end{pmatrix}, \quad \langle \rho^0 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_\rho \\ 0 \end{pmatrix}, \\ \langle \chi^0 \rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ v_\chi \end{pmatrix} \end{aligned} \tag{6}$$

with

$$v_\eta^2 + v_\rho^2 = (246\,\mathrm{GeV})^2 \tag{7}$$

In order to obtain the neutral and charged currents involving fermions and the neutral and charged bosons, we introduce the covariant derivative:

$$D_u \equiv \partial_\mu - i\,g\,T^b\,W_\mu^b - i\,g_X\,\frac{X}{2}\,B_\mu, \tag{8}$$

where g and W_μ^b ($b = 1,..,8$) are the coupling constant and gauge boson octet related with the $SU(3)_L$ group respectively. In a similar way, g_X and B_μ are the coupling constant and gauge boson singlet related with the $U(1)_X$ group. Using the fundamental representation of the Gell-Mann matrices, we obtain the matrix for electroweak gauge bosons:

$$T^bW_\mu^b = \frac{1}{2}\begin{pmatrix} W_\mu^3 + \frac{W_\mu^8}{\sqrt{3}} & \sqrt{2}W_\mu^+ & \sqrt{2}V_\mu^{+\mathcal{Q}_1} \\ \sqrt{2}W_\mu^- & -W_\mu^3 + \frac{W_\mu^8}{\sqrt{3}} & \sqrt{2}U_\mu^{+\mathcal{Q}_2} \\ \sqrt{2}V_\mu^{-\mathcal{Q}_1} & \sqrt{2}U_\mu^{-\mathcal{Q}_2} & -\frac{2}{\sqrt{3}}W_\mu^8 \end{pmatrix} \tag{9}$$

we define the charged and non-Hermitian gauge bosons as:

$$W_\mu^\pm \equiv \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp iW_\mu^2\right) \tag{10}$$

$$V_\mu^{\pm\mathcal{Q}_1} \equiv \frac{1}{\sqrt{2}}\left(W_\mu^4 \mp iW_\mu^5\right) \tag{11}$$

$$U_\mu^{\pm\mathcal{Q}_2} \equiv \frac{1}{\sqrt{2}}\left(W_\mu^6 \mp iW_\mu^7\right) \tag{12}$$

the charge assignment of the gauge bosons is obtained using $[\mathcal{Q}, \psi] = -q\psi$ for a general β:

$$\begin{aligned} \mathcal{Q}\ \left(W_\mu^\pm\right) &= \pm 1, \quad \mathcal{Q}\left(V_\mu^{\pm\mathcal{Q}_1}\right) = \pm\frac{1}{2}\left(1 + \beta\sqrt{3}\right), \\ \mathcal{Q}\ \left(U_\mu^{\pm\mathcal{Q}_2}\right) &= \mp\frac{1}{2}\left(1 - \beta\sqrt{3}\right) \end{aligned} \tag{13}$$

The particular choice $\beta = 1/\left(3\sqrt{3}\right)$ leads:

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(W_\mu^1 \mp iW_\mu^2\right) \tag{14}$$

$$V_\mu^{\pm 2/3} = \frac{1}{\sqrt{2}}\left(W_\mu^4 \mp iW_\mu^5\right) \tag{15}$$

$$U_\mu^{\pm 1/3} = \frac{1}{\sqrt{2}}\left(W_\mu^6 \mp iW_\mu^7\right) \tag{16}$$

The new charged vector bosons carry fractional charge $\pm 2e/3$ and $\pm e/3$. The masses of the charge gauge bosons are:

$$\begin{aligned} M_{W^\pm}^2 &= \frac{g^2}{2}\left(v_\rho^2 + v_\eta^2\right), \quad M_{V^{\pm 2/3}}^2 = \frac{g^2}{2}\left(v_\chi^2 + v_\eta^2\right), \\ M_{U^{\pm 1/3}}^2 &= \frac{g^2}{2}\left(v_\chi^2 + v_\rho^2\right) \end{aligned} \tag{17}$$

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Notice that

$$v_\chi \gg v_\rho, v_\eta \tag{18}$$

in order to keep the new gauge bosons $V^{\pm 2/3}$, $U^{\pm 1/3}$ sufficient large to have coherence with low-energy phenomenology [3].

The neutral physical gauge bosons in the (W^3,W^8, B) basis with $\beta = 1/\left(3\sqrt{3}\right)$, are [10]:

$$\begin{aligned} A_\mu &= s_W W^3_\mu + \frac{c_W t_W}{\sqrt{27}} W^8_\mu + c_W \sqrt{1 - \frac{t_W^2}{27}}\, B_\mu \\ Z_\mu &= c_W W^3_\mu - \frac{s_W t_W}{\sqrt{27}} W^8_\mu - s_W \sqrt{1 - \frac{t_W^2}{27}}\, B_\mu \\ Z'_\mu &= \sqrt{1 - \frac{t_W^2}{27}}\, W^8_\mu + \frac{t_W}{\sqrt{27}}\, B_\mu \end{aligned} \tag{19}$$

where $s_W \equiv \sin(\theta_W)$, $c_W \equiv \cos(\theta_W)$, $t_W \equiv \tan(\theta_W)$ and θ_W is the Weinberg angle. The masses of these neutral states are:

$$\begin{aligned} M_A^2 &= 0, \\ M_Z^2 &\simeq \frac{g^2}{2} \left(\frac{g^2 + \frac{28}{27} g_X^2}{g^2 + \frac{g_X^2}{27}} \right) \left(v_\rho^2 + v_\eta^2 \right), \\ M_{Z'}^2 &\simeq 2 \left(\frac{g^2 + \frac{g_X^2}{27}}{3} \right) v_\chi^2 \end{aligned} \tag{20}$$

The relation between the coupling constants for a general β, is given by [10],[11]:

$$\frac{g_X^2}{g^2} = \frac{s_W^2(M_{Z'})}{1 - \left[1 + \beta^2\right] s_W^2(M_{Z'})} \tag{21}$$

with $\beta = 1/\left(3\sqrt{3}\right)$, s_W^2 has to be smaller than 0.96 to avoid $g_X(M_{Z'})$ becomes infinite and a Landau-like pole arises. The difference with respect to minimal 3-3-1 model ($\beta = \pm\sqrt{3}$) is that in our case we do not undergo constraints imposes by the perturbative conditions [12], [13] favoring a high $SU(3)_L$ symmetry breaking scale and considerable heavier gauge bosons [14]. The charged current lagrangian that contains the new heavy leptons of the model is

$$\begin{aligned} \mathcal{L}_{\rm CC} = &- \frac{g}{\sqrt{2}} \overline{E_i^{-2/3}} \gamma_\mu \left(1 - \gamma_5\right) (U^{1/3})^\mu e_i \\ &- \frac{g}{\sqrt{2}} \overline{E_i^{-2/3}} \gamma_\mu \left(1 - \gamma_5\right) (V^{-2/3})^\mu \nu_i + \text{h.c.} \end{aligned} \tag{22}$$

The Yukawa Lagrangian for the leptons in terms of the symmetry eigenstates have the form

$$-\mathcal{L}_Y^{\rm leptons} = G^e_{ab}\, \overline{\psi}_{aL}\, \rho\, e^-_{bR} + G^E_{ab}\, \overline{\psi}_{aL}\, \chi\, E^{-2/3}_{bR} + \text{h.c.} \tag{23}$$

We do not employ the scalar η in the above expression because this leads to couplings with right-handed neutrinos, which are not considered in the studied model.
The Yukawa couplings for the new fractional charged lepton E is

$$-\mathcal{L}_Y^{\text{leptons},E} = G_{ab}^{e}\,\overline{E_{aL}^{-2/3}}\,\rho_3^{1/3}\,e_{bR}^{-} + G_{ab}^{E}\,\overline{e_{aL}^{-}}\,\chi_2^{-1/3}\,E_{bR}^{-2/3} + \text{h.c.} \tag{24}$$

The reference [?] shows that the symmetry and physical scalar fields are related in the following way:

$$\rho_3^{\pm 1/3} = \frac{v_\rho}{\sqrt{v_\rho^2 + v_\chi^2}}\,\phi_3^{\pm 1/3} + \frac{v_\chi}{\sqrt{v_\rho^2 + v_\chi^2}}\,H^{\pm 1/3} \tag{25}$$

$$\chi_2^{\pm 1/3} = -\frac{v_\chi}{\sqrt{v_\rho^2 + v_\chi^2}}\,\phi_3^{\pm 1/3} + \frac{v_\rho}{\sqrt{v_\rho^2 + v_\chi^2}}\,H^{\pm 1/3} \tag{26}$$

where $\phi_3^{\pm 1/3}$ and $H^{\pm 1/3}$ are a Goldstone boson and a charged physical Higgs respectively. Then

$$-\mathcal{L}_{Y_{eEH}} = \overline{E^{-2/3}}\,(A_R P_R + A_L P_L)\;H^{1/3}\,e^- + \text{h.c.} \tag{27}$$

Table 1. Couplings of exotic lepton with the gauge bosons U, V and the charged Higgs $H^{1/3}$. The projectors are defined as $P_L \equiv (1-\gamma_5)/2$ and $P_R \equiv (1+\gamma_5)/2$. And the coefficients are $A_R = \left(\sqrt{2}\,m_e\,v_\chi\right)/\left(v_\rho\,\sqrt{v_\rho^2+v_\chi^2}\right)$ and $A_L = \left(\sqrt{2}\,m_E\,v_\rho\right)/\left(v_\chi\,\sqrt{v_\rho^2+v_\chi^2}\right)$.

Vertex	$E^{2/3}U^{1/3}e^-$	$E^{2/3}V^{-2/3}\nu_e$	$E^{2/3}H^{1/3}e^-$
Coupling	$\frac{g}{\sqrt{2}}\gamma^\mu P_L$	$\frac{g}{\sqrt{2}}\gamma^\mu P_L$	$A_R\,P_R + A_L\,P_L$

3. Exotic leptons branching ratios

In this section, we examine the total decay width (Γ) for the exotic lepton $E^{-2/3}$ and their respective branching ratios (BR). From the gauge and Yukawa interactions, presented in the Table 1, the two-body decay modes for the exotic lepton are

$$E^{-2/3} \to U^{+1/3} + \ell \tag{28}$$

$$E^{-2/3} \to V^{-2/3} + \nu_\ell \tag{29}$$

$$E^{-2/3} \to H^{+1/3} + \ell \tag{30}$$

where $\ell = e^-, \mu^-, \tau^-$ and $U^{+1/3}$, $V^{-2/3}$ and $H^{+1/3}$ are the exotic gauge bosons and one of the charged Higgs respectively. In order to study the properties of the new particle, the $3-3-1$ model with $\beta = 1/\left(3\sqrt{3}\right)$ was implemented in the LanHep package [15] in interface with CalcHep [16]. In particular, to analize Γ and the BR of this exotic particle, some parameters of the model have to be fixed. For example, combining the equations (17), (18), (20) and (21) for $\beta = 1/\left(3\sqrt{3}\right)$ we obtain

$$\frac{M_V}{M_{Z'}} \approx \frac{M_U}{M_{Z'}} \approx \frac{\sqrt{27 - 28 s_W^2}}{6\, c_W} \tag{31}$$

Hence, it can be observed from the above expression that once the mass of the Z' boson is chosen, the gauge bosons masses will be fixed. From relation (20), if we select $v_\chi = 5600$ GeV, we obtain $M_{Z'} = 3000$ GeV. As a consequence, the new gauge bosons masses will be fixed to $M_V \approx M_U \approx 2600$ GeV. In addition, according with the condition (7) we choose $v_\rho = 225$ GeV in order to set the constant coupling among the heavy lepton, the electron and the exotic Higgs, that appears in Table 1. In Fig. 3, we display the total decay width for this exotic lepton in function of its mass, for values between 400 and 4000 GeV.

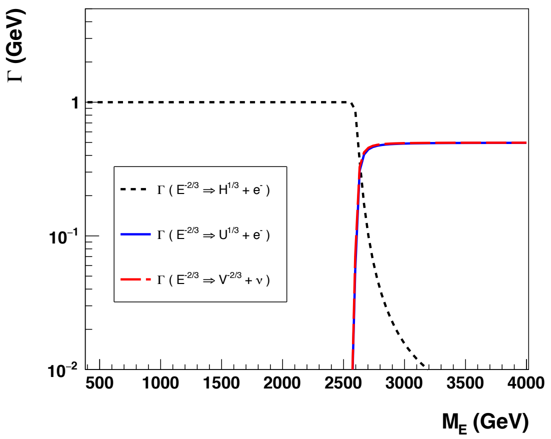

Figure 1. Decay width of the new heavy lepton $E^{-2/3}$ for a mass range of 400 to 4000 GeV and for different two-body decay channels. In this case we use M_H= 300 GeV, $M_{Z'}$= 3000 GeV and v_χ=5600 GeV.

4. Conclusions

In this work, we have presented a new version of the 331 model, defined by $\beta = 1/\left(3\sqrt{3}\right)$. This particular construction contains new fermions and bosons with fractionally electric charges. Specifically, it predicts leptons with $q = \pm 2e/3$, gauge bosons with $q = \pm 2e/3$, $q = \pm 1e/3$, electrically neutral quarks, and scalar particles with exotic charges, beyond the SM particle content. In addition, we show the decay width for the new fractionally charged lepton (E) in terms of a new fractionally charged Higgs and gauge bosons.

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