Heavy long-lived fractionally charged leptons in novel $3 - 3 - 1$ model

Elmer Ramirez Barret$^a$ and David Romero Abad$^b$

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

Abstract

It was explored a new $SU(3)_L \otimes U(1)_X$ electroweak extension of the Standard Model, where new particles arise with peculiar signatures as heavy fractionally charged leptons and electrical neutral quarks, among others. We examine the branching fraction and the lifetime of new heavy leptons in order to discriminate if they could be identified as long-lived particle candidates. In addition, it was compared the production cross-section for these exotic leptons through a Drell-Yan process for the LHC and future hadron facilities.

---

$^a$ elmerraba@gmail.com

$^b$ dromero@usil.edu.pe
I. INTRODUCTION

The Large Hadron Collider (LHC) experiment collected an enormous amount of data since the year 2010, but have not yet exhibited any proof of physics beyond the standard model (SM). As a consequence, the investigation of atypical final state signatures that could escape from the standard analysis techniques has increased [1–5].

An extensive range of physics models that enlarge the SM such as R-parity violating (RPV) supersymmetry (SUSY) [6], split SUSY [7], hidden valley models [8], and the minimal B-L extension of the SM [9] predict the appearance of new, massive and long-lived particles (LLPs).

Usually, LLPs have lifetimes greater than a few nanoseconds and can cross distances larger than the extent of a conventional collider detector and seem quasi-stable. Due to their large mass, the LLPs are expected to be slow in comparison with ordinary final state particles [10]. Another feature that LLPs could have is to carry a fractional electric charge. This condition is proposed by some theoretical models [11, 12] and both ATLAS and CMS Collaborations have already performed searches of new heavy lepton-like particles with non-standard electric charge [13–15]. In particular, CMS exclude at 95% confidence level such particles with electric charge $\pm 2e/3$, with masses below 310 GeV, and those with charge $\pm e/3$, with masses below 140 GeV [16]. Experimentally LLPs may be misidentified or unobserved since charged particle identification algorithms generally assume that particles have speeds close to the speed of light and charges of $\pm 1e$ [4].

In the last years, the interest in this type of particles with exotic properties has raised, triggering in the joint work of experimental collaborations such as ATLAS, CMS, LHCb, milliQan, MoEDAL, MATHUSLA, FASER, Codex-b, to define a plan in the search for this signature in the coming years [17].

The possibility of having fermions with exotic charges within non-supersymmetric constructions beyond the SM has been the object of several studies [18–19]. For example, in models based on the local gauge group $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$ called hereafter $3-3-1$ models for short. In this context, the relation among the electric charge operator ($Q$), the $SU(3)_L$ group generators ($T_3, T_8$) and the $X$ charge of $U(1)_X$, is given by

$$Q = T_3 + \beta T_8 + XI$$ \hspace{1cm} (1)

where $\beta$ fixes the matter content of the model. We can find $3-3-1$ versions containing
quarks with exotic electric charges \((-4/5 \, e \text{ and } +5/3 \, e)\) for \(\beta = \pm \sqrt{3}\) \([20, 23]\). 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, we have new gauge and scalar bosons with charges \(\pm 1/2 \, e\) \([24]\).

In a similar way, we propose in this work a new version of the \(3 - 3 - 1\) model, set by the condition \(\beta = 1/(3\sqrt{3})\). 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 \(Z'\). Our proposal maintains the special features of the \(3 - 3 - 1\) models, such as the relation between the number of fermionic families and the number of colors in QCD, and the quantization of the electrical charge independent of the naturalness of the neutrinos among others \([25]\). Specifically, associated with the electric charge, this new \(3 - 3 - 1\) version differs from the previous case \((\beta = 0)\) in that all the extra particles in the model acquire electric charge values compatible with \(Q = \pm 1/3\,e\), that happens in grand unified theories (GUTs) for example \([26]\). From the phenomenological point of view, the chance that the exotic lepton may have a large lifetime of the order of the nanoseconds makes our proposal interesting given the experimental interest in looking for signs of long-lived particles through their production and decay.

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.

II. THE MODEL

As already mentioned, the \(3 - 3 - 1\) models are constructions with \(SU(3)_C \otimes SU(3)_L \otimes U(1)_X\) gauge symmetry, where the electric charge operator through the \(\beta\) 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 \(\beta = 1/(3\sqrt{3})\), we have the leptons assigned in \(SU(3)_L\) triplets:

\[
\begin{align*}
\text{SU}(2)_L \otimes \text{SU}(1)_Y & \\
\text{SU}(3)_C & \\
\end{align*}
\]
\[
\psi_{iL} = \left( \nu_i, e_i^-, E_i^{2/3} \right)^T_L \sim (1, 3, -5/9), \quad i = 1, 2, 3.
\]
\[
e_{iR}^- \sim (1, 1, -1), \quad E_{iR}^{-2/3} \sim (1, 1, -2/3),
\]

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

\[
Q_aL = (d_a, -u_a, D_a^c)^T_L \sim (3, 3^*, 2/9), \quad u_{aR} \sim (3, 1, 2/3)
\]
\[
d_{aR} \sim (3, 1, -1/3), \quad D_{aR}^c \sim (3, 1, 1/3), \quad a = 1, 2
\]

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

\[
Q_3L = (t, b, T_0^0)^T_L \sim (3, 3, 1/9), \quad t_R \sim (3, 1, 2/3),
\]
\[
b_R \sim (3, 1, -1/3), \quad T_0^R \sim (3, 1, 0)
\]

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 \[27\]

\[
\eta = \begin{pmatrix} \eta^0 \\ \eta_1^- \\ \eta_2^{-2/3} \end{pmatrix} \sim (1, 3, -5/9), \quad \rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^{+1/3} \end{pmatrix} \sim (1, 3, 4/9),
\]
\[
\chi = \begin{pmatrix} \chi^{2/3} \\ \chi^{-1/3} \\ \chi^0 \end{pmatrix} \sim (1, 3, 1/9)
\]

where the charges were assigned using the charge operator matrix, Eq.(1) with \(\beta = 1/(3\sqrt{3})\). 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

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

$$\langle \chi^0 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ v_\chi \end{pmatrix}$$

(6)

with

$$v_\eta^2 + v_\rho^2 = (246 \text{ GeV})^2$$

(7)

The hierarchical symmetry breaking produced by the Higgs triplets is the following:

$$SU(3)_C \otimes SU(3)_L \otimes U(1)_X$$

$$\langle \chi \rangle$$

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

$$\langle \eta, \rho \rangle$$

$$SU(3)_C \otimes U(1)_{em}$$

(8)

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

$$D_u \equiv \partial_\mu - ig T^b W^b_\mu - ig X \frac{X}{2} B_\mu,$$

(9)

where $g$ and $W^b_\mu$ ($b = 1, \ldots, 8$) are the coupling constant and gauge boson octet related with the $SU(3)_L$ group respectively. In a similar way, $g_X$ and $B_\mu$ 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:

$$T^b W^b_\mu = \frac{1}{2} \begin{pmatrix} W^3_\mu + \frac{W^8_\mu}{\sqrt{3}} & \sqrt{2} W^+_\mu & 2 V^{Q_1}_\mu \\
\sqrt{2} W^-_\mu & -W^3_\mu + \frac{W^8_\mu}{\sqrt{3}} & 2 U^{Q_2}_\mu \\
\sqrt{2} V^{-Q_1}_\mu & \sqrt{2} U^{-Q_2}_\mu & -\frac{2}{\sqrt{3}} W^8_\mu \end{pmatrix}$$

(10)
we define the charged and non-Hermitian gauge bosons as:

\[ W_\mu^\pm \equiv \frac{1}{\sqrt{2}} (W^1_\mu \mp iW^2_\mu) \quad (11) \]

\[ V^\pm Q_1_\mu \equiv \frac{1}{\sqrt{2}} (W^4_\mu \mp iW^5_\mu) \quad (12) \]

\[ U^\pm Q_2_\mu \equiv \frac{1}{\sqrt{2}} (W^6_\mu \mp iW^7_\mu) \quad (13) \]

the charge assignment of the gauge bosons is obtained using \([Q, \psi] = -q\psi\) for a general \(\beta\):

\[ Q(W^\pm_\mu) = \pm 1, \quad Q(V^{\pm Q_1}_\mu) = \pm \frac{1}{2} \left(1 + \beta \sqrt{3}\right), \]

\[ Q(U^{\pm Q_2}_\mu) = \mp \frac{1}{2} \left(1 - \beta \sqrt{3}\right) \quad (14) \]

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

\[ W^\pm_\mu = \frac{1}{\sqrt{2}} (W^1_\mu \mp iW^2_\mu) \quad (15) \]

\[ V^{\pm 2/3}_\mu = \frac{1}{\sqrt{2}} (W^4_\mu \mp iW^5_\mu) \quad (16) \]

\[ U^{\pm 1/3}_\mu = \frac{1}{\sqrt{2}} (W^6_\mu \mp iW^7_\mu) \quad (17) \]

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

\[ M^2_{W^\pm} = \frac{g^2}{2} (v^2_\rho + v^2_\eta), \quad M^2_{V^{\pm 2/3}} = \frac{g^2}{2} (v^2_\chi + v^2_\eta), \]

\[ M^2_{U^{\pm 1/3}} = \frac{g^2}{2} (v^2_\chi + v^2_\rho) \quad (18) \]

Notice that

\[ v_\chi \gg v_\rho, v_\eta \quad (19) \]

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 [20].

The neutral physical gauge bosons in the \((W^3, W^8, B)\) basis with \(\beta = 1/ (3\sqrt{3})\), are [28] :

\[ A_\mu = s_W W^3_\mu + c_W t_W W^8_\mu + c_W \sqrt{1 - \frac{t^2_W}{27}} B_\mu \]

\[ Z_\mu = c_W W^3_\mu - s_W t_W W^8_\mu - s_W \sqrt{1 - \frac{t^2_W}{27}} B_\mu \]

\[ Z'_\mu = \sqrt{1 - \frac{t^2_W}{27}} W^8_\mu + \frac{t_W}{\sqrt{27}} B_\mu \quad (20) \]
where \( s_W \equiv \sin(\theta_W) \), \( c_W \equiv \cos(\theta_W) \), \( t_W \equiv \tan(\theta_W) \) and \( \theta_W \) is the Weinberg angle. The masses of these neutral states are:

\[
\begin{align*}
    M_{A}^2 & = 0, \\
    M_{Z}^2 & \approx \frac{g^2}{2} \left( \frac{g^2 + \frac{28}{27}g_X^2}{g^2 + \frac{g_X^2}{27}} \right) (v^2_{\rho} + v^2_{\eta}), \\
    M_{Z'}^2 & \approx 2 \left( \frac{g^2 + \frac{g_X^2}{27}}{3} \right) v^2_{X}
\end{align*}
\]

(21)

The relation between the coupling constants for a general \( \beta \), is given by \[29\],[28]:

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

(22)

with \( \beta = 1/(3\sqrt{3}) \), \( s_W^2 \) 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 imposed by the perturbative conditions \[30\],[31] favoring a high \( SU(3)_L \) symmetry breaking scale and considerable heavier gauge bosons \[32\].

On the other hand, the charged current lagrangian that contains the new heavy leptons of the model is

\[
L_{CC} = - \frac{g}{\sqrt{2}} E_{i}^{2/3} \gamma_{\mu} (1 - \gamma_5) (U^{1/3})^{\mu} e_i \\
- \frac{g}{\sqrt{2}} E_{i}^{-2/3} \gamma_{\mu} (1 - \gamma_5) (V^{-2/3})^{\mu} \nu_i + H.c.
\]

(23)

In a similar way, the neutral currents involving the \( Z \) and new \( Z' \) bosons have the form

\[
L_{NC} = - \frac{g}{2 \cos \theta_W} \sum_f \left[ \bar{\ell} \gamma^\mu (g_V + g_A \gamma^5) f Z_\mu \\
+ \bar{\ell} \gamma^\mu (g'_V + g'_A \gamma^5) f Z'_\mu \right],
\]

(24)

where \( f \) can be leptons and quarks and \( g \) is the weak coupling constant, \( g_V \) and \( g_A \) are the known SM couplings, whereas the new couplings \( g'_V \) and \( g'_A \) are presented in the Table.
TABLE I. Vector and axial-vector couplings of fermions and massive new neutral boson ($Z'$).

| Fermion ($f$) | $g'_V$ | $g'_A$ |
|--------------|--------|--------|
| $\nu_i$     | \(3 - 2 s_W^2\) | \(3 - 2 s_W^2\) |
| $2\sqrt{27 - 28 s_W^2}$ | $2\sqrt{27 - 28 s_W^2}$ |
| $e_i$       | \(3\) | $-3 + 4 s_W'\) |
| $2\sqrt{27 - 28 s_W^2}$ | $2\sqrt{27 - 28 s_W^2}$ |
| $E_i$       | \(9 - 13 s_W^2\) | \(9 - 13 s_W^2\) |
| $3\sqrt{27 - 28 s_W^2}$ | $3\sqrt{27 - 28 s_W^2}$ |
| $d_a$       | \(9 - 10 s_W^2\) | $-3 + 2 s_W'\) |
| $6\sqrt{27 - 28 s_W^2}$ | $2\sqrt{27 - 28 s_W^2}$ |
| $u_a$       | \(9 - 4 s_W^2\) | $-3 + 4 s_W'\) |
| $6\sqrt{27 - 28 s_W^2}$ | $2\sqrt{27 - 28 s_W^2}$ |
| $D_a$       | $-9 + 11 s_W^2$ | \(3(1 - s_W')\) |
| $3\sqrt{27 - 28 s_W^2}$ | $3\sqrt{27 - 28 s_W^2}$ |
| $t$         | $-9 + 14 s_W^2$ | $-3 + 2 s_W'\) |
| $6\sqrt{27 - 28 s_W^2}$ | $2\sqrt{27 - 28 s_W^2}$ |
| $b$         | $-9 + 8 s_W^2$ | $-3 + 4 s_W'\) |
| $6\sqrt{27 - 28 s_W^2}$ | $2\sqrt{27 - 28 s_W^2}$ |
| $T^0$       | \(3(1 - s_W^2)\) | \(3(1 - s_W^2)\) |
| $2\sqrt{27 - 28 s_W^2}$ | $2\sqrt{27 - 28 s_W^2}$ |

Below the electroweak scale, the phenomenology predicted by the new model involving the $\gamma$ and the $Z$, coincides with the SM one.

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

$$-\mathcal{L}_{Yl} = G_{ab} \overline{\psi}_{aL} \rho e_{bR} + G'_{ab} \overline{\psi}_{aL} \chi E^{-2/3}_{bR} + \text{H.c.} \quad (25)$$

We do not employ the scalar $\eta$ in the above expression because this leads to couplings with right-handed neutrinos, which are not considered in the studied model. By another hand, after the symmetry breaking, the states $\chi^{-1/3}$, $\chi^{2/3}$ from (5) that are coupled to $E^{-2/3}$ will be related with Goldstone bosons whereas $\rho$ will be associated with the new charged Higgs boson, as can be observed in \[28\]

$$H^{\pm 1/3} \approx \rho^{\pm 1/3} \quad (26)$$

Using (5),(6) and (26) we finally obtain the Yukawa term that relate the exotic Higgs with
the electron and the new heavy lepton

\[-\mathcal{L}_{\psi, EH} = \frac{\sqrt{2} M_e}{v_\rho} E^{-2/3}_{\alpha L} H^{1/3} e_{bR} \tag{27}\]

In addition, from the expression (25) it is obtained that the mass of the new lepton \( M_E \) is proportional to the corresponding Yukawa coupling and \( v_\chi \).

**TABLE II. 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 \( P_R \equiv (1 + \gamma_5) / 2 \).

| Vertex | \( E^{2/3}U^{1/3}e^- \) | \( E^{2/3}V^{-2/3}e^- \) | \( E^{2/3}H^{1/3}e^- \) |
|--------|----------------|----------------|----------------|
| Coupling | \( g \sqrt{2} \gamma^\mu P_L \) | \( g \sqrt{2} \gamma^\mu P_L \) | \( \frac{\sqrt{2} M_e}{v_\rho} P_R \) |

**III. EXOTIC LEPTONS LIFETIME AND BRANCHING RATIOS**

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

\[
E^{-2/3} \rightarrow U^{+1/3} + \ell \tag{28}
\]

\[
E^{-2/3} \rightarrow V^{-2/3} + \nu_\ell \tag{29}
\]

\[
E^{-2/3} \rightarrow H^{+1/3} + \ell \tag{30}
\]

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 \( \beta = 1 / (3\sqrt{3}) \) was implemented in the LanHep package \[33\] in interface with CalcHep \[34\]. In particular, to analyze \( \Gamma \) and the BR of this exotic particle, some parameters of the model have to be fixed. For example, combining the equations (18), (19), (21) and (22) for \( \beta = 1 / (3\sqrt{3}) \) we obtain
\[
\frac{M_V}{M_{Z'}} \approx \frac{M_U}{M_{Z'}} \approx \frac{\sqrt{27 - 28s_W^2}}{6c_W}
\]  

(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 (21), if we select \(v_\chi = 5700\) GeV, we obtain \(M_{Z'} = 3000\) GeV, which is compatible with the current experimental limits for this neutral exotic boson. 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 II.

Therefore, it is clear that decay channels for the exotic lepton \(E^{-2/3}\) involving gauge bosons in association with SM leptons are forbidden for masses below 2600 GeV. In this scenario, the exotic lepton can only decay into SM leptons and an extra charged Higgs \(H^{1/3}\) as it is show in the Fig. [1]. In Fig. [2] we display the total decay width for this exotic lepton in function of its mass, for values between 500 and 5000 GeV.

On the other hand, the proper lifetime of a particle, \(\tau\), is given by

\[
\tau^{-1} = \Gamma = \frac{1}{2m_X} \int d\Pi_f |M_{m_X \rightarrow p_f}|^2
\]

(32)

where \(m_X\) is the mass of the particle, \(M\) is the matrix element for its decay into \(p_f\), and \(d\Pi_f\) is the Lorentz-invariant phase space for the decay \(^1\). In this way, for a particle to be considered as long-lived, there must be a small matrix element and/or limited phase space for the decay. In our case, the phase space is limited by the mass splitting \(M_E - M_H\) and thus, if we take \(M_E = 500\) GeV and \(M_H = 490\) GeV, the width for the exotic lepton is \(\sim 10^{-12}\) GeV and as consequence such new lepton has a lifetime \(\sim 10^{-8}\) s and could be considered as a LLP. Notice from Fig. [2] that for \(M_E > 2600\) GeV, the decay width increase due to the new open channels and the new lepton could not be considered as a LLP anymore.

**IV. PRODUCTION OF \(E^{\pm2/3}\)**

In this section, we consider the pair production of exotic leptons through the Drell-Yan process

\[
q + \bar{q} \rightarrow \gamma, Z, Z' \rightarrow E^{2/3} + E^{-2/3}
\]

(33)

\(^1\) In this expression, we consider \(\hbar = c = 1\).
FIG. 1. Branching Ratios for the two-body decays of the new heavy lepton $E^{-2/3}$ as a function of its mass for a range values from 500 to 5000 GeV.

FIG. 2. Decay width of the new heavy lepton $E^{-2/3}$ for a mass range of 500 to 5000 GeV.

for current and future colliders such as HL-LHC (High-Luminosity LHC) ($\sqrt{s} = 14$ TeV) [35], HE-LHC (High-Energy LHC) ($\sqrt{s} = 27$ TeV) [36] and FCC-hh (Future Circular Collider hh) ($\sqrt{s} = 100$ TeV) [37] in our analysis.

Let us first focus on the experimental bounds of the exotic charged lepton masses. As it was explained in the introduction, the experimental limit for heavy leptons with exotic electric charge $\pm 2e/3$ was established by the CMS collaborations to be $> 310$ GeV. Then, we choose as a start point the value $M_E = 500$ GeV. Another input in our study is the mass of the new neutral gauge boson $Z'$. From the mass relation (31), we have for $v_\chi = 5700$ GeV, $M_{Z'} = 3000$ GeV and $\Gamma_{Z'} = 90$ GeV.
FIG. 3. Production cross-section of the new lepton $E^{-2/3}$ for collision energies of 14, 27 and 100 TeV as a function of its mass for a range values from 500 to 1000 GeV.

In Fig. 3 we present our results for the $E^{-2/3}$ pair production total cross section using the above scheme. All calculations were performed using CalcHep package at leading order adopting the CTEQ6L parton distribution functions, with renormalization/factorization scales fixed at the exotic lepton mass. It can be observed from the figure that the total cross section fluctuates between 4 fb up to 200 fb for an exotic lepton with $M \sim 500$ GeV. In Table III we show the expected number of events for different collision energies and luminosities assuming an exotic lepton mass of 500 GeV.

| Energy ($\sqrt{s}$) (TeV) | Signal cross section (fb) | Integrated Luminosity (fb$^{-1}$) | Expected number of signal events |
|---------------------------|---------------------------|-----------------------------------|---------------------------------|
| 14                        | 4                         | $3 \times 10^3$                   | $1.2 \times 10^4$               |
| 27                        | 20                        | $1.5 \times 10^4$                 | $3 \times 10^5$                 |
| 100                       | 200                       | $3 \times 10^4$                   | $6 \times 10^6$                 |

From the experimental side, after it was created, the long-lived particle $E^{-2/3}$ could directly interact with the detector while traversing it. Depending on its lifetime, the LLP can deposit energy in only the innermost sub detectors, or even travel through all layers and leave signals throughout it. Thus, we must consider diverse approaches in order to identify...
LLPs such as high ionization energy loss and delayed arrival in distant detector subsystems \[10, 17\].

V. CONCLUSIONS AND PERSPECTIVES

In this work, we have presented a new version of the 3 − 3 − 1 model, defined by \( \beta = 1/(3\sqrt{3}) \). 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 the analysis about the new exotic lepton lifetime, we found that for \( M_E \) below the gauge bosons masses, the exotic lepton decay channel is \( E^{-2/3} \rightarrow H^{+1/3} + e^- \) and for a mass splitting of \( \Delta M(H^{+1/3}, E^{-2/3}) < 10 \text{ GeV} \), the decay width of the exotic lepton is \( \Gamma_E \sim 10^{-12} \text{ GeV} \) which correspond to \( \tau \sim 10^{-8} \text{s} \). As was explained in the introduction, usually a LLP has a lifetime greater than a few nanoseconds, which allow in our case to identify the exotic lepton as a long-lived particle.

From the results of the pair production cross-section, we think that our proposal to generate an exotic lepton \( E^{\pm 2/3} \) with \( M \sim 500 \text{ GeV} \), at the LHC, and in future hadron colliders is attractive given the high number of expected events shown in Table III. The difficulty resides in detect such particles given the peculiar signature they have. ATLAS and CMS have developed interesting techniques to identify these new particles such as measurements of ionization energy loss \((dE/dx)\), the observation of a stopped particle decay signature, displaced vertices, etc. [1–5].

Finally, we call the attention that another interesting possibility is to analyze the case of \( \beta = -1/(3\sqrt{3}) \). In this situation, the new lepton acquires electric charge of \( \pm 1/3 e \) and in the quark sector appears two neutral quark and one quark with charge \( 1/3 e \). The phenomenological consequences implied by such a model are appealing and will be the
subject of further study by our side.

[1] ATLAS Collaboration. Search for heavy charged long-lived particles in proton-proton collisions at $\sqrt{s} = 13$ TeV, using an ionisation measurement with the atlas detector. *Physics Letters B*, 788:96 – 116, 2019.

[2] The CMS collaboration. Search for decays of stopped exotic long-lived particles produced in proton-proton collisions at $\sqrt{s} = 13$ TeV. *Journal of High Energy Physics*, 2018(5):127, May 2018.

[3] CMS Collaboration. Search for long-lived particles with displaced vertices in multijet events in proton-proton collisions at $\sqrt{s} = 13$ TeV. *Phys. Rev. D*, 98:092011, Nov 2018.

[4] CMS Collaboration. Search for long-lived charged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV. *Phys. Rev. D*, 94:112004, Dec 2016.

[5] ATLAS Collaboration. Search for metastable heavy charged particles with large ionization energy loss in $pp$ collisions at $\sqrt{s} = 13$ TeV using the atlas experiment. *Phys. Rev. D*, 93:112015, Jun 2016.

[6] R. Barbier, C. Brat, M. Besanon, M. Chemtob, A. Deandrea, E. Dudas, P. Fayet, S. Lavignac, G. Moreau, E. Perez, and Y. Sirois. R-parity-violating supersymmetry. *Physics Reports*, 420(1):1 – 195, 2005.

[7] JoAnne L Hewett, Ben Lillie, Manuel Masip, and Thomas G Rizzo. Signatures of long-lived gluinos in split supersymmetry. *Journal of High Energy Physics*, 2004(09):070–070, oct 2004.

[8] Matthew J. Strassler and Kathryn M. Zurek. Echoes of a hidden valley at hadron colliders. *Physics Letters B*, 651(5):374 – 379, 2007.

[9] Lorenzo Basso, Alexander Belyaev, Stefano Moretti, and Claire H. Shepherd-Themistocleous. Phenomenology of the minimal $b-l$ extension of the standard model: $Z'$ and neutrinos. *Phys. Rev. D*, 80:055030, Sep 2009.

[10] Tobias Golling. Lhc searches for exotic new particles. *Progress in Particle and Nuclear Physics*, 90:156 – 200, 2016.

[11] Paul Langacker and Gary Steigman. Requiem for a fractionally charged, massive particle. *Phys. Rev. D*, 84:065040, Sep 2011.

[12] S. Davidson, B. Campbell, and D. Bailey. Limits on particles of small electric charge. *Phys.
ATLAS Collaboration. Search for magnetic monopoles and stable particles with high electric charges in 8 tev \( pp \) collisions with the atlas detector. *Phys. Rev. D*, 93:052009, Mar 2016.

ATLAS Collaboration. Search for heavy long-lived multi-charged particles in \( pp \) collisions at \( \sqrt{s} = 8 \) TeV using the atlas detector. *The European Physical Journal C*, 75(8):362, Aug 2015.

CMS Collaboration. Searches for long-lived charged particles in \( pp \) collisions at \( \sqrt{s} = 7 \) and 8 TeV. *Journal of High Energy Physics*, 2013(7):122, Jul 2013.

CMS Collaboration. Search for fractionally charged particles in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV. *Phys. Rev. D*, 87:092008, May 2013.

Juliette Alimena et al. Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider. 2019.

Paul H. Frampton, P.Q. Hung, and Marc Sher. Quarks and leptons beyond the third generation. *Physics Reports*, 330(5):263 – 348, 2000.

Alexandre Alves, E. Ramirez Barreto, D. A. Camargo, and A. G. Dias. A model with chiral quarks of electric charges 4/3 and 5/3. *Journal of High Energy Physics*, 2013(7):129, Jul 2013.

F. Pisano and V. Pleitez. \( \text{SU}(3) \otimes \text{U}(1) \) model for electroweak interactions. *Phys. Rev. D*, 46:410–417, Jul 1992.

P. H. Frampton. Chiral dilepton model and the flavor question. *Phys. Rev. Lett.*, 69:2889–2891, Nov 1992.

M. Singer, J. W. F. Valle, and J. Schechter. Canonical neutral-current predictions from the weak-electromagnetic gauge group \( \text{SU}(3) \otimes \text{U}(1) \). *Phys. Rev. D*, 22:738–743, Aug 1980.

V. Pleitez and M. D. Tonasse. Heavy charged leptons in an \( \text{SU}(3)_L \otimes \text{U}(1)_N \) model. *Phys. Rev. D*, 48:2353–2355, Sep 1993.

Le Tho Hue and Le Duc Ninh. The simplest 3-3-1 model. *Modern Physics Letters A*, 31(10):1650062, 2016.

C. A. de S. Pires and O. P. Ravinez. Electric charge quantization in a chiral bilepton gauge model. *Phys. Rev. D*, 58:035008, Jul 1998.

Paul Langacker. Grand unified theories and proton decay. *Physics Reports*, 72(4):185 – 385, 1981.

Rodolfo A. Diaz, R. Martínez, and F. Ochoa. Scalar sector of the \( \text{SU}(3)_c \otimes \text{SU}(3)_L \otimes \text{U}(1)_N \) model. *Phys. Rev. D*, 69:095009, May 2004.
[28] Rodolfo A. Diaz, R. Martinez, and F. Ochoa. \( su(3)_C \otimes su(3)_L \otimes u(1)_X \) models for \( \beta \) arbitrary and families with mirror fermions. *Phys. Rev. D*, 72:035018, Aug 2005.

[29] Daniel Ng. Electroweak theory of \( su(3) \otimes u(1) \). *Phys. Rev. D*, 49:4805–4811, May 1994.

[30] Paul H. Frampton. Strong-electroweak unification at about 4 tev. *Modern Physics Letters A*, 18(20):1377–1382, 2003.

[31] A. G. Dias, R. Martinez, and V. Pleitez. Concerning the landau pole in 3-3-1 models. *The European Physical Journal C - Particles and Fields*, 39(1):101–107, Jan 2005.

[32] S. Descotes-Genon, M. Moscati, and G. Ricciardi. Nonminimal 331 model for lepton flavor universality violation in \( b \to s\ell\ell \) decays. *Phys. Rev. D*, 98:115030, Dec 2018.

[33] A. Semenov. Lanhep a package for automatic generation of feynman rules from the lagrangian. *Computer Physics Communications*, 115(2):124 – 139, 1998. Computer Algebra in Physics Research.

[34] Alexander Belyaev, Neil D. Christensen, and Alexander Pukhov. Calchep 3.4 for collider physics within and beyond the standard model. *Computer Physics Communications*, 184(7):1729 – 1769, 2013.

[35] HL/HE-LHC Yellow Report Volume II. Technical Report ATL-PHYS-PUB-2019-006, CERN, Geneva, Feb 2019.

[36] Xabier Cid Vidal et al. Beyond the Standard Model Physics at the HL-LHC and HE-LHC. 2018.

[37] Michelangelo Mangano. Physics at the FCC-hh, a 100 TeV pp collider. *CERN Yellow Rep. Monogr.*, 3, 2017.