DECAY OF Z' BOSONS IN 3-3-1 MODEL FOR $\sqrt{s}$ UP TO 100 TeV

DECAIMIENTO DEL BOSÓN Z' DEL MODELO 3-3-1 PARA $\sqrt{s}$ DE HASTA 100 TeV

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Abstract

The branching ratios and total decay widths of the gauge boson Z' have been calculated in the version of the 3-3-1 Model with heavy leptons. We analyze the total decay width, the decay rates and determine the most likely channels to occur in order to identify the most relevant final events.

Keywords: Z' bosons, 3-3-1 model, decays.

Resumen

Los ratios de desintegración y la anchura total del bosón Z' han sido calculados en la versión del modelo 3-3-1 con leptones pesados. Se analizaron la anchura total de decaimiento y sus relaciones y determinamos los canales con mayor probabilidad de ocurrencia para identificar los eventos finales más relevantes.

Palabras clave: bosón Z', modelo 3-3-1, decaimientos.

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Introduction

The observation of the Higgs boson at the LHC [1–3], not only signified a realization of the Standard Model (SM), as it also means that is crucial to understanding physics beyond the SM. Like an exotic particle, the gauge boson Z' can exist in many extensions of the SM, particularly in the 3-3-1 model with exotic leptons, which emerge from a model based on the $\mathrm{SU}(3)_C \otimes \mathrm{SU}(3)_L \otimes \mathrm{U}(1)_N$ (3-3-1 for short) semi simple symmetry group [4–6].

In this model, the new leptons do not require new generations, as occur in most heavy-lepton models [7]. This is a chiral electroweak model whose left-handed charged heavy-leptons, which we denote by $P_a = E$, M and T, together with the associated ordinary charged leptons and their respective neutrinos, are accommodate in $\mathrm{SU}(3)_L$ triplets.

Different types of gauge exotic bosons, if they exist, may lead us into new realms of physics beyond the SM. Since the SM is indisputably incomplete, it leaves many questions open, there are several extensions. For example, if the Grand Unified Theory (GUT) contains the SM at high energies, then the gauge exotic bosons associated with GUT symmetry breaking must have extremely high masses-around the GUT scale of order $M_B \sim \mathcal{O}(10^{16})$ GeV. Supersymmetry [8–12] provides a solution to hierarchy problem through the cancellation of the quadratic divergences via fermionic and bosonic loop contributions. Moreover, the Minimal Supersymmetric extension of the SM can be derived as an effective theory of supersymmetric GUT [13–15].

Among these extensions of the SM, there are also other classes of models based on $\mathrm{SU}(3)_C \otimes \mathrm{SU}(3)_L \otimes \mathrm{U}(1)_N$ gauge symmetry (3-3-1 model) [4–6], where the anomaly cancellation mechanisms occur when the three basic fermion families are considered, and not family by family as in the SM. This mechanism is peculiar because it requires that the number of families be an integer multiple of the number of colors. This feature, combined with asymptotic freedom– which is a property of quantum chromodynamics– requires that the number of families be three. Moreover, according to these models, the Weinberg angle is restricted to the value $s_W^2 = \sin^2\theta_W < 1/4$ in the version of heavy-leptons [4]. Hence, the 3-3-1 model is one of the most interesting extensions of the SM and it is phenomenologically well motivated to be probed at the LHC and other accelerators.

In this present work, a short review of the 3-3-1 Model with heavy leptons is presented. The total decay width of the gauge boson Z' is determined, and the most important decay ratios are calculated. It is necessary to determine the mean channels in order to have some guidance in the search for a new physics, which must manifest itself in TeV's energy scales. To verify the decays of this particle, it can only be done at the High Energy LHC (HE-LHC) and the Future Circular Collider (FCC), which are expected to reach energies of up to 27 and 100 TeV. The work is organized as follows. In Sec. II, we give the relevant features of the model in the gauge sector. In Sec. III, we calculate the decay rates, and Sec. IV contains our results and conclusions.

3-3-1 Model in the Gauge Sector

The three Higgs triplets of the model are

$$\eta = \begin{pmatrix} \eta^0 \\ \eta_1^- \\ \eta_2^+ \end{pmatrix}, \quad \rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^{++} \end{pmatrix}, \chi = \begin{pmatrix} \chi^- \\ \chi^{--} \\ \chi^0 \end{pmatrix} \tag{1}$$

transforming as $(\mathbf{3}, 0)$, $(\mathbf{3}, 1)$ and $(\mathbf{3}, -1)$, respectively.

The neutral scalar fields develop the vacuum expectation values (VEVs) $\langle\eta^0\rangle \equiv v_\eta$, $\langle\rho^0\rangle \equiv v_\rho$ and $\langle\chi^0\rangle \equiv v_\chi$, with $v_\eta^2 + v_\rho^2 = v_W^2 = (246\text{ GeV})^2$. The pattern of symmetry breaking is $\mathrm{SU}(3)_L \otimes \mathrm{U}(1)_N \overset{\langle\chi\rangle}{\longmapsto} \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \overset{\langle\eta,\rho\rangle}{\longmapsto} \mathrm{U}(1)_{\mathrm{em}}$ and so, we can expect $v_\chi \gg v_\eta, v_\rho$. The η and ρ scalar triplets give masses to the ordinary fermions and gauge bosons, while the χ scalar triplet gives masses to the new fermions and new gauge bosons. The most general, gauge invariant and renormalizable Higgs potential is:

$$\begin{aligned} V(\eta,\rho,\chi) = {} & \mu_1^2\eta^\dagger\eta + \mu_2^2\rho^\dagger\rho + \mu_3^2\chi^\dagger\chi + \lambda_1\left(\eta^\dagger\eta\right)^2 + \lambda_2\left(\rho^\dagger\rho\right)^2 + \\ & \lambda_3\left(\chi^\dagger\chi\right)^2 + \left(\eta^\dagger\eta\right)\left[\lambda_4\left(\rho^\dagger\rho\right) + \lambda_5\left(\chi^\dagger\chi\right)\right] + \end{aligned}$$

$$
\lambda_6 \left(\rho^\dagger \rho\right) \left(\chi^\dagger \chi\right) + \lambda_7 \left(\rho^\dagger \eta\right) \left(\eta^\dagger \rho\right) + \lambda_8 \left(\chi^\dagger \eta\right) \left(\eta^\dagger \chi\right) +
\lambda_9 \left(\rho^\dagger \chi\right) \left(\chi^\dagger \rho\right) + \lambda_{10} \left(\eta^\dagger \rho\right) \left(\eta^\dagger \chi\right) +
\frac{1}{2} \left(f \epsilon^{ijk} \eta_i \rho_j \chi_k + \text{H. c.}\right). \tag{2}
$$

Here μ_i $(i = 1, 2, 3)$, f are constants with dimension of mass and the λ_i, $(i = 1, \ldots, 10)$ are dimensionalless constants. f and λ_3 are negative from the positivity of the scalar masses. The term proportional to λ_{10} violates lepto-barionic number, therefore it was not considered in the analysis of the Ref. [16] (another analysis of the 3-3-1 scalar sector are given in Ref. [17] and references cited therein). We can notice that this term contributes to the mass matrices of the charged scalar fields, but not to the neutral ones. However, it can be checked that in the approximation $v_\chi \gg v_\eta, v_\rho$ we can still work with the masses and eigenstates given in Ref. [16]. Here, this term is important for the decay of the lightest exotic fermion. Therefore, we will keep it in the Higgs potential (2).
As usual, symmetry breaking is implemented by shifting the scalar neutral field as $\varphi = v_\varphi + \xi_\varphi + i\zeta_\varphi$, with $\varphi = \eta^0,\ \rho^0,\ \chi^0$. Thus, the physical neutral scalar eigenstates H_1^0, H_2^0, H_3^0 and h^0 are related to the shifted fields as

$$
\begin{pmatrix} \xi_\eta \\ \xi_\rho \end{pmatrix} \approx \frac{1}{v_W} \begin{pmatrix} v_\eta & v_\rho \\ v_\rho & -v_\eta \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}, \tag{3}
$$

$$
\xi_\chi \approx H_3^0, \qquad \zeta_\chi \approx h^0, \tag{4}
$$

and in the charge scalar sector we have

$$
\eta_1^+ \approx \frac{v_\rho}{v_W} H_1^+, \qquad \rho^+ \approx \frac{v_\eta}{v_W} H_2^+, \tag{5}
$$

$$
\chi^{++} \approx \frac{v_\rho}{v_\chi} H^{++}, \tag{6}
$$

with the condition that $v_\chi \gg v_\eta, v_\rho$ [16].
In addition to the intermediate particles of SM (γ, $W^\pm$ and Z), the 3-3-1 Model predicts the existence of the neutral boson Z', two singly charged bosons $V^\pm$ and two doubly charged bosons $U^{\pm\pm}$.
The interaction between gauge and Higgs bosons results from the lagrangian:

$$
\mathcal{L}_{GH} = \sum_\varphi (\mathcal{D}_\mu \varphi)^\dagger (\mathcal{D}^\mu \varphi) \tag{7}
$$

where the covariant derivative is given by:

$$\mathcal{D}_\mu \varphi_i = \partial_\mu \varphi_i - ig\left(\vec{W}_\mu . \frac{\vec{\lambda}}{2}\right)_i^j \varphi_j - ig' N_\varphi \varphi_i B_\mu \tag{8}$$

where N_φ are the charges of the group $U(1)_N$ for the triplets $(\varphi = \eta, \rho, \chi)$, $\vec{W}_\mu$ and B_μ are the gauge fields of $SU(2)$ and $U(1)$, $\vec{\lambda}$ are the Gell-Mann matrices, and g and g' are the coupling constants for $SU(2)$ and $U(1)$, respectively [4, 16, 18].
The masses of the new bosons as a function of the Weinberg angle θ_W, of the expected values of the vacuum and the elemental charge e of the electron, are:

$$m_{Z'}^2 \approx \left(\frac{ev_\chi}{s_W}\right)^2 \frac{2(1-s_W^2)}{3(1-4s_W^2)}; \quad m_V^2 = \left(\frac{e}{s_W}\right)^2 \frac{v_\eta^2 + v_\chi^2}{2};$$
$$m_U^2 = \left(\frac{e}{s_W}\right)^2 \frac{v_\rho^2 + v_\chi^2}{2} \tag{9}$$

where:

$$s_W^2 = \sin^2\theta_W = \frac{t^2}{1+4t^2}; \quad t = \frac{g'}{g}$$

Decay of $\mathbf{Z'}$

The Z' gauge boson decays, [18, 19] in exotic leptons P^-P^+, standard leptons $\ell_i^-\ell_i^+$, neutrinos $\nu_l(\bar{\nu}_l)$, standard and exotic quarks $q\bar{q}\left(J\bar{J}\right)$, new vector gauge bosons $\times^-\times^+$, neutral Higgs bosons $H_1^0H_1^0$ $(H_2^0H_2^0)$, neutral Higgs bosons $H_1^0H_2^0$, charged Higgs bosons $H_1^-H_1^+$ $(H_2^-H_2^+)$, neutral Higgs boson, gauge boson H_1^0Z (H_2^0Z) and doubly charged Higgs bosons $H^{\pm\pm}H^{\mp\mp}$.

$$\begin{aligned}\Gamma\left(Z' \to \text{all}\right) \;=\; & \Gamma_{Z'\to P^-P^+} + \Gamma_{Z'\to \ell_i^-\ell_i^+} + \Gamma_{Z'\to \nu_i\bar{\nu}_i} + \Gamma_{Z'\to q\bar{q}\left(J\bar{J}\right)} \\ & + \Gamma_{Z'\to \times^-\times^+} + \Gamma_{Z'\to H_1^0H_1^0} + \Gamma_{Z'\to H_2^0H_2^0} + \Gamma_{Z'\to H_1^0H_2^0} \\ & + \Gamma_{Z'\to H_1^-H_1^+} + \Gamma_{Z'\to H_2^-H_2^+} + \Gamma_{Z'\to H_1^0Z} \\ & + \Gamma_{Z'\to H_2^0Z} + \Gamma_{Z'\to H^{\pm\pm}H^{\mp\mp}},\end{aligned}$$

where $i = e, \mu$ and τ, $\times^\pm = V^\pm$ or $U^{\pm\pm}$.

We have for $\Gamma_{Z'\to H^{\pm\pm}H^{\mp\mp}}$ the following expression

$$\Gamma_{Z'\to H^{\pm\pm}H^{\mp\mp}} = \frac{\alpha}{192\, m_{Z'}} \sqrt{1 - \frac{4\, m^2_{H^{\pm\pm}}}{m^2_{Z'}}} \left(m^2_{Z'} - 4\, m^2_{H^{\pm\pm}}\right) \times \left[\frac{2\,(1-7\sin^2\theta_W)\, v_\chi^2 - (1-10\sin^2\theta_W)\, v_\eta^2}{\sin\theta_W \cos\theta_W \sqrt{3\big(1-4\sin^2\theta_W\big)}\, (v_\eta^2+v_\chi^2)}\right]^2$$

Results and Conclusions

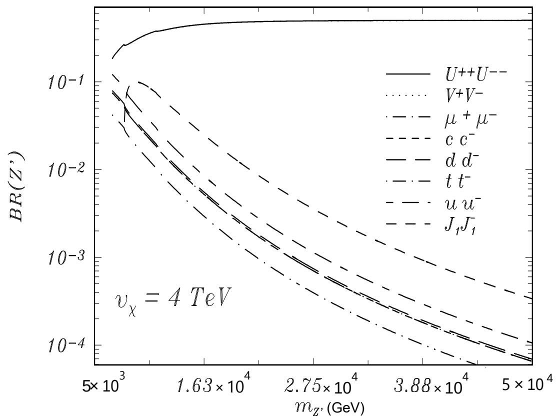
In this work, we present the widths of the Z' for $v_\chi = 4.0$, 6.0 and 17.0 TeV, accordingly with the estimates [20–22]. For the $\lambda-$parameters and the VEV, we obtain: $\lambda_1 = 1.54 \times 10^{-1}$, $\lambda_2 = 1.0$, $\lambda_3 =$ -2.5 $\times 10^{-2}$, $\lambda_4 =$ 2.14, $\lambda_5 =$-1.57, $\lambda_6 = 1.0$, $\lambda_7 =$-2.0, $\lambda_8 =$-5.0 $\times 10^{-1}$, $\lambda_9 = 0.0$, $v_\eta = 195$ GeV and $v_\rho = 149.97$ GeV. These parameters and the VEV's are used to estimate the masses of the particles, which are presented in Table 1. We put still the mass $m_{H_1^0} = 125.5$ GeV, since it is a standard particle then the mass does not depend on v_χ, which was already defined by [1, 2].

TABLE 1. Masses of the particles used in this work in GeV, $m_{H^{\pm\pm}} =$ 3227.70(4839.32, 13711.44) GeV for $v_\chi = 4.0(6.0, 17.0)$ TeV and $m_T = 2v_\chi$.

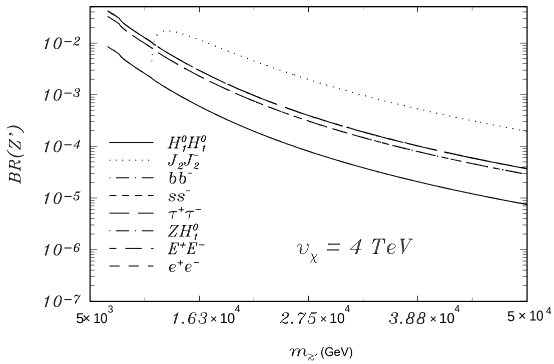
f	v_χ, m_{J_1}	m_E	m_M	$m_{H_3^0}$	m_{h^0}	$m_{H_2^0}$	m_V	m_U	$m_{Z'}$
-4000.00	4000.00	595.60	3500.02	1264.91	5756.99	4068.75	1837.72	1836.83	6830.21
-5999.00	6000.00	893.40	5250.00	1897.37	8632.75	6103.12	2754.76	2754.17	10245.31
-17008.40	17000.78	2531.30	14875.00	5376.12	24462.03	17292.96	7801.91	7801.70	29029.72

Differently from what we did in our other papers [18, 19, 23], where arbitrary parameters were taken, in this work we take for the parameters and the VEV the following representative values given above. This model, in particular, includes heavy leptons and also the condition $-f \simeq v_\chi$, which is different from other models; therefore, the phenomenology must be different. Consequently, it should be noted that the decay widths of Z', depend on the parameters shown in Table 1, which also determine the size of various decay modes.

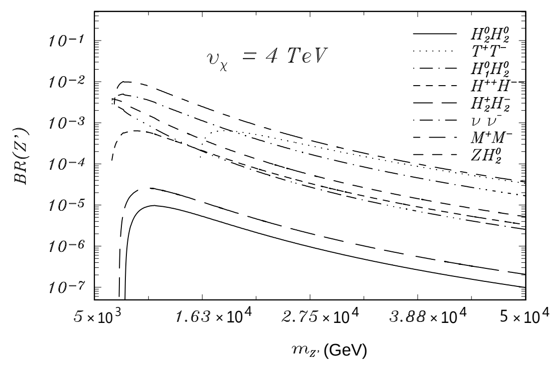
Since the Z' has greater masses than 6830.21(10245.31, 29029.72) GeV for $v_\chi = 4.0(6.0, 17.0)$ TeV, they can be considered super heavy particles. From figures 1a, 2a and 3a, it is shown that, for $v_\chi = 4(6, 17)$ TeV, the channel $Z' \to V^+V^-(U^{++}U^{--})$ can give a significant contribution to the signal in the Z' mass range from 5 to 50 TeV.



(a)

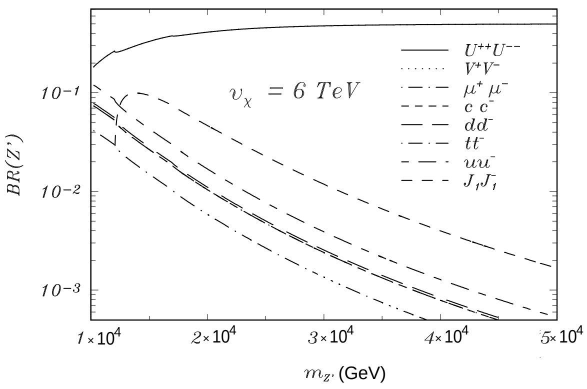


(b)

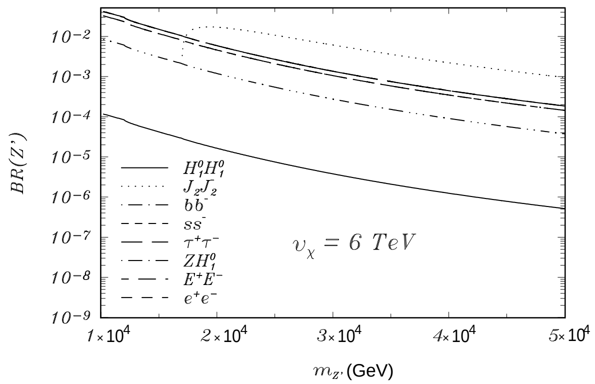


(c)

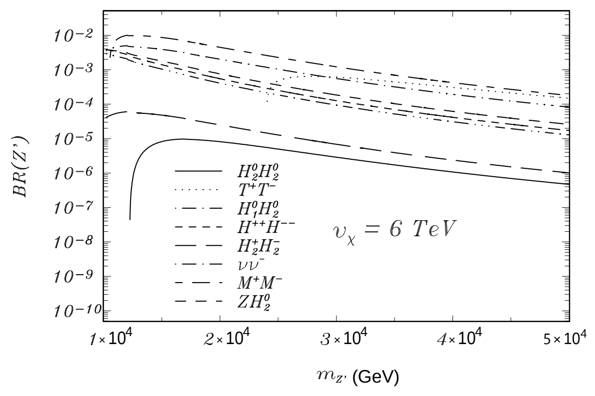
FIGURE 1. Branching ratios for the Z' decays as a function of $m_{Z'}$ for $v_\chi = 4$ TeV



(a)

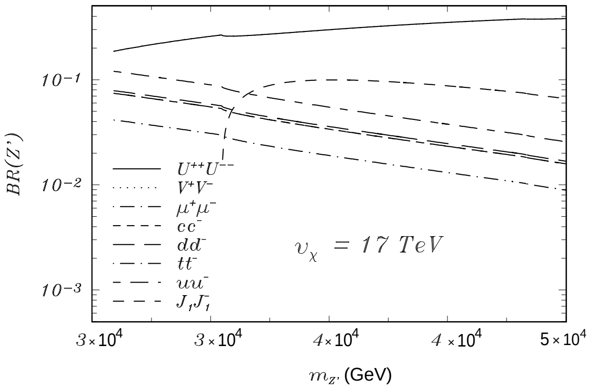


(b)

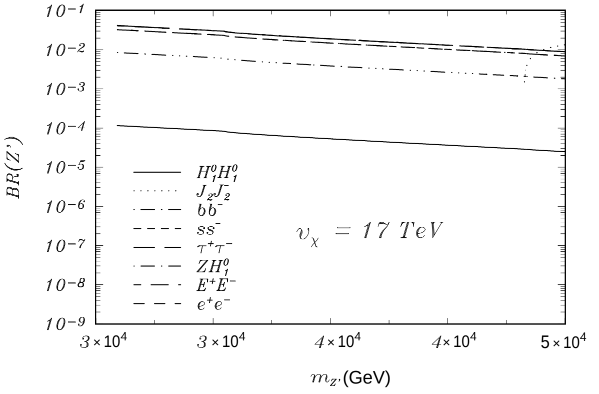


(c)

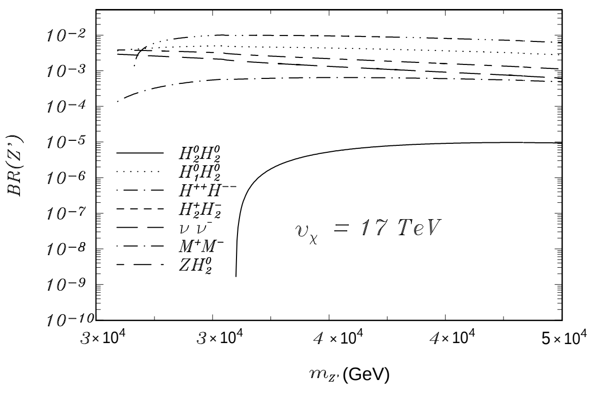
FIGURE 2. Branching ratios for the Z' decays as a function of $m_{Z'}$ for $\upsilon_\chi = 6$ TeV



(a)



(b)



(c)

FIGURE 3. Branching ratios for the Z' decays as a function of $m_{Z'}$ for $\upsilon_\chi = 17$ TeV

Using the same figures the other channels such as $Z' \rightarrow u\bar{u}, J_1\bar{J}_1, d\bar{d}, c\bar{c}, t\bar{t}, \mu^+\mu^-$ can also contribute to the detection of Z', but in small rates.

Other channels, namely:
$Z' \rightarrow J_2\bar{J}_2, b\bar{b}, s\bar{s}, \tau^+\tau^-, e^+e^-, E^+E^-, ZH_1^0, H_1^0H_1^0, ZH_2^0, H_1^0H_2^0, \nu\bar{\nu}, M^+M^-, T^+T^-, H_2^+H_2^-, H_2^0H_2^0$ can also give a very little contribution to detect the Z', as the figures 1b, 1c, 2b, 2c, 3b and 3c show, but naturally it will depend on the cross section and the luminosity.

According to the estimated data, the Z' particle has a very short lifetime and instantaneously decays into a low energy particle. Through the data from the figures 1a, 2a and 3a, the decay rate and lifetime of $Z' \rightarrow V^+V^-(U^{++}U^{--})$ (considering that the widths for these particles are similar), were determined. According to the obtained plots, the decay rate and lifetime were $4.74 \times 10^2(7.26 \times 10^2; 2.1 \times 10^3)$ GeV and $1.39 \times 10^{-27}(9.00 \times 10^{-28}; 3.13 \times 10^{-28})$ sec, for $v_\chi = 4(6;17)$ TeV. From here it can be concluded that Z' has a very large widths and very small lifetimes and it could be that this is the reason why Z' was not yet detected.

Figure 4 shows the total width of the Z' boson, indicating that at high energies the lifetime will be very small.

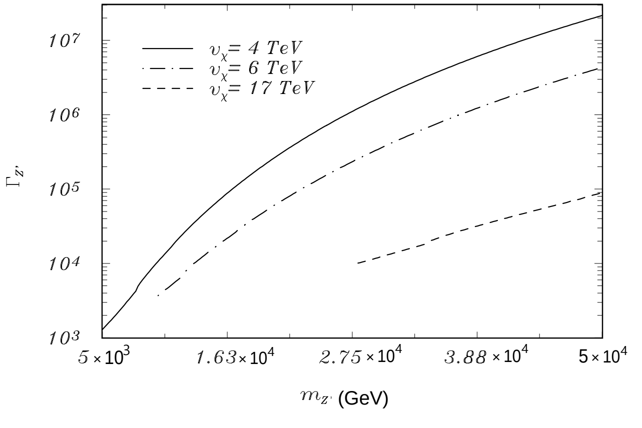


FIGURE 4. The Z' decay as a function of $m_{Z'}$ for (a) $v_\chi = 4$ TeV (solid line), (b) $v_\chi = 6$ TeV (dash-dotted line) and (c) $v_\chi = 17$ TeV (dashed line)

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