Signatures of doubly charged Higgs in the $\mathrm{SU}(3)_L \otimes \mathrm{U}(1)_N$ model at the CERN LHC

J. E. Cieza Montalvo,[1] Nelson V. Cortez, Jr.,[2] and M. D. Tonasse[3]

[1]*Instituto de Física, Universidade do Estado do Rio de Janeiro, Rua São Francisco Xavier 524, 20559-900 Rio de Janeiro, RJ, Brazil*
[2]*Rua Justino Boschetti 40, 02205-050 São Paulo, SP, Brazil*
[3]*Unidade de Registro, Campus Experimental de Registro, Universidade Estadual Paulista, Rua Tamekishi Takano 5, 11900-000, Registro, SP, Brazil*

(Received 25 October 2006; revised manuscript received 25 July 2007; published 7 December 2007)

The scalar sector of the simplest version of the 3-3-1 electroweak model is constructed with three Higgs triplets only. We show that a relation involving two of the constants of the model, two vacuum expectation values of the neutral scalars, and the mass of the doubly charged Higgs boson leads to important information concerning the signals of this scalar particle.

DOI: 10.1103/PhysRevD.76.117703 PACS numbers: 11.15.Ex, 12.60.Fr, 14.80.Cp

Although theoretical and experimental efforts were made in these last decades for the understanding of the electroweak theory, little progress was made in the scalar sector, which remains as the less understood of the standard model (SM). Extensions of the SM, particularly when the gauge group is extended, lead to an increase of the number of scalar particles. Among them extra neutral scalars can appear, as well as scalars with one and two units of electric charge. Doubly charged Higgs bosons (DCHBs) are scalar particles which appear in several extensions of the SM [1]. In some of them it can be associated with the seesaw scheme for neutrino masses [2].

DCHBs appearing in left-right symmetric models have already been looked for in accelerators without success. As a result of these searches, the scalars have a lower bound on their masses of order of 100 GeV, which also leads to imposing some bounds on the Yukawa coupling strengths [3].

The 3-3-1 models are the simplest chiral extensions of the SM [4]. In these models, the $\mathrm{SU}(2)_L$ electroweak doublets of the leptonic matter fields of the SM are extended to triplets of $\mathrm{SU}(3)_L$ containing a neutrino, the corresponding known charged lepton, and another charged lepton which can be its antiparticle. This content of leptonic matter predicts the existence of two doubly charged vectorial bosons. One of the consequences of this structure of matter content for the scalar sector is the presence of two DCHBs, among others.

In contrast to other extensions of electroweak theory, experimental data on a 3-3-1 model do not yet exist. The 3-3-1 model has an upper bound for the energy scale of the order of 4–8 TeV [5]. Therefore, the model can be ruled out for the next generation of particle accelerators. These models have several other interesting features. The most important of them is the prediction of the correct number of families of fermions through a simple relation involving the mechanism of cancellation of anomalies and the number of colors. Therefore the 3-3-1 model deserves to be seriously considered for searches in the current and next particle accelerators.

In this paper, we work with a version of the 3-3-1 model that contains one heavy lepton ($P^+ = E^+, M^+, T^+$) and one heavy quark (J_1, J_2, J_3) in each generation in triplet representation of the gauge group [6]. The minimal scalar sector of the model has three triplets (η, ρ, and χ), transforming as $(\mathbf{3}, 0)$, $(\mathbf{3}, 1)$, and $(\mathbf{3}, -1)$, respectively. The neutral components of these scalar triplets develop nonzero vacuum expectation values (VEVs), $\langle\eta^0\rangle = v_\eta$, $\langle\rho^0\rangle = v_\rho$, and $\langle\chi^0\rangle = v_\chi$, with $v_\eta^2 + v_\rho^2 = v_W^2 = (246\ \mathrm{GeV})^2$. The underlying electroweak group of symmetry is $\mathrm{SU}(3)_L \otimes \mathrm{U}(1)_N$ and it follows the pattern $\mathrm{SU}(3)_L \otimes \mathrm{U}(1)_N \overset{\langle\chi\rangle}{\mapsto} \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \overset{\langle\eta,\rho\rangle}{\mapsto} \mathrm{U}(1)_{\mathrm{em}}$ of symmetry breaking. The square masses of the neutral scalars are given by

$$m_{01}^2 \approx 4\frac{\lambda_2 v_\rho^4 - 2\lambda_1 v_\eta^4}{v_\eta^2 - v_\rho^2}, \qquad m_{02}^2 \approx \frac{v_W^2 v_\chi^2}{2v_\eta v_\rho}, \tag{1a}$$

$$m_{03}^2 \approx -4\lambda_3 v_\chi^2, \tag{1b}$$

$$m_h^2 = -\frac{f v_\chi}{v_\eta v_\rho}\left[v_W^2 + \left(\frac{v_\eta v_\rho}{v_\chi}\right)^2\right]. \tag{1c}$$

It must be noticed that Eqs. (1b) and (1c) impose $\lambda_3 < 0$ and $f < 0$, respectively. The approximations in Eqs. (1a) and (1b) are valid for $v_\eta, v_\rho \ll v_\chi$. For the charged scalars we have

$$m_{+1}^2 = \frac{v_W^2}{2v_\eta v_\rho}(f v_\chi - 2\lambda_7 v_\eta v_\rho), \tag{1d}$$

$$m_{+2}^2 = \frac{v_\eta^2 + v_\chi^2}{2v_\eta v_\chi}(f v_\rho - 2\lambda_8 v_\eta v_\chi), \tag{1e}$$

$$m_{++}^2 = \frac{v_\rho^2 + v_\chi^2}{2v_\rho v_\chi}(f v_\eta - 2\lambda_9 v_\rho v_\chi). \tag{1f}$$

In Eqs. (1) λ_i ($i = 1, \ldots, 9$) are adimensional constants and f is a constant with dimension of mass [7].

The gauge sector of the 3-3-1 model of Ref. [6] accommodates one extra Z' neutral boson, two singly charged

($V^{\pm}$), and two doubly charged ($U^{\pm\pm}$) bosons beyond the standards Z and $W^{\pm}$. The spectrum of the square masses of the extra gauge bosons is $m^2_{Z'} = (e v_\eta / s_w)^2/2(1 - s_w)$, $m^2_V = e^2(v^2_\eta + v^2_\chi)/2s^2_W$, and $m^2_U = e^2(v^2_\rho + v^2_\chi)/2s^2_W$, where $s_W = \sin\theta_W$ and θ_W is the Weinberg angle. The heavy fermions have masses of the order of v_χ.

In this paper we wish to analyze the signals of the DCHBs when we consider particular values for the adimensional parameter λ_9 in Eq. (1f) and for the vacuum expectation value v_χ. The production and signals for the DCHBs of the 3-3-1 models at CERN LHC have been investigated in Ref. [8], where no good signatures have been found for them. However, in this paper we show that these signatures are very significant for a particular set of values of the parameters which were not examined in Ref. [8]. Although the model has a reasonable number of free parameters [see Eqs. (1)] it establishes strong bounds among them. We are taking into account the values of the SM parameters, $m_Z = 91.1876$ GeV, $s^2_W = 0.23122$, and $m_W = 80.403$ GeV [3]. For the 3-3-1 model we take two parameter sets (see Table I).

We fix the general bounds of the adimensional constants as $-3 \leq \lambda_i \leq 3$ ($i = 1, \ldots, 9$) to guarantee approximately the perturbative regime. Thus, from Eq. (1f) we can see that the inequality $-3 \leq \lambda_9 \leq 0$ is satisfied from the positivity of m^2_{++} because $f \leq 0$. On the other hand, if we consider $-f \approx v_\chi \gg v_\eta, v_\rho$, we have $\lambda_4 \approx 2(\lambda_2 v^2_\rho - \lambda_1 v^2_\eta)/(v^2_\eta - v^2_\rho)$ and $\lambda_5 v^2_\eta + 2\lambda_6 v^2_\rho \approx -v_\eta v_\rho/2$ [7]. A simple analysis of Eq. (1f) also shows that the lowest values for λ_9 and f, such to produce values for m_{++} between 100 GeV and 200 GeV, for $v_\chi = 1500$ GeV and $v_\rho = 195$ GeV are $\lambda_9 = -4.50 \times 10^{-3}$, $f = -0.23$ GeV and $\lambda_9 = -1.80 \times 10^{-2}$, $f = -0.92$ GeV; that is, by decreasing the value of λ_9 we increase the value of m_{++} with negative f. On the other hand, the values for the parameters λ_5 and λ_6 lead to the constraint $v_\eta > 40.5$ GeV. In the approximation $-f \approx v_\chi$, it is appropriate to choose the parameter $-1.2 \leq \lambda_9 \leq -0.8$ (see Table II) for the mass of $m_{++} = 500$ GeV.

Figure 1 shows the possible values of f, varying the values of m_{++} for $v_\chi = (1000, 1500, 1700)$ GeV and considering $\lambda_9 = -0.8$ and $\lambda_9 = -1.2$ for $v_\eta = 195$ GeV. Considering $\lambda_9 = -0.8$ we can conclude from Fig. 1 that for $v_\chi = 1000$ GeV we have the acceptable masses up to $m_{++} \simeq 903$ GeV, for $v_\chi = 1500$ GeV we will have up to $m_{++} \simeq 1346$ GeV, and for $v_\chi = 1700$ GeV we have consequently up to $m_{++} \simeq 1525$ GeV. If we now consider $\lambda_9 = -1.2$ and $v_\chi = 1000$ GeV, also from Fig. 1 we see that the acceptable masses will be up to $m_{++} \simeq 1107$ GeV, for $v_\chi = 1500$ GeV we will have up to $m_{++} \simeq 1651$ GeV, and for $v_\chi = 1700$ GeV we have consequently up to $m_{++} \simeq 1869$ GeV. It should be noticed that the VEVs v_η and v_ρ have very little influence on m_{++}, so, for example, for $\lambda_9 = -0.5$, $v_\chi = 1500$ GeV, and $v_\eta = 50$ GeV, the acceptable mass will be $m_{++} = 1074$ GeV, for $v_\eta = 150$ GeV it will be $m_{++} = 1069.5$ GeV, and for $v_\eta = 240$ GeV it will be $m_{++} = 1061$ GeV. If we take $\lambda_9 = -1.2$, $v_\chi = 1500$ GeV, and $v_\eta = 50$ GeV, then the acceptable mass will be $m_{++} = 1664$ GeV, for $v_\eta = 150$ GeV we will have $m_{++} = 1656$ GeV, and consequently for $v_\eta = 240$ GeV we have $m_{++} = 1644$ GeV. All this happens because in Eq. (1f) the v_η and v_ρ are

TABLE I. The two parameter sets used in this work. Values of the other variables are given throughout the text.

Set	λ_9	v_η (GeV)	λ_1	λ_2	λ_6	λ_7	λ_8
1	-0.8	195	-1.2	-1	1	-2	-1
2	-1.2						

TABLE II. The parameter sets used in this work. Values of f and v_χ are in 10^3 GeV; other variables are given throughout the text.

$-f$	0.25	0.88	1.50	2.75	3.99	0.91	1.62	2.55	4.42	6.52
v_χ	1.01	1.01	1.01	1.01	1.01	1.51	1.51	1.51	1.51	1.51
$-\lambda_9$	0.40	0.80	1.20	2.00	2.80	0.50	0.80	1.20	2.00	2.90

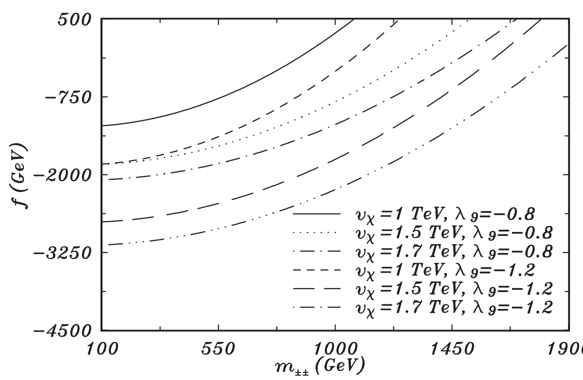

FIG. 1. Parameter f as a function of mass of DCHBs for $\lambda_9 = -0.8$ and $\lambda_9 = -1.2$.

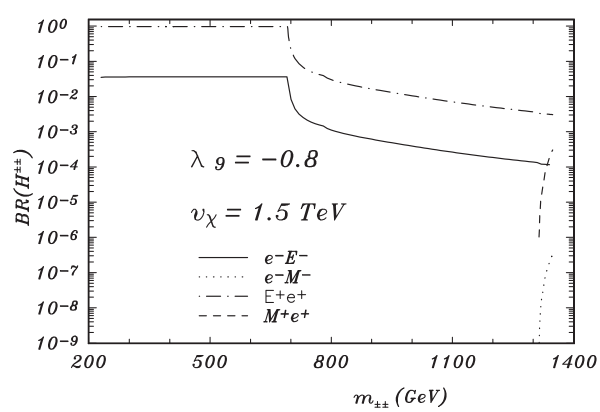

FIG. 2. Branching ratios for the DCHB decays as a function of m_{++} for $\lambda_9 = -0.8$ for the fermionic sector.

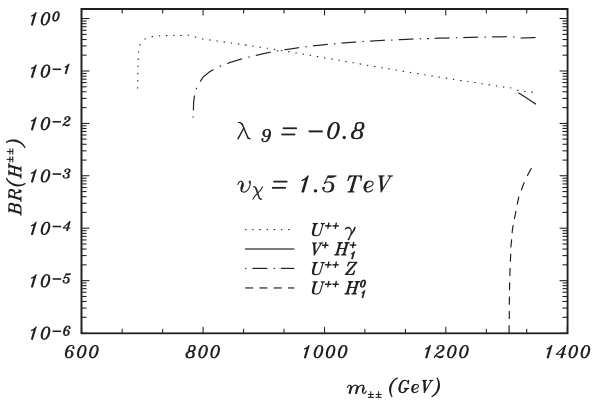

FIG. 3. Branching ratios for the DCHB decays as a function of m_{++} for $\lambda_9 = -0.8$ for the bosonic sector.

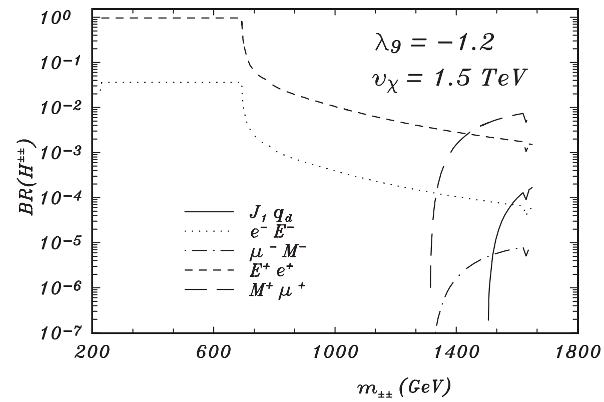

FIG. 4. Branching ratios for the DCHB decays as a function of m_{++} for $\lambda_9 = -1.2$ for the leptonic sector.

TABLE III. Values of the masses for $v_\eta = 195$ GeV and the sets of parameters given in the text. All the values in this table are given in GeV.

v_χ	m_E	m_M	m_T	m_{02}	m_{03}	m_V
1000	148.9	875	2000	1017.2	2000	467.5
1500	223.3	1312.5	3000	1525.8	3000	694.1
1700	251.3	1487.5	3400	1729.2	3400	785.2

v_χ	m_U	$m_{Z'}$	m_{J_1}	m_{J_2}	m_{J_3}
1000	464	1707.6	1000	1410	1410
1500	691.8	2561.3	1500	2115	2115
1700	783.1	2902.8	1700	2397	2397

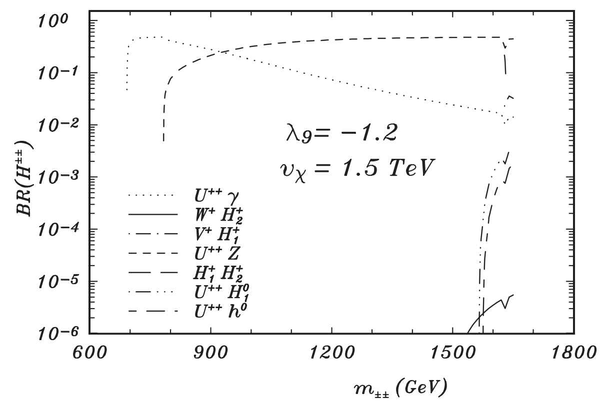

FIG. 5. Branching ratios for the DCHB decays as a function of m_{++} for $\lambda_9 = -1.2$ for the bosonic sector.

related by $v_\eta^2 + v_\rho^2 = (246\text{ GeV})^2$ and v_ρ is smaller compared with v_χ.

Figures 2 and 3, show the branching ratios for the Higgs decays, $H^{\pm\pm} \to$ all, where we have chosen for the parameters, masses which are given by Table III, and the VEV the following representative values: $\lambda_1 = -1.2$, $\lambda_2 = \lambda_3 = -\lambda_6 = \lambda_8 = -1$, $\lambda_4 = 2.98$ $\lambda_5 = -1.57$, $\lambda_7 = -2$ and $\lambda_9 = -0.8$, $v_\eta = 195$ GeV, and $v_\chi = 1500$ GeV. From Fig. 1 we see that the others particles, such as $J_{1,2,3}, T, U^{\pm\pm}, Z', H_2^\pm, H_{2,3}^0$, and h^0, do not take part in this process because their masses are larger than the mass of the DCHBs.

In Figs. 4 and 5 we exhibit the branching ratios for the same particle and for the same parameters, masses, and VEV as considered in Fig. 2, except that we consider $\lambda_9 = -1.2$. Considering this value, and from Fig. 1, we see that the acceptable mass for m_{++} is larger, and consequently, more particles will take part in this process, as is clearly seen from Figs. 4 and 5.

Figure 6 shows the cross section for the process $pp \to H^{++}H^{--}$, which is given in Ref. [8], for the same values of λ's, v_η, and particles masses given in Table III considered before, except for $\lambda_9 = -0.8$. It is to notice that the masses of m_h, m_{+1} and m_{+2} depend on the parameter f and therefore they cannot be fixed by any value of v_χ.

We have chosen $v_\chi = 1700$ GeV as the maximum value because it is constrained by the mass of $m_{Z'} = (0.5\text{–}3)$ TeV, which is proportional to v_χ [4]. In our numerical analysis we have not considered the contribution of gluon-gluon fusion because it is, at least, 4 orders of magnitude smaller than that of the Drell-Yan process. To make this work more complete, we introduce the width of $H^{\pm\pm} \to Uh^0$, that is, $\Gamma = (AK/32\pi m_{\pm\pm})(m_{\pm\pm}^4/2m_U^2 - m_{\pm\pm}^2 m_h^2/m_U^2 - m_{\pm\pm}^2 + m_U^2/2 + m_h^4/2m_U^2 - m_h^2/2)$ where $A^2 = (1+\xi_+)(1-\xi_-)$ with $\xi_\pm = (m_U \pm m_h/m_{++})^2$ and $K = iev_\rho/2s_W\sqrt{2(v_\rho^2 + v_\chi^2)}$. Considering that the expected integrated luminosity for the LHC will be of order of $3 \times 10^5\ \text{pb}^{-1}/\text{yr}$, then the statistics give a total of $\simeq 3.9 \times 10^6$ events per year for the Drell-Yan process, if we take the mass of the Higgs boson to be $m_{++} = 500$ GeV, $v_\chi = 1500$ GeV, $m_{+2} = 1163.7$ GeV, $m_h = 2229.9$ GeV, and $\lambda_9 = -0.8$. Considering that the signal for $H^{\pm\pm}$ production will be e^-P^- and e^+P^+ and taking into account that the branching ratios for both particles would be $\text{BR}(H^{--} \to e^-P^-) = 3.6\%$ and $\text{BR}(H^{++} \to e^+P^+) = 96.4\%$ (see Fig. 2), we would have

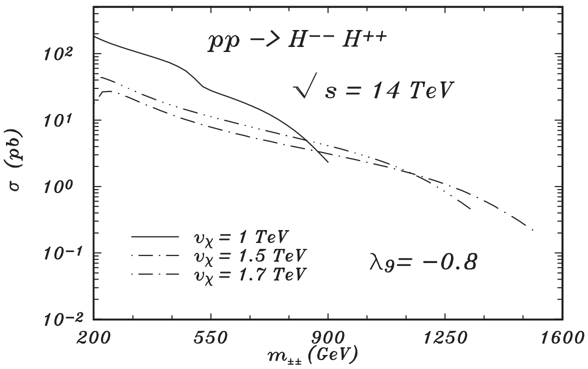

FIG. 6. Total cross section for the process $pp \to H^{--}H^{++}$ as a function of m_{++} for $\lambda_9 = -0.8$.

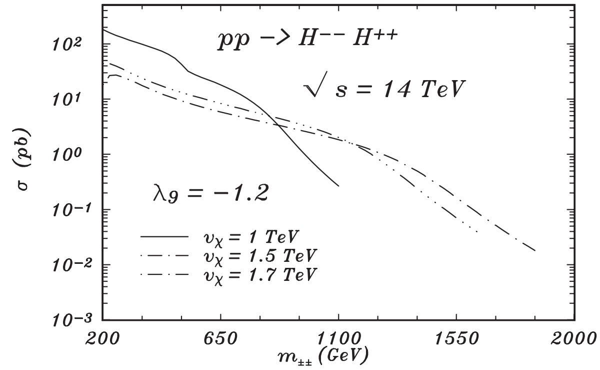

FIG. 7. Total cross section for the process $pp \to H^{--}H^{++}$ as a function of m_{++} for $\lambda_9 = -1.2$.

TABLE IV. Numbers of events per year for DCHBs with respect to their masses and branching ratios. The total number of events per year for $m_{++} = 500$ GeV is 3.9×10^6 and for $m_{++} = 700$ GeV is 2.2×10^6. BR($H^{\pm\pm}$) stands for BR($H^{\pm\pm} \to e^\pm E^\pm$).

BR(H^{--})	BR(H^{++})	$m^2_{H^{++}}$ (GeV)	Events/yr
3.6%	96.4%	500	5.5×10^4
0.8%	22%	700	1.6×10^3

approximately 1.3×10^5 events per year for the Drell-Yan process (see Table IV). Taking now $m_{++} = 700$ GeV, $v_\chi = 1500$ GeV, $m_{+2} = 1223.6$ GeV, $m_h = 2052.2$ GeV, and $\lambda_9 = -0.8$, we then have a total of $\simeq 2.2 \times 10^6$. We then have a total of $\simeq 2.2 \times 10^6$ events per year for the Drell-Yan process. Considering now the same signal as above, whose branching ratios are equal to BR($H^{--} \to e^- P^-$) = 0.8% and BR($H^{++} \to e^+ P^+$) = 22%, we will have a total of approximately 3.9×10^3 events for the Drell-Yan process (see Table IV).

In Fig. 7 we show the cross section for the process $pp \to H^{++}H^{--}$ for the same parameter values of λ's, $v_\eta = 195$ GeV and other particle masses considered above except for $\lambda_9 = -1.2$, which gives for $m_{++} = 500$ GeV, $v_\chi = 1500$ GeV the values of $m_{+2} = 901.6$ GeV and $m_h = 2802.7$ GeV; in this case the statistics will be equal as in Fig. 6, because the cross sections are nearly equal and the branching ratios, where the same particles participate for the mass $m_{+2} = 500(700)$ GeV, are also equal. So, from this analysis we conclude that varying the value of λ_9 from $-3 < \lambda_9 < 0$, where in our case we choose $\lambda_9 = -0.8$ and $\lambda_9 = -1.2$, and choosing the same signals, we obtain results nearly equal. Then we can conclude that we will have a very striking signal; the DCHB will deposit 4 times more ionization energy than the characteristic single-charged particle; that is, if we see this signal, we will not only be seeing the DCHB but also the heavy leptons. The main background for this signal, $pp \to H^{--}H^{++} \to e^- P^-(e^+ P^+)$, could come from the process $pp \to ZZ$ and another small background from $pp \to W^- W^+ Z$. All these backgrounds can be eliminated (see Ref. [9]).

In summary, through this work, we have shown that in the context of the 3-3-1 model the signatures for DCHBs can be significant at the LHC. Our study indicates the possibility of obtaining a clear signal of these new particles with a satisfactory number of events.

[1] V. Barger *et al.*, Phys. Rev. D **26**, 218 (1982); R. N. Mohapatra and J. D. Vergados, Phys. Rev. Lett. **47**, 1713 (1981); G. B. Gelmini and M. Roncadelli, Phys. Lett. **99B**, 411 (1981).
[2] B. Dutta and R. N. Mohapatra, Phys. Rev. D **59**, 015018 (1998).
[3] W.-M. Yau *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006).
[4] F. Pisano and V. Pleitez, Phys. Rev. D **46**, 410 (1992); P. H. Frampton, Phys. Rev. Lett. **69**, 2889 (1992); R. Foot, O. F. Hernandez, F. Pisano, and V. Pleitez, Phys. Rev. D **47**, 4158 (1993).
[5] A. G. Dias, Phys. Rev. D **71**, 015009 (2005); A. G. Dias, R. Martinez, and V. Pleitez, Eur. Phys. J. C **39**, 101 (2005).
[6] V. Pleitez and M. D. Tonasse, Phys. Rev. D **48**, 2353 (1993).
[7] M. D. Tonasse, Phys. Lett. B **381**, 191 (1996).
[8] J. E. Cieza Montalvo, N. V. Cortez, J. Sa Borges, and M. D. Tonasse, Nucl. Phys. **B756**, 1 (2006).
[9] J. E. Cieza Montalvo and P. P. Queiróz Filho, Phys. Rev. D **66**, 055003 (2002).