Testing models with a nonminimal Higgs sector through the decay $t \rightarrow q + WZ$

J. L. Díaz Cruz and D. A. López Falcón

Instituto de Física, BUAP, Apartado Postal J-48, 72570 Puebla, Puebla, México

(Received 9 November 1999; published 8 February 2000)

We study the contribution of the charged Higgs boson to the rare decay of the top quark $t \rightarrow q + WZ$ ($q = d, s, b$) in models with Higgs sectors that include doublets and triplets. Higgs doublets are needed to couple a charged Higgs boson with quarks, whereas the Higgs triplets are required to generate the nonstandard vertex HWZ at the tree level. It is found that within a model that respects the custodial $SU(2)_c$ symmetry and avoids flavor-changing neutral current (FCNC) by imposing discrete symmetries, the decay mode $t \rightarrow b + WZ$ can reach a branching ratio (BR) of order 10^{-2}, whereas the decay modes $t \rightarrow (d,s) + WZ$, can reach a similar BR in models where FCNC are suppressed by flavor symmetries.

INTRODUCTION

The mass of the top quark, which is larger than any other fermion mass in the standard model (SM) and almost as large as its scale of electroweak symmetry breaking (EWSB), cannot be explained within the SM [1]. This has originated speculations about the possible relationship between the top quark and the nature of the mechanism responsible for EWSB. Several models have been proposed, where such large mass can be accommodated or plays a significant role. In the supersymmetric (SUSY) extensions of the SM [2], the large value of the top quark mass can drive the radiative breaking of the electroweak symmetry; furthermore within the context of SUSY grand unified theories (GUT's) the fermions of the third family can be accommodated in schemes where their masses arise from a single Yukawa term [3]. On the other hand, in some top-condensate (TC) models [4] it is postulated that new strong interactions bind the heavy top quark into a composite Higgs scenario.

From a more phenomenological point of view, it is also intriguing to notice that the top quark decay seems to be dominated by the SM mode ($t \rightarrow bW$), not only within the SM but also in theories beyond it, which makes the top quark decay width almost insensitive to the presence of new physics; unless the scale of new physics is lighter than the top quark mass itself, such that new states can appear in its decays. This is the case, for instance, in the so-called two Higgs doublet model III (THDM–III) [5], where the flavor changing mode $t \rightarrow c + h$ can be important for a light Higgs boson (h), or in SUSY models with light stop quark and neutralinos, in whose case the decay $t \rightarrow \tilde{t} + \tilde{\chi}^0$ can also be relevant. But in general, the rare decays of the top quark have undetectable branching ratios (BR's); for instance, the flavor-changing neutral current (FCNC) rare decays $t \rightarrow cV$ ($V = \gamma, Z, g$) have a very small BR in the SM, of the order 10^{-11} [6], and are out of reach of present and future colliders. A similar result is obtained in several extensions of the SM; for instance in the two Higgs doublet models (THDM), minimal SUSY extensions of the SM (MSSM) and left-right models, to mention some cases [7].

The rare decay $t \rightarrow qWZ$ ($q = b, s, d$), may be above the threshold for the production of a real WZ state, provided that $m_t \geq m_q + m_W + m_Z$. The possibilities to satisfy this relation depend on the final state q and the precise value of the top quark mass, which according to the Particle Data Group [8] is $m_t = 173.8 \pm 5.2$ GeV. For the case when $q = b$, the top quark mass must satisfy $m_t \geq 176.1 \pm 0.5$ GeV, where the uncertainty on the right-hand side is mostly due to the ambiguity in the bottom quark mass, thus $t \rightarrow bWZ$ can occur on-shell only if m_t takes its upper allowed value (at 1σ). However, if $q = d$ or s, the decays $t \rightarrow qWZ$ can occur even when m_t takes its central value.

The value of BR($t \rightarrow bWZ$) predicted in SM is 5.4×10^{-7} [9], which is beyond the sensitivity of Tevatron Run II or even CERN Large Hadron Collider (LHC); thus its observation would truly imply the presence of new physics. For $q = d, s$ the SM result is even smaller, since the amplitude is supressed by the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements V_{tq}. On the other hand, the decay mode $t \rightarrow qWZ$ can proceed through an intermediate charged Higgs boson that couples to both tq and WZ currents, and thus can be used to test the couplings of Higgs sectors beyond the SM [10].

The construction of extensions the Higgs sector of the SM must satisfy the constraints imposed by the successful phenomenological relation $\rho \equiv m_W^2 / m_Z^2 \cos \theta_w = 1$, which also measures the ratio between the neutral and charged current couplings strength. At tree level this relation is satisfied naturally in models that include only Higgs doublets, but in more general scenarios, there could be tree-level contributions to $\rho - 1$. Since the vertex HWZ arises at tree level only for Higgs bosons lying in representations higher than the usual SM Higgs doublet, there could be violations of the constraints imposed by the ρ parameter. However, tree level deviations of the electroweak ρ parameter from unity can be avoided by arranging the nondoublet fields and the vacuum expectation values (VEV's) of their neutral members, so that a custodial $SU(2)_c$ symmetry is maintained [11]. On the other hand, a generic coupling of the charged Higgs boson with fermions may be associated with the possible appearence of FCNC in the Higgs-Yukawa sector. FCNC are automatically absent in the minimal SM with one Higgs doublet, however in multiscalar models large FCNC can appear if each quark flavor couples to more than one Higgs doublet

[12]. FCNC can be avoided either by impossing some *ad hoc* discrete symmetry to the Yukawa Lagrangian, i.e., by coupling each type of fermion only to one Higgs doublet; or by using flavor symmetries. The former case is used in the so-called two Higgs doublet models I and II, whereas the last one is associated with model III, here FCNC's are only suppressed by some ansatz for the Yukawa matrices, for instance the Li-Sher one: $(Y_q)_{ij} = \sqrt{m_i m_j}/m_W$, whose phenomenology was studied in [13,14].

In this Rapid Communication we shall consider, in a very general setting, the contribution of a charged Higgs boson to the decay $t \rightarrow qWZ$, and present the results in terms of two factors that parametrize the doublet-triplet mixing and the nonminimal Yukawa couplings, respectively. Then, we discuss the values that these parameters can take for specific extensions of the SM, when the constraints from both the custodial symmetry and FCNC are satisfied, and present the predicted values for BR $(t \rightarrow qWZ)$.

THE DECAY $t \rightarrow qWZ$

We are interested in studying the contribution of charged Higgs boson to the rare decay of the top quark $t \rightarrow qWZ$ ($q = d, s, b$), within the context of models with extended Higgs sector that include additional Higgs doublets and triplets. The charged Higgs will be assumed to be the lightest charged mass eigenstate that results from the general mixing of doublets and triplets in the charged sector.[1]

Higgs doublets are needed in order to couple the charged Higgs with quarks; the vertex $tqH^{\pm}$ will be written as follows:

$$\frac{ig}{2\sqrt{2}m_W} \eta_{tq} \cos \alpha [(m_t \cot \beta + m_q \tan \beta)$$

$$+ (m_t \cot \beta - m_q \tan \beta)\gamma_5], \quad (1)$$

which can be considered as a modification of the result obtained for the Yukawa sector of the general THDM, where $\cos \alpha$ is included to account for the doublet-triplet mixing; $\tan \beta$ is the ratio of the VEV's of the two scalar doublets. The charged Higgs coupling to the quarks is also determined by the parameters η_{tq}, which is equal to the CKM mixing matrix only for model-II, i.e., $\eta_{tq}^{II} = V_{tq}$; however, in the general case (THDM-III), one can have $\eta_{tq}^{III} > V_{tq}$ [5].

On the other hand, we require a representation higher than the doublet, in order to obtain a sizeable coupling HWZ at tree level, which is written as

$$-\frac{igm_W}{\cos \theta_w} \sin \alpha g_{\mu\nu}. \quad (2)$$

In order to evaluate the decay $t \rightarrow qWZ$, we shall write a general amplitude to describe the contribution of the inter-

mediate charged Higgs, neglecting the SM contribution, which is a good approximation since the corresponding BR is very suppressed. To calculate the amplitude one also needs to take into account the finite width of the intermediate charged Higgs boson with momentum p_H, mass m_H, and width Γ_H, for this we shall use the relativistic Breit-Wigner form of the propagator in the unitary gauge. Then, the amplitude can be written in general as

$$\mathcal{M} = A[\bar{u}(p_q)(a + b\gamma_5)u(p_t)] \left(\frac{-i}{p_H^2 - \hat{m}_H^2} \right) [g_{\mu\nu} \epsilon_W^{*\mu} \epsilon_Z^{*\nu}], \quad (3)$$

where $\hat{m}_H \equiv m_H + (i/2)\Gamma_H$; a, b, and A are constants related to the parameters α and η_{tq} previously mentioned

$$a = m_t \cot \beta + m_q \tan \beta,$$

$$b = m_t \cot \beta - m_q \tan \beta, \quad (4)$$

$$A = \frac{g^2}{2\sqrt{2} \cos \theta_w} \eta_{tq} \cos \alpha \sin \alpha.$$

To calculate the partial decay width of this decay, we shall perform a numerical integration of the expression for the squared amplitude, over the standard three-body phase space, namely

$$\Gamma(t \rightarrow qWZ) = \frac{1}{(2\pi)^3} \frac{1}{32m_t^3} \int |\bar{\mathcal{M}}|^2 ds\, dt. \quad (5)$$

$|\bar{\mathcal{M}}|^2$ denotes the squared amplitude, averaged over initial spins and summed over final polarizations, it has the form

$$|\bar{\mathcal{M}}|^2 = \frac{|A|^2[(a^2+b^2)(m_t^2+m_q^2-s)+(a^2-b^2)2m_t m_q]}{(s-m_H^2)^2 + m_H^2\Gamma_H^2}$$

$$\times \left[2 + \left(\frac{s-m_W^2-m_Z^2}{2m_W m_Z} \right)^2 \right]. \quad (6)$$

The integration limits are

$$(m_W + m_Z)^2 \leq s \leq (m_t - m_q)^2, \quad (7)$$

and

$$t^- \leq t \leq t^+, \quad (8)$$

where

$$t^{\pm} = m_t^2 + m_Z^2 - \frac{1}{2s}[(s+m_t^2-m_q^2)(s+m_Z^2-m_W^2)$$

$$\mp \lambda^{1/2}(s,m_t^2,m_q^2)\lambda^{1/2}(s,m_Z^2,m_W^2)], \quad (9)$$

and $\lambda(x,y,z) = (x+y-z)^2 - 4xy$.

---

[1]This is justified by our explicit analysis of the Higgs potential for several models with Higgs doublets and triplets, which will be presented elsewhere.
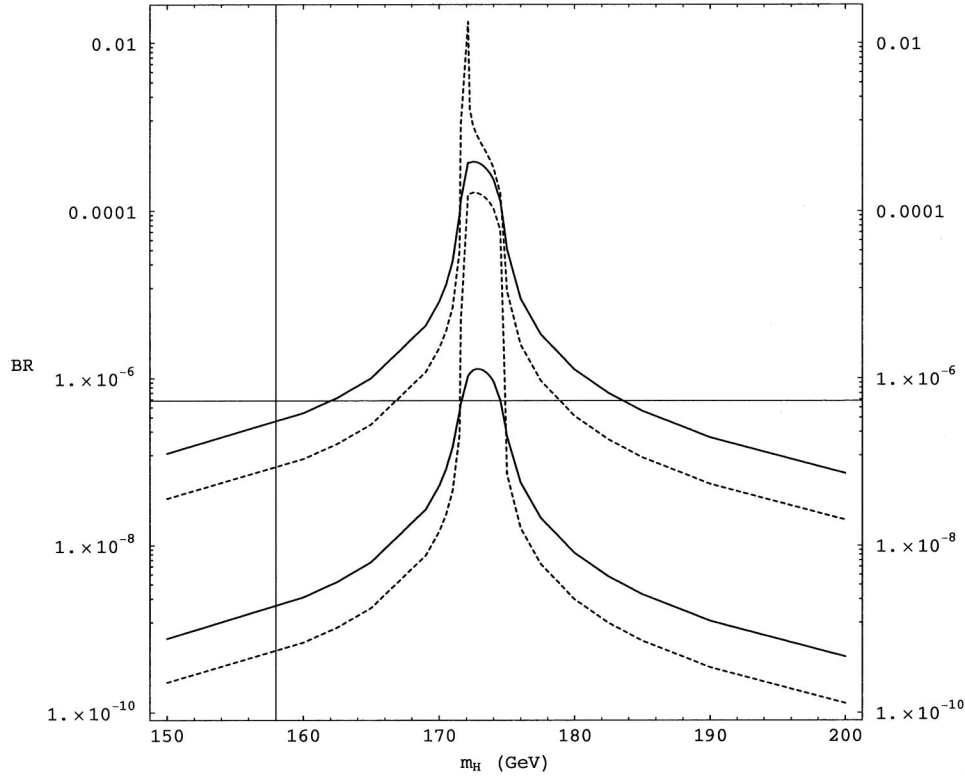
FIG. 1. Branching ratio for the decay $t \to bWZ$, as a function of m_H for $\cos\alpha\sin\alpha = \frac{1}{2}$ (upper curves) and $\sin\alpha = 0.04$ (lower curves); and for $\tan\beta = m_t/m_b$ (solid curves) and $\tan\beta = 2$ (dashed curves); it is also assumed that $\eta_{tq} = V_{tq}$. The line indicate the SM prediction.

The branching ratio for this decay is obtained as the ratio of Eq. (5) to the total width of the top quark, which will include the modes $t \to qW$ and $t \to qH$; the expressions for the widths are

$$\Gamma(t \to qW^+) = \frac{G_F m_t^3}{8\pi\sqrt{2}} V_{tq} \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{m_W^2}{m_t^2}\right)$$
$$\times \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right], \qquad (10)$$

and

$$\Gamma(t \to qH^+) = \frac{g^2}{128\pi m_W^2 m_t}\, \eta_{tq}\cos^2\alpha [a^2[(m_t+m_q)^2 - m_H^2]$$

$$+ b^2[(m_t - m_q)^2 - m_H^2]]\lambda^{1/2}\left(1, \frac{m_q^2}{m_t^2}, \frac{m_H^2}{m_t^2}\right). \qquad (11)$$

On the other hand, the Higgs width will include the fermionic decays into $H \to c\bar{s}$ and $H \to \tau\nu_\tau$; adding them we obtain

$$\Gamma(H^+ \to f\bar{f}') = \frac{g^2 m_H}{32\pi m_W^2}\cos^2\alpha [3\,\eta_{cs}(m_c^2\cot^2\beta + m_s^2\tan^2\beta)$$

$$+ m_\tau^2\tan^2\beta] \qquad (12)$$

as well as the bosonic mode $H \to WZ$

$$\Gamma(H^+ \to W^+ Z) = \frac{g^2 m_H}{64\pi}\sin^2\alpha \left[1 + \left(\frac{m_W^2}{m_H^2}\right)^2 + \left(\frac{m_Z^2}{m_H^2}\right)^2 - 2\frac{m_W^2}{m_H^2}\right.$$

$$\left. -2\frac{m_Z^2}{m_H^2} + 10\frac{m_W^2}{m_H^2}\frac{m_Z^2}{m_H^2}\right]$$

$$\times \lambda^{1/2}\left(\frac{m_H^2}{m_W^2}, \frac{1}{\cos^2\theta_w}, 1\right). \qquad (13)$$

RESULTS AND CONCLUSIONS

In order to present the results for the mode $t \to bWZ$, i.e., $q = b$, we shall assume that the top quark mass takes its upper allowed value, and will consider a Yukawa sector similar to the model-II, in whose case the factor η_{tb} is equal to the CKM matrix element $V_{tb}(\simeq 1)$; the results are shown for two values of $\tan\beta$ (2, and m_t/m_b) which are acceptable for GUT-Yukawa unification. For the factor $\cos\alpha\sin\alpha$, which is part of the constant A, we shall consider first the value $\frac{1}{2}$, which corresponds to the maximum value that can be expected to arise in an scenario where the custodial symmetry is respected, for instance in a model with one Higgs doublet and two Higgs triplets of hypercharges 0 and 2, respectively, where one can align the VEV's to respect the custodial sym-
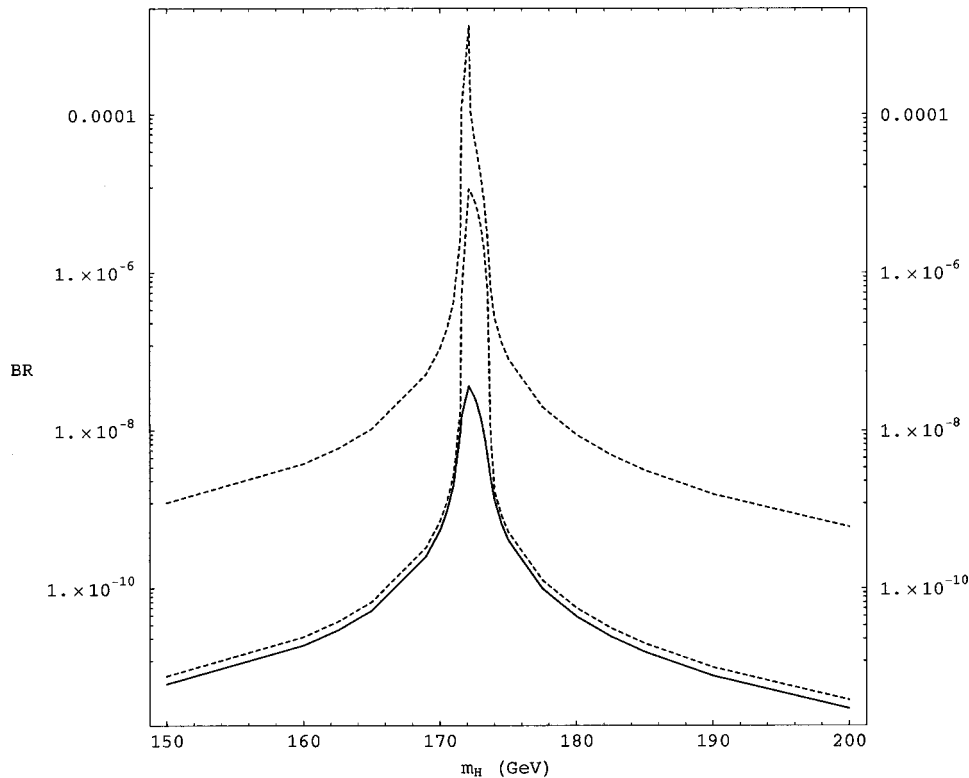
FIG. 2. Branching ratio for the decay $t \to sWZ$, as a function of m_H for $\cos \alpha \sin \alpha = \frac{1}{2}$ (upper dashed and solid curve) and $\sin \alpha = 0.04$ (middle curve); and for $\tan \beta = m_t/m_b$ (solid curve) and $\tan \beta = 2$ (dashed curves); taking also $\eta_{tq} = 1$.

metry and obtaining $\rho = 1$ [11].[2] On the other hand, to consider a model without a custodial symmetry, we take the value $\sin \alpha = 0.04$, which corresponds to the maximum value that is allowed by the experimental error in the ρ parameter [15]. With all these considerations, we shown in Fig. 1 our results for the BR of the decay $t \to bWZ$; we notice that it can reach a maximum value of order 1.78×10^{-2}.

For the decays into the light quarks, still working within the framework of model II, we obtain a very suppressed result, where we are taking now the central value for the top quark mass, namely, for $t \to sWZ$ we get a maximum value for the BR of order 1.95×10^{-6} for $\sin \alpha \cos \alpha = \frac{1}{2}$ and $\tan \beta = 2$; for $t \to dWZ$ we get results even smaller and thus uninteresting. On the other hand, if we consider a model with a Yukawa sector of the type THDM-III, the coupling of the charged Higgs with the quarks is not determined by the CKM mixing matrix, then the couplings $t\bar{d}H^-$ and $t\bar{s}H^-$ may not be suppressed. Although in model III there can be dangerous FCNC, it happens that such effects have not been tested by top quark decays, and thus can give large and detectable effects [14]. For the parameter α we take the same values of the previous case, assuming also $\eta_{ts} = \eta_{td}$ we get a maximum value for the BR of order 1.31×10^{-3} for both $t \to (d,s) + WZ$, as shown in Fig. 2.

We conclude from our results that there exist a region of parameters where it is possible to obtain a large BR for the decay $t \to bWZ$. Moreover, for $m_H = 162$ to $m_H = 182$ GeV, $\cos \alpha \sin \alpha = \frac{1}{2}$, and $\tan \beta = m_t/m_b$ we obtain a BR larger than the one predicted by the SM. Furthermore, the maximum value for the BR, of order 10^{-2}, seems factible to be detected at the future CERN LHC, where about 10^8 top quark pairs could be produced, and one would have 10^6 events of interest with only one top quark decaying rarely, if we also include the decays of the W and Z into leptonic modes, to allow a clear signal, one would end with about 1.3×10^4 events, which is interesting enough to perform a future detailed study of backgrounds; however this is beyond the scope of present work. On the other hand, we observe from Fig. 2 that even within models without a custodial symmetry with $\sin \alpha = 0.04$, it is possible to get BR for the decay $t \to sWZ$ larger than the SM result, or the result obtained within models where $\sin \alpha \cos \alpha = \frac{1}{2}$ depending on the value of $\tan \beta$; in some cases it can reach BR of order 1.31×10^{-3}.

In conclusion, we find that the decay $t \to qWZ$ is sensitive to the contribution of new physics, in particular from a charged Higgs boson, which makes this mode an interesting arena for testing physics beyond the SM.

---

[2]Although our framework is similar to the one of Ref. [11], in our case we are allowing full mixing between all the scalar multiplets of the model, which allows us to have charged and neutral Higgs bosons that couple simultaneously to both fermion and gauge boson pairs.

[1] W. Hollik, in *Radiative Corrections: Application of Quantum Field Theory to Phenomenology: Proceedings*, edited by Joan Solà (World Scientific, Singapore, 1999).

[2] H.P. Nilles, Phys. Rep. **110**, 1 (1984); H. Haber and G.L. Kane, *ibid.* **117**, 75 (1985).

[3] H. Arason *et al.*, Phys. Rev. Lett. **67**, 2933 (1991); A. Giveon, L.J. Hall, and U. Sarid, Phys. Lett. B **271**, 138 (1991).

[4] W.A. Bardeen, C.T. Hill, and M. Lindner, Phys. Rev. D **41**, 1647 (1990).

[5] T. Cheng and M. Sher, Phys. Rev. D **35**, 3484 (1987); M. Sher and Y. Yuan, *ibid.* **44**, 1461 (1991); J.L. Díaz Cruz and G. Lopez Castro, Phys. Lett. B **301**, 405 (1993).

[6] J.L. Díaz Cruz *et al.*, Phys. Rev. D **41**, 891 (1990).

[7] See for instance: G. Eilam, J.L. Hewett, and A. Soni, Phys. Rev. D **44**, 1473 (1991).

[8] Particle Data Group, C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998).

[9] R. Decker, M. Nowakowski, and A. Pilaftsis, Z. Phys. C **57**, 339 (1993); G. Mahlon and S. Parke, Phys. Lett. B **347**, 394 (1995); E. Jenkins, Phys. Rev. D **56**, 458 (1997); G. Mahlon, ''Theoretical Expectations in Radiative Top Decays,'' talk given at the Physics at Run II: Workshop on Top Physics, Batavia, IL, 1998.

[10] T.G. Rizzo, Phys. Rev. D **41**, 1504 (1990); K. Cheung, R.J.N. Phillips, and A. Pilaftsis, *ibid.* **51**, 4731 (1995); D. A. López-Falcón and J. L. Díaz Cruz, in Particles and Fields, edited by Juan Carlos D'Olivo, Gabriel López Castro, and Myriam Mondragón, AIP Conf. Proc. 490 (AIP, Melville, NY, 1999), p. 374.

[11] For a detailed discussion of models with Higgs triplets, see J.F. Gunion, R. Vega, and J. Wudka, Phys. Rev. D **42**, 1673 (1990).

[12] J. F. Gunion, H. E. Haber, G. Kane, and S. Dawson. *The Higgs Hunter's Guide* (Addison-Wesley, Reading, MA, 1990), Chap. 4, p. 203.

[13] J.L. Díaz Cruz, J.J. Godina, and G. López Castro, Phys. Rev. D **51**, 5263 (1995); D. Atwood, L. Reina, and A. Soni, *ibid.* **55**, 3156 (1997).

[14] J.L. Díaz Cruz *et al.*, Phys. Rev. D **60**, 115014 (1999).

[15] T.G. Rizzo, Mod. Phys. Lett. A **6**, 1961 (1991).