

Top quark rare three-body decays in the littlest Higgs model with T parity

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In the littlest Higgs model with T -parity (LHT), the mirror quarks have flavor structures and will contribute to the top quark flavor changing neutral current. In this work, we perform an extensive investigation of the top quark rare three-body decays $t \rightarrow cVV$, ($V = \gamma, Z, g$) and $t \rightarrow cf\bar{f}$, ($f = b, \tau, \mu, e$) at one-loop level. Our results show that the branching ratios of $t \rightarrow cgg$ and $t \rightarrow cb\bar{b}$ could reach $\mathcal{O}(10^{-3})$ in the favorite parameter space of the littlest Higgs model with T -parity, which implies that these decays may be detectable at the LHC or ILC, while for the other decays, their rates are too small to be observable at the present or future colliders.

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I. INTRODUCTION

Top quark physics is among the central physical topics at the Tevatron and will continue to be so at the Large Hadron Collider (LHC) in the next few years. Compared to other lighter SM fermions, the top quark is the only fermion with mass at the electroweak symmetry breaking scale, so it is widely speculated that the properties of the top quark are sensitive to new physics. Among various top quark processes at present and future colliders, the flavor changing neutral current (FCNC) processes are often utilized to probe new physics (NP) because in the SM, the FCNC processes are highly suppressed [1], while in NP models, there may be no such suppression. Therefore, searching for top FCNC at colliders can serve as an effective way to hunt for NP.

The two-body FCNC decays of top quark such as $t \rightarrow cg, c\gamma, cZ, cH$ received much attention in the past. In the SM, the rates of these decays are less than 10^{-11} [2], which is far below the reaches of the LHC [3,4] and the International Linear Collider (ILC) [5], while in many NP models these decays may be enhanced to detectable levels [6]. By now, the two-body processes $t \rightarrow cg, c\gamma, cZ, cH$ have been extensively investigated in the minimal supersymmetric standard model (MSSM) [7], the left-right supersymmetric models [8], the supersymmetric model with R-parity violation [9], the two-Higgs doublet model (2HDM) [10], the topcolor-assisted technicolor model (TC2) [11], as well as models with extra singlet quarks [12]. Beside this, some three-body FCNC decays of the top quark, such as $t \rightarrow cVV$, ($V = \gamma, Z, g$) and $t \rightarrow cf\bar{f}$, ($f = b, \tau, \mu, e$), were also studied in the framework of the SM [13–16], 2HDM [15–17], MSSM [16,18–20], TC2 [21–24], or in a model-independent way [25].

The aim of this work is to perform a comprehensive analysis of the FCNC top quark decays $t \rightarrow cVV$, ($V = \gamma, Z, g$) and $t \rightarrow cf\bar{f}$, ($f = b, \tau, \mu, e$) in the little Higgs

model with T -parity (LHT) [26]. In the LHT model, the related two-body decays $t \rightarrow cg, c\gamma, cZ, cH$ and the three-body decays $t \rightarrow cl\bar{l}$, ($l = b, \tau, \mu, e$) have been studied in [27,28,28] respectively, and these studies show that, compared with the SM, the rates of these decays can be greatly enhanced. So taking the completeness and the phenomenon of higher-order dominance into consideration [14], it is necessary to consider all the three-body decays, which will be done in this work.

This paper is organized as follows. In Sec. II a brief review of the LHT is given. In Sec. III we present the details of our calculation of the decays $t \rightarrow cVV$ and $t \rightarrow cf\bar{f}$, and show some numerical results. Finally, we give a short conclusion in Sec. IV.

II. A BRIEF REVIEW OF THE LHT

One of the major motivations for the little Higgs model [29,30] is to resolve the little hierarchy problem [31], in which the quadratic divergence of the Higgs mass term at one-loop level was canceled by the new diagrams with additional gauge bosons and a heavy top-quark partner. It was soon recognized that the scale of the new particles should be in the multi-TeV range in order to satisfy the constraints from electroweak precision measurements, which in turn reintroduces the little hierarchy problem [32]. This problem has been eased in the LHT model where a new \mathbb{Z}_2 discrete symmetry called “ T -parity” is introduced, and in this way, all dangerous tree-level contribution to the precision measurements are forbidden [26].

Just like the little Higgs model, in the LHT model the assumed global symmetry $SU(5)$ is spontaneously broken down to $SO(5)$ at a scale $f \sim \mathcal{O}(TeV)$, and the embedded $[SU(2) \otimes U(1)]^2$ gauge symmetry is simultaneously broken at f to the diagonal subgroup $SU(2)_L \otimes U(1)_Y$, which is identified with the SM gauge group. From the $SU(5)/SO(5)$ breaking, there arise 14 Goldstone bosons which are described by the “pion” matrix Π , given explicitly by

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$$\Pi = \begin{pmatrix} -\frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} & -\frac{\omega^+}{\sqrt{2}} & -i\frac{\pi^+}{\sqrt{2}} & -i\phi^{++} & -i\frac{\phi^+}{\sqrt{2}} \\ -\frac{\omega^-}{\sqrt{2}} & \frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} & \frac{v+h+i\pi^0}{2} & -i\frac{\phi^+}{\sqrt{2}} & \frac{-i\phi^0+\phi^P}{\sqrt{2}} \\ i\frac{\pi^-}{\sqrt{2}} & \frac{v+h-i\pi^0}{2} & \sqrt{4/5}\eta & -i\frac{\pi^+}{\sqrt{2}} & \frac{v+h+i\pi^0}{2} \\ i\phi^{--} & i\frac{\phi^-}{\sqrt{2}} & i\frac{\pi^-}{\sqrt{2}} & -\frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} & -\frac{\omega^-}{\sqrt{2}} \\ i\frac{\phi^-}{\sqrt{2}} & \frac{i\phi^0+\phi^P}{\sqrt{2}} & \frac{v+h-i\pi^0}{2} & -\frac{\omega^+}{\sqrt{2}} & \frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} \end{pmatrix}. \quad (1)$$

Among the Goldstone bosons, the fields ω^0 , ω^\pm and η are eaten by the new heavy gauge bosons Z_H , W_H^\pm and A_H so that the gauge bosons acquire following masses:

$$\begin{aligned} M_{W_H^\pm} &= M_{Z_H} = gf \left(1 - \frac{v^2}{8f^2}\right), \\ M_{A_H} &= \frac{g'}{\sqrt{5}} f \left(1 - \frac{5v^2}{8f^2}\right). \end{aligned} \quad (2)$$

Likewise, the fields π^0 and π^\pm are eaten by the SM gauge bosons Z and W^\pm , but one minor difference from the SM is the masses of these bosons, up to $\mathcal{O}(v^2/f^2)$, are given by

$$M_{W_L} = \frac{gv}{2} \left(1 - \frac{v^2}{12f^2}\right), \quad M_{Z_L} = \frac{gv}{2\cos\theta_W} \left(1 - \frac{5v^2}{12f^2}\right), \quad (3)$$

where g and g' are the SM $SU(2)$ and $U(1)$ gauge couplings, respectively, and $v = 246$ GeV.

In the framework of the LHT model, all the SM particles are assigned to be T -parity even, and the other particles, such as the new gauge bosons, are assigned to T -parity odd. In particular, in order to implement the T -parity symmetry, each SM fermion must be accompanied by one heavy fermion called the mirror fermion. In the following, we denote the mirror fermions by u_H^i and d_H^i with $i = 1, 2, 3$ being the generation index. At the order of $\mathcal{O}(v^2/f^2)$, their masses are given by

$$m_{d_H^i}^i = \sqrt{2}\kappa_i f, \quad m_{u_H^i}^i = m_{d_H^i}^i \left(1 - \frac{v^2}{8f^2}\right), \quad (4)$$

where the Yukawa couplings κ_i generally depend on the fermion species i .

Since the T -parity is conserved in the LHT model, the fermion pairs interacting with the T -odd gauge boson must

contain one SM fermion and one mirror fermion. In this case, due to the misalignment of the mass matrices for the SM fermions and for the mirror fermions, new gauge bosons can mediate flavor changing interactions. As pointed out in [33,34], these interactions can be described by two correlated CKM-like unitary mixing matrices V_{H_u} and V_{H_d} satisfying $V_{H_u}^\dagger V_{H_d} = V_{\text{CKM}}$ with the subscripts u and d denoting which type of the SM fermion is involved in the interaction. The details of the Feynman rules for such interactions were given in Ref. [34], and in order to clarify our results, we list some of them:

$$\bar{u}_H^i \eta u^j: -\frac{ig'}{10m_{A_H}} (m_{H_i}^u P_L - m_u^j P_R) (V_{H_u})_{ij}, \quad (5)$$

$$\bar{u}_H^i \omega^0 u^j: \frac{ig'}{2m_{Z_H}} (m_{H_i}^u P_L - m_u^j P_R) (V_{H_u})_{ij}, \quad (6)$$

$$\bar{d}_H^i \omega^- u^j: \frac{g}{\sqrt{2}m_{W_H}} (m_{H_i}^d P_L - m_u^j P_R) (V_{H_u})_{ij}, \quad (7)$$

$$\bar{u}_H^i A_H u^j: -\frac{ig'}{10} (V_{H_u})_{ij} \gamma^\mu P_L, \quad (8)$$

$$\bar{u}_H^i Z_H u^j: -\frac{ig}{2} (V_{H_u})_{ij} \gamma^\mu P_L, \quad (9)$$

$$\bar{d}_H^i W_H^{-\mu} u^j: \frac{ig}{\sqrt{2}} (V_{H_u})_{ij} \gamma^\mu P_L. \quad (10)$$

The unitary matrix V_{H_d} is usually parametrized with three angles θ_{12}^d , θ_{23}^d , θ_{13}^d and three phases δ_{12}^d , δ_{23}^d , δ_{13}^d [35]:

$$V_{H_d} = \begin{pmatrix} c_{12}^d c_{13}^d & s_{12}^d c_{13}^d e^{-i\delta_{12}^d} & s_{13}^d e^{-i\delta_{13}^d} \\ -s_{12}^d c_{23}^d e^{i\delta_{12}^d} - c_{12}^d s_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{23}^d)} & c_{12}^d c_{23}^d - s_{12}^d s_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{12}^d - \delta_{23}^d)} & s_{23}^d c_{13}^d e^{-i\delta_{23}^d} \\ s_{12}^d s_{23}^d e^{i(\delta_{12}^d + \delta_{23}^d)} - c_{12}^d c_{23}^d s_{13}^d e^{i\delta_{13}^d} & -c_{12}^d s_{23}^d e^{i\delta_{23}^d} - s_{12}^d c_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{12}^d)} & c_{23}^d c_{13}^d \end{pmatrix} \quad (11)$$

and with the relation $V_{H_u}^\dagger V_{H_d} = V_{\text{CKM}}$, one can determine the expression of V_{H_u} .

III. CALCULATIONS

A. The loop-level FC couplings $t\bar{c}V(V = \gamma, Z, g)$ in the LHT model

As introduced above, in the LHT model new contributions to the FCNC top quark coupling $t\bar{c}V$ come from the new gauge interactions mediated by (A_H, Z_H, W_H^\pm) , which are shown in Fig. 1. Since we use Feynman gauge in our calculation, the Goldstone bosons η, ω^0 and ω^\pm also appear in the diagrams. The heavy scalar triplet Φ , in principle, may also contribute to the FCNC coupling, but since such a contribution is suppressed by the factor v^2/f^2 , we neglect it hereafter. It should be noted that the rules in (1)–(10) imply that the form factors of the loop-induced $t\bar{c}V$ interaction, F , must take the following form

$$F \propto \sum_{i=1}^3 (V_{H_u}^\dagger)_{ii} f(m_{H_i}) (V_{H_u})_{ic} \quad (12)$$

where $f(m_{H_i})$ is a universal function for three-generation mirror quarks, but its value depends on the mass of i th-generation mirror quark, m_{H_i} . Obviously, for the degeneracy of the three-generation mirror quarks, F vanishes exactly due to the unitarity of V_{H_u} , while for the degeneracy of the first two generations as discussed below, the factor behaviors like $(V_{H_u}^\dagger)_{i3}(f(m_{H3}) - f(m_H))(V_{H_u})_{3c}$ with m_H being the common mass of the first two generations. In the case of very heavy third-generation mirror quarks, $f(m_{H3})$

vanish, that is its effect decouples, then F is proportional to $(V_{H_u}^\dagger)_{i3}f(m_H)(V_{H_u})_{3c}$, which are independent of m_{H3} .

The Feynman diagrams for the top quark decays $t \rightarrow cV$ and $t \rightarrow cf\bar{f}$ are shown in Fig. 2 with the black square denoting the loop-induced $t\bar{c}V$ vertex. One important difference of the effective $t\bar{c}V$ vertices in Figs. 2(a), 2(d), and 2(e) from those in Figs. 2(b) and 2(c) is for the former cases, both top and charm quarks are on-shell, while for the latter case, either top or charm quark is off-shell. In order to simplify our calculation, we adopt the calculation method introduced in [19] which uses a universal form of the effective $t\bar{c}V$ vertexes, but is valid for all the cases. In Appendix we give the analytical expressions of the effective vertices $t\bar{c}V$ and use the codes LoopTools [36] to get the numerical results of the relevant loop functions. To secure the correctness of our results, we recalculated the two-body decay $t \rightarrow cV$ and find our results agree with those in Ref. [27].

B. Amplitude for $t \rightarrow cV$ in the LHT model

Since the expressions of the amplitudes for $t \rightarrow cgg, cg\gamma, cgZ, c\gamma\gamma$ are quite similar, we only list the result for $t \rightarrow cgg$, which is given by

$$\mathcal{M}(t \rightarrow cgg) = \mathcal{M}_a^g + \mathcal{M}_b^g + \mathcal{M}_c^g \quad (13)$$

with

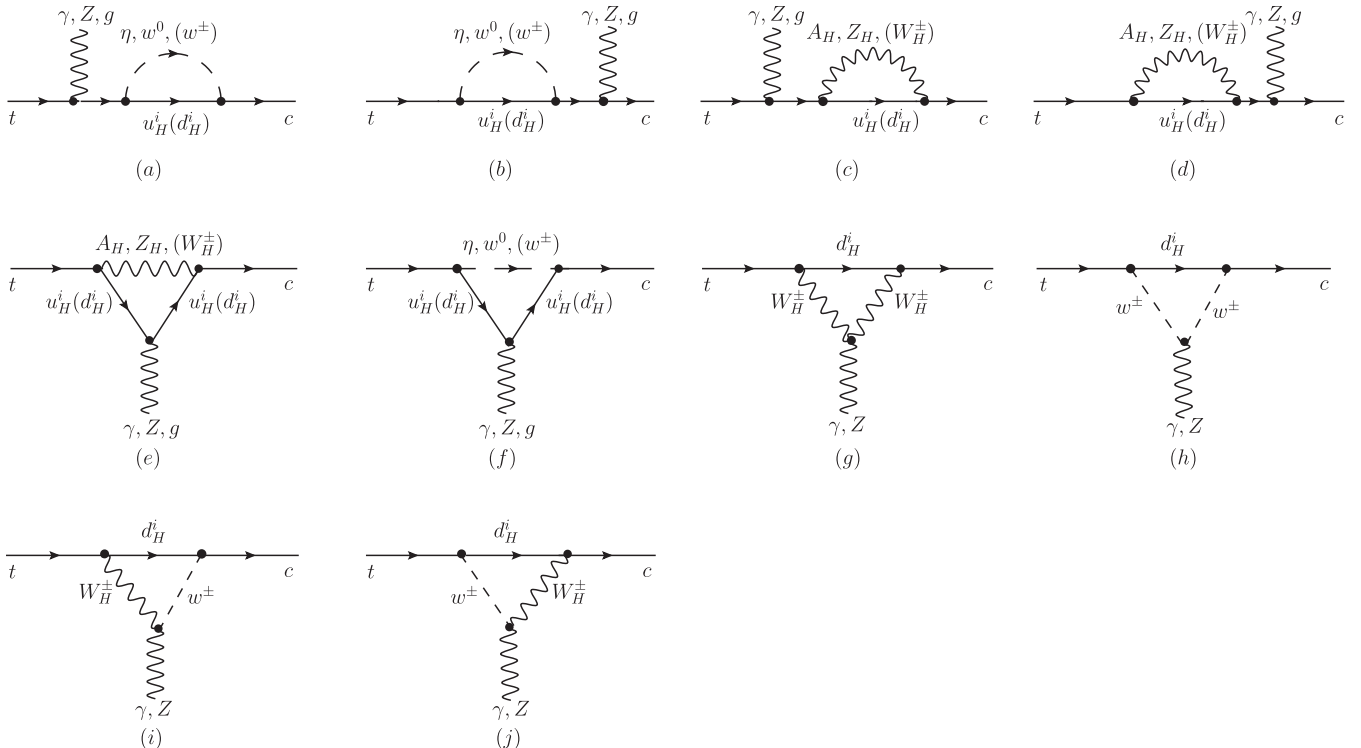
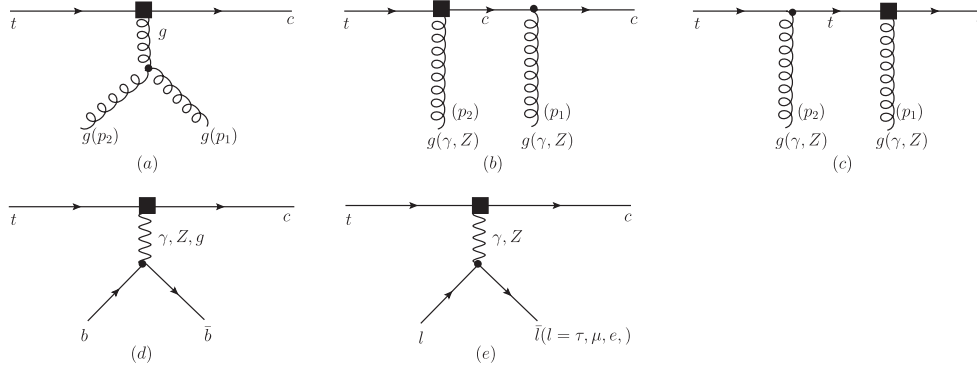


FIG. 1. The Feynman diagrams of the LHT model contributing to the FCNC couplings $t\bar{c}V(V = \gamma, Z, g)$.


 FIG. 2. The Feynman diagrams for the decays $t \rightarrow cV V$ and $t \rightarrow c f \bar{f}$, ($f = b, e, \mu, \tau$) in the LHT.

$$\begin{aligned} \mathcal{M}_a^g &= -i g_s f^{abc} G(p_t - p_c, 0) \bar{u}_c^i(p_c) \Gamma_{tcg}^{\mu c j i} \\ &\times [(p_1 - p_2)_\mu \varepsilon^a(p_1) \cdot \varepsilon^b(p_2) \\ &+ 2 p_2 \cdot \varepsilon^a(p_1) \varepsilon_\mu^b(p_2) \\ &- 2 p_1 \cdot \varepsilon^b(p_2) \varepsilon_\mu^a(p_1)] u_t^j(p_t) \end{aligned} \quad (14)$$

$$\begin{aligned} \mathcal{M}_b^g &= g_s T^{aki} G(p_t - p_2, m_c) \bar{u}_c^i(p_c) \varepsilon_1^a(p_1) \\ &\times (\not{p}_t - \not{p}_2 + m_c) \Gamma_{tcg}^{\mu b j k} (p_t - p_2, p_c) \varepsilon_\mu^b(p_2) u_t^j(p_t) \end{aligned} \quad (15)$$

$$\begin{aligned} \mathcal{M}_c^g &= g_s T^{bjk} G(p_t - p_2, m_t) \bar{u}_c^i(p_c) \Gamma_{tcg}^{\mu a k i} (p_c, p_t - p_1) \\ &\times \varepsilon_\mu^a(p_1) (\not{p}_t - \not{p}_2 + m_t) \varepsilon_2^b(p_2) u_t^j(p_t). \end{aligned} \quad (16)$$

In above expressions, $P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$ are the left and right chirality projectors, p_t is the top quark momentum, p_c, p_1, p_2 are the momentum of the charm quark and gluons, respectively, ε s are wave functions of the gluons, and $G(p, m)$ is defined as $\frac{1}{p^2 - m^2}$. In actual calculation, we compute the amplitudes numerically by using the method of Ref. [19], instead by calculating the amplitude square analytically. This greatly simplifies our calculations.

C. Numerical results for $t \rightarrow cV V$ and $t \rightarrow c f \bar{f}$ in the LHT model

In this work, we take the SM parameters as $m_t = 172.0$ GeV, $m_c = 1.27$ GeV, $m_e = 0.00051$ GeV, $m_\mu = 0.106$ GeV, $m_\tau = 1.777$ GeV, $m_b = 4.2$ GeV, $m_Z = 91.2$ GeV, $\sin^2 \theta_W = 0.231$, $\alpha_e = 1/128.8$, $\alpha_s(m_t) = 0.107$ [37]. For the parameters in the LHT model, the breaking scale f , the three-generation mirror quark masses m_{H_i} ($i = 1, 2, 3$) and six mixing parameters (θ_{ij}^d and δ_{ij}^d with $i, j = 1, 2, 3$ and $i \neq j$) in Eq. (11) are involved. The breaking scale f determines the new gauge boson masses, and it has been proven that, as long as $f \geq 500$ GeV, the LHT model can be consistent with the precision electro-weak data [38]. So we set $f = 500$ GeV, 1000 GeV as two representative cases. The matrix elements of V_{H_d} have been severely constrained by the FCNC processes in K, B and D

meson systems [34,39]. To simplify our discussion, we consider two scenarios which can easily escape the constraints [27,28,40]:

$$\text{Case I: } V_{H_d} = \mathbf{I}, \quad V_{H_u} = V_{\text{CKM}}^\dagger \quad (17)$$

$$\begin{aligned} \text{Case II: } s_{23}^d &= 1/\sqrt{2}, \quad s_{12}^d = s_{13}^d = 0, \\ \delta_{12}^d &= \delta_{23}^d = \delta_{13}^d = 0. \end{aligned} \quad (18)$$

As for the mirror quark masses, it has been shown that the experimental bounds on four-fermi interactions require $m_{H_i} \leq 4.8 f^2 / \text{TeV}$ [38]. In our discussion, we take this bound. We also assume a common mass for the first two-generation up-type mirror quarks, i.e. $m_{H_1} = m_{H_2} = 500$ GeV and let the third-generation quark mass m_{H_3} to vary from 600 GeV to 1200 GeV for $f = 500$ GeV and from 600 GeV to 4800 GeV for $f = 1000$ GeV. To make our predictions more realistic, we apply some kinematic cuts as in Ref. [41], that is, we require the energy of each decay product larger than 15 GeV in the top quark rest frame.

In Fig. 3 we show the dependence of the rates for $t \rightarrow c g g, c g Z, c g \gamma, c \gamma \gamma$ on m_{H_3} . This figure indicates that the dependence is quite strong, i.e. more than 1 order of magnitude change when m_{H_3} varies from 600 GeV to 1200 GeV in Figs. 3(a) and 3(c) and from 600 GeV to 4800 GeV in Figs. 3(b) and 3(d). The reason is, as explained in Eq. (12) and below, the cancellation between the third-generation mirror quark contribution and the first two-generation mirror quark contribution is alleviated with the increase of m_{H_3} . This figure also indicates that the rates $t \rightarrow c g g, c g Z, c g \gamma, c \gamma \gamma$ are also sensitive to the parametrization scenarios of V_{H_d} when one compares the results in Figs. 3(a) and 3(b) with those in Figs. 3(c) and 3(d). This character can be easily understood from the expression in Eq. (12). From Fig. 3, one may conclude that in the LHT model, the rate for the decay $t \rightarrow c g g$ is much larger than the others, reaching 10^{-3} in optimal cases, while the rates of the decays $t \rightarrow c g Z, c g \gamma, c \gamma \gamma$ are all below 10^{-5} .

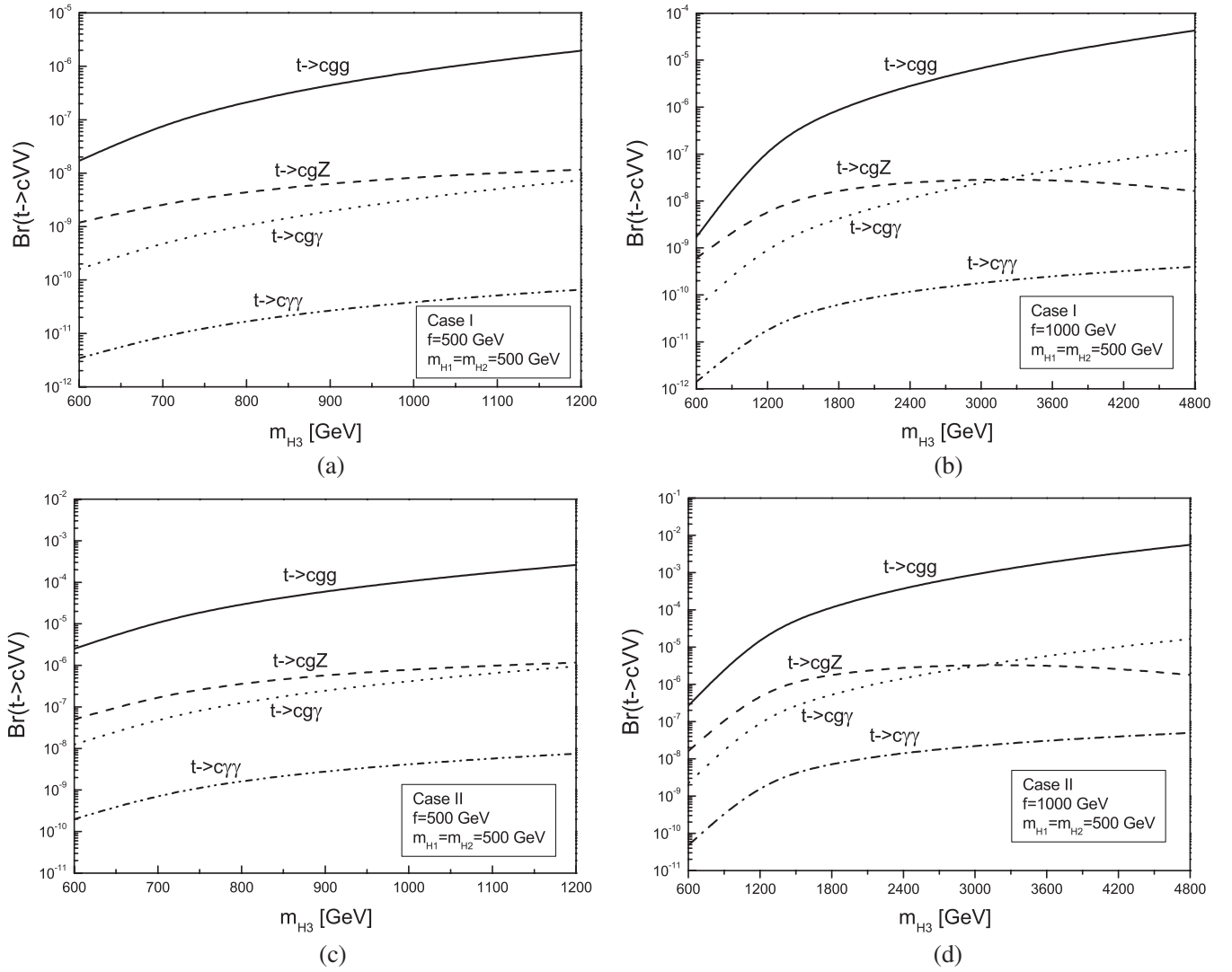


FIG. 3. The rates for $t \rightarrow cgg, cgZ, cg\gamma, c\gamma\gamma$ as a function of m_{H_3} for different values of f and V_{H_d} . We take a common mass for the first two-generation mirror quarks, i.e. $m_{H_1} = m_{H_2} = 500$ GeV.

We investigate the same dependence of the decays $t \rightarrow cff$, ($f = b, e, \mu, \tau$) in Fig. 4. Since the lepton masses are small compared with top quark mass, the rates for the decay $t \rightarrow c\bar{l}l$ with $l = e, \mu, \tau$ are approximately equal. This figure shows that the dependence of $t \rightarrow cff$ on m_{H_3} is similar to that of $t \rightarrow cV\bar{V}$ shown in Fig. 3. This figure also shows that the rate of the decay $t \rightarrow cb\bar{b}$ can reach 10^{-3} in the optimum case, while the rate of the decay $t \rightarrow c\bar{l}l$ is usually less than 10^{-6} .

The authors of [42] have roughly estimated the discovery potentials of the high-energy colliders in probing top quark FCNC decay for 100 fb^{-1} of integrated luminosity, and they obtained

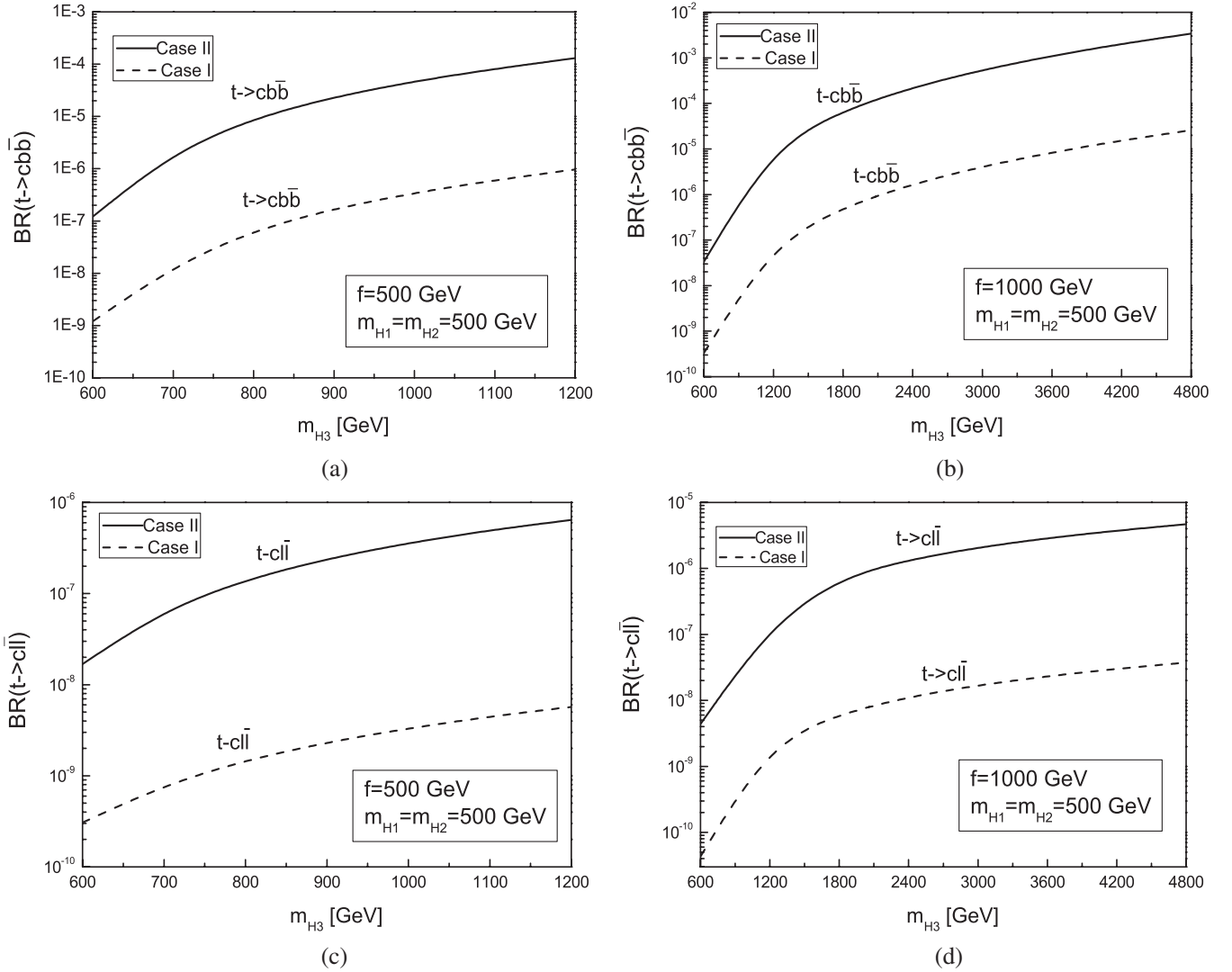
$$\text{LHC: } Br(t \rightarrow cX) \geq 5 \times 10^{-5} \quad (19)$$

$$\text{ILC: } Br(t \rightarrow cX) \geq 5 \times 10^{-4} \quad (20)$$

$$\text{TEV 33: } Br(t \rightarrow cX) \geq 5 \times 10^{-3}. \quad (21)$$

Then by the results presented in Figs. 3 and 4, one can learn that the LHT model can enhance the decays $t \rightarrow cgg(b\bar{b})$ to the observable level of the LHC. So we may conclude that the LHC is capable in testing the flavor structure of the LHT model.

Finally, we summarize the LHT model predictions for the FCNC three-body decays $t \rightarrow cgg, cb\bar{b}, c\bar{l}l$ in comparison with the predictions of the SM, the MSSM, the TC2, and the 2HDM in Table I. This table indicates that the optimum rates of the decays in the LHT model are comparable with those in the TC2 model, and the predictions of the two models are significantly larger than the corresponding predictions of the SM and the MSSM. As far as the decays $Br(t \rightarrow cb\bar{b})$ are concerned, their branching ratios may reach 10^{-3} . So if the decays $t \rightarrow cgg$ and $t \rightarrow cb\bar{b}$ are observed at the LHC, more careful theoretical analysis and


 FIG. 4. Same as Fig. 3, but for the rates of $t \rightarrow cf\bar{f}$, ($f = b, e, \mu, \tau$).

more precise measurement are needed to distinguish the models; while on the other hand, if these decays are not observed, one can constrain the parameter space of the LHT model. This table also indicates that, even in the optimum cases, the rate for $t \rightarrow cl\bar{l}$ is only 10^{-6} , which implies that it is difficult to detect such decay.

IV. CONCLUSION

In this work, we investigate the FCNC three-body decays $t \rightarrow cV\bar{V}$, ($V = \gamma, Z, g$) and $t \rightarrow cf\bar{f}$, ($f = b,$

e, μ, τ) in the LHT. We conclude that: (i) The rates of these decays strongly depend on the mirror quark mass splitting. (ii) The rates rely significantly on the flavor structure of the mirror quarks, namely V_{H_u} and V_{H_d} . (iii) In the optimum case of the LHT model, the rates for the decays $t \rightarrow cgg$ and $t \rightarrow cb\bar{b}$ are large enough to be observed at present or future colliders, and with the running of the LHC, one get some useful information about the flavor structure of the LHT model by detecting these decays.

 TABLE I. Optimum predictions for the decays $t \rightarrow cgg, cb\bar{b}, cl\bar{l}$ in different models.

	SM	MSSM	TC2	2HDM	LHT Case I/Case II
$Br(t \rightarrow cgg)$	$\mathcal{O}(10^{-9})$ [13]	$\mathcal{O}(10^{-4})$ [19]	$\mathcal{O}(10^{-3})$ [22]	$\mathcal{O}(10^{-3})$ [15]	$\mathcal{O}(10^{-5})/\mathcal{O}(10^{-3})$
$Br(t \rightarrow cl\bar{l})$	(10^{-14}) [16]	$\mathcal{O}(10^{-7})$ [20]	$\mathcal{O}(10^{-6})$ [23]	$\mathcal{O}(10^{-8})$ [17]	$\mathcal{O}(10^{-8})/\mathcal{O}(10^{-6})$
$Br(t \rightarrow cb\bar{b})$	$\mathcal{O}(10^{-5})$ [24]	$\mathcal{O}(10^{-7})$ [24]	$\mathcal{O}(10^{-3})$ [24]	...	$\mathcal{O}(10^{-5})/\mathcal{O}(10^{-3})$

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APPENDIX A: EXPRESSIONS OF THE EFFECTIVE $t\bar{c}V$ VERTEX

The effective $t\bar{c}V$ vertex can be obtained by calculating directly the diagrams in Fig. 1 and with the help of the formula in [19]. The loop functions in the effective vertex are defined by the convention of [43] with p_t defined as the incoming momentum while p_c as the outgoing momentum. In our calculation, higher-order terms, namely, terms proportional to v^2/f^2 , in the masses of new gauge bosons and in the Feynman rules are ignored.

$$\begin{aligned}\Gamma_{t\bar{c}\gamma}^\mu(p_c, p_t) &= \Gamma_{t\bar{c}\gamma}^\mu(\eta) + \Gamma_{t\bar{c}\gamma}^\mu(\omega^0) + \Gamma_{t\bar{c}\gamma}^\mu(\omega^\pm) \\ &+ \Gamma_{t\bar{c}\gamma}^\mu(A_H) + \Gamma_{t\bar{c}\gamma}^\mu(Z_H) + \Gamma_{t\bar{c}\gamma}^\mu(W_{\bar{H}}^\pm) \\ &+ \Gamma_{t\bar{c}\gamma}^\mu(W_{\bar{H}}^\pm, \omega^\pm).\end{aligned}$$

$$\begin{aligned}C &= [-m_{H_i}^4 C_0^1 \gamma^\mu P_L - m_t m_c m_{H_i}^2 C_0^1 \gamma^\mu P_R + m_{H_i}^2 m_c C_\alpha^1 \gamma^\alpha \gamma^\mu P_L + m_c m_{H_i}^2 (-\gamma^\mu \not{p}_c C_0^1 + \gamma^\mu \not{p}_t C_0^1 + \gamma^\mu \gamma^\alpha C_\alpha^1) P_L \\ &+ m_{H_i}^2 m_t C_\alpha^1 \gamma^\alpha \gamma^\mu P_R + m_{H_i}^2 m_t (\gamma^\mu \gamma^\alpha C_\alpha^1 - \gamma^\mu \not{p}_c C_0^1 + \gamma^\mu \not{p}_t C_0^1) P_R + m_{H_i}^2 (\gamma^\alpha \gamma^\mu \not{p}_c C_\alpha^1 - \gamma^\alpha \gamma^\mu \not{p}_t C_\alpha^1 \\ &- \gamma^\alpha \gamma^\mu \gamma^\beta C_{\alpha\beta}^1) P_L + m_t m_c (\gamma^\alpha \gamma^\mu \not{p}_c C_\alpha^1 - \gamma^\alpha \gamma^\mu \not{p}_t C_\alpha^1 - \gamma^\alpha \gamma^\mu \gamma^\beta C_{\alpha\beta}^1) P_R].\end{aligned}$$

$$\Gamma_{t\bar{c}\gamma}^\mu(\omega^0) = \frac{i}{16\pi^2} \frac{eg^2}{6M_{Z_H}^2} (V_{Hu})_{it}^* (V_{Hu})_{ic} (D + E + F),$$

$$D = A(B_0^a \rightarrow B_0^c, B_1^a \rightarrow B_1^c),$$

$$E = B(B_0^b \rightarrow B_0^d, B_1^b \rightarrow B_1^d),$$

$$F = C(C_{\alpha\beta}^1 \rightarrow C_{\alpha\beta}^2, C_\alpha^1 \rightarrow C_\alpha^2, C_0^1 \rightarrow C_0^2).$$

$$\begin{aligned}J &= m_{H_i}^2 m_c (p_t^\mu C_0^4 - p_c^\mu C_0^4 + 2C_\mu^4) P_L + m_{H_i}^2 m_t (p_t^\mu C_0^4 - p_c^\mu C_0^4 + 2C_\mu^4) P_R \\ &- m_{H_i}^2 [p_{\mu\alpha} (p_t^\mu - p_c^\mu + 2C_\mu^4) + (p_t^\mu - p_c^\mu) C_\alpha^4 + 2C_{\mu\alpha}^4] \gamma^\alpha P_L \\ &- m_t m_c [p_{t\alpha} (p_t^\mu - p_c^\mu + 2C_\mu^4) + (p_t^\mu - p_c^\mu) C_\alpha^4 + 2C_{\mu\alpha}^4] \gamma^\alpha P_L,\end{aligned}$$

$$G = A(B_0^a \rightarrow B_0^e, B_1^a \rightarrow B_1^e),$$

$$H = B(B_0^b \rightarrow B_0^f, B_1^b \rightarrow B_1^f),$$

$$I = C(C_{\alpha\beta}^1 \rightarrow C_{\alpha\beta}^3, C_\alpha^1 \rightarrow C_\alpha^3, C_0^1 \rightarrow C_0^3).$$

$$\Gamma_{t\bar{c}\gamma}^\mu(\eta) = \frac{i}{16\pi^2} \frac{eg'^2}{150M_{A_H}^2} (V_{Hu})_{it}^* (V_{Hu})_{ic} (A + B + C),$$

$$\begin{aligned}A &= \frac{1}{p_c^2 - m_t^2} [m_{H_i}^2 (m_t^2 B_0^a + p_c^2 B_1^a) \gamma^\mu P_L \\ &+ m_t m_c (m_{H_i}^2 B_0^a + p_c^2 B_1^a) \gamma^\mu P_R \\ &+ m_c (m_{H_i}^2 B_0^a + m_t^2 B_1^a) \not{p}_c \gamma^\mu P_L \\ &+ m_{H_i}^2 m_t (B_0^a + B_1^a) \not{p}_c \gamma^\mu P_R],\end{aligned}$$

$$\begin{aligned}B &= \frac{1}{p_t^2 - m_c^2} [m_{H_i}^2 (m_c^2 B_0^b + p_t^2 B_1^b) \gamma^\mu P_L \\ &+ m_t m_c (m_{H_i}^2 B_0^b + p_t^2 B_1^b) \gamma^\mu P_R \\ &+ m_c m_{H_i}^2 (B_0^b + B_1^b) \gamma^\mu \not{p}_t P_L \\ &+ m_t (m_{H_i}^2 B_0^b + m_c^2 B_1^b) \gamma^\mu \not{p}_t P_R],\end{aligned}$$

$$\begin{aligned}\Gamma_{t\bar{c}\gamma}^\mu(\omega^\pm) &= \frac{i}{16\pi^2} \frac{eg^2}{2M_{W_H}^2} (V_{Hu})_{it}^* (V_{Hu})_{ic} \\ &\times \left[\frac{2}{3} G + \frac{2}{3} H - \frac{1}{3} I + J \right],\end{aligned}$$

$$\Gamma_{t\bar{c}\gamma}^\mu(A_H) = \frac{i}{16\pi^2} \frac{eg'^2}{75} (V_{Hu})_{it}^* (V_{Hu})_{ic} (K + L + M),$$

$$K = \frac{1}{p_c^2 - m_t^2} [p_c^2 B_1^a + m_t \not{p}_c B_1^a] \gamma^\mu P_L,$$

$$L = \frac{1}{p_t^2 - m_c^2} [p_t^2 B_1^b + m_c \not{p}_t B_1^b] \gamma^\mu P_L,$$

$$M = [(\not{p}_t - \not{p}_c) C_\alpha^1 \gamma^\mu \gamma^\alpha - m_{Hi}^2 C_0^1 \gamma^\mu - C_{\alpha\beta}^1 \gamma^\alpha \gamma^\mu \gamma^\beta] P_L.$$

$$\Gamma_{i\bar{c}\gamma}^\mu(Z_H) = \frac{i}{16\pi^2} \frac{eg^2}{3} (V_{Hu})_{it}^* (V_{Hu})_{ic} (N + O + P),$$

$$N = K(B_1^a \rightarrow B_1^c),$$

$$O = L(B_1^b \rightarrow B_1^d),$$

$$P = M(C_{\alpha\beta}^1 \rightarrow C_{\alpha\beta}^2, C_\alpha^1 \rightarrow C_\alpha^2, C_0^1 \rightarrow C_0^2).$$

$$\Gamma_{i\bar{c}\gamma}^\mu(W_H^\pm) = \frac{i}{16\pi^2} \frac{eg^2}{2} (V_{Hu})_{it}^* (V_{Hu})_{ic} \left(\frac{4}{3} Q + \frac{4}{3} R - \frac{2}{3} S - T \right),$$

$$\begin{aligned} T = & [2\gamma^\mu (b_0 + m_{WH}^2 C_0^4) + 4\gamma^\alpha C_{\mu\alpha} + 2(P_t^\mu - P_c^\mu) \gamma^\alpha C_\alpha \\ & - \gamma^\mu \gamma^\alpha C_\alpha + \gamma^\mu \not{p}_t \gamma^\alpha C_\alpha + \gamma^\mu \gamma^\alpha (\not{p}_c - \not{p}_t) C_\alpha \\ & + 2(\not{p}_t - \not{p}_c) \gamma^\alpha \gamma^\mu C_\alpha + \gamma^\alpha \not{p}_t \gamma^\mu C_\alpha + 4\not{p}_t C_\mu \\ & + 2\not{p}_t (p_t^\mu - p_c^\mu) + p_t^2 \gamma^\mu C_0^4 + \gamma^\mu \not{p}_t \not{p}_c C_0^4 \\ & - 2\not{p}_t \not{p}_c \gamma^\mu C_0^4] P_L, \end{aligned}$$

$$Q = K(B_1^a \rightarrow B_1^e),$$

$$R = L(B_1^b \rightarrow B_1^f),$$

$$S = M(C_{\alpha\beta}^1 \rightarrow C_{\alpha\beta}^3, C_\alpha^1 \rightarrow C_\alpha^3, C_0^1 \rightarrow C_0^3).$$

$$\begin{aligned} \Gamma_{i\bar{c}\gamma}^\mu(W_H^\pm, \omega^\pm) = & \frac{i}{16\pi^2} \frac{g^2 e}{2} (V_{Hu})_{it}^* (V_{Hu})_{ic} [m_t (\gamma^\mu \gamma^\alpha C_\alpha^4 \\ & + 2p_t^\mu C_0^4 - \not{p}_t \gamma^\mu C_0^4) P_R + (m_c \not{p}_t C_0^4 \\ & + m_c \gamma^\alpha C_\alpha^4 - 2m_{Hi}^2 C_0^4) \gamma^\mu P_L]. \end{aligned}$$

$$\begin{aligned} \Gamma_{i\bar{c}Z}^\mu(p_c, p_t) = & \Gamma_{i\bar{c}Z}^\mu(\eta) + \Gamma_{i\bar{c}Z}^\mu(\omega^0) + \Gamma_{i\bar{c}Z}^\mu(\omega^\pm) \\ & + \Gamma_{i\bar{c}Z}^\mu(A_H) + \Gamma_{i\bar{c}Z}^\mu(Z_H) + \Gamma_{i\bar{c}Z}^\mu(W_H^\pm) \\ & + \Gamma_{i\bar{c}Z}^\mu(W_H^\pm, \omega^\pm). \end{aligned}$$

$$\Gamma_{i\bar{c}Z}^\mu(\eta) = \frac{i}{16\pi^2} \frac{g}{\cos\theta_W} \frac{g'^2}{100M_{A_H}^2} (V_{Hu})_{it}^* (V_{Hu})_{ic} (A' + B' + C'),$$

$$\begin{aligned} A' = & \frac{1}{p_c^2 - m_t^2} \left[\left(\frac{1}{2} - \frac{2}{3} \sin^2\theta_W \right) m_{Hi}^2 (m_t^2 B_0^a + p_c^2 B_1^a) \gamma^\mu P_L \right. \\ & - \frac{2}{3} \sin^2\theta_W m_t m_c (m_{Hi}^2 B_0^a + p_c^2 B_1^a) \gamma^\mu P_R \\ & + \left(\frac{1}{2} - \frac{2}{3} \sin^2\theta_W \right) m_c (m_{Hi}^2 B_0^a + m_t^2 B_1^a) \not{p}_c \gamma^\mu P_L \\ & \left. - \frac{2}{3} \sin^2\theta_W m_{Hi}^2 m_t (B_0^a + B_1^a) \not{p}_c \gamma^\mu P_R \right], \end{aligned}$$

$$\begin{aligned} B' = & \frac{1}{p_t^2 - m_c^2} \left[\left(\frac{1}{2} - \frac{2}{3} \sin^2\theta_W \right) m_{Hi}^2 (m_c^2 B_0^b + p_t^2 B_1^b) \gamma^\mu P_L \right. \\ & - \frac{2}{3} \sin^2\theta_W m_t m_c (m_{Hi}^2 B_0^b + p_t^2 B_1^b) \gamma^\mu P_R \\ & + \left(\frac{1}{2} - \frac{2}{3} \sin^2\theta_W \right) m_t (m_{Hi}^2 B_0^b + m_c^2 B_1^b) \gamma^\mu \not{p}_t P_R \\ & \left. - \frac{2}{3} \sin^2\theta_W m_c m_{Hi}^2 (B_0^b + B_1^b) \gamma^\mu \not{p}_t P_L \right], \end{aligned}$$

$$C' = \left(\frac{1}{2} - \frac{2}{3} \sin^2\theta_W \right) C.$$

$$\begin{aligned} \Gamma_{i\bar{c}Z}^\mu(\omega^0) = & \frac{i}{16\pi^2} \frac{g}{\cos\theta_W} \\ & \times \frac{g^2}{4M_{Z_H}^2} (V_{Hu})_{it}^* (V_{Hu})_{ic} m_{Hi}^2 (D' + E' + F'), \end{aligned}$$

$$D' = A'(B_0^a \rightarrow B_0^e, B_1^a \rightarrow B_1^e),$$

$$E' = B'(B_0^b \rightarrow B_0^d, B_1^b \rightarrow B_1^d),$$

$$F' = C'(C_{\alpha\beta}^1 \rightarrow C_{\alpha\beta}^2, C_\alpha^1 \rightarrow C_\alpha^2, C_0^1 \rightarrow C_0^2).$$

$$\begin{aligned} \Gamma_{i\bar{c}Z}^\mu(\omega^\pm) = & \frac{i}{16\pi^2} \frac{g}{\cos\theta_W} \\ & \times \frac{g^2}{2M_{W_H}^2} (V_{Hu})_{it}^* (V_{Hu})_{ic} (G' + H' + I' + J'), \end{aligned}$$

$$G' = A'(B_0^a \rightarrow B_0^e, B_1^a \rightarrow B_1^e),$$

$$H' = B'(B_0^b \rightarrow B_0^d, B_1^b \rightarrow B_1^d),$$

$$I' = C'(C_{\alpha\beta}^1 \rightarrow C_{\alpha\beta}^3, C_\alpha^1 \rightarrow C_\alpha^3, C_0^1 \rightarrow C_0^3),$$

$$J' = \cos^2\theta_W J.$$

$$\Gamma_{i\bar{c}Z}^\mu(A_H) = \frac{i}{16\pi^2} \frac{g}{\cos\theta_W} \frac{g'^2}{100} (V_{Hu})_{it}^* (V_{Hu})_{ic} (K' + L' + M'),$$

$$K' = \frac{1}{p_c^2 - m_t^2} \left[\left(\frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) p_c^2 B_1^a - \frac{2}{3} \sin^2 \theta_W m_t \not{p}_c B_1^a \right] \gamma^\mu P_L,$$

$$L' = \frac{1}{p_t^2 - m_c^2} \left[\left(\frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) p_t^2 B_1^b - \frac{2}{3} \sin^2 \theta_W m_c \not{p}_t B_1^b \right] \gamma^\mu P_L,$$

$$M' = \left(\frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) [(\not{p}_t - \not{p}_c) C_\alpha^1 \gamma^\mu \gamma^\alpha - m_{H_i}^2 C_0^1 \gamma^\mu - C_{\alpha\beta}^1 \gamma^\alpha \gamma^\mu \gamma^\beta] P_L.$$

$$\Gamma_{i\bar{c}Z}^\mu(Z_H) = \frac{i}{16\pi^2} \frac{g}{\cos\theta_W} \frac{g^2}{4} (V_{Hu})_{it}^* (V_{Hu})_{ic} (N' + O' + P'),$$

$$N' = K'(B_1^a \rightarrow B_1^c),$$

$$O' = L'(B_1^b \rightarrow B_1^d),$$

$$P' = M'(C_{\alpha\beta}^1 \rightarrow C_{\alpha\beta}^2, C_\alpha^1 \rightarrow C_\alpha^2, C_0^1 \rightarrow C_0^2).$$

$$\Gamma_{i\bar{c}Z}^\mu(W_H^\pm) = \frac{i}{16\pi^2} \frac{g}{\cos\theta_W} g^2 (V_{Hu})_{it}^* (V_{Hu})_{ic} \times (Q' + R' + S' + T'),$$

$$Q' = K'(B_1^a \rightarrow B_1^e),$$

$$R' = L'(B_1^b \rightarrow B_1^f),$$

$$S' = \left(-\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W \right) [(\not{p}_t - \not{p}_c) \times C_\alpha^3 \gamma^\mu \gamma^\alpha - m_{H_i}^2 C_0^3 \gamma^\mu - C_{\alpha\beta}^3 \gamma^\alpha \gamma^\mu \gamma^\beta] P_L,$$

$$T' = \cos^2 \theta_W T.$$

$$\Gamma_{i\bar{c}Z}^\mu(W_H^\pm, \omega^\pm) = \frac{i}{16\pi^2} \frac{g^3 \cos\theta_W}{2} (V_{Hu})_{it}^* (V_{Hu})_{ic} \times [m_t (\gamma^\mu \gamma^\alpha C_\alpha^4 + 2p_t^\mu C_0^4 - \not{p}_t \gamma^\mu C_0^4) P_R + (m_c \not{p}_t C_0^4 + m_c \gamma^\alpha C_\alpha^4 - 2m_{H_i}^2 C_0^4) \gamma^\mu P_L]$$

$$\Gamma_{i\bar{c}g}^{\mu aj}(p_c, p_t) = \Gamma_{i\bar{c}g}^{\mu aj}(\eta^0) + \Gamma_{i\bar{c}g}^{\mu aj}(\omega^0) + \Gamma_{i\bar{c}g}^{\mu aj}(\omega^\pm) + \Gamma_{i\bar{c}g}^{\mu aj}(A_H) + \Gamma_{i\bar{c}g}^{\mu aj}(Z_H) + \Gamma_{i\bar{c}g}^{\mu aj}(W_H^\pm),$$

$$\Gamma_{i\bar{c}g}^{\mu aj}(\eta^0) = \frac{i}{16\pi^2} \frac{g^2}{100M_{A_H}^2} (V_{Hu})_{it}^* (V_{Hu})_{ic} g_s T^{aj}(A + B + C),$$

$$\Gamma_{i\bar{c}g}^{\mu aj}(\omega^0) = \frac{i}{16\pi^2} \frac{g^2}{4M_{Z_H}^2} (V_{Hu})_{it}^* (V_{Hu})_{ic} g_s T^{aj}(D + E + F),$$

$$\Gamma_{i\bar{c}g}^{\mu aj}(\omega^\pm) = \frac{i}{16\pi^2} \frac{g^2}{2M_{W_H}^2} (V_{Hu})_{it}^* (V_{Hu})_{ic} g_s T^{aj}(G + H + I),$$

$$\Gamma_{i\bar{c}g}^{\mu aj}(A_H) = \frac{i}{16\pi^2} \frac{g^2}{100} (V_{Hu})_{it}^* (V_{Hu})_{ic} g_s T^{aj}(K + L + M),$$

$$\Gamma_{i\bar{c}g}^{\mu aj}(Z_H) = \frac{i}{16\pi^2} \frac{g^2}{4} (V_{Hu})_{it}^* (V_{Hu})_{ic} g_s T^{aj}(N + O + P),$$

$$\Gamma_{i\bar{c}g}^{\mu aj}(W_H^\pm) = \frac{i}{16\pi^2} \frac{g^2}{2} (V_{Hu})_{it}^* (V_{Hu})_{ic} g_s T^{aj}(Q + R + S).$$

The two-point and three-point loop functions B_0, B_1, C_0, C_{ij} in the above expressions are defined as

$$C_{ij}^1 = C_{ij}^1(-p_c, p_t, m_{H_i}, M_{A_H}, m_{H_i}), C_{ij}^2$$

$$= C_{ij}^2(-p_c, p_t, m_{H_i}, M_{Z_H}, m_{H_i}), C_{ij}^3$$

$$= C_{ij}^3(-p_c, p_t, m_{H_i}, M_{W_H}, m_{H_i}),$$

$$C_{ij}^4 = C_{ij}^4(p_c, -p_t, M_{W_H}, m_{H_i}, M_{W_H}),$$

$$B^a = B^a(-p_c, m_{H_i}, M_{A_H}), \quad B^b = B^b(-p_t, m_{H_i}, M_{A_H}),$$

$$B^c = B^c(-p_c, m_{H_i}, M_{Z_H}), \quad B^d = B^d(-p_t, m_{H_i}, M_{Z_H}),$$

$$B^e = B^e(-p_c, m_{H_i}, M_{W_H}),$$

$$B^f = B^f(-p_t, m_{H_i}, M_{W_H}).$$

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