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R-parity violating effects in top quark flavor-changing neutral-current production at LHC

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In the minimal supersymmetric model the R-parity violating top quark interactions, which are so far weakly constrained, can induce various flavor-changing neutral-current (FCNC) productions for the top quark at the large hadron collider (LHC). In this work we assume the presence of the B-violating couplings and examine their contributions to the FCNC productions proceeding through the parton processes $cg \to t$, $gg \to t\bar{c}$, $cg \to t\gamma$, $cg \to tZ$ and $cg \to th$. We find that all these processes can be greatly enhanced relative to the R-parity preserving predictions. In the parameter space allowed by current experiments, all the production channels except $cg \to th$ can reach the 3σ sensitivity, in contrast to the R-parity preserving case in which only $cg \to t$ can reach the 3σ sensitivity.

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I. INTRODUCTION

Top quark is speculated to be a sensitive probe for new physics beyond the standard model (SM) since it is the heaviest fermion with a mass at weak scale [1]. So far its properties are measured with a rough precision due to the limited statistics at the Fermilab Tevatron and hence there remains a plenty of room for new physics in top quark sector. As a top quark factory, the LHC will scrutinize the top quark nature, either unravelling or further constraining the new physics related to the top quark.

Concerning the probe of new physics through the top quark, the FCNC processes at the LHC may play an important role, just like the FCNC transitions of the bottom quark in B-factories. The extremely suppressed FCNC interactions for the top quark in the SM [2] imply that any observation of such processes can serve as a smoking gun for new physics. Actually, it is found that the top quark FCNC interactions can be greatly enhanced by the enriched flavor structure in many new physics models [3], such as the minimal supersymmetric model (MSSM) [4–8], the technicolor models [9,10] and the other miscellaneous models [11]. Although all these models can allow for great enhancement for the top quark FCNC processes relative to the SM predictions, they exhibit different features and predict very different rates for such FCNC processes. Take the popular MSSM as an example. In the R-conserving scenario, with the consideration of various current experimental constraints on the parameter space, only $t \to ch$ among the FCNC decays and $cg \to t$ among the FCNC productions can possibly reach the observable level at the LHC [4]. But in the presence of R-violating couplings, top quark FCNC processes such as $t \to cV$ ($V = g, Z, \gamma$) and $t \to ch$ can be significantly enhanced relative to the R-conserving scenario [6].

We note that while for the R-conserving MSSM various FCNC productions of the top quark at the LHC have been comprehensively studied [4], for the R-violating case only one FCNC production channel, i.e., $gg \to t\bar{c}$, has been studied in the literature [8]. Given the central role of the LHC in high energy physics and also considering the fact that the R-violating top quark interactions are so far weakly constrained, it is necessary to complete the study by examining all possible FCNC production channels induced by R-violating couplings. In this work we perform such a collective study considering the productions proceeding through the parton processes $cg \to t$, $gg \to t\bar{c}$, $cg \to t\gamma$, $cg \to tZ$ and $cg \to th$. We find that all these productions can be greatly enhanced relative to the R-conserving predictions. In the parameter space allowed by current experiments, all the production channels except $cg \to th$ can reach the 3σ sensitivity, in contrast to the R-parity preserving case in which only $cg \to t$ can reach the 3σ sensitivity.

This paper is arranged as follows. In Sec. II, we recapitulate the R-violating couplings and perform the calculations for the top FCNC productions at the LHC. In Sec. III, we present some numerical results for the rates of the productions and for each channel we show the parameter space accessible at 3σ at the LHC. Finally, a summary is given in Sec. IV.

II. CALCULATIONS

The R-violating trilinear terms in the superpotential of the MSSM, consistent with the gauge symmetries of the SM, supersymmetry and renormalizability, are given by [12]

$$\frac{1}{2}\lambda_{ijk}L_iL_jE_k^c + \lambda'_{ijk}L_iQ_jD_k^c + \frac{1}{2}\lambda''_{ijk}U_i^cD_j^cD_k^c \quad (1)$$

where $L_i(Q_i)$ and $E_i^c(U_i^c, D_i^c)$ are the left-handed lepton (quark) doublet and right-handed lepton (quark) singlet chiral superfields, and i, j, k are generation indices. The λ_{ijk} and λ'_{ijk} violate lepton number while λ''_{ijk} violate baryon number. Although it is theoretically possible to have both B-violating and L-violating interactions, the non-observation of proton decay prohibits their simultaneous presence. The couplings λ' and λ'' can contribute to various top quark processes at the LHC:

(i) Through exchanging a squark or slepton at tree-level, they can contribute to top pair production $pp \to t\bar{t} + X$ [13] and single top production $pp \to t\bar{b} + X$ [14], and also can cause some exotic top quark decays [15].

(ii) At loop-level they can induce top-charm FCNC interactions and thus lead to top quark FCNC productions proceeding through the parton processes

$$gg \to t\bar{c}, \qquad cg \to t, \qquad cg \to tZ, \qquad cg \to t\gamma, \qquad cg \to th \tag{2}$$

As mentioned in the preceding section, among these production channels induced by the R-violating couplings, only $gg \to t\bar{c}$ has been studied in the literature. In the following we examine these productions collectively.

TABLE I. Current upper limits on the B-violating couplings λ''_{ijk} taken from [17].

couplings	bounds	sources
λ''_{112}, λ''_{113}	10^{-6}	$n - \bar{n}$ oscillation
λ''_{123}, λ''_{212}, λ''_{213}, λ''_{223}	1.25	perturbativity
λ''_{312}, λ''_{313}	10^{-3}	$n - \bar{n}$ oscillation
λ''_{323}	0.96	Z-decays

Note that both the B-violating couplings λ'' and the L-violating couplings λ' can induce the top quark FCNC productions in Eq. (2). In our study we assume the existence of the B-violating couplings λ'' to show the results. The results for the L-violating couplings λ' take the similar form and have the same behavior (e.g. the same dependence on the couplings and the sparticle mass).

In terms of the four-component Dirac notation, the Lagrangian of the B-violating couplings is given by

$$\mathcal{L}_{\lambda''} = -\frac{1}{2}\lambda''_{ijk}[\tilde{d}_R^{k*}\bar{u}_R^i d_L^{jc} + \tilde{d}_R^{j*}\bar{u}_R^i d_L^{kc} + \tilde{u}_R^{i*}\bar{d}_R^j d_L^{kc}] + \text{H.c.} \tag{3}$$

The current upper limits on all the R-violating couplings are summarized in [16,17]. Table I is a list of current limits for the B-violating couplings taken from [17], which are from the analysis of $n - \bar{n}$ oscillation [18], the perturbativity requirement [19] and the Z-decays [20]. The couplings involved in our study are λ''_{2jk} and λ''_{3jk}, which are so far weakly constrained. Note that these bounds are obtained for the sparticle mass of 100 GeV and for heavier sparticles they become weak. For example, the dependence of the λ''_{323} bound on squark mass is $0.96 \times (m_{\tilde{d}_R}/100\text{ GeV})$.

In our calculations for the loop processes in Eq. (2), some loop-induced vertices (like vertex tcg) appear repeatedly in different diagrams. To simplify the calculations we define the so-called effective vertex [4]. For example, we define the effective tcg vertex as

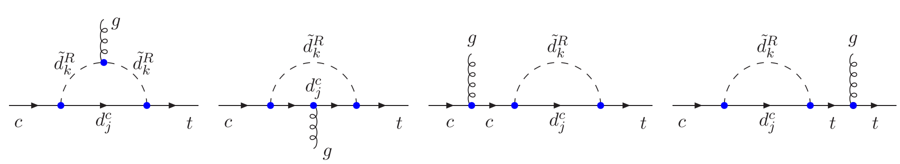

FIG. 1 (color online). Feynman diagrams for the effective vertex tcg at one-loop level.

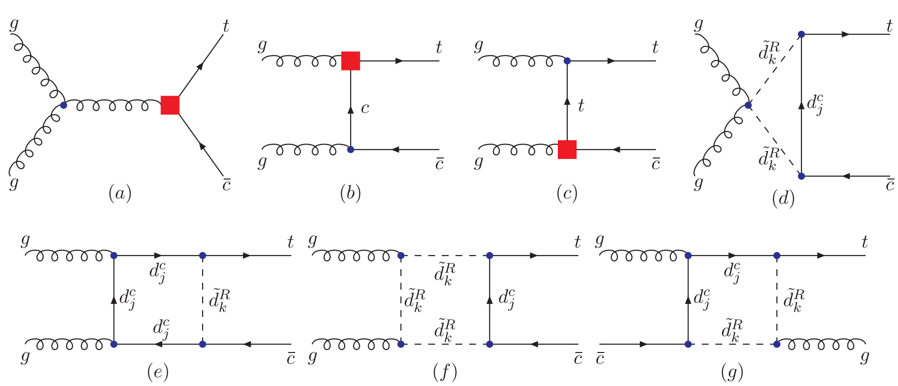

FIG. 2 (color online). Feynman diagrams for $gg \to t\bar{c}$ at one loop level. The effective tcg vertex in (a-c) is defined in Fig. 1.

$$\Gamma_\mu^{\rm eff}(p_t, p_c) = \Gamma_\mu^{\bar{t}cg}(p_t, p_c) + i\Sigma(p_t)\frac{i(\not{p}_t + m_c)}{m_t^2 - m_c^2}\Gamma_\mu^{\bar{c}cg} + \Gamma_\mu^{\bar{t}tg}\frac{i(\not{p}_c + m_t)}{m_c^2 - m_t^2} i\Sigma(p_c), \quad (4)$$

where $\Gamma_\mu^{\bar{q}qg}(q = c, t)$ is the usual QCD vertex, and $\Gamma_\mu^{\bar{t}cg}$, $\Sigma(p_t)$ and $\Sigma(p_c)$ are, respectively, the contributions from vertex and self-energy loops shown in Fig. 1, whose expressions are shown in Appendix A. In terms of the effective tcg vertex, the Feynman diagrams for $gg \to t\bar{c}$ are shown in Fig. 2. In this way the analytic amplitudes are quite compact and the Fortran codes are also simplified. Of course, we need to calculate box diagrams in Fig. 2 and their expressions are presented in Appendix A.

Similarly, other processes listed in Eq. (2) can be calculated. Take $cg \to th$ as an example, where h is the lightest CP-even Higgs boson in the MSSM. In order to get the effective vertex tch from Fig. 1, we only need to replace the gluon with the Higgs boson in the vertex. For the amplitude of $cg \to th$, we can obtain it by replacing the gluon with the Higgs boson in Fig. 2 and removing the diagrams (a) and (d). In Appendix A, we list the explicit forms for all effective vertices used in our calculations.

III. NUMERICAL RESULTS AND DISCUSSIONS

The SM parameters used in our numerical calculation are [21]

$$m_t = 171.2 \text{ GeV}, \qquad m_Z = 91.19 \text{ GeV},$$
$$\sin\theta_W = 0.2228, \qquad \alpha_s(m_t) = 0.1095, \qquad \alpha = 1/128. \quad (5)$$

The SUSY parameters involved in our calculations are the squark mass and the B-violating couplings λ''_{3jk} and λ''_{2jk}, whose upper limits are listed in Table I. About the constraint on squark mass, the strongest bound is from the Tevatron experiment. For example, from the search for the inclusive production of squarks and gluinos in R-conserving minimal supergravity model with $A_0 = 0$, $\mu < 0$ and $\tan\beta = 5$, the CDF gives a bound of 392 GeV at the 95% C.L. [22] for degenerate gluinos and squarks. Obviously, this bound may be not applicable to the R-violating scenario because the SUSY signal in case of R-violation is very different from the R-conserving case. The most robust bounds on sparticle masses come from the LEP results, which give a bound of about 100 GeV on squark mass [23]. In our calculations we use CTEQ6L [24]

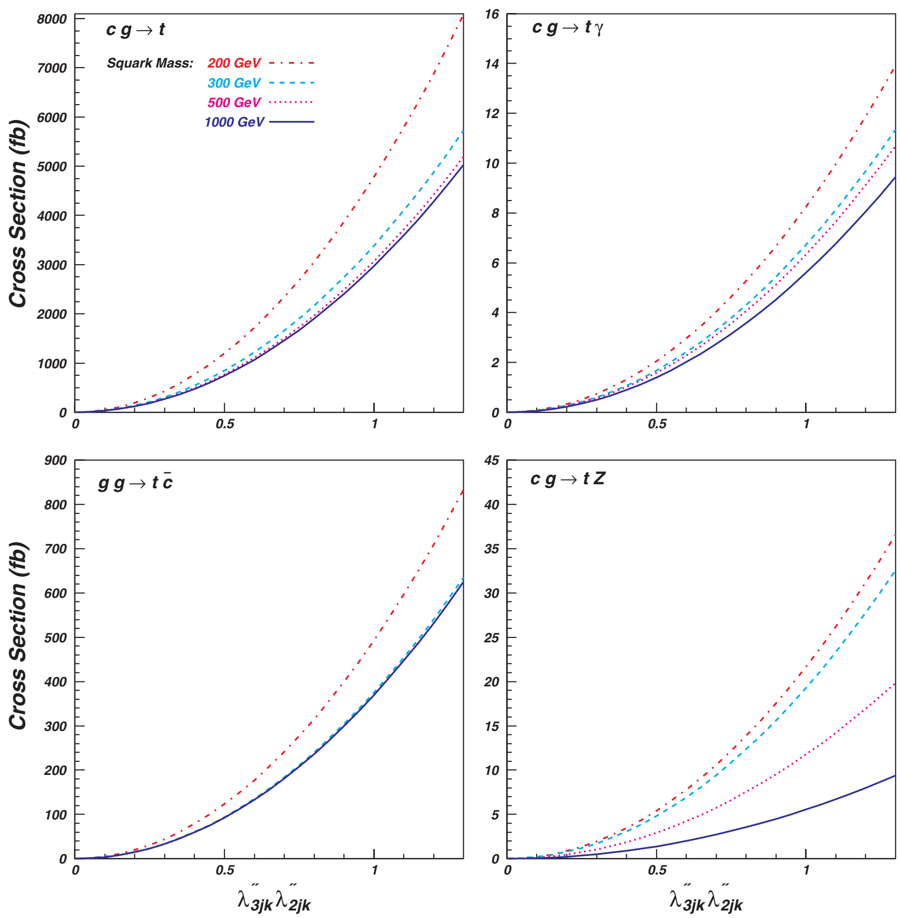

FIG. 3 (color online). The hadronic cross sections of top quark FCNC productions at the LHC versus $\lambda''_{3jk}\lambda''_{2jk}$.

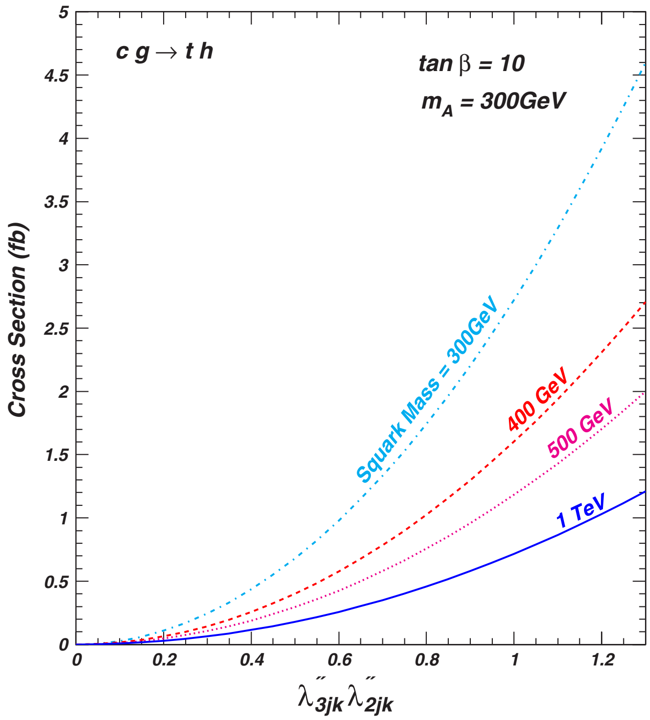

FIG. 4 (color online). The hadronic cross section of $cg \to th$ at the LHC versus $\lambda''_{3jk}\lambda''_{2jk}$.

for parton distributions, with the renormalization scale μ_R and factorization scale μ_F chosen to be $\mu_R = \mu_F = m_t$. In the following we use the parton processes to label the corresponding hadronic processes and all the cross sections displayed in our numerical results are the hadronic cross sections. Also, we take into account the charge-conjugate channel for each process.

Note that our results depend on the squark mass and the coupling product $\lambda''_{3jk}\lambda''_{2jk}$. Here the product can be understood either as a single product ($\lambda''_{312}\lambda''_{212}$, $\lambda''_{313}\lambda''_{213}$ or $\lambda''_{323}\lambda''_{223}$) or a sum over the indices j and k. In the latter case the mass degeneracy should be assumed for different down squarks appearing in the loops in Figs. 1 and 2.

In Figs. 3 and 4 we plot the hadronic cross sections versus $\lambda''_{3jk}\lambda''_{2jk}$ for different squark masses. From the figures we see that cross sections increase with $|\lambda''_{3jk}\lambda''_{2jk}|^2$ and decrease with squark mass. Note that in Fig. 4 the mass of the Higgs boson h is determined by M_A, $\tan\beta$ and the varying squark mass (we assume the mass degeneracy for all squarks including the top squarks). For the parameters chosen in Fig. 4, the Higgs boson h is slightly above 100 GeV.

In Table II we display the hadronic cross sections in R-violating MSSM in comparison with the results in the top-color assisted technicolor (TC2) and the R-conserving MSSM. Also we listed the 3σ sensitivity for each production channel at the LHC with a luminosity of 100 fb^{-1}. We see that the R-violating couplings allow for much larger cross sections than the R-conserving MSSM and all channels except $cg \to th$ can reach the 3σ level in the allowed parameter space.

In Fig. 5 we plot the 3σ contours of the hadronic cross sections in the plane of $\lambda''_{3jk}\lambda''_{2jk}$ versus squark mass. The region above each curve is the corresponding observable region at 3σ. We see that among these channels the production proceeding through $cg \to t$ is most powerful for probing such R-violating SUSY. The peaks of the curves near the top quark mass show the resonance behavior of the top quark self-energy which involve a squark and a light quark in the loops.

Finally, we remark that there may be some correlation between top quark FCNC interactions and b or c physics, as discussed by using the model-independent effective operators [29]. In case of B-violating couplings, the coexistence of two couplings can induce some b or c processes. For example, the coexistence of λ''_{312} and λ''_{313} can induce $b \to s$ transition and thus the product $\lambda''_{312}\lambda''_{313}$ is constrained by $b \to s\gamma$. A complete list of such bounds on the product of two couplings from b or c physics is presented in [17]. For the product $\lambda''_{3jk}\lambda''_{2jk}$ involved in our study, it is not constrained by those b or c processes since the coexistence of λ''_{3jk} and λ''_{2jk} cannot trigger those processes (in other words, for λ''_{3jk} or λ''_{2jk} to trigger those

TABLE II. The hadronic cross sections of top quark FCNC productions at the LHC in R-violating MSSM (for squark mass of 300 GeV and the value of $\lambda''_{3jk}\lambda''_{2jk}$ summed over j, k with $\lambda''_{3jk} = 1$ and $\lambda''_{2jk} = 1.25$) in comparison with the maximal values in the R-conserving MSSM and the top-color assisted technicolor (TC2) model. The corresponding charge-conjugate channels are also included. The LHC 3σ sensitivities in the last column are estimated for an integrated luminosity of 100 fb^{-1}.

	MSSM		TC2	LHC 3σ sensitivity
	R-conseving	R-violating		
$gg \to t\bar{c}$	700 fb [4]	5 pb	30 pb [9]	1500 fb [25]
$cg \to t$	950 fb [4]	47 pb	1.5 pb [9]	800 fb [26]
$cg \to t\gamma$	1.8 fb [4]	94 fb	20 fb [9]	5 fb [27]
$cg \to tZ$	5.7 fb [4]	305 fb	100 fb [9]	35 fb [27]
$cg \to th$	24 fb [4]	37 fb	600 fb [9]	200 fb [28]

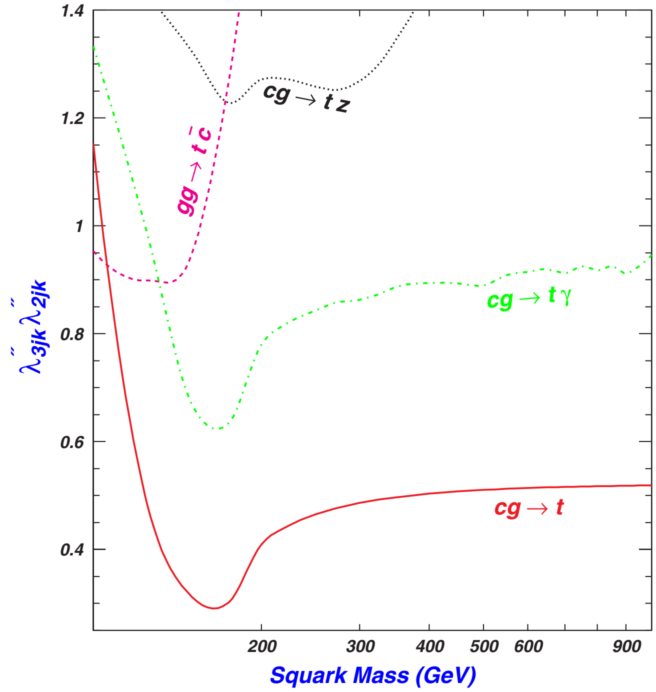

FIG. 5 (color online). The 3σ contour of the hadronic cross sections at the LHC. The region above each curve is the corresponding 3σ observable region.

processes, another coupling different from these two must be present).

IV. CONCLUSION

In the MSSM the R-violating top quark interactions are so far weakly constrained, which can induce various FCNC productions for the top quark at the LHC. We assumed the presence of the B-violating top quark couplings and examined the induced FCNC productions which proceed through the parton-level processes $cg \to t$, $gg \to t\bar{c}$, $cg \to t\gamma$, $cg \to tZ$ and $cg \to th$. We found that all these processes can be greatly enhanced relative to the R-parity preserving predictions. In the parameter space allowed by current experiments, all the production channels except $cg \to th$ can reach the 3σ sensitivity, in contrast to the R-parity preserving case in which only $cg \to t$ can reach the 3σ sensitivity. Recall that among the FCNC decays of the top quark, only $t \to ch$ could marginally be accessible at the LHC in the R-conserving MSSM [4], while in the R-violating MSSM all the FCNC decay modes could reach the observable level at the LHC [6]. So, if supersymmetry is proven to the true story at the LHC, these FCNC productions and decays of the top quark could shed some light on R-parity conservation or violation.

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APPENDIX A: EXPRESSIONS OF LOOP RESULTS

Here we list the expressions for $\Sigma(p)$ and $\Gamma_\mu^{\bar{t}cg}$ in the effective tcg vertex of Eq. (4), and also list the expressions for $\Gamma_\mu^{\bar{t}c\gamma}$, $\Gamma_\mu^{\bar{t}cZ}$ and $\Gamma^{\bar{t}ch}$ appearing, respectively, in the effective $tc\gamma$, tcZ and tch vertex. Their expressions are given by

$$\Sigma(p) = aB_\alpha^1 \gamma^\alpha P_R, \tag{A1}$$

$$\Gamma_\mu^{\bar{t}cg} = ag_s[C_{\alpha\beta}^1 \gamma^\alpha \gamma_\mu \gamma^\beta - C_\alpha^1 \gamma^\alpha \gamma_\mu (\not{p}_t + \not{p}_c) - 2C_{\mu\alpha}^2 \gamma^\alpha + C_\alpha^2 \gamma^\alpha (p_t - p_c)_\mu] P_R \tag{A2}$$

$$\Gamma^{\bar{t}ch} = -ae\{Y_d m_{d_j}[2C_\alpha^3 \gamma^\alpha + C_0^3(\not{p}_c - \not{p}_t)] + Y_{\tilde{d}_R} C_\alpha^4 \gamma^\alpha\} P_R, \tag{A3}$$

$$\Gamma_\mu^{\bar{t}c\gamma} = -\frac{2}{3} ae[C_{\alpha\beta}^1 \gamma^\alpha \gamma_\mu \gamma^\beta - C_\alpha^1 \gamma^\alpha \gamma_\mu (\not{p}_t + \not{p}_c) - 2C_{\mu\alpha}^2 \gamma^\alpha + C_\alpha^2 \gamma^\alpha (p_t - p_c)_\mu] P_R \tag{A4}$$

$$\Gamma_\mu^{\bar{t}cZ} = ae\{(v_f + a_f)[C_{\alpha\beta}^5 \gamma^\alpha \gamma_\mu \gamma^\beta - C_\alpha^5 \gamma^\alpha \gamma_\mu (\not{p}_t + \not{p}_c)] - b[2C_{\mu\alpha}^6 \gamma^\alpha - C_\alpha^6 \gamma^\alpha (p_t - p_c)_\mu]\} P_R, \tag{A5}$$

with p_t and p_c denoting, respectively, the momenta of the top and charm quark, and the constants given by

$$a = \frac{i}{16\pi^2} \lambda_{3jk}'' \lambda_{2jk}'', \qquad b = -\frac{\sin\theta_W}{3\cos\theta_W}, \tag{A6}$$

$$a_f = -\frac{1}{4\sin\theta_W \cos\theta_W}, \qquad v_f = a_f\left(1 - \frac{4}{3}\sin^2\theta_W\right). \tag{A7}$$

For the loop functions B and C in Eqs. (A1)–(A5), we adopted the definitions in [30] and use LoopTools [31] in the calculations. The loop functions' dependence on the momenta and the masses is given by

$$C^1 = C(-p_t - p_c, p_c, m_{d_j}^2, m_{d_j}^2, m_{\tilde{d}_k^R}^2), \tag{A8}$$

$$C^2 = C(-p_t, p_t + p_c, m_{d_j}^2, m_{\tilde{d}_k^R}^2, m_{\tilde{d}_k^R}^2), \tag{A9}$$

$$C^3 = C(p_c - p_t, -p_c, m_{d_j}^2, m_{d_j}^2, m_{\tilde{d}_k^R}^2), \tag{A10}$$

$$C^4 = C(-p_t, p_t - p_c, m_{d_j}^2, m_{\tilde{d}_k^R}^2, m_{\tilde{d}_k^R}^2), \tag{A11}$$

$$C^5 = C(-p_t, p_c, m_{d_j}^2, m_{d_j}^2, m_{\tilde{d}_k^R}^2), \tag{A12}$$

$$C^6 = C(-p_t, p_t - p_c, m_{d_j}^2, m_{\tilde{d}_k^R}^2, m_{\tilde{d}_k^R}^2), \quad \text{(A13)}$$

$$B^1 = B(-p, m_{\tilde{d}_k^R}^2, m_{d_j}^2). \quad \text{(A14)}$$

The expressions for Yukawa couplings Y_d and $Y_{\tilde{d}_R}$ in Eqs. (A3) are given by

$$Y_d = \frac{m_d \sin\alpha}{2m_W \sin\theta_W \cos\beta}, \quad \text{(A15)}$$

$$Y_{\tilde{d}_R} = -\frac{1}{3} m_Z \tan\theta_W \sin(\alpha + \beta) + \frac{m_d^2 \sin\alpha}{m_W \sin\theta_W \cos\beta}. \quad \text{(A16)}$$

The amplitudes of the box diagrams in Fig. 2(a)–2(g) are given, respectively, by

$$M_{(d)} = -a g_s^2 T_1 \varepsilon_\rho^a(p_1) \varepsilon_\sigma^b(p_2) g^{\rho\sigma} \bar{u}(p_t)(C_\alpha \gamma^\alpha) P_R v(p_c), \quad \text{(A17)}$$

$$\begin{aligned} M_{(e)} = {}& a g_s^2 T_2 \varepsilon_\rho^a(p_1) \varepsilon_\sigma^b(p_2) \bar{u}(p_t)[D_{\alpha\beta\delta}^1 \gamma^\alpha \gamma^\rho \gamma^\beta \gamma^\sigma \gamma^\delta \\ & - D_{\alpha\beta}^1 \gamma^\alpha \gamma^\rho \not{p}_1 \gamma^\sigma \gamma^\beta - D_{\alpha\beta}^1 \gamma^\alpha \gamma^\rho \gamma^\beta \gamma^\sigma (\not{p}_c + \not{p}_t) \\ & + D_\alpha^1 \gamma^\alpha \gamma^\rho \not{p}_1 \gamma^\sigma (\not{p}_c + \not{p}_t)] P_R v(p_c), \end{aligned} \quad \text{(A18)}$$

$$\begin{aligned} M_{(f)} = {}& a g_s^2 T_2 \varepsilon_\rho^a(p_1) \varepsilon_\sigma^b(p_2) \bar{u}(p_t)[4 D_{\rho\sigma\alpha}^2 \gamma^\alpha \\ & + 2 D_{\rho\alpha}^2 \gamma^\alpha (2p_1 + p_2 - 2p_t)_\sigma \\ & - 2 D_\sigma^2 \alpha \gamma^\alpha (2p_t - p_1)_\rho \\ & - D_\alpha^2 \gamma^\alpha (2p_t - p_1)_\rho (2p_c - p_2)_\sigma] P_R v(p_c), \end{aligned} \quad \text{(A19)}$$

$$\begin{aligned} M_{(g)} = {}& a g_s^2 T_3 \varepsilon_\rho^a(p_1) \varepsilon_\sigma^b(p_2) \bar{u}(p_t)[2 D_{\sigma\alpha\beta}^3 \gamma^\alpha \gamma^\rho \gamma^\beta \\ & - 2 D_{\sigma\alpha}^3 \gamma^\alpha \gamma^\rho \not{p}_1 - D_{\alpha\beta}^3 \gamma^\alpha \gamma^\rho \gamma^\beta (2p_t - p_2)_\sigma \\ & + D_\alpha^3 \gamma^\alpha \gamma^\rho \not{p}_1 (2p_t - p_2)_\sigma] P_R v(p_c), \end{aligned} \quad \text{(A20)}$$

where

$$T_1 = \varepsilon_{mlk} \varepsilon_{nli} (T^a T^b + T^b T^a)_{ik},$$
$$T_2 = \frac{1}{2} \delta_{ab} \delta_{mn} - (T^b T^a)_{mn}, \qquad T_3 = \varepsilon_{mlk} \varepsilon_{nij} T_{il}^a T_{jk}^b, \quad \text{(A21)}$$

with m, n, a, b being, respectively, the color indices of the top, charm and the two gluons, and p_1 and p_2 being the momenta of the two gluons. The loop functions' dependence is given by

$$C = C(-p_t, p_t + p_c, m_{d_j}^2, m_{\tilde{d}_k^R}^2, m_{\tilde{d}_k^R}^2), \quad \text{(A22)}$$

$$D^1 = D(-p_t, -p_c, p_2, m_{d_j}^2, m_{\tilde{d}_k^R}^2, m_{d_j}^2, m_{d_j}^2), \quad \text{(A23)}$$

$$D^2 = D(-p_t, p_1, p_2, m_{d_j}^2, m_{\tilde{d}_k^R}^2, m_{\tilde{d}_k^R}^2, m_{\tilde{d}_k^R}^2), \quad \text{(A24)}$$

$$D^3 = D(-p_t, p_2, -p_c, m_{d_j}^2, m_{\tilde{d}_k^R}^2, m_{\tilde{d}_k^R}^2, m_{d_j}^2). \quad \text{(A25)}$$

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