Top quark FCNC decays and productions at the LHC in the littlest Higgs model with T-parity postprint

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Full Text

Preamble

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Abstract

In the littlest Higgs model with T-parity (LHT), the newly introduced mirror quarks have flavor-changing couplings with the Standard Model (SM) quarks and may enhance the flavor-changing neutral-current (FCNC) top quark interactions, which are extremely suppressed in the SM. In this work, we perform a comprehensive study of the contributions of these mirror fermions to various top quark FCNC decays and productions at the LHC, including the decays $t \to cV$ $(V = g, \gamma, Z)$, $t \to cgg$ and the production processes $cg \to t$, $gg \to t\bar{c}$, $cg \to t\gamma$ and $cg \to tZ$. We find that although these FCNC processes can be greatly enhanced by the LHT contributions, they are hardly accessible at the LHC. Therefore, the LHT model may not cause an FCNC problem in the top quark sector if the top quark properties are proved to be SM-like at the LHC.

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Introduction

As a possible solution to the hierarchy problem, the little Higgs theory was proposed [?, ?, ?, ?, ?] and remains a popular candidate for new physics beyond the Standard Model (SM).

The littlest Higgs model [?, ?, ?, ?] is an economical implementation of the little Higgs idea, but it is found to be subject to strong constraints from electroweak precision tests [?, ?, ?, ?, ?, ?], which would require raising the mass scale of the new particles far above the TeV scale and thus reintroduce fine-tuning in the Higgs potential [?]. To tackle this problem, a discrete symmetry called T-parity is proposed [?, ?, ?, ?], which forbids tree-level contributions from heavy gauge bosons to observables involving only SM particles as external states. With the LHC now running, these little Higgs models will soon be put to the test. To unravel hints of these models, Higgs boson processes may be of primary importance because these models significantly alter the properties of the Higgs boson [?, ?, ?, ?, ?, ?, ?, ?].

Another sensitive probe for new physics such as these little Higgs models is top quark processes. As the heaviest known elementary particle, the top quark may provide a window into TeV-scale physics. So far, top quark properties have not been precisely measured at the Tevatron collider due to limited statistics, leaving plenty of room for new physics in the top quark sector. As a top quark factory, the LHC will allow detailed scrutiny of the top quark' s nature, which may provide clues to new physics [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. For the littlest Higgs model with T-parity (LHT), one aspect of its phenomenology in the top quark sector is that the newly introduced mirror quarks have flavor-changing couplings with SM quarks and may enhance the flavor-changing neutral-current (FCNC) top quark interactions, which are extremely suppressed in the SM [?, ?, ?, ?]. Just like their effects in rare decays of K and B mesons [?, ?] as well as in rare decays of the Higgs and Z bosons [?, ?, ?, ?], their contributions to various top quark FCNC decays and productions at the LHC may be significant and should be carefully examined.

In this work, we collectively study the LHT contributions to top quark FCNC decays and productions at the LHC, including the decay modes $t \to cV$ ($V = g, \gamma, Z$), $t \to cgg$ and the production processes $cg \to t$, $gg \to t\bar{c}$, $cg \to t\gamma$ and $cg \to tZ$. Some of these processes have been studied in the literature [?, ?], while the decay $t \to cgg$ and the production $cg \to t$ have not yet been considered. As found in other new physics models, such as supersymmetric models [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?] and technicolor models [?, ?, ?, ?, ?, ?, ?, ?, ?, ?], these two channels have the largest rates among FCNC top quark processes. On the other hand, contributions from box diagrams, which were not included in previous calculations, should also be considered because their contributions to the production processes are of the same order as the vertex loops. Furthermore, since all these decays and productions depend on the same set of parameters and are strongly correlated, they should be studied and displayed collectively and comparatively.

This paper is organized as follows. In Sec. II we recapitulate the LHT model and discuss the new flavor-violating interactions that contribute to the FCNC processes considered in this work. In Sec. III we calculate the LHT contributions to the top quark FCNC processes and present numerical results. Finally, we give our conclusions in Sec. IV.

II. The Littlest Higgs Model with T-Parity

The LHT model [?] is based on a non-linear sigma model describing the spontaneous breaking of a global $SU(5)$ symmetry down to a global $SO(5)$ by a 5×5 symmetric tensor at the scale f (TeV). From the $SU(5)/SO(5)$ breaking, there arise 14 Goldstone bosons described by the "pion" matrix Π, given explicitly by

$$\Pi = \begin{pmatrix} -\frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} & -\frac{\omega^+}{\sqrt{2}} & -i\frac{\pi^+}{\sqrt{2}} & \cdots \\ -\frac{\omega^-}{\sqrt{2}} & \frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} & \frac{v+h+i\pi^0}{2} & \cdots \\ i\frac{\pi^-}{\sqrt{2}} & \frac{v+h-i\pi^0}{2} & \sqrt{2}\phi^0 + \phi^P & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

Under T-parity, the SM Higgs doublet $H = \begin{pmatrix} \pi^+ \\ (v+h+i\pi^0)/\sqrt{2} \end{pmatrix}$ is T-even while other fields are T-odd. A subgroup $[SU(2) \times U(1)]^2$ of the $SU(5)$ is gauged and at the scale f it is broken into the SM electroweak symmetry $SU(2)_L \times U(1)_Y$. The Goldstone bosons $\omega^0, \omega^\pm$ and η are respectively eaten by the new T-odd gauge bosons Z_H, W_H and A_H, which obtain masses at $\mathcal{O}(v^2/f^2)$:

$$M_{W_H} = M_{Z_H} = fg\left(1 - \frac{v^2}{8f^2}\right), \quad M_{A_H} = \frac{fg'}{\sqrt{5}}\left(1 - \frac{v^2}{8f^2}\right)$$

with g and g' being the SM $SU(2)$ and $U(1)$ gauge couplings, respectively.

The Goldstone bosons π^0 and $\pi^\pm$ are eaten by the T-even Z and W bosons of the SM, which obtain masses at $\mathcal{O}(v^2/f^2)$:

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

The photon A_L is also T-even and remains massless.

For each SM quark, a copy of mirror quark with T-odd quantum number is added to preserve T-parity. We denote them by u_i^H and d_i^H, where $i = 1, 2, 3$ are generation indices. Their masses are given at $\mathcal{O}(v^2/f^2)$ by

$$m_{u_i^H} = \sqrt{2}\kappa_{q_i} f \left(1 - \frac{v^2}{8f^2}\right), \quad m_{d_i^H} = \sqrt{2}\kappa_{q_i} f \left(1 - \frac{v^2}{8f^2}\right)$$

where κ_{q_i} are the diagonalized Yukawa couplings of the mirror quarks.

Note that new flavor interactions arise between the mirror fermions and SM fermions, mediated by T-odd gauge bosons or T-odd Goldstone bosons. In general, besides charged-current flavor-changing interactions, FCNC interactions between mirror fermions and SM fermions can also arise from the mismatch of rotation matrices. For example, there exist FCNC interactions between the mirror up-type (down-type) quarks and SM up-type (down-type) quarks, where the mismatched mixing matrix is denoted by V_{H_u} (V_{H_d}) with $V_{H_u}^\dagger V_{H_d} = V_{\mathrm{CKM}}$. We follow [?] to parameterize V_{H_d} with three angles $\theta_{12}^d, \theta_{13}^d, \theta_{23}^d$ and three phases $\delta_{12}^d, \delta_{13}^d, \delta_{23}^d$:

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

where $s_{ij}^d = \sin\theta_{ij}^d$ and $c_{ij}^d = \cos\theta_{ij}^d$.

III. FCNC Top Quark Processes in the LHT Model

The LHT contributions to FCNC top quark processes arise from interactions between SM quarks and T-odd mirror quarks, mediated by heavy T-odd gauge bosons or Goldstone bosons. The relevant Feynman diagrams for the LHT contributions are shown in Figs. 1-3. The Feynman diagrams for $cg \to t$, $gg \to t\bar{c}$ and $cg \to tg$ are similar to Figs. 1-3 and are not plotted here.

The calculations of the loop diagrams are straightforward. Each loop diagram is composed of scalar loop functions [?], which are calculated using LOOPTOOLS [?, ?]. The relevant Feynman rules can be found in [?]. The analytic expressions for the amplitudes of these processes are lengthy and tedious. Here, as an example, we list the expressions for the amplitudes of $t \to cg$ and $t \to cgg$ in Appendix A. Note that we have checked that the divergences cancel at $\mathcal{O}(v^2/f^2)$ for all processes except the channel $t \to cZ$. This so-called left-over divergence in the LHT model was understood as the sensitivity of the decay amplitudes to the ultraviolet completion of the theory [?]. In our numerical calculations, we follow [?] to remove the divergent term $1/\epsilon$ and take the renormalization scale $\mu = \Lambda$ with $\Lambda = 4\pi f$ being the cutoff scale of the LHT model. Note that in [?] a similar divergence in processes with down-type quarks or leptons as external particles can be cancelled via modified interactions of the up-type mirror fermions with the Z boson. We checked that such a modification cannot lead to the cancellation of the divergence in our case.

In our numerical calculations we take the SM parameters as $m_t = 171.4$ GeV, $m_Z = 91.187$ GeV, $m_W = 80.425$ GeV, $m_c = 1.25$ GeV, $\alpha = 1/128$ and $\alpha_s = 0.107$. The LHT parameters relevant to our study are the scale f, the mirror quark masses and parameters in the matrices V_{H_u} and V_{H_d}. For the scale f, its value may be as low as 500 GeV [?]. For the mirror quark masses, from Eq.(4) we get $m_{u_i^H} = m_{d_i^H} = \sqrt{2}\kappa_{q_i} f(1-v^2/8f^2)$ and further we assume $m_{u_1^H} = m_{u_2^H} = m_{d_1^H} = m_{d_2^H} \equiv m_{12}$ and $m_{u_3^H} = m_{d_3^H} \equiv m_3$.

For the matrices V_{H_u} and V_{H_d}, considering the constraints in [?], we follow [?] to consider two scenarios:

(I) $V_{H_d} = 1$, $V_{H_u} = V^\dagger_{\mathbf{CKM}}$. In this scenario, the constraints on the mass spectrum of the mirror fermions can be relaxed [?]. The decay branching ratios in this scenario are plotted in Fig. 4, where we fix $m_{12} = 300$ GeV and $f = 500$ GeV for the left frame, while for the right frame we assume $m_{12} = 0.6f$ and $m_3 = 3f$ (which corresponds to fixing the Yukawa couplings κ_{q_i} in Eq. 4).

(II) $s^d_{12} = s^d_{23} = 1/\sqrt{2}$, $s^d_{13} = 0$, $\delta^d_{12} = \delta^d_{13} = \delta^d_{23} = 0$. In this scenario, the D-meson system can give strong constraints on the relevant parameters [?]. Considering these constraints, we fix $f = 1000$ GeV and $m_{12} = 500$ GeV for the results shown in the left frame of Fig. 5. In the right frame of Fig. 5 we show the results as a function of the scale f under the assumption $m_{12} = 0.5f$ and $m_3 = 1.2f$.

As shown in the left frames of Figs. 4 and 5, the branching ratios increase with the mass of the third-generation mirror fermions. The reason is that the decays are enhanced by the large mass splitting $m_3 - m_{12}$, which increases as m_3 gets large since we fix the value of m_{12}. From our numerical calculation we found that the contribution of each Feynman diagram in Fig. 1 increases drastically with m_3, but there is a strong cancellation between different diagrams for the decays $t \to cg$, $c\gamma$, cgg. For the decay $t \to cZ$, such cancellation is weak because of the left-over divergence. Therefore, the enhancement with m_3 is rapid for $t \to cZ$ but mild for other decay modes. As shown in the right frames of Figs. 4 and 5, the branching ratios drop as the scale f (together with m_{12} and m_3) gets large, showing the decoupling behavior of the scale f in FCNC top quark decays.

From Figs. 4 and 5 we see that the branching ratio of $t \to cgg$ is larger than that of $t \to cg$. Such a feature was also found in the SM [?, ?, ?, ?] and the minimal supersymmetric model [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?], and the reason is explained in the literature [?]. Another peculiar and unexpected phenomenon is that the branching ratio of $t \to cZ$ is the largest. This is unique to the LHT model. The reason is that, unlike other decay modes, $t \to cZ$ is special since it has the left-over divergence and is sensitive to the cutoff scale.

Now we turn to the top quark FCNC productions at the LHC and present some numerical results. In our calculations we use CTEQ6L [?] 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 cross sections displayed in our numerical results are the hadronic cross sections. Also, we take into account the charge-conjugate channel for each process.

The cross sections are plotted in Figs. 6 and 7 for scenarios I and II, respectively. The behavior of the curves is similar to those in Figs. 4 and 5, i.e., they increase with m_3 and decrease with the scale f. Also, similar to the decay $t \to cZ$, the production rate of $cg \to tZ$ increases rapidly with m_3 because of its left-over divergence at $\mathcal{O}(v^2/f^2)$.

For the top FCNC decays, the LHC sensitivity with an integrated luminosity of 100 fb^{-1} is about 10^{-5} for $t \to c\gamma$ and $t \to cZ$ [?, ?, ?, ?] while for $t \to cg$ and $t \to cgg$ the sensitivity may be much worse [?]. From Figs. 4 and 5 we see that the decay branching ratios are below 10^{-7} and thus are not accessible at the LHC.

For the top FCNC productions, the LHC sensitivity is at the pb level for $cg \to t$, $gg \to t\bar{c}$ and $cg \to tg$ while at the fb level for $cg \to tZ$ and $cg \to t\gamma$ [?, ?, ?, ?]. From Figs. 6 and 7 we see that the top FCNC productions in the LHT model are not accessible at the LHC.

Therefore, we conclude that although the LHT model can enhance the top quark FCNC processes relative to the SM predictions, its contributions are not large enough to be accessible at the LHC. This is in contrast to topcolor-assisted technicolor models which give exceedingly large contributions above the LHC sensitivity [?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. The minimal supersymmetric model with R-parity conservation gives quite mild contributions to these FCNC processes of the top quark, and only a couple of channels can marginally reach the LHC sensitivity in a tiny part of the parameter space [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. If R-parity is violated, then the minimal supersymmetric model can give large contributions [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. So, if the top quark properties are proved to be SM-like at the LHC and hence the top FCNC processes are not observed, topcolor-assisted technicolor models and R-parity violation in supersymmetric models will be severely constrained, while the R-conserving minimal supersymmetric model will be very mildly constrained and the LHT model will not be constrained.

Note that in [?] the LHT contributions to some FCNC top decay processes were found to be quite large. Unfortunately, our calculations cannot reproduce such large effects. Our results indicate that the LHT model does not cause a flavor problem for the top quark sector.

IV. Conclusions

In the littlest Higgs model with T-parity, the T-odd mirror quarks have flavor-changing couplings with Standard Model quarks and may enhance the FCNC top quark interactions. We performed a comprehensive study of the contributions of these mirror fermions to various top quark FCNC decays and productions at the LHC. We found that although these FCNC processes can be greatly enhanced by the contributions of the mirror quarks, they are hardly accessible at the LHC. Therefore, this model may not cause an FCNC problem in the top quark sector if the top quark properties are proved to be SM-like at the LHC.

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Appendix A: The Amplitudes of $t \to cg$ and $t \to cgg$ in LHT

The amplitudes for various top FCNC processes are complicated and lengthy. Here, we only take $t \to cg$ and $t \to cgg$ as examples. The amplitude of $t \to cg$ is given by

$$\mathcal{M}(t \to cg) = \frac{ig_s T^a}{16\pi^2}\bar{u}_c(p_2)[(L_1 q^\mu + L_2 p_1^\mu + L_3\gamma^\mu)P_L + (R_1 q^\mu + R_2 p_1^\mu + R_3\gamma^\mu)P_R]u_t(p_1)\epsilon_\mu(q,\lambda),$$

where p_1, p_2, and q are the momenta of the top quark, charm quark, and gluon respectively, $\epsilon_\mu(q,\lambda)$ is the polarization vector of the gluon, $P_{L,R} = (1 \mp \gamma_5)/2$, and T^a are the generators of $SU(3)_C$. The factors $L_i, R_i (i = 1,2,3)$ are the LHT contributions from the diagrams in Fig. 1, which include scalar parts $(L_i)_S, (R_i)_S$ and vector parts $(L_i)_V, (R_i)_V$.

The scalar parts are given by:

$$\begin{aligned}
(L_1)_S &= 2m_c b_2 a_3(C_{21} + C_{11}) + 2m_t a_2 b_3(C_{23} + C_{12}) + 2m_f a_2 a_3(C_{11} + C_0),\\
(L_2)_S &= 2m_c b_2 a_3(C_{21} + C_{11} - C_{12}) + 2m_t a_2 b_3(C_{22} - C_{23} - C_{12}) + 2m_f a_2 a_3(C_{12} - C_{11} - C_0),\\
(L_3)_S &= b_2 a_3[m_c^2(C_{23} + C_{12} - C_{11}) + m_t^2 C_{21} - m_f^2(C_{23} - C_{11}) + m_f(m_t b_2 b_3 + m_c a_2 a_3 + m_f b_2 a_3)C_0 + C_{22}) + \\
&\quad + a_2 b_3 m_c m_t(C_{12} - C_{11}) + b_2 a_3[m_c^2(B_0(p_1) + B_1(p_1)) - m_t^2(B_0(p_1) + B_1(p_1)) - m_c^2(B_0(p_2) + B_1(p_2))]\\
&\quad + b_2 b_3 m_f m_t(B_0(p_1) - B_0(p_2)) + a_2 a_3 m_f m_c(B_0(p_1) - B_0(p_2)),
\end{aligned}$$

$$\begin{aligned}
(R_1)_S &= 2m_t b_2 a_3(C_{23} + C_{12}) - 2m_c a_2 b_3(C_{21} + C_{11}) + 2m_f b_2 b_3(C_{11} + C_0),\\
(R_2)_S &= 2m_t b_2 a_3(C_{22} - C_{23} - C_{12}) - 2m_c a_2 b_3(C_{21} + C_{11} - C_{12}) + 2m_f b_2 b_3(C_{12} - C_{11} - C_0),\\
(R_3)_S &= a_2 b_3[m_c^2(C_{23} + C_{12} - C_{11}) + m_t^2 C_{21} - m_f^2(C_{23} - C_{11}) + m_f(b_2 b_3 m_c + a_2 a_3 m_t + a_2 b_3 m_f)C_0 + C_{22}) + \\
&\quad + b_2 a_3 m_c m_t(C_{12} - C_{11}) + a_2 b_3[m_c^2(B_0(p_1) + B_1(p_1)) - m_t^2(B_0(p_1) + B_1(p_1)) - m_c^2(B_0(p_2) + B_1(p_2))]\\
&\quad + a_2 a_3 m_f m_t(B_0(p_1) - B_0(p_2)) + b_2 b_3 m_f m_c(B_0(p_1) - B_0(p_2)),
\end{aligned}$$

where $C_{ij}(p_2, p_1, m_f, m_S, m_f)$, $B_i(p_1)(p_1, m_S, m_f)$ and $B_i(p_2)(p_2, m_S, m_f)$ are loop functions [**?**].

The vector parts are given by:

$$
\begin{aligned}
(L_1)_V &= 4m_c c_2 c_3 (C_{21} + C_{11}),\\
(L_2)_V &= 4m_c c_2 c_3 (C_{23} - C_{21}),\\
(L_3)_V &= 2c_2 c_3 [m_c^2 (C_{21} - C_{23}) + m_t^2 (C_{22} + C_{12} - C_{23} - C_{11}) + m_f^2 C_0 + 2C_{24} - \frac{1}{2} + m_c^2 (2B_0(p_2) + 2B_1(p_2)) -\\
(R_1)_V &= 4m_t c_2 c_3 (C_{23} + C_{11}),\\
(R_2)_V &= 4m_t c_2 c_3 (C_{23} + C_{11} - C_{12}),\\
(R_3)_V &= 2c_2 c_3 m_c m_t (C_{12} - C_{11}) + 2c_2 c_3 m_c m_t [B_0(p_2) + B_1(p_2) - B_0(p_1) - B_1(p_1)],
\end{aligned}
$$

with $C_{ij}(p_2, p_1, m_f, m_V, m_f)$, $B_i(p_1)(p_1, m_V, m_f)$ and $B_i(p_2)(p_2, m_V, m_f)$. Other relevant parameters are from the vertices:

$$
S\bar{c}f : a_2 P_L + b_2 P_R, \quad S\bar{f}t : a_3 P_L + b_3 P_R, \quad V\bar{c}f : i\gamma_\mu c_2 P_L, \quad V\bar{f}t : i\gamma_\mu c_3 P_L,
$$

where V represents gauge bosons and S represents scalar particles. These couplings represent the five different classes of vertices involved in our calculation. In each class of vertices, the parameters $a_2, b_2, a_3, b_3, c_2, c_3$ take different values for every concrete coupling. The analytic expressions of these parameters are complicated at $\mathcal{O}(v^2/f^2)$ and can be found in [**?**].

Now we give the amplitude of $t \to cgg$. The expressions for Figs. 2(a-c) are simple and can be obtained straightforwardly from the effective tcg vertex. For the box diagrams (d) and (e) in Fig. 2, their expressions are given by

$$
\mathcal{M}_{\rm box}^{(S)} = \frac{g_s^2}{16\pi^2} T_{ij}^a T_{jk}^b \bar{u}_c(p_2)(a_2 P_L + b_2 P_R) S_{\rm box} (a_3 P_L + b_3 P_R) u_t(p_1),
$$

$$
\mathcal{M}_{\rm box}^{(V)} = \frac{g_s^2}{16\pi^2} T_{ij}^a T_{jk}^b \bar{u}_c(p_2) \gamma^\rho c_2 P_L S_{\rm box} c_3 P_L \gamma^\rho u_t(p_1),
$$

where

$$
\begin{aligned}
S_{\rm box} = {} & D_{\alpha\beta\gamma\gamma} \gamma^\alpha \epsilon_1^{*\beta} \gamma^\gamma \epsilon_2^{*\gamma} + D_{\alpha\beta} [m_f \gamma^\alpha \epsilon_1^{*\beta} \epsilon_2^{*\gamma} + \gamma^\alpha \epsilon_1^{*\beta} (m_f \epsilon_2^{*\gamma})]\\
& + D_\alpha [m_f (m_f \epsilon_2^{*\gamma}) \gamma^\alpha + m_f \gamma^\alpha \epsilon_1^{*\beta} (m_f \epsilon_2^{*\gamma})] + D_0 m_f (m_f \epsilon_1^{*\beta})(m_f \epsilon_2^{*\gamma}),
\end{aligned}
$$

with $D(p_2, p_1, q_1, q_2, m_f, m_{S(V)}, m_f, m_f)$ being the 4-point loop function [**?**], p_1, p_2, q_1 and q_2 being respectively the momenta of the top quark, charm quark, and two emitting gluons, and ϵ_1 and ϵ_2 being the polarization vectors of the gluons.

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