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Supersymmetric QCD flavor-changing top quark decay

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We present a detailed and complete calculation of the gluino and scalar quarks contribution to the flavor-changing top quark decay into a charm quark and a photon, gluon, or a Z^0 boson within the minimal supersymmetric standard model including flavor-changing gluino-quark-scalar-quark couplings in the right-handed sector. We compare the results with the ones presented in an earlier paper where we considered flavor-changing couplings only in the left-handed sector. We show that these new couplings have important consequences leading to a large enhancement when the mixing of the scalar partners of the left- and right-handed top quark is included. Furthermore CP violation in the flavor-changing top quark decay will occur when a SUSY phase is taken into account. [S0556-2821(97)07419-5]

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I. INTRODUCTION

Flavor-changing top quark decay modes are a promising test ground for models beyond the standard model (SM). While in the SM the branching ratios of the decays $t\rightarrow c\gamma$, cg, and cZ are far away from experimental reach [1–5], the authors of [5,6] showed that they are enhanced by several (3–4) orders of magnitude in two-Higgs-doublet models (THDM's).

Nowadays, the Collider Detector at Fermilab (CDF) [7,8] and D0 Collaborations [9] have begun to explore flavor-changing top quark decays and interesting bounds have been reported [8]. A systematic examination of anomalous top quark interactions is actively pursued [10–15].

Within supersymmetry, the decays $t\rightarrow cV$ were first considered in [16] and the authors obtained the same enhancement as in the THDM's. However as we have pointed out in a recent paper [17], in their calculation of the QCD corrections they had an inconsistency basically due to the lack of gauge invariance arising from the omission of the gluino-gluino-gluon coupling. They also did not include the non-negligible mixing of the scalar partners of the left- and right-handed quarks. In a very recent paper [18] the calculations were redone for the weak sector with charginos and neutralinos within the relevant loops including the mixing of the scalar quarks, where it was shown that supersymmetric contributions to $t\rightarrow cV$ can be up to 5 orders of magnitude larger than their SM counterparts.

In our previous paper [17] the results of the gluino and scalar quarks contribution to the flavor-changing top quark decay into a charm quark and a photon, a gluon, or a Z^0 boson within the minimal supersymmetric standard model (MSSM) were presented. We included the mixing of the scalar partners of the left- and right-handed top quark and showed that it has several effects, the most important of which is to enhance greatly the cZ decay mode for large values of the soft SUSY-breaking scalar mass m_S and to give rise to a Glashow-Iliopoulos-Maiani- (GIM-) like suppression in the $c\gamma$ mode for certain combinations of parameters.

However the analysis of [17] considered flavor-changing strong interactions between the gluino, the quarks, and their scalar partners only in the left-handed sector and kept the right-handed sector flavor-diagonal. This is a common assumption within the MSSM (see [17] and references therein) and might not be necessarily the case in any kind of extension of the MSSM, or more general assumptions within the MSSM.

The goal of this paper is to recalculate the flavor-changing top quark decays including flavor-changing couplings within the right-handed sector. We will assume maximal flavor-changing in both sectors and analyze how the previous results will be changed. Furthermore we show that flavor-changing couplings in the left- and right-handed sectors lead to a CP-violating term proportional to the gluino mass for the top quark decay modes under consideration, which will be investigated in a further paper [19].

The Feynman diagrams and the couplings leading to the decay modes $t\rightarrow c\gamma$, cZ, and cg as well as the mass matrix of the scalar top quark are given in [17]. The only difference will be the flavor-changing gluino-scalar quark-quark coupling in Eq. (6) of [17], which will be taken in the present paper in the most general way:

$$\mathcal{L}_{\mathcal{FC}}=-\sqrt{2}g_sT^a\overline{\tilde{g}_a}[K_L^{\tilde{g}}(c_\Theta\tilde{q}_1-s_\Theta\tilde{q}_2)P_L-K_R^{\tilde{g}}(s_\Theta\tilde{q}_1+c_\Theta\tilde{q}_2)P_R]q+\text{H.c.} \tag{1}$$

Here $K_{L,R}^{\tilde{g}}$ is the supersymmetric version of the Kobayashi-Maskawa matrix and Θ is the mixing angle of the scalar partners of the left- and right-handed quarks. $\tilde{q}_1$ and $\tilde{q}_2$ are the mass eigenstates which are related to the current eigenstates $\tilde{q}_L$ and $\tilde{q}_R$ by

$$\tilde{q}_1=\cos\Theta\,\tilde{q}_L+\sin\Theta\,q_R,\quad \tilde{q}_2=-\sin\Theta\,\tilde{q}_L+\cos\Theta\,q_R. \tag{2}$$

II. SUSY QCD FLAVOR-CHANGING TOP QUARK DECAY

After summation over all diagrams, we obtain the following effective tcV vertex, neglecting the charm quark mass:

$$M^{\alpha}_{\mu V}=-i\frac{\alpha_s}{2\pi}\overline{u}_{p_2}\bigg[\gamma_\mu(P_L V^{\alpha}_{VL}+P_R V^{\alpha}_{VR})+\frac{P_\mu}{m_{\rm top}}(P_L T^{\alpha}_{VL}+P_R T^{\alpha}_{VR})\bigg]u_{p_1}, \tag{3}$$

$$V^{\alpha}_{\gamma L}=ee_q C_2(F)\bigg\{K^{*\tilde g}_{\alpha 2L}K^{\tilde g}_{\alpha 3L}[c^2_{\Theta_\alpha}(C^{11\alpha}_{\epsilon}-C^{1\alpha}_{\rm SE})+s^2_{\Theta_\alpha}(C^{22\alpha}_{\epsilon}-C^{2\alpha}_{\rm SE})]+K^{*\tilde g}_{\alpha 2L}K^{\tilde g}_{\alpha 3R}c_{\Theta_\alpha}s_{\Theta_\alpha}\frac{m_{\tilde g}}{m_{\rm top}}\times(C^{1\alpha}_{\rm SEG}-C^{1\alpha}_{\rm SEG}|_{m^2_{\rm top}=0}-C^{2\alpha}_{\rm SEG}+C^{2\alpha}_{\rm SEG}|_{m^2_{\rm top}=0})\bigg\},$$

$$V^{\alpha}_{\gamma R}=ee_q C_2(F)\bigg\{K^{*\tilde g}_{\alpha 2R}K^{\tilde g}_{\alpha 3R}[s^2_{\Theta_\alpha}(C^{11\alpha}_{\epsilon}-C^{1\alpha}_{\rm SE})+c^2_{\Theta_\alpha}(C^{22\alpha}_{\epsilon}-C^{2\alpha}_{\rm SE})]+K^{*\tilde g}_{\alpha 2R}K^{\tilde g}_{\alpha 3L}c_{\Theta_\alpha}s_{\Theta_\alpha}\frac{m_{\tilde g}}{m_{\rm top}}\times(C^{1\alpha}_{\rm SEG}-C^{1\alpha}_{\rm SEG}|_{m^2_{\rm top}=0}-C^{2\alpha}_{\rm SEG}+C^{2\alpha}_{\rm SEG}|_{m^2_{\rm top}=0})\bigg\},$$

$$T^{\alpha}_{\gamma L}=ee_q C_2(F)[K^{*\tilde g}_{\alpha 2R}K^{\tilde g}_{\alpha 3R}(s^2_{\Theta_\alpha}C^{11\alpha}_{\rm top}+c^2_{\Theta_\alpha}C^{22\alpha}_{\rm top})-K^{*\tilde g}_{\alpha 2R}K^{\tilde g}_{\alpha 3L}c_{\Theta_\alpha}s_{\Theta_\alpha}(C^{11\alpha}_{\tilde g\,\rm top}-C^{22\alpha}_{\tilde g\,\rm top})],$$

$$T^{\alpha}_{\gamma R}=ee_q C_2(F)[K^{*\tilde g}_{\alpha 2L}K^{\tilde g}_{\alpha 3L}(c^2_{\Theta_\alpha}C^{11\alpha}_{\rm top}+s^2_{\Theta_\alpha}C^{22\alpha}_{\rm top})-K^{*\tilde g}_{\alpha 2L}K^{\tilde g}_{\alpha 3R}c_{\Theta_\alpha}s_{\Theta_\alpha}(C^{11\alpha}_{\tilde g\,\rm top}-C^{22\alpha}_{\tilde g\,\rm top})],$$

$$V^{\alpha}_{gL}=g_sT^a\bigg\{K^{*\tilde g}_{\alpha 2L}K^{\tilde g}_{\alpha 3L}\bigg\{\bigg(-\frac12 C_2(G)+C_2(F)\bigg)(c^2_{\Theta_\alpha}C^{11\alpha}_{\epsilon}+s^2_{\Theta_\alpha}C^{22\alpha}_{\epsilon})-C_2(F)(c^2_{\Theta_\alpha}C^{1\alpha}_{\rm SE}+s^2_{\Theta_\alpha}C^{2\alpha}_{\rm SE})+\frac12 C_2(G)\times[c^2_{\Theta_\alpha}(C^{\tilde g 1\alpha}_{\epsilon}+C^{1\alpha}_{\tilde g}+C^{1\alpha}_{q^2}+C^{1\alpha}_{t})+s^2_{\Theta_\alpha}(C^{\tilde g 2\alpha}_{\epsilon}+C^{2\alpha}_{\tilde g}+C^{2\alpha}_{q^2}+C^{2\alpha}_{t})]\bigg\}+K^{*\tilde g}_{\alpha 2L}K^{\tilde g}_{\alpha 3R}c_{\Theta_\alpha}s_{\Theta_\alpha}\bigg[C_2(F)\frac{m_{\tilde g}}{m_{\rm top}}(C^{1\alpha}_{\rm SEG}-C^{1\alpha}_{\rm SEG}|_{m^2_{\rm top}=0}-C^{2\alpha}_{\rm SEG}+C^{2\alpha}_{\rm SEG}|_{m^2_{\rm top}=0})-\frac12 C_2(G)\frac{m_{\rm top}}{m_{\tilde g}}(C^{1\alpha}_{\tilde g}-C^{2\alpha}_{\tilde g})\bigg]\bigg\},$$

$$V^{\alpha}_{gR}=g_sT^a\bigg\{K^{*\tilde g}_{\alpha 2R}K^{\tilde g}_{\alpha 3R}\bigg[\bigg(-\frac12 C_2(G)+C_2(F)\bigg)(s^2_{\Theta_\alpha}C^{11\alpha}_{\epsilon}+c^2_{\Theta_\alpha}C^{22\alpha}_{\epsilon})-C_2(F)(s^2_{\Theta_\alpha}C^{1\alpha}_{\rm SE}+c^2_{\Theta_\alpha}C^{2\alpha}_{\rm SE})+\frac12 C_2(G)\times[s^2_{\Theta_\alpha}(C^{\tilde g 1\alpha}_{\epsilon}+C^{1\alpha}_{\tilde g}+C^{1\alpha}_{q^2}+C^{1\alpha}_{t})+c^2_{\Theta_\alpha}(C^{\tilde g 2\alpha}_{\epsilon}+C^{2\alpha}_{\tilde g}+C^{2\alpha}_{q^2}+C^{2\alpha}_{t})]\bigg]+K^{*\tilde g}_{\alpha 2R}K^{\tilde g}_{\alpha 3L}c_{\Theta_\alpha}s_{\Theta_\alpha}\bigg[C_2(F)\frac{m_{\tilde g}}{m_{\rm top}}\times(C^{1\alpha}_{\rm SEG}-C^{1\alpha}_{\rm SEG}|_{m^2_{\rm top}=0}-C^{2\alpha}_{\rm SEG}+C^{2\alpha}_{\rm SEG}|_{m^2_{\rm top}=0})-\frac12 C_2(G)\frac{m_{\rm top}}{m_{\tilde g}}(C^{1\alpha}_{\tilde g}-C^{2\alpha}_{\tilde g})\bigg]\bigg\},$$

$$T^{\alpha}_{gL}=g_sT^a\bigg(K^{*\tilde g}_{\alpha 2R}K^{\tilde g}_{\alpha 3R}\bigg[\bigg(-\frac12 C_2(G)+C_2(F)\bigg)(s^2_{\Theta_\alpha}C^{11\alpha}_{\rm top}+c^2_{\Theta_\alpha}C^{22\alpha}_{\rm top})-\frac12 C_2(G)(s^2_{\Theta_\alpha}C^{1\alpha}_{t}+c^2_{\Theta_\alpha}C^{2\alpha}_{t})\bigg]-K^{*\tilde g}_{\alpha 2R}K^{\tilde g}_{\alpha 3L}c_{\Theta_\alpha}s_{\Theta_\alpha}\bigg\{\bigg(-\frac12 C_2(G)+C_2(F)\bigg)\times(C^{11\alpha}_{\tilde g\,\rm top}-C^{22\alpha}_{\tilde g\,\rm top})+\frac12 C_2(G)\bigg[C^{1\alpha}_{\tilde g t}-C^{2\alpha}_{\tilde g t}-\frac{m_{\rm top}}{m_{\tilde g}}(C^{1\alpha}_{\tilde g}-C^{2\alpha}_{\tilde g})\bigg]\bigg\}\bigg),$$

$$T^{\alpha}_{gR}=g_sT^a\bigg(K^{*\tilde g}_{\alpha 2L}K^{\tilde g}_{\alpha 3L}\bigg[\bigg(-\frac12 C_2(G)+C_2(F)\bigg)(c^2_{\Theta_\alpha}C^{11\alpha}_{\rm top}+s^2_{\Theta_\alpha}C^{22\alpha}_{\rm top})-\frac12 C_2(G)(c^2_{\Theta_\alpha}C^{1\alpha}_{t}+s^2_{\Theta_\alpha}C^{2\alpha}_{t})t\bigg]-K^{*\tilde g}_{\alpha 2L}K^{\tilde g}_{\alpha 3R}c_{\Theta_\alpha}s_{\Theta_\alpha}\bigg\{\bigg(-\frac12 C_2(G)+C_2(F)\bigg)\times(C^{11\alpha}_{\tilde g\,\rm top}-C^{22\alpha}_{\tilde g\,\rm top})+\frac12 C_2(G)\bigg[C^{1\alpha}_{\tilde g t}-C^{2\alpha}_{\tilde g t}-\frac{m_{\rm top}}{m_{\tilde g}}(C^{1\alpha}_{\tilde g}-C^{2\alpha}_{\tilde g})\bigg]\bigg\}\bigg),$$

$$V^{\alpha}_{ZL}=\frac{e}{s_Wc_W}C_2(F)\bigg\{K^{*\tilde g}_{\alpha 2L}K^{\tilde g}_{\alpha 3L}[(T_{3L}c^2_{\Theta_\alpha}-e_qs^2_W)c^2_{\Theta_\alpha}C^{11\alpha}_{\epsilon}+(T_{3L}s^2_{\Theta_\alpha}-e_qs^2_W)s^2_{\Theta_\alpha}C^{22\alpha}_{\epsilon}+T_{3L}c^2_{\Theta_\alpha}s^2_{\Theta_\alpha}\times(C^{12\alpha}_{\epsilon}+C^{21\alpha}_{\epsilon})-(T_{3L}-e_qs^2_W)(c^2_{\Theta_\alpha}C^{1\alpha}_{\rm SE}+s^2_{\Theta_\alpha}C^{2\alpha}_{\rm SE})]+K^{*\tilde g}_{\alpha 2L}K^{\tilde g}_{\alpha 3R}c_{\Theta_\alpha}s_{\Theta_\alpha}(T_{3L}-e_qs^2_W)\frac{m_{\tilde g}}{m_{\rm top}}\times(C^{1\alpha}_{\rm SEG}-C^{1\alpha}_{\rm SEG}|_{m^2_{\rm top}=0}-C^{2\alpha}_{\rm SEG}+C^{2\alpha}_{\rm SEG}|_{m^2_{\rm top}=0})\bigg\},$$

$$V^{\alpha}_{ZR}=\frac{e}{s_Wc_W}C_2(F)\bigg\{K^{*\tilde g}_{\alpha 2R}K^{\tilde g}_{\alpha 3R}[(T_{3L}c^2_{\Theta_\alpha}-e_qs^2_W)s^2_{\Theta_\alpha}C^{11\alpha}_{\epsilon}+(T_{3L}s^2_{\Theta_\alpha}-e_qs^2_W)c^2_{\Theta_\alpha}C^{22\alpha}_{\epsilon}-T_{3L}c^2_{\Theta_\alpha}s^2_{\Theta_\alpha}\times(C^{12\alpha}_{\epsilon}+C^{21\alpha}_{\epsilon})+e_qs^2_W(s^2_{\Theta_\alpha}C^{1\alpha}_{\rm SE}+c^2_{\Theta_\alpha}C^{2\alpha}_{\rm SE})]-K^{*\tilde g}_{\alpha 2L}K^{\tilde g}_{\alpha 3R}c_{\Theta_\alpha}s_{\Theta_\alpha}e_qs^2_W\frac{m_{\tilde g}}{m_{\rm top}}(C^{1\alpha}_{\rm SEG}-C^{1\alpha}_{\rm SEG}|_{m^2_{\rm top}=0}-C^{2\alpha}_{\rm SEG}+C^{2\alpha}_{\rm SEG}|_{m^2_{\rm top}=0})\bigg\},$$

$$T_{ZL}^{\alpha}=\frac{e}{s_W c_W}C_2(F)\{K^{*\tilde{g}}_{\alpha 2R}K^{\tilde{g}}_{\alpha 3R}[(T_{3L}c^2_{\Theta_\alpha}-e_q s_W^2)s^2_{\Theta_\alpha}C^{11\alpha}_{\text{top}}+(T_{3L}s^2_{\Theta_\alpha}-e_q s_W^2)c^2_{\Theta_\alpha}C^{22\alpha}_{\text{top}}-T_{3L}c^2_{\Theta_\alpha}s^2_{\Theta_\alpha}(C^{12\alpha}_{\text{top}}+C^{21\alpha}_{\text{top}})]-K^{*\tilde{g}}_{\alpha 2R}K^{\tilde{g}}_{\alpha 3L}c_{\Theta_\alpha}s_{\Theta_\alpha}\times[(T_{3L}c^2_{\Theta_\alpha}-e_q s_W^2)C^{11\alpha}_{\tilde{g}\text{top}}-(T_{3L}s^2_{\Theta_\alpha}-e_q s_W^2)C^{22\alpha}_{\tilde{g}\text{top}}-T_{3L}(c^2_{\Theta_\alpha}C^{12\alpha}_{\tilde{g}\text{top}}-s^2_{\Theta_\alpha}C^{21\alpha}_{\tilde{g}\text{top}})]\},$$

$$T_{ZR}^{\alpha}=\frac{e}{s_W c_W}C_2(F)\{K^{*\tilde{g}}_{\alpha 2L}K^{\tilde{g}}_{\alpha 3L}[(T_{3L}c^2_{\Theta_\alpha}-e_q s_W^2)c^2_{\Theta_\alpha}C^{11\alpha}_{\text{top}}+(T_{3L}s^2_{\Theta_\alpha}-e_q s_W^2)s^2_{\Theta_\alpha}C^{22\alpha}_{\text{top}}+T_{3L}c^2_{\Theta_\alpha}s^2_{\Theta_\alpha}(C^{12\alpha}_{\text{top}}+C^{21\alpha}_{\text{top}})]-K^{*\tilde{g}}_{\alpha 2L}K^{\tilde{g}}_{\alpha 3R}c_{\Theta_\alpha}s_{\Theta_\alpha}\times[(T_{3L}c^2_{\Theta_\alpha}-e_q s_W^2)C^{11\alpha}_{\tilde{g}\text{top}}-(T_{3L}s^2_{\Theta_\alpha}-e_q s_W^2)C^{22\alpha}_{\tilde{g}\text{top}}+T_{3L}(s^2_{\Theta_\alpha}C^{12\alpha}_{\tilde{g}\text{top}}-c^2_{\Theta_\alpha}C^{21\alpha}_{\tilde{g}\text{top}})]\},$$

$$C^{kl\alpha}_{\epsilon}=\int_0^1 d\alpha_1\int_0^{1-\alpha_1}d\alpha_2\left(\frac{1}{\epsilon}-\gamma+\ln(4\pi\mu^2)-\ln(f^{\alpha}_{kl})\right),$$

$$C^{kl\alpha}_{\text{top}}=\int_0^1 d\alpha_1\int_0^{1-\alpha_1}d\alpha_2\frac{m^2_{\text{top}}\alpha_1(1-\alpha_1-\alpha_2)}{f^{\alpha}_{kl}},$$

$$C^{kl\alpha}_{\tilde{g}\text{top}}=\int_0^1 d\alpha_1\int_0^{1-\alpha_1}d\alpha_2\frac{m_{\tilde{g}}\, m_{\text{top}}(1-\alpha_1-\alpha_2)}{f^{\alpha}_{kl}},$$

$$C^{k\alpha}_{\text{SE}}=\int_0^1 d\alpha_1\alpha_1\left(\frac{1}{\epsilon}-\gamma+\ln(4\pi\mu^2)-\ln(g^{\alpha}_k)\right),$$

$$C^{k\alpha}_{\text{SEG}}=\frac{1}{\alpha_1}C^{k\alpha}_{\text{SE}},$$

$$C^{\tilde{g}k\alpha}_{\epsilon}=\int_0^1 d\alpha_1\int_0^{1-\alpha_1}d\alpha_2\left(\frac{1}{\epsilon}-\gamma-1+\ln(4\pi\mu^2)-\ln(h^{\alpha}_k)\right),$$

$$C^{k\alpha}_{\tilde{g}}=\int_0^1 d\alpha_1\int_0^{1-\alpha_1}d\alpha_2\frac{m^2_{\tilde{g}}}{h^{\alpha}_k},$$

$$C^{k\alpha}_{q^2}=\int_0^1 d\alpha_1\int_0^{1-\alpha_1}d\alpha_2\frac{q^2\alpha_1\alpha_2}{h^{\alpha}_k},$$

$$C^{k\alpha}_{t}=\int_0^1 d\alpha_1\int_0^{1-\alpha_1}d\alpha_2\frac{m^2_{\text{top}}\alpha_1(1-\alpha_1-\alpha_2)}{h^{\alpha}_k},$$

$$C^{k\alpha}_{\tilde{g}t}=\int_0^1 d\alpha_1\int_0^{1-\alpha_1}d\alpha_2\frac{m_{\tilde{g}}m_{\text{top}}(1-\alpha_1-\alpha_2)}{h^{\alpha}_k},$$

$$f^{\alpha}_{kl}=m^2_{\tilde{g}}-(m^2_{\tilde{g}}-m^2_{\tilde{q}^{\alpha}_k})\alpha_1-(m^2_{\tilde{g}}-m^2_{\tilde{q}^{\alpha}_l})\alpha_2-m^2_{\text{top}}\alpha_1(1-\alpha_1-\alpha_2)-q^2\alpha_1\alpha_2,$$

$$g^{\alpha}_k=m^2_{\tilde{g}}-(m^2_{\tilde{g}}-m^2_{\tilde{q}^{\alpha}_k})\alpha_1-m^2_{\text{top}}\alpha_1(1-\alpha_1),$$

$$h^{\alpha}_k=m^2_{\tilde{q}^{\alpha}_k}-(m^2_{\tilde{q}^{\alpha}_k}-m^2_{\tilde{g}})(\alpha_1+\alpha_2)-m^2_{\text{top}}\alpha_1(1-\alpha_1-\alpha_2)-q^2\alpha_1\alpha_2,$$

where $\epsilon=2-d/2$, $C_2(F)=4/3$, and $C_2(G)=3$ for SU(3). If $\alpha\neq\text{top}$ we have $c_{\Theta_\alpha}=1$. Using the spin-1 condition $[q_\mu=(p_1-p_2)_\mu=0]$ we can write $P_\mu=(p_1+p_2)_\mu=2p_{1\mu}$. $K^{g}_{\alpha iL,R}$ is the supersymmetric- (SUSY-) Kobayashi-Maskawa matrix; which, as explained in [17], will be parametrized by a small number ε (not to be confused with the ϵ above) to be taken as $\varepsilon^2=1/4$ [16,20]. It is straightforward at this point to verify that all divergent terms cancel exactly in a nontrivial way, without making use of the GIM mechanism. The results of [17] are reproduced with $K^{\tilde{g}}_{\alpha 2,3R}=0$, that is $V_{VR}=0=T_{VL}$. Note that with $K^{\tilde{g}}_{\alpha 2,3R}\neq 0$ we obtain terms proportional to the gluino mass, which might become dominant for large gluino masses.

A further crucial test is also provided by the nature of the current. Using the identity

$$\overline{u}_{p_2}\frac{P^{\mu}}{m_{\text{top}}}P_{L,R}u_{p_1}\equiv\overline{u}_{p_2}\left(\gamma_\mu P_{R,L}+i\sigma_{\mu\nu}\frac{q^{\mu}}{m_{\text{top}}}P_{L,R}\right)u_{p_1} \quad (4)$$

and after Feynman integration with

$$(C^{ii\alpha}_{\epsilon}+C^{ii\alpha}_{\text{top}}-C^{i\alpha}_{\text{SE}})_{q^2=0}\equiv 0,$$

$$(C^{ii\alpha}_{\epsilon}+C^{ii\alpha}_{\text{top}}-C^{\tilde{g}i\alpha}_{\epsilon}-C^{i\alpha}_{\tilde{g}})_{q^2=0}\equiv 0,$$

$$\left[\frac{m_{\tilde{g}}}{m_{\text{top}}}(C^{i\alpha}_{\text{SEG}}-C^{i\alpha}_{\text{SEG}}|_{m^2_{\text{top}}=0})-C^{ii\alpha}_{\tilde{g}\text{top}}\right]_{q^2=0}\equiv 0,$$

$$[C^{ii\alpha}_{\tilde{g}\text{top}}-C^{ii\alpha}_{\tilde{g}t}]_{q^2=0}\equiv 0, \quad (5)$$

we can show that the quantity in front of the γ^{μ} term vanishes in the limit $q^2\to 0$, as required by gauge invariance, that is $V_{VL,R}=-T_{VR,L}$ for $V=\gamma,g$. For $V=Z$, that is $q^2=m^2_Z$, the relations above do not hold anymore. We do the first Feynman integration by hand and the second one numerically.[1]

In a recent paper [22] one of us (H.K.) considered the gluino and neutralino contributions to the direct CP-violating parameter ϵ'. The Feynman diagrams and calculations were similiar. It is straightforward to show that Eq. (3) reproduces the Eq. (A.9) in [22] by replacing m_{top} with m_s and putting the down quark there to zero.

We assumed that both couplings of the gluino to the left- and right-handed quarks and their superpartners are flavor nondiagonal and to be of the same order, that is we take

[1]We think that in the computer age it is not necessary to present the results in the form of the Passarino-Veltman functions, which would make the results only more difficult to read, but refer the interested reader to [21], where similiar calculations have been done. See also [18,23].

$K_{abR}^{\tilde{g}} = e^{-i\Phi_S} K_{ab}$ and $K_{abL}^{\tilde{g}} = e^{+i\Phi_S} K_{ab}$, where Φ_S is a supersymmetric CP-violation phase [22].

In Eq. (3) this phase only comes in when $K_L^{\tilde{g}}$ is multiplied by $K_R^{\tilde{g}}$ and, as can be seen, these terms are proportional to the gluino mass. However this SUSY CP-violating phase is strongly bounded by the electric dipole moment of the neutron (EDMN) to be of the order of $10^{-2} - 10^{-3}$, if not the SUSY masses are heavier than several TEV's (see references given in [22]). We are not interested here in the consequences of this phase leading to CP-violating flavor changing top quark decay, which will be presented elsewhere [19]. In the following we put $\Phi_S = 0$.

When summing over all scalar quarks within the loops, the scalar up quark contributions cancels because of the unitarity of K_{ab}, and with $K_{23} = -K_{32}$ the mass splitting of the scalar top quark and the scalar charm quark comes into account. This was taken to be $m_{\tilde{c}} = 0.9 m_{\tilde{t}}$ in [16], and therefore too small for a top quark mass of 174 GeV. If all scalar quark masses would be the same, the decay rate of $t \to cV$ would be identical to 0. As a final result we obtain

$$\Gamma_S(t \to cV) = \frac{\alpha_s^2}{128\pi^3} m_{\text{top}} \left(1 - \frac{m_V^2}{m_{\text{top}}^2}\right)^2 \varepsilon^2 \Bigg[(V_{VL}^2 + V_{VR}^2) \times \left(2 + \frac{m_{\text{top}}^2}{m_V^2}\right) - 2(V_{VL}T_{VR} + V_{VR}T_{VL}) \left(1 - \frac{m_{\text{top}}^2}{m_V^2}\right) - (T_{VL}^2 + T_{VR}^2) \left(2 - \frac{m_V^2}{m_{\text{top}}^2} - \frac{m_{\text{top}}^2}{m_V^2}\right) \Bigg], \tag{6}$$

where $V_{VL,R} = V_{VL,R}^{\tilde{t}} - V_{VL,R}^{\tilde{c}}$ and $T_{VL,R} = T_{VL,R}^{\tilde{t}} - T_{VL,R}^{\tilde{c}}$. As explained above for $V = \gamma, g$ we have $V_{VL,R} = -T_{VR,L}$ and all terms containing m_V^2 are absent.

We define [5]: $B(t \to cV) = \Gamma_S(t \to cV)/\Gamma_W(t \to bW^+)$, where

$$\Gamma_W(t \to bW^+) = \frac{\alpha}{16 \sin^2\Theta_W} m_{\text{top}} \left(1 - \frac{m_{W^+}^2}{m_{\text{top}}^2}\right)^2 \left(2 + \frac{m_{\text{top}}^2}{m_{W^+}^2}\right). \tag{7}$$

Our input parameters are $m_{\text{top}} = 174$ GeV and the strong coupling constant $\alpha_s = 1.4675/\ln(m_{\text{top}}^2/\Lambda_{\text{QCD}}^2) = 0.107$ with $\Lambda_{\text{QCD}} = 0.18$ GeV [5].

III. DISCUSSIONS

To compare the new results with flavor-changing couplings in the right- and left-handed sector with the ones already presented in [17], where flavor-changing couplings only in the left-handed sector was considered, we present the same plots as in [17]. The general discussion remains the same and we will only present the changes when flavor changing in the right-handed sector is included.

In Fig. 1 we present the branching ratio $B(t \to cZ)$ as a function of the scalar mass m_S for a gluino mass of 100 GeV. We see that without mixing, the branching ratio decreases rapidly with increasing scalar mass and is hardly changed when flavor changing in the right-handed sector is included. However the mixing has a drastic effect. It enhances the branching ratio by up to 4 orders of magnitude for large m_s and is enhanced by another factor of 5 when flavor changing occurs in both sectors.

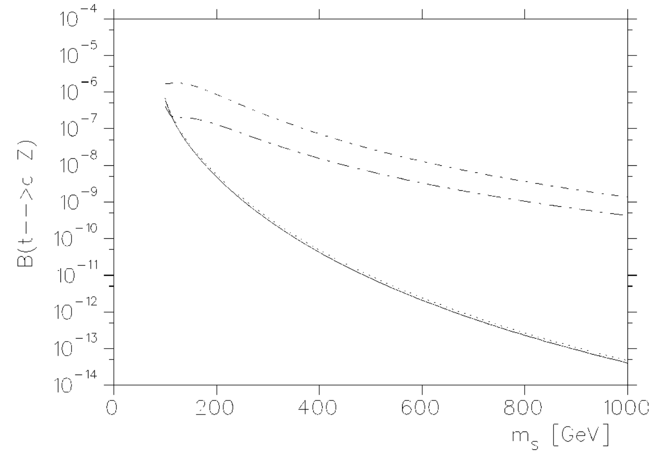

FIG. 1. The ratio Γ_S/Γ_W of the top quark decay into a charm quark and Z^0 boson as a function of the scalar mass m_S. The gluino mass was taken to be 100 GeV. The solid line is the unphysical case with no mixing ($\mu = 0 = A_{\text{top}}$) and $\tan\beta = 10$, the dotted line the same case when flavor changing $g - q - \tilde{q}$ in the right-handed sector is included. The other cases are with mixing ($A_{\text{top}} = m_S$). The dashed-dotted ones with $\mu = 500$ GeV and $\tan\beta = 10$. The shorter ones are with flavor changing in both sectors.

In Fig. 2 we consider the same cases as in Fig. 1, but for $B(t \to cg)$. As before without mixing the results remain almost the same whether or not flavor changing in the right-handed sector is included. However when mixing is taken into account the results are changed drastically up to 7 orders of magnitude for large values of the scalar mass m_S when flavor changing is considered in both sectors, compared with the case where flavor changing occurs only in the left-handed sector.

In Fig. 3 we consider the branching ratio $B(t \to c\gamma)$. As in the cases before, without mixing there is almost no difference between the results with flavor changing only in the left-handed sector or in both sectors. As in Fig. 2 the results are changed drastically, up to 6–7 orders of magnitude for large values of the scalar mass, when mixing is taken into

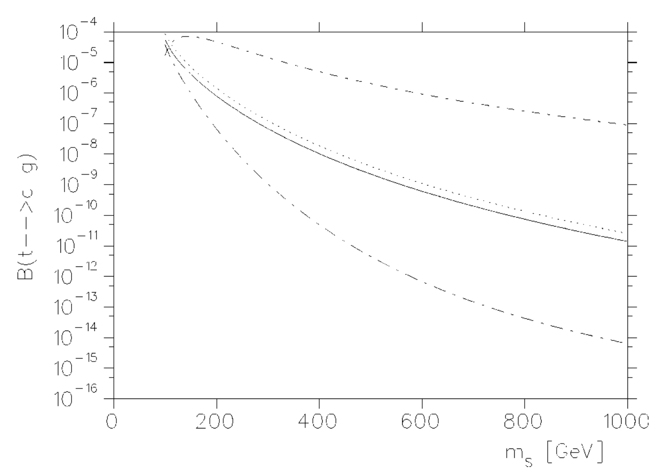

FIG. 2. The same as Fig. 1, but for the decay of the top quark into a charm quark and a gluon.

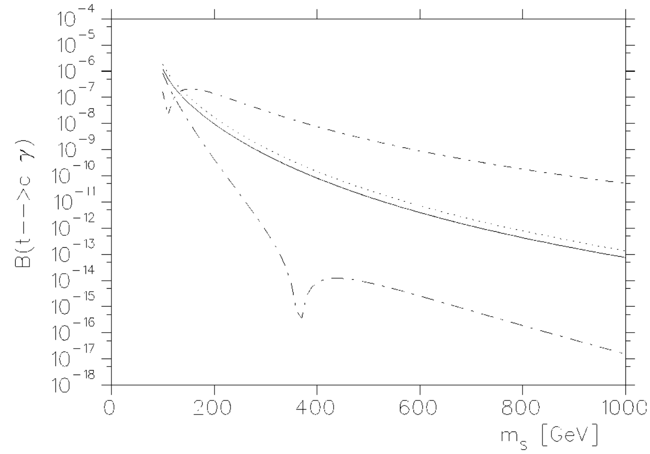

FIG. 3. The same as Fig. 1, but for the decay of the top quark into a charm quark and a photon.

account and flavor changing is considered in the left- and right-handed sector, compared with the case where flavor changing occurs only in left-handed sector.

A further important consequence is that the GIM-like supression where the contribution of the top quark exactly cancels the contribution from the c quark is pushed to much smaller values of the scalar mass m_S. We have tried many different combinations of μ and $m_{\tilde{g}}$ and the cancellation is always pushed to smaller values of the scalar mass.

IV. CONCLUSIONS

In this paper we presented the supersymmetric QCD 1-loop correction to the flavor-changing decay rate $t\to cV$. We included flavor-changing $g-q-\tilde{q}$ couplings in the left- and right-handed sector, thus extending the previous analysis of [17], where flavor changing was only considered in the left-handed sector. We have shown that the results remain almost the same when mixing of the scalar top quark is neglected. This remains true for the $t\to cZ$ decay rate even when mixing is included. However the results are changed drastically, up to 7 orders of magnitude for the decay rates $t\to cg$ and $t\to c\gamma$ when mixing of the scalar top quark is included and flavor-changing couplings are taken in both sectors. Furthermore in the $t\to c\gamma$ decay mode the GIM-like cancellation of the scalar top and charm quarks is pushed to much smaller values of the scalar mass m_S.

We must also conclude that, in spite of these spectacular enhancements, these particular decays are beyond the reach of planned accelerators such as LHC, upgraded Tevatron (for example through jets with high transverse momentum) and the next linear collider [24], except maybe the $t\to cg$ in a very narrow part of parameter space. Therefore, if these decays were observed at these accelerators, it would be a clear signal of physics beyond the SM and most likely beyond the MSSM.

Note added: While completing this work we have seen a paper by an Italian group [23], where the same processes were considered. Their statement is that the SUSY mixing angle between the second and the third generation ($K_{23}=\varepsilon$) has been overestimated by at least 1 order of magnitude in our first paper [17]. There and in this present paper we took ε as a free parameter and have taken it pretty large following the spirit of former papers. From Eq. (6) it is obvious that the results are diminished drastically if smaller values are taken for ε. However the authors of [23] showed that relaxing the universitality constraints on soft SUSY mass breaking terms of the off-diagonal squark masses between $\tilde{c}$ and $\tilde{t}$ reintroduces a large ε, that is a large mixing angle between $\tilde{c}$ and $\tilde{t}$.

They also find a difference in the result for the amplitude which can be traced back to the omission in [17] of the diagrams involving a helicity flip in the gluino line, which dominate the branching ratios when the gluino mass gets large. However in [17] we considered flavor changing only in the left-handed sector as is usually done in the MSSM and therefore no gluino helicity flip was possible, that is no term proportional to the gluino mass is introduced. In the present work, we also took into account flavor changing in the right-handed sector and as a consequence the mentioned effect occurs, which is expressed by the new terms proportional to the gluino mass in Eq. (3).

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