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$t \to cV$ via SUSY FCNC couplings in the unconstrained MSSM

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Abstract

We recalculate the branching ratios for $t \to cV$ $(V = g, \gamma, Z)$ induced by SUSY FCNC couplings within the general unconstrained MSSM framework using mass eigenstate approach. Our results show that the branching ratios for these decays are larger than ones reported in previous literatures in the MSSM with R-parity conservation, and they can reach $\sim 10^{-4}$, $\sim 10^{-6}$, and $\sim 10^{-6}$, respectively, for favorable parameter values allowing by current precise experiments. Thus, the branching ratios for $t \to cg$ and $t \to c\gamma$ may be measurable at the LHC.

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1. Introduction

The top quark flavor changing neutral current (FCNC) processes $t \to cV$ $(V = g, \gamma, Z)$ have tiny branching ratios in the standard model (SM) [1], and are too small to be measurable in the future colliders, and thus any detected signal of these rare decay events definitely indicates some new physics beyond the SM. Actually, $t \to cV$ $(V = g, \gamma, Z)$ have been studied in various new physics models beyond the SM in detail, such as the two-Higgs-doublet model (2HDM) [1,2], the technicolor model (TC) [3], the top-color-assisted technicolor model (TC2) [4], the models with extra vector-like quark singlets [5], the minimal supersymmetry (SUSY) extension of the SM (MSSM) with R-parity conservation [6–11] and without R-parity conservation [12]. The decay branching ratios for $t \to cV$ $(V = g, \gamma, Z)$ are enhanced in general several orders of magnitude in these new physics models. The MSSM, which is believed as one of the most attractive candidates of new physics model, has gotten many attentions,

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Table 1
$t \to cV$ ($V = g, \gamma, Z$) branching ratios of previous calculations. 'CKM1' and 'CKM2' refer to models with extra vector-like up-type quark singlets and down-type quark singlets, respectively [5], and 'RPV' refers to SUSY models allowing R-parity violation

Decay mode	SM	2HDM	TC	TC2	CKM1	CKM2	RPV	MSSM					
								[6]	[7]	[8]	[9]	[10]	[11]
$t \to cg$	10^{-13}	10^{-5}	10^{-6}	10^{-5}	10^{-11}	10^{-7}	10^{-3}	10^{-6}	10^{-5}	10^{-5}	10^{-5}	10^{-5}	10^{-6}
$t \to c\gamma$	10^{-14}	10^{-7}	10^{-8}	10^{-7}	10^{-12}	10^{-8}	10^{-5}	10^{-8}	10^{-7}	10^{-7}	10^{-7}	10^{-6}	
$t \to cZ$	10^{-15}	10^{-6}	10^{-7}	10^{-5}	10^{-4}	10^{-4}	10^{-4}	10^{-8}	10^{-6}	10^{-6}	10^{-7}	10^{-6}	

and the investigation of $t \to cV$ ($V = g, \gamma, Z$) in the MSSM is a long story. Li et al. studied one-loop SUSY-QCD and SUSY-EW contributions in Ref. [6], subsequently G. Couture et al. recalculated and generalized the SUSY-QCD corrections to include the left-hand (LH) squark mixing in Ref. [7] and the right-hand (RH) squark mixing in Ref. [8]. All works above are within the framework of the MSSM with flavor-universal soft SUSY breaking terms. Later J.L. Lopez et al. further generalized the SUSY-EW corrections to the case of including neutralino-quark-squark loops in Ref. [9]. and de Divitiis et al. reinvestigated $t \to cV$ ($V = g, \gamma, Z$) in the universal case as well as non-universal case in Ref. [10], and obtained different results from Refs. [6,7] due to the calculation of the relevant SUSY mixing angles and diagrams involving a helicity flip in the gluino line, which was confirmed by J. Guasch et al. in a RG-based framework for $t \to cg$ decay [11]. All the above results of the MSSM are summarized in Table 1 (for comparing, we also list the results of the SM and new physics models mentioned above), one can find that they are all below 5×10^{-5}, which is the roughly estimated sensitivities for the measurements of top rare decay at the LHC with 100 fb^{-1} of integrated luminosity [11].

However, all the previous works are limited to some constrained MSSM, in which some strong assumptions or additional parameters besides ones in the MSSM are introduced to describe the FCNC couplings, but no any strong theoretical reasons of them have been found so far. It is necessary to study the FCNC top quark decays in the unconstrained MSSM [13], where the assumptions about the soft SUSY breaking terms are relaxed and new sources of flavor violation are presented in the mass matrices of sfermions, and consequently, some large contributions to FCNC processes induced by SUSY FCNC couplings (neutralino–quark–squark coupling and gluino–quark–squark coupling) can be obtained. Since the contributions to the top FCNC decays mediated by the charged current interactions (from $W^\pm$, $H^\pm$, $G^\pm$ and $\tilde{\chi}^\pm$) are invisibly small as shown in the previous works [6–11] and cannot be enhanced in this framework, in this paper we will reinvestigate the $t \to cV$ ($V = g, \gamma, Z$) only via SUSY FCNC couplings in the unconstrained MSSM, and try to show what are the maximal branching ratios for $t \to cV$ ($V = g, \gamma, Z$) in the MSSM using SUSY parameters allowed by current data, and whether they can be detected at the LHC.

2. The $t \to cV$ ($V = g, \gamma, Z$) process induced by SUSY FCNC

In the super-CKM basis [13], in which the mass matrices of the quark fields are diagonal by rotating the superfields, the up squark mass matrix $\mathcal{M}^2_{\tilde{U}}$ is a 6×6 matrix, which has the form:

$$\begin{pmatrix} (M^2_{\tilde{U}})_{LL} + \left(m_u^2 \cos 2\beta m_Z^2 \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right)\right)\mathbb{1}_3 & (M^2_{\tilde{U}})_{LR} - \mu(m_u \cot\beta)\mathbb{1}_3 \\ (M^2_{\tilde{U}})^\dagger_{LR} - \mu(m_u \cot\beta)\mathbb{1}_3 & (M^2_{\tilde{U}})_{RR} + \left(m_u^2 \cos 2\beta m_Z^2 \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right)\right)\mathbb{1}_3 \end{pmatrix}, \quad (1)$$

where θ_W is the Weinberg angle, $\mathbb{1}_3$ stands for the 3×3 unit matrix, the angle β is defined by $\tan\beta \equiv v_2/v_1$, the ratio of vacuum expectation values of the two Higgs doublets, μ is the Higgs mixing parameter in the superpotential, and $(M^2_{\tilde{U}})_{LL}$, $(M^2_{\tilde{U}})_{RR}$, and $(M^2_{\tilde{U}})_{LR}$ contain the flavor-changing entries, which are given by

$$\left(M^2_{\tilde{U}}\right)_{LL} = V^U_L M^2_Q V^{U\dagger}_L, \qquad \left(M^2_{\tilde{U}}\right)_{RR} = V^U_R (M^2_U)^T V^{U\dagger}_R, \qquad \left(M^2_{\tilde{U}}\right)_{LR} = -\frac{v\sin\beta}{\sqrt{2}} V^U_L A^*_U V^{U\dagger}_R, \tag{2}$$

respectively. Here M^2_Q, $M^2_{U,D}$ and $A_{U,D}$ are the soft broken $SU(2)$ doublet squark mass squared matrix, the $SU(2)$ singlet squark mass squared matrix and the trilinear coupling matrix, respectively. They are directly related to the mechanism of SUSY breaking, and are in general not diagonal in the super-CKM basis. Furthermore, $(M^2_{\tilde{U}})_{LR}$, arising from the trilinear terms in the soft potential, namely $A_{U,ij} H_U \tilde{U}_i \tilde{U}^c_j$, is not Hermitian. The matrix $\mathcal{M}^2_{\tilde{U}}$ can further be diagonalized by an additional 6×6 unitary matrix Z_U to give the up squark mass eigenvalues

$$\left(\mathcal{M}^2_{\tilde{U}}\right)^{\text{diag}} = Z^\dagger_U \mathcal{M}^2_{\tilde{U}} Z_U. \tag{3}$$

Thus, we get new sources of flavor-changing neutral current: neutralino–quark–squark coupling and gluino–quark–squark coupling, which arise from the off-diagonal elements of $(M^2_{\tilde{U}})_{LL}$, $(M^2_{\tilde{U}})_{LR}$ and $(M^2_{\tilde{U}})_{RR}$, and can be written as ($I=1,2,3$, $i=1,\ldots,6$, $j=1,2,3,4$)

$$\begin{aligned}
&\tilde{g}^a - \tilde{q}_{ir} - q_{Is}: \quad i\sqrt{2}g_s T^a_{rs}\left[-(Z_U)_{Ii}P_L + (Z_U)_{(I+3)i}P_R\right] \\
&\tilde{\chi}^0_j - \tilde{q}_{ir} - q_{Is}: \quad i\delta_{rs}\left\{\left[\frac{-e}{\sqrt{2}s_W c_W}(Z_U)_{Ii}\left(\frac{1}{3}s_W(Z_N)_{1j} + c_W(Z_N)_{2j}\right) - Y^I_u(Z_U)_{(I+3)i}(Z_N)_{4j}\right]P_L\right. \\
&\qquad\qquad\left. + \left[\frac{2\sqrt{2}e}{3c_W}(Z_U)_{(I+3)i}(Z_N)_{1j} - Y^I_u(Z_U)_{Ii}(Z_N)_{4j}\right]P_R\right\}.
\end{aligned}$$

Here $s_W \equiv \sin\theta_W$, $c_W \equiv \cos\theta_W$, $P_{L,R} \equiv (1\mp\gamma_5)/2$, T^a_{rs} is the $SU(3)$ color matrix with color index a, r, s, and the unitary transformation Z_N diagonalizes mass matrix of gauginos and higgsinos to obtain the neutralinos. Thus the flavor changing effects of soft broken terms M^2_Q, M^2_U and A_U on the observables can be obtained through the matrix Z_U.

For the aim of this Letter, the following strategy in the numerical calculations of the decay branching ratios of $t\to cV$ will be used: first we deal with the LL, LR, RL and RR blocks of the matrix $\mathcal{M}^2_{\tilde{U}}$ separately and in each block we only consider the effects of individual element on the top quark rare decays, and then we investigate the interference effects between some different entries within one block and the interference effects between different blocks. In order to simplify the calculation we further assume that all diagonal entries in $(M^2_{\tilde{U}})_{LL}$, $(M^2_{\tilde{U}})_{LR}$, $(M^2_{\tilde{U}})_{RL}$ and $(M^2_{\tilde{U}})_{RR}$ are set to be equal to the common value M^2_{SUSY}, and then normalize the off-diagonal elements to M^2_{SUSY} [14,15],

$$\begin{aligned}
&\left(\delta^{ij}_U\right)_{LL} = \frac{(M^2_{\tilde{U}})^{ij}_{LL}}{M^2_{\text{SUSY}}}, \qquad \left(\delta^{ij}_U\right)_{RR} = \frac{(M^2_{\tilde{U}})^{ij}_{RR}}{M^2_{\text{SUSY}}}, \\
&\left(\delta^{ij}_U\right)_{LR} = \frac{(M^2_{\tilde{U}})^{ij}_{LR}}{M^2_{\text{SUSY}}}, \qquad \left(\delta^{ij}_U\right)_{RL} = \frac{(M^2_{\tilde{U}})^{ij}_{RL}}{M^2_{\text{SUSY}}}, \quad i\neq j,\ i,j=1,2,3.
\end{aligned} \tag{4}$$

Thus $(M^2_{\tilde{U}})_{LL}$ can be written as follows:

$$\left(M^2_{\tilde{U}}\right)_{LL} = M^2_{\text{SUSY}}\begin{pmatrix} 1 & (\delta^{12}_U)_{LL} & (\delta^{13}_U)_{LL} \\ (\delta^{21}_U)_{LL} & 1 & (\delta^{23}_U)_{LL} \\ (\delta^{31}_U)_{LL} & (\delta^{32}_U)_{LL} & 1 \end{pmatrix}, \tag{5}$$

and analogously for all the other blocks.

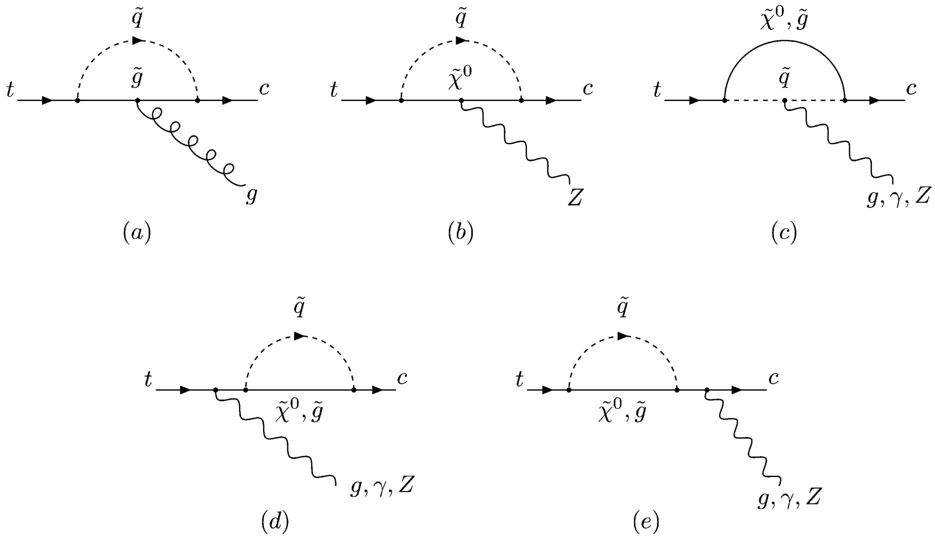

Fig. 1. Feynman diagrams for $t \to cV$ $(V = g, \gamma, Z)$.

The related Feynman diagrams for $t \to cV$ $(V = g, \gamma, Z)$ induced by the SUSY FCNC are shown in Fig. 1. Neglecting the charm quark mass, the amplitude of the decay process is given by

$$M = \bar{u}(p_c)V^{\mu}u(p_t)\epsilon_{\mu}(k, \lambda), \tag{6}$$

where p_t, p_c, and k are the momenta of the top-quark, charm-quark, and gauge boson, respectively, and $\epsilon_{\mu}(k, \lambda)$ is the polarization vector for the gauge boson. The vertex V^{μ} can be written as

$$V^{\mu} = -i\gamma^{\mu}\left(P_L F^L_{V1} + P_R F^R_{V1}\right) - i\frac{p_t^{\mu}}{m_t}\left(P_L F^L_{V2} + P_R F^R_{V2}\right), \tag{7}$$

where $F^{L(R)}_{V1(2)}$ are the form factors, and their explicit expressions through the SUSY-QCD FCNC $(\tilde{g}^a - \tilde{q}_i - q_I)$ are:

$$F^L_{g1} = \frac{-iT^a_{rs}}{96\pi^2 m_t}\sum_{l=1}^{6}\Big\{m_{\tilde{g}}V_{7R}\left(9C_0^b m_t^2 V_{5L}V_6 + 8V_4V_{5R}B_0^f\right) + m_t V_{7L}\Big[2V_{5L}C_{00}^d V_3 + 9V_6V_{5L}$$
$$\left(2C_{00}^b + C_0^b\left(m_{\tilde{g}}^2 - m_{\tilde{q}_l}^2\right) - C_2^b m_t^2 - B_0^d\right) - 8V_4V_{5R}B_1^f\Big] - 8m_{\tilde{g}}V_4V_{5L}V_{7R}B_0^e\Big\}, \tag{8}$$

$$F^R_{g1} = F^L_{g1}(V_{5L,R} \leftrightarrow V_{5R,L},\, V_{7L,R} \leftrightarrow V_{7R,L}), \tag{9}$$

$$F^L_{g2} = \frac{-iT^a_{rs}}{48\pi^2}\sum_{l=1}^{6} m_t V_{5L}\Big\{m_t V_{7L}\Big[\left(C_{12}^d + C_2^d + C_{22}^d\right)V_3 + 9\left(C_{12}^b + C_2^b + C_{22}^b\right)V_6\Big]$$
$$- m_{\tilde{g}}V_{7R}\Big[\left(C_0^d + C_1^d + C_2^d\right)V_3 - 9\left(C_1^b + C_2^b\right)V_6\Big]\Big\}, \tag{10}$$

$$F^R_{g2} = F^L_{g2}(V_{5L,R} \leftrightarrow V_{5R,L},\, V_{7L,R} \leftrightarrow V_{7R,L}), \tag{11}$$

$$F^L_{\gamma 1} = \frac{i\delta_{rs}}{12\pi^2 m_t}\sum_{l=1}^{6}\Big[m_t V_{7L}\left(2C_{00}^d V_3 V_{5L} + V_4' V_{5R}B_1^f\right) + m_{\tilde{g}}V_4' V_{7R}\left(V_{5L}B_0^e - V_{5R}B_0^f\right)\Big], \tag{12}$$

$$F^R_{\gamma 1} = F^L_{\gamma 1}(V_{5L,R} \leftrightarrow V_{5R,L},\, V_{7L,R} \leftrightarrow V_{7R,L}), \tag{13}$$

$$F^L_{\gamma 2} = \frac{i\delta_{rs}}{6\pi^2}\sum_{l=1}^{6} m_t V'_3 V_{5L}\big[m_t\big(C^d_{12}+C^d_2+C^d_{22}\big)V_{7L} - m_{\tilde g}\big(C^d_0+C^d_1+C^d_2\big)V_{7R}\big], \tag{14}$$

$$F^R_{\gamma 2} = F^L_{\gamma 2}(V_{5L,R}\leftrightarrow V_{5R,L},\, V_{7L,R}\leftrightarrow V_{7R,L}), \tag{15}$$

$$F^L_{Z1} = \frac{i\delta_{rs}}{12\pi^2 m_t}\sum_{l=1}^{6}\left[m_t V_{7L}\left(\sum_{l'=1}^{6} 2C^e_{00}V''_3 V_{5L} + V''_{4L}V_{5R}B^f_1\right) + m_{\tilde g}V''_{4L}V_{7R}\big(V_{5L}B^e_0 - V_{5R}B^f_0\big)\right], \tag{16}$$

$$F^R_{Z1} = F^L_{Z1}(V''_{4L}\to V''_{4R},\, V_{5L,R}\leftrightarrow V_{5R,L},\, V_{7L,R}\leftrightarrow V_{7R,L}), \tag{17}$$

$$F^L_{Z2} = \frac{i\delta_{rs}}{6\pi^2}\sum_{l,l'=1}^{6} m_t V''_3 V_{5L}\big[m_t\big(C^e_{12}+C^e_2+C^e_{22}\big)V_{7L} - m_{\tilde g}\big(C^e_0+C^e_1+C^e_2\big)V_{7R}\big], \tag{18}$$

$$F^R_{Z2} = F^L_{Z2}(V_{5L,R}\leftrightarrow V_{5R,L},\, V_{7L,R}\leftrightarrow V_{7R,L}), \tag{19}$$

and the explicit expressions through the SUSY-EW FCNC ($\tilde\chi^0_k - \tilde q_i - q_I$) are:

$$F^L_{g1} = \frac{iT^a}{16\pi^2 m_t}\sum_{l=1}^{6}\sum_{k=1}^{4}\big\{2C^a_{00}m_t V_{1L}V_{2L}V_3 + \big[\big(B^a_0 m_{\tilde\chi^0_k}V_{1L} + B^b_1 m_t V_{1R}\big)V_{2R} - B^b_0 m_{\tilde\chi^0_k}V_{1R}V_{2L}\big]V_4\big\}, \tag{20}$$

$$F^R_{g1} = F^L_{g1}(V_{1L,R}\leftrightarrow V_{1R,L},\, V_{2L,R}\leftrightarrow V_{2R,L}), \tag{21}$$

$$F^L_{g2} = \frac{iT^a}{8\pi^2}\sum_{l=1}^{6}\sum_{k=1}^{4} m_t V_{1L}V_3\big[\big(C^a_{12}+C^a_2+C^a_{22}\big)m_t V_{2L} - \big(C^a_0+C^a_1+C^a_2\big)m_{\tilde\chi^0_k}V_{2R}\big], \tag{22}$$

$$F^R_{g2} = F^L_{g2}(V_{1L,R}\leftrightarrow V_{1R,L},\, V_{2L,R}\leftrightarrow V_{2R,L}), \tag{23}$$

$$F^{L,R}_{\gamma 1,2} = F^{L,R}_{g1,2}\big(V_3\to V'_3,\, V_4\to V'_4,\, T^a\to 1\big), \tag{24}$$

$$\begin{aligned} F^L_{Z1} = \frac{i}{16\pi^2 m_t}\sum_{l=1}^{6}\sum_{k=1}^{4}\Bigg\{ & \sum_{l'=1}^{6} 2C^f_{00}m_t V_{1L}V_{2L}V''_3 \\ & + V''_{4L}\big(-B^b_0 m_{\tilde\chi^0_k}V_{1R}V_{2L} + B^b_1 m_t V_{1R}V_{2R} + B^a_0 m_{\tilde\chi^0_k}V_{1L}V_{2R}\big) \\ & + \sum_{k'=1}^{4} m_t V_{1L}\big[\big(m^2_{\tilde q_l}V_{2L}V_{8R} - m_{\tilde\chi^0_k}(m_t V_{2R} + m_{\tilde\chi^0_{k'}}V_{2L}\big)V_{8L})C^c_0 \\ & + V_{2L}V_{8R}B^c_0 - 2V_{2L}V_{8R}C^c_{00} + \big(m^2_t V_{2L}V_{8R} + m_t m_{\tilde\chi^0_{k'}}V_{2R}V_{8R} - m_t m_{\tilde\chi^0_k}V_{2R}V_{8L}\big)C^c_2\big]\Bigg\}, \end{aligned} \tag{25}$$

$$\begin{aligned} F^L_{Z2} = \frac{i}{8\pi^2}\sum_{l=1}^{6}\sum_{k=1}^{4} m_t V_{1L}\Bigg\{ & \sum_{l'=1}^{6} V''_3\big[\big(C^a_{12}+C^a_2+C^a_{22}\big)m_t V_{2L} - \big(C^a_0+C^a_1+C^a_2\big)m_{\tilde\chi^0_k}V_{2R}\big] \\ & + \sum_{k'=1}^{4}\big[-m_{\tilde\chi^0_k}V_{2R}V_{8L}C^c_1 - V_{8R}\big(m_t V_{2L}C^c_{12} + (m_t V_{2L} + m_{\tilde\chi^0_{k'}}V_{2R})C^c_2 + m_t V_{2L}C^c_{22}\big)\big]\Bigg\}, \end{aligned} \tag{26}$$

$$F^R_{Z1,2} = F^L_{Z1,2}\big(V_{1L,R}\leftrightarrow V_{1R,L},\, V_{2L,R}\leftrightarrow V_{2R,L},\, V''_{4L,R}\leftrightarrow V''_{4R,L},\, V_{8L,R}\leftrightarrow V_{8R,L}\big). \tag{27}$$

Here

$$B^a_i = B_i\big(0, m^2_{\tilde\chi^0_k}, m^2_{\tilde q_l}\big), \qquad B^b_i = B_i\big(m^2_t, m^2_{\tilde\chi^0_k}, m^2_{\tilde q_l}\big), \qquad B^c_i = B_i\big(0, m^2_{\tilde\chi^0_k}, m^2_{\tilde\chi^0_{k'}}\big),$$

$$B^d_i = B_i\big(0, m^2_{\tilde g}, m^2_{\tilde g}\big), \qquad B^e_i = B_i\big(0, m^2_{\tilde g}, m^2_{\tilde q_l}\big), \qquad B^f_i = B_i\big(m^2_t, m^2_{\tilde g}, m^2_{\tilde q_l}\big),$$

$$C^a_{i,ij} = C_{i,ij}\big(0, 0, m_t^2, m^2_{\tilde\chi^0_k}, m^2_{\tilde q_l}, m^2_{\tilde q_l}\big), \qquad C^b_{i,ij} = C_{i,ij}\big(0, 0, m_t^2, m^2_{\tilde q_l}, m^2_{\tilde g}, m^2_{\tilde g}\big),$$
$$C^c_{i,ij} = C_{i,ij}\big(0, 0, m_t^2, m^2_{\tilde q_l}, m^2_{\tilde\chi^0_k}, m^2_{\tilde\chi^0_{k'}}\big), \qquad C^d_{i,ij} = C_{i,ij}\big(0, 0, m_t^2, m^2_{\tilde g}, m^2_{\tilde q_l}, m^2_{\tilde q_l}\big),$$
$$C^e_{i,ij} = C_{i,ij}\big(0, 0, m_t^2, m^2_{\tilde g}, m^2_{\tilde q_{l'}}, m^2_{\tilde q_{l'}}\big) \quad \text{and} \quad C^f_{i,ij} = C_{i,ij}\big(0, 0, m_t^2, m^2_{\tilde\chi^0_k}, m^2_{\tilde q_l}, m^2_{\tilde q_{l'}}\big)$$

are 2 and 3-point one-loop integrals [16]. And the relevant couplings are:

$$V_{1L} = i\left\{\frac{-e}{\sqrt{2}s_W c_W}(Z_U)_{2l}\left[\frac{1}{3}s_W(Z_N)_{1k} + c_W(Z_N)_{2k}\right] - Y_u^I(Z_U)_{5l}(Z_N)_{4k}\right\},$$
$$V_{1R} = i\left[\frac{2\sqrt{2}e}{3c_W}(Z_U)_{5l}(Z_N)_{1k} - Y_u^I(Z_U)_{2l}(Z_N)_{4k}\right],$$
$$V_{2L} = i\left\{\frac{-e}{\sqrt{2}s_W c_W}(Z_U)_{3l}\left[\frac{1}{3}s_W(Z_N)_{1k} + c_W(Z_N)_{2k}\right] - Y_u^I(Z_U)_{6l}(Z_N)_{4k}\right\},$$
$$V_{2R} = i\left[\frac{2\sqrt{2}e}{3c_W}(Z_U)_{6l}(Z_N)_{1k} - Y_u^I(Z_U)_{3l}(Z_N)_{4k}\right],$$
$$V_3 = V_4 = -ig_s, \qquad V_3' = V_4' = -i\frac{2}{3}e,$$
$$V_3'' = -i\frac{e}{2s_W c_W}\left[\sum_{I=1}^{3}(Z_U)_{Il}(Z_U)_{Il'} - \frac{4}{3}s_W^2\delta^{ll'}\right],$$
$$V_{4L}'' = -i\frac{e}{6s_W c_W}\big(-3 + 4s_W^2\big), \qquad V_{4R}'' = i\frac{2es_W}{3c_W},$$
$$V_{5L} = -i\sqrt{2}g_s(Z_U)_{2l}, \qquad V_{5R} = i\sqrt{2}g_s(Z_U)_{5l}, \qquad V_6 = -ig_s,$$
$$V_{7L} = -i\sqrt{2}g_s(Z_U)_{3l}, \qquad V_{7R} = i\sqrt{2}g_s(Z_U)_{6l},$$
$$V_{8L} = i\frac{e}{2s_W c_W}\big[(Z_N)_{4k}(Z_N)_{4k'} - (Z_N)_{3k}(Z_N)_{3k'}\big],$$
$$V_{8R} = -i\frac{e}{2s_W c_W}\big[(Z_N)_{4k}(Z_N)_{4k'} - (Z_N)_{3k}(Z_N)_{3k'}\big].$$

After squaring the decay amplitude and multiplying by the phase space factor, one obtains the decay width of $t \to cV$ $(V = g, \gamma, Z)$:

$$\Gamma(t \to cg, c\gamma) = \frac{1}{96\pi}m_t\big[\big(2F^R_{V1} - F^L_{V1}\big)F^{L*}_{V1} + \big(2F^L_{V1} - F^R_{V2}\big)F^{R*}_{V1} - \big(F^L_{V1} + F^R_{V2}\big)F^{L*}_{V2} - \big(F^R_{V1} + F^L_{V2}\big)F^{R*}_{V2}\big], \tag{28}$$

$$\begin{aligned}\Gamma(t \to cZ) = \frac{1}{384\pi m_Z^2 m_t^5}\big(m_t^2 - m_Z^2\big)^2\big\{&2m_t^2F^{L*}_{Z1}\big[m_Z^2\big(4F^R_{Z1} - F^L_{Z2}\big) + m_t^2\big(2F^R_{Z1} + F^L_{Z2}\big)\big]\\ &+ 2m_t^2F^{R*}_{Z1}\big[m_Z^2\big(4F^L_{Z1} - F^R_{Z2}\big) + m_t^2\big(2F^L_{Z1} + F^R_{Z2}\big)\big]\\ &- \big(m_t^2 - m_Z^2\big)\big[F^{L*}_{Z2}\big(m_Z^2F^R_{Z2} - m_t^2\big(2F^L_{Z1} + F^R_{Z2}\big)\big)\\ &+ F^{R*}_{Z2}\big(m_Z^2F^L_{Z2} - m_t^2\big(2F^R_{Z1} + F^L_{Z2}\big)\big)\big]\big\},\end{aligned} \tag{29}$$

and we define the branching ratio as Ref. [1]:

$$\mathrm{Br}(t \to cV) \equiv \frac{\Gamma(t \to cV)}{\Gamma(t \to bW^+)}, \tag{30}$$

which will be the main object of our numerical study.

3. Numerical calculation and discussion

In our numerical calculations the SM parameters were taken to be $m_t = 174.3$ GeV, $M_W = 80.423$ GeV, $M_Z = 91.1876$ GeV, $\sin^2\theta_W = 0.23113$ and $\alpha_s(M_Z) = 0.1172$ [17]. The relevant SUSY parameters are μ, $\tan\beta$, M_{SUSY} and $m_{\tilde{g}}$, which are unrelated to flavor changing mechanism, and may be fixed from flavor conserving observables at the future colliders. And they are chosen as follows: $M_{\mathrm{SUSY}} = 400,\ 1000$ GeV, $\tan\beta = 4,\ 40$, $m_{\tilde{g}} = 200,\ 300$ GeV and $\mu = 200$ GeV. As for the range of the flavor mixing parameters, $(\delta_U^{ij})_{LL}$ are constrained by corresponding $(\delta_D^{ij})_{LL}$ [14,15,18,19], in which $(\delta_U^{12})_{LL}$ also is constrained by the chargino contributions to K–$\bar{K}$ mixing [20], and D_0–$\bar{D}_0$ mixing makes constraints on $(\delta_U^{12})_{LL}$, $(\delta_U^{12})_{LR}$ and $(\delta_U^{12})_{RL}$ [21]. And $(\delta_U^{31})_{LL}$, $(\delta_U^{32})_{LL}$, $(\delta_U^{31})_{RL}$ and $(\delta_U^{32})_{RL}$ are constrained by the chargino contributions to B_d–$\bar{B}_d$ mixing [18]. Finally, there also are constraints on the up squark mass matrix from the chargino contributions to $b \to s\gamma$ [14,22]. Taking into account above constraints, in our numerical calculations, we use the following limits:

(i) $(\delta_U^{12})_{LL}$, $(\delta_U^{12})_{LR}$ and $(\delta_U^{12})_{RL}$ is less than $0.08 M_{\mathrm{SUSY}}/(1\ \mathrm{TeV})$;
(ii) $(\delta_U^{12})_{RR}$ and $(\delta_U^{13})_{LL}$ are limited below $0.2 M_{\mathrm{SUSY}}/(1\ \mathrm{TeV})$;
(iii) $(\delta_U^{23})_{LL}$, $(\delta_U^{23})_{LR}$, $(\delta_U^{23})_{RL}$, $(\delta_U^{23})_{RR}$, $(\delta_U^{13})_{LR}$, $(\delta_U^{13})_{RL}$ and $(\delta_U^{13})_{RR}$ vary from 0 to 1.

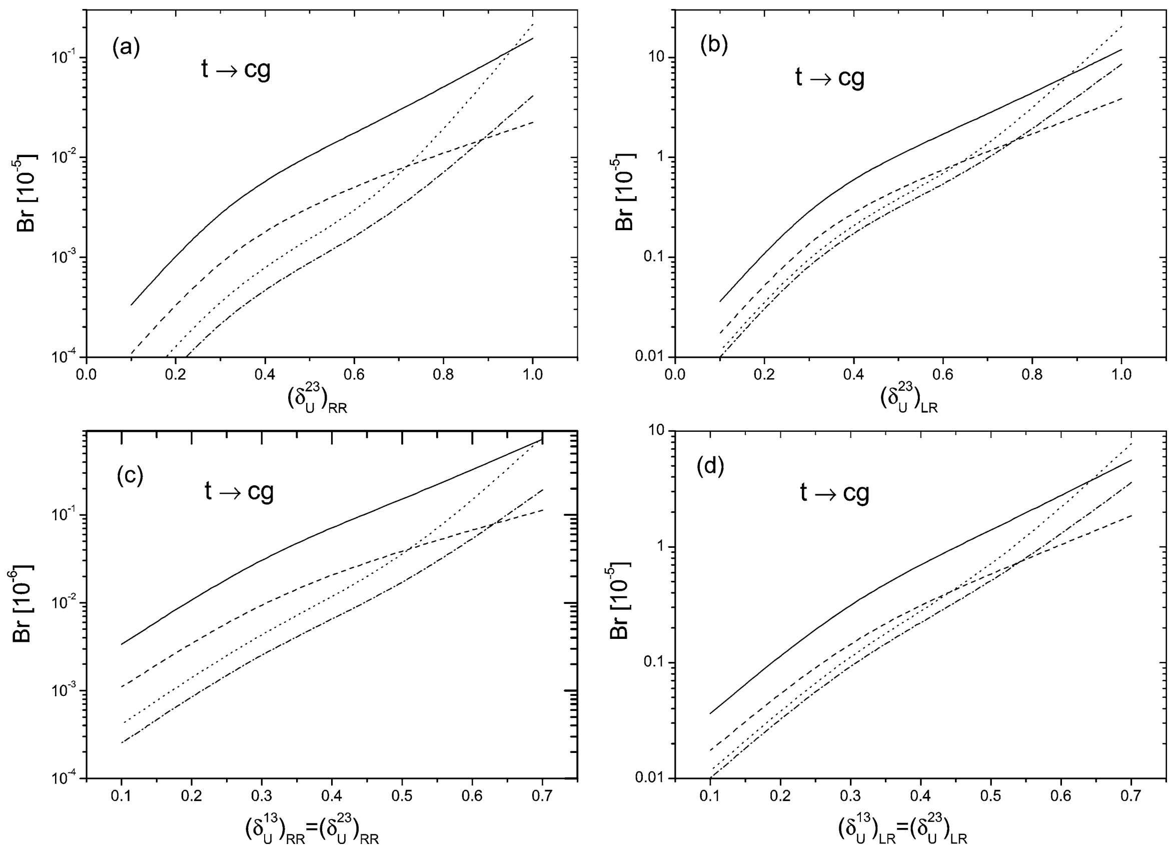

Fig. 2. The decay branching ratios for the $t \to cg$ with mixed RR off-diagonal elements (a) and LR off-diagonal elements (b), and the typical interference effects of RR block (c) and LR block (d). Here, solid line: $m_{\tilde{g}} = 200$ GeV, $M_{\mathrm{SUSY}} = 400$ GeV; dashed line: $m_{\tilde{g}} = 300$ GeV, $M_{\mathrm{SUSY}} = 400$ GeV; dotted line: $m_{\tilde{g}} = 200$ GeV, $M_{\mathrm{SUSY}} = 1000$ GeV; dash-dotted line: $m_{\tilde{g}} = 300$ GeV, $M_{\mathrm{SUSY}} = 1000$ GeV.

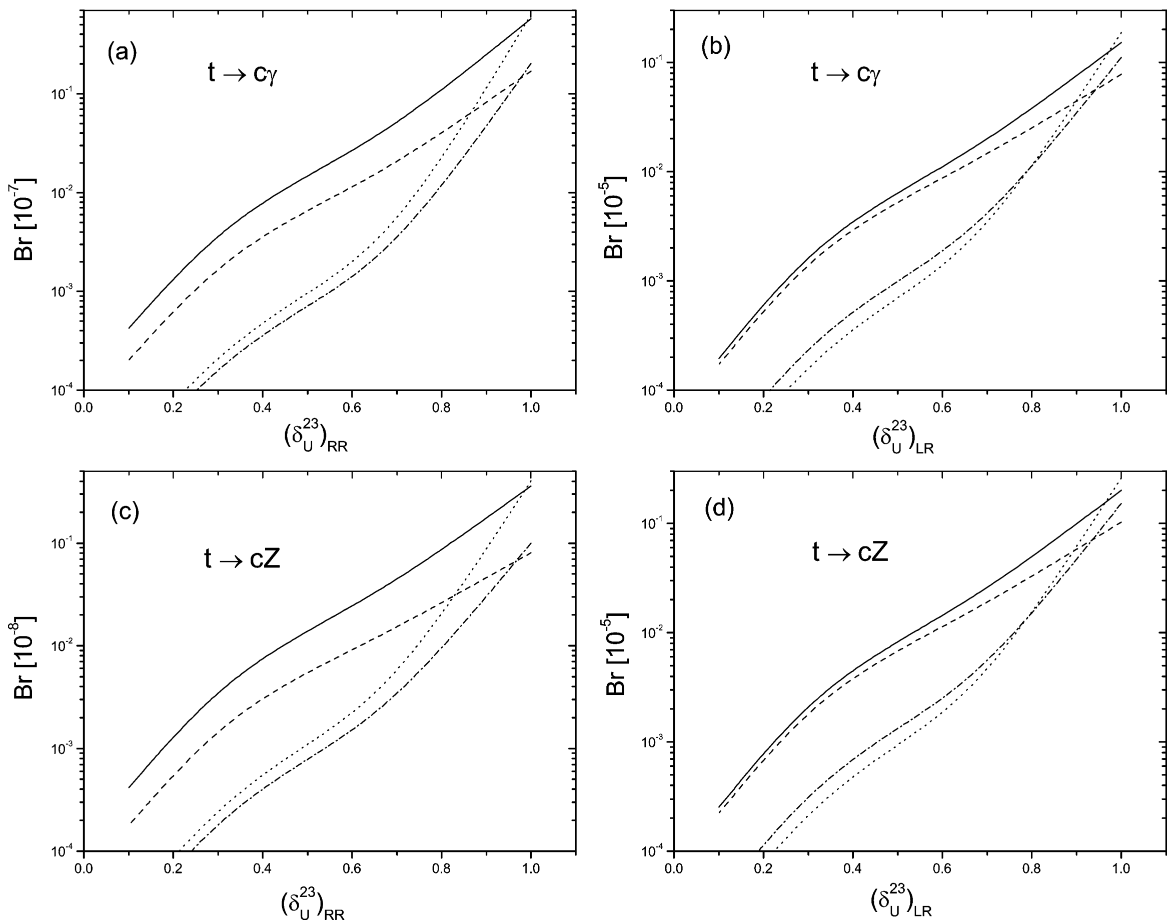

Fig. 3. The decay branching ratios for the $t \to c\gamma$ with mixed RR off-diagonal elements (a) and LR off-diagonal elements (b), and the decay branching ratios for the $t \to cZ$ with mixed RR off-diagonal elements (c) and LR off-diagonal elements (d). Here, solid line: $m_{\tilde{g}} = 200$ GeV, $M_{\text{SUSY}} = 400$ GeV; dashed line: $m_{\tilde{g}} = 300$ GeV, $M_{\text{SUSY}} = 400$ GeV; dotted line: $m_{\tilde{g}} = 200$ GeV, $M_{\text{SUSY}} = 1000$ GeV; dash-dotted line: $m_{\tilde{g}} = 300$ GeV, $M_{\text{SUSY}} = 1000$ GeV.

First of all we should point out that the contributions arising from SUSY-EW FCNC are in general at least one magnitude of order smaller than ones arising from SUSY-QCD FCNC, and the dominant contributions to the decay branching ratios come from the latter. Furthermore, our calculations show that the decay branching ratios only weakly depends on $\tan\beta$, so we only discuss the results in the case of $\tan\beta = 40$ below. Our results are shown in Figs. 2, 3, where there are three common features of these curves: the first is that the branching ratio increases rapidly with the mixing parameters increasing, and the second is that the branching ratio depends strongly on the gluino mass $m_{\tilde{g}}$, and the last is that the dependence of branching ratio on the M_{SUSY} is medium comparing with above two parameters.

For each decay modes $t \to cV$ $(V = g, \gamma, Z)$, in Figs. 2 and 3 we show the dependence of the decay branching ratios on RR and LR off-diagonal elements, respectively. (We do not show the results for LL off-diagonal elements as their contributions are similar to the ones for RR off-diagonal elements). We find that for $t \to cV$ the largest results come from the LR block, which arises from the soft trilinear couplings A_U. We also give the results of the interference effects on the branching ratios for $t \to cg$ in Fig. 2(c) and (d). In general, these interference effects increase the decay branching ratios, and since the interference effects between different blocks are similar, we do not show them for the space of this paper. The results of decay $t \to c\gamma, cZ$ are about two orders of magnitude smaller than ones of decay $t \to cg$, as shown in Figs. 2 and 3. From these figures, we can find that the decay branching ratios for $t \to cV$ $(V = g, \gamma, Z)$ induced by the SUSY FCNC couplings can reach $\sim 10^{-4}$, $\sim 10^{-6}$ and $\sim 10^{-6}$, respectively, for the favorable parameter values allowed by current precise experiments, and they are larger than all the previous ones in the MSSM with R-parity conservation (it should be pointed out that the results of Ref. [6–8] in Table 1 are obtained at $m_{\tilde{g}} = 100$ GeV, which is disfavored by current data).

According to the analysis of T. Han et al. [23], the sensitivities for $t \to c\gamma$ and $t \to cZ$ at the LHC with 100 fb^{-1} integrated luminosity are 5×10^{-6} and 2×10^{-4}, respectively, and our results show that the rare decay $t \to c\gamma$ may be detectable. Later T. Han et al. [24] and M. Hosch et al. [25] studied the sensitivities to the top quark anomalous FCNC couplings at the LHC for single top quark and direct top quark productions, respectively, and the corresponding decay $t \to cg$ branching ratios transferred from their results are 4.9×10^{-5} and 2.7×10^{-5}, respectively. Thus, our results of the branching ratios for $t \to cg$ indicate that the top quark FCNC production processes (both for single top and direct top) may be measurable at the LHC. But if we use the 5×10^{-5} as the sensitivity for the FCNC decay $t \to cV$ at the LHC with 100 fb^{-1} integrated luminosity as shown in Ref. [11], our results show that the rare decay $t \to cg$ are also potentially measurable at the LHC.

In conclusion, we have calculated the top quark rare decay $t \to cV$ $(V = g, \gamma, Z)$ induced by SUSY-FCNC couplings in the general unconstrained MSSM using mass eigenstate approach. Our results show that the branching ratios for these decays are larger than ones reported in previous literatures in the MSSM with R-parity conservation, and especially, the branching ratios for the rare decay modes $t \to cg, c\gamma$ we calculated are very hopefully to be measurable at the LHC for the favorable parameter values allowed by current precise experiments. Moreover, we find that the decay branching ratios for $t \to cV$ $(V = g, \gamma, Z)$ strongly depend on the soft trilinear couplings A_U, and it is possible to get some valuable information of soft SUSY breaking parameters by measuring the branching ratio for the top quark rare decay at the LHC.

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