Testing flavor-changing neutral currents in the rare top quark

decays $t \rightarrow cV_iV_j$ *

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Abstract

We discuss the flavor-changing neutral currents (FCNC) decays of the top quark $t \rightarrow cV_iV_j$ ($V_i = \gamma, Z, g$) in the framework of the Standard Model (SM) and in a two-Higgs doublet model (2HDM) with tree-level FCNC couplings. While in the SM the expected branching ratios are extremely small, in the 2HDM they may be sizable, of order $10^{-4} - 10^{-5}$, and thus accessible at the CERN Large Hadron Collider. We conclude with the interesting observation that the FCNC decay modes $t \rightarrow cV_iV_j$ may not be equally suppressed as their corresponding decays $t \rightarrow cV_i$ in this 2HDM.

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Rare decay modes of the top quark have received considerable attention recently because they might be a source of possible new physics effects to be searched at future colliders. Since the top quark has a mass of about 175 GeV [1], the following rare processes may be kinematically allowed:

\[ t \rightarrow c\gamma [2], \]

\[ t \rightarrow cg, cZ [3], \]

\[ t \rightarrow bW^+Z [4], \]

\[ t \rightarrow cW^+W^- [4,5], \]

and

\[ t \rightarrow cZZ [5]. \]

Even though Standard Model (SM) predicts the branching fractions for these rare decays to be unobservably small, it is believed that the search for large signatures from flavor-changing neutral currents (FCNC) involving the top quark may serve as a unique test of the SM [5,18]. The aim of this communication is to point out that the FCNC transitions

\[ t \rightarrow c\gamma\gamma, \]

\[ t \rightarrow c\gamma Z \] and \[ t \rightarrow cgg \] also provide a detailed test of the SM and some of its extensions, e. g., the two-Higgs doublet model (2HDM).

Just as it is the case with the FCNC one-vector boson decays \[ t \rightarrow cV_i (V_i = \gamma, g, Z) \] [2,3], the two-vector boson decay modes \[ t \rightarrow cV_iV_j \] are expected to be negligible in the SM because they are induced at one-loop level and in addition the Glashow-Illichopoulos-Maiani (GIM) mechanism suppresses effectively FCNC transitions involving virtual down-type quarks. However, in the most general version of the 2HDM (known as Model III), where quarks are allowed to couple simultaneously to more than one scalar doublet [7], it is possible that important effects will emerge in scalar FCNC couplings involving quarks of the second and third generations. Unlike earlier versions of the 2HDM, in Model III no ad hoc symmetries are invoked to eliminate tree-level scalar FCNC couplings, but instead a more realistic pattern for the Yukawa matrices is imposed and constraints on the scalar FCNC are derived from phenomenology [8]. The tree-level scalar FCNC interactions are given by

\[ \mathcal{L}^{III}_{Y, FCNC} = \xi_{ij} \sin \alpha \bar{f}_i f_j h^0 + \xi_{ij} \cos \alpha \bar{f}_i f_j H^0 + \xi_{ij} \cos \alpha \bar{f}_i \gamma^5 f_j A^0 + \text{h.c.}, \]

(1)

where we are using the Higgs mass-eigenstate basis with the light and heavy CP-even Higgs bosons \( h^0 \) and \( H^0 \), respectively, and the CP-odd Higgs boson \( A^0 \), \( \alpha \) denotes the mixing angle, and \( \xi_{ij} \) corresponds to the off-diagonal Yukawa couplings. It is convenient to use the parametrization introduced in [9]: \( \xi_{ij} = \lambda_{ij} \sqrt{m_{V_i} m_{V_j}} \), where the mass factor gives the strength of the interaction while the dimensionless parameters \( \lambda_{ij} \) are fixed by low energy experiments. Although there are strong bounds on couplings involving light quarks, no stringent bounds exist for \( \lambda_{tc} \), and it is feasible a less suppressed strength for the interaction \( tcc^0 \), with \( c_0 \) any of the three physical Higgses of Model III.

In the SM and Model III the FCNC decays \( t \rightarrow cV_iV_j \) may proceed through the resonant diagram shown in Fig. 1, where \( \phi_k^0 \) represents the exchanged Higgs, and the dots denote the couplings of this scalar with the particles in the initial and final states. The amplitude for this diagram can be written in general as

\[ \mathcal{M}(t \rightarrow cV_iV_j) = \sum_k P_{\phi_k^0}(s) \mathcal{M}(t \rightarrow c\phi_k^0 \ast) \mathcal{M}(\phi_k^0 \ast \rightarrow V_iV_j), \]

(2)

where \( P_{\phi_k^0}(s) \) is the resonant propagator of the exchanged Higgs, which transfers a squared 4-momentum \( s = (k_1 + k_2)^2 \), which in turn is restricted by kinematics to lie in the range \( (m_{V_i} + m_{V_j}) \leq \sqrt{s} \leq (m_t - m_c) \). The partial amplitudes in Eq. (2) can be expressed in terms of the \( \phi_k^0 \) couplings

\[ \mathcal{M}(t \rightarrow c\phi_k^0 \ast) = \bar{u}(q) \Gamma_{tc\phi_k^0} v(p), \]

(3)
\[ M(\phi^0_k \to V_i V_j) = i \Gamma_{\phi^0_k}^{V_i V_j} \varepsilon^\mu(k_1, \lambda_1)\varepsilon^\nu(k_2, \lambda_2), \]

where \( \Gamma_{\phi^0_k} \) characterizes the coupling \( tc\phi^0_k \), which in the SM arises at one-loop level but in Model III it is a tree-level effect, whereas \( \Gamma^{V_i V_j} \) characterizes the one-loop level coupling \( \phi^0_k V_i V_j \) [11]. In the case of the channel \( t \to cg \), Eq. (4) must be modified to account for the SU(3) gauge structure of gluons. The decay width \( \Gamma(t \to V_i V_j) \) can be obtained in the usual way and it is given by

\[ \Gamma(t \to V_i V_j) = \frac{1}{256\pi^3 m_t} \int_{(m_t-m_{V_i}+m_{V_j})^2}^{(mt-m_c)^2} \lambda(m_t, m_c, \sqrt{s}) \lambda(\sqrt{s}, m_{V_i}, m_{V_j}) |M(t \to V_i V_j)|^2 ds, \]

where \( \lambda(x, y, z) \) is a phase space factor.

To realize how the top quark decays \( t \to V_i V_j \) get enhanced in Model III, it is necessary to examine the branching ratios in the SM, where only the FCNC two-vector boson decay \( t \to W^+W^- \) occurs at tree-level with a branching ratio of order \( 10^{-14} - 10^{-12} \) [11]. As far as the decay modes \( t \to cg, t \to c\gamma Z \) and \( t \to cg \) are concerned, in addition to the one-loop Feynman graphs, the resonant diagram shown in Fig. 1 contributes to the decay amplitude. In this case the SM Higgs \( \phi^0_{SM} \) is the mediator and the coupling \( tc\phi^0_{SM} \) is induced at one-loop level. The contribution of this diagram seems to be of order \( g^6 \), but a careful analysis shows that on-resonance it becomes of order \( g^4 \), being the dominant contribution for light bosons and competing with the one-loop contributions [11]. The SM coupling \( tc\phi^0_{SM} \) can be expressed as

\[ \Gamma_{tc\phi^0_{SM}} = \sum_{k=d, s, b} V_{ik} V_{kc}^* \left( A_L(s, m_k^2)P_L + A_R(s, m_k^2)P_R \right), \]

where \( P_L \) and \( P_R \) are, respectively, the left- and right-handed chirality projectors, whereas \( A_L \) and \( A_R \) are given in terms of scalar integrals. We have calculated \( \Gamma_{tc\phi^0_{SM}} \) and our result [11] agrees with the one presented in [12] and later reproduced in [13][14] for the SM decay \( t \to cg \). This coupling has also been studied in the Minimal Supersymmetric Standard Model [15]. In the zero charm quark mass limit the function \( A_R \) vanishes and can be neglected in the calculation. From Eqs. (2)-(3) it is straightforward to obtain, after dividing by the main top quark width \( \Gamma(t \to bW) \), the SM values \( B(t \to c\gamma\gamma) \approx 10^{-15} - 10^{-16} \), \( B(t \to c\gamma Z) \approx 10^{-15} - 10^{-16} \), and \( B(t \to cg) \approx 10^{-14} - 10^{-15} \) for \( m_Z \leq m_{\phi^0_{SM}} \leq m_t \).

In the framework of Model III we have studied the decays \( t \to c\gamma\gamma, t \to c\gamma Z, t \to cg \), and for completeness also the channel \( t \to cW^-W^+ \), for which we agree with the results found in [16]. We will not discuss the mode \( t \to cZZ \) because it is highly restricted by phase space. Since the most relevant phenomenological tree-level FCNC effects are due to the light scalar \( h^0 [8] \), the heavy ones \( H^0 \) and \( A^0 \) are unimportant for our present discussion. In fact one can assign to them an arbitrary large mass, namely 750 TeV. The same value was assigned to the charged Higgs mass \( m_{H^\pm} \), which enters in the expressions for the one-loop induced coupling \( \phi^0_k V_i V_j \), though we found that the results for the decay widths are not sensitive to this choice. For simplicity we have chosen \( \lambda_{tc} \) to be real, thus the branching ratios obtained from Eq. (5), after dividing by \( \Gamma(t \to bW) \), turn out to be proportional to the factor \( f_{\lambda} = \lambda_{tc} \sin \alpha \cos \alpha \). Plots for the branching ratios scaled by the factor \( f_{\lambda} \) are shown in Fig. 2 as a function of the Higgs mass \( m_{h^0} \). This graph teaches us that the branching ratios reach their most significant enhancement in the resonance region \( (m_{V_i} + m_{V_j}) \leq m_{h^0} \leq (m_t - m_c) \),
where the channels $t \to c\gamma\gamma$ and $t \to c\gamma Z$ may have branching fractions as high as $10^{-5}$-$10^{-4}$, while those of the modes $t \to cW^+W^-$ and $t \to cgg$ may reach values up to $10^{-4}$. The enhancement is due to the combined effect of the tree-level FCNC and the resonance of the Higgs boson. On-resonance, the decay $t \to cV_iV_j$ proceeds in two stages: first the top quark decays as $t \to c h^0$, with the on-shell Higgs decaying then as $h^0 \to V_iV_j$. This contrasts with the pure three-body decay that occurs outside the resonance region. Although in Model III the decay $t \to cW^+W^-$ is induced at tree-level, it is highly suppressed by phase space, and its width is only one order of magnitude greater those for the decays $t \to c\gamma\gamma$ and $t \to c\gamma Z$.

The possibility of detecting FCNC top quark transitions at the Tevatron has been previously investigated, for instance through the reaction $c+g \to t+A^0$ \[10\]. Here we will discuss the mode $t \to c+\gamma\gamma$ as a representative case of new signatures associated with FCNC top quark decays. This reaction turn out to be very clean when it is attempted to separate the signal from background. Let us consider the situation at the Tevatron, where it will be possible a production of top quark pairs through quark and gluon fusion with a cross-section of $5 \times 10^3$ fb \[7\]. If the top quark decays into $c+\gamma\gamma$ with a branching ratio of order $10^{-5}$, an integrated luminosity of $10^5$ fb$^{-1}$ would be needed in order to produce at least one event, which exceeds the planned luminosity (of order 1 fb$^{-1}$). Then it seems hopeless to detect the FCNC two-photon top quark decay at the Tevatron. Nevertheless it remains the possibility of detecting the Higgs decay $A^0 \to t\bar{c}$, which may have a branching ratio of order unity for $m_{A^0} \geq m_t + m_c$. At the Tevatron the cross-section for the reaction $gg \to A^0 \to t\bar{c}$ is about $10^3$ fb, and the same is true for the cross-section of the main background, which is expected to come from the charged-current reaction $q+b \to c+t$. Thus it seems feasible that an adequate implementation of cuts will allow to identify the signal.

On the other hand, the situation looks more promising at the CERN Large Hadron Collider (LHC), where the cross-section to produce top quark pairs will be $4.3 \times 10^5$ fb, and a branching ratio of order $10^{-5}$ will reduce this cross-section down to 4.3 fb. We will use a conservative efficiency (0.05) for the production of the $t+c+\gamma+\gamma$ events at the LHC. We obtained this efficiency from the detailed study of T. Han et al. \[18\] on the single top quark production via FCNC couplings at hadron colliders. With an integrated luminosity of 100 fb$^{-1}$ we then get only 21 $t+c+\gamma+\gamma$ events per year at the LHC. The main background to this signal comes from the production of $qb \to t+c+\gamma+\gamma$ and $q\bar{q} \to t+b+\gamma+\gamma$ events, where the final $b$ may be misidentified as $c$. The analysis in \[18\] for the single top quark production can be used also to show that, after the inclusion of the suppression factor $(\frac{4\alpha}{\pi})^2$ to account for the two emitted photons, these background processes will have less than one event at the LHC and thus will make feasible the detection of our signal. Even more, our $t+c+\gamma+\gamma$ signal is so distinctive that its detection should be difficult to miss at the LHC: two highly monochromatic photons with an invariant mass peaked at $m_{\phi\phi}$ plus a single quark and a jet. A more systematic study of all possible backgrounds is, of course, beyond the scope of the present rapid communication.

Let us consider another implications of our results. If we assume $\lambda_{tc}$ to be of order unity, the branching ratios for $t \to cV_iV_j$ may reach values up to $10^{-4}$ in the 2HDM, while the branching ratios for the decays $t \to c V_i$ ($V_i = \gamma, Z, g$) could be of order $10^{-5}$ - $10^{-11}$, depending on the Higgs boson masses and the value of $\tan \beta = \frac{v_2}{v_1}$, with $v_{1,2}$ the vacuum expectation values of the two Higgs doublets \[13\]. Thus, we find that for a light Higgs the three-body decay modes $t \to cV_iV_j$ may not be equally suppressed as the two-body decays.
in the 2HDM. Our result represents an explicit realization of the scenario previously conjectured in studies of the rare processes $b \rightarrow s\gamma\gamma$ [19], $\mu \rightarrow e\gamma\gamma$ [20] and $\nu' \rightarrow \nu\gamma\gamma$ [21], where the corresponding branching ratios get enhanced in comparison with those of the one-photon processes.

A large two-photon FCNC transition may also have implications for the decay $B^0_s \rightarrow \gamma\gamma$, which can occur through an annihilation graph mediated by the Higgs boson $A^0$. A simple PCAC evaluation shows that the corresponding branching ratio is of order $10^{-7}$, which is comparable to the SM result. In order to obtain further conclusions one needs to include QCD corrections, as has been done recently for the SM and virtual contributions of the charged Higgs [22].

To close this communication we would like to stress the relevance of our results. Even though the SM is a well established theory supported by a plethora of experimental data, it leaves us with some unanswered questions. In particular, the scalar sector with its elusive Higgs boson remains as the SM most puzzling piece. Supersymmetric Grand Unified Theories allow for a relatively light Higgs boson in the range $100 - 200$ GeV [23], and it is possible that in the next years it will occur the milestone discovery of a light Higgs boson. Meanwhile there is an incessant search for any evidence of new physics that could enlighten the road to a more comprehensive theory of elementary interactions. In this context, the results presented in this rapid communication open up the possibility of looking for signals from physics beyond the SM in the FCNC top quark decays $t \rightarrow c\gamma\gamma$, $t \rightarrow c\gamma Z$, $t \rightarrow cW^+W^-$, and $t \rightarrow cgg$. 
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FIG. 1. The decay $t \rightarrow cV_iV_j$ in the SM and Model III. The dots denote couplings that can be induced at tree or one-loop level.

FIG. 2. Scaled branching ratios for $t \rightarrow cV_iV_j$ in Model III: $t \rightarrow c\gamma\gamma$ (solid line), $t \rightarrow c\gamma Z$ (points), $t \rightarrow cW^+W^-$ (hollow circles), and $t \rightarrow cgg$ (full circles). A value of 750 TeV is used for the masses $m_{A^0}$, $m_{H^0}$ and $m_{H^\pm}$. 