Top quark decays with flavor violation in extended models

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Abstract. We analyze the top quark decays $t \to cg$ and $t \to c\gamma$ mediated by a new neutral gauge boson, identified as $Z'$, in the context of the sequential $Z$ model. We focus our attention on the corresponding branching ratios, which are a function of the $Z'$ boson mass. The study range is taken from 2 TeV to 6 TeV, which is compatible with the resonant region of the dileptonic channel reported by ATLAS and CMS Collaborations. Finally, our preliminary results tell us that the branching ratios of $t \to cg$ and $t \to c\gamma$ processes can be of the order of $10^{-11}$ and $10^{-13}$, respectively.

1. Introduction
The Standard Model of elementary particles (SM) is the most successful physical theory developed so far because it has offered very precise predictions of numerous experimental results. The SM is a theory which includes the study of the three fundamental interactions, the electromagnetic, weak and strong; however, to date, it is known that the SM can not explain several questions such as the flavor problem; the phenomena of flavor violation can arise in many of its well-motivated extensions. One interesting feature of most models beyond the SM is the presence of generalized neutral current sectors, which favor nondiagonal transitions mediated by neutral massive spin-1 particles. The presence of a new neutral massive gauge boson $Z'$ is predicted in the context of numerous extensions of the SM. The simplest extended model that predicts the existence of the neutral weak gauge boson is based on the extended electroweak gauge group $SU_C(3) \times SU_L(2) \times U_Y(1) \times U'(1)$ [1].

Today it is well known the existence of neutrino oscillations, which implies that lepton flavor conservation is violated in nature. Moreover, only signals of lepton flavor violation coming from transitions between neutral leptons have been detected. Therefore, flavor-violating transitions between charged fermions constitute an interesting topic, since if they occur in nature are additional evidence of flavor violation. The purpose of this work is to study the effect of the flavor violation of the up-quark sector mediated by $Z'$ through $t \to cg$ and $t \to c\gamma$ processes, particularly, our interest is to calculate the branching ratios of both processes, and then, to contrast these with the SM predictions.

Currently, exhaustive searches for the processes mentioned above are in progress at the LHC, but so far they have not been detected and only upper limits have been established [2, 3].
now, the ATLAS Collaboration has imposed the most stringent bound over the $t \to cg$ decay, i.e., $Br(t \to cg) < 2.7 \times 10^{-4}$ via single top production coming from the $pp \to qg \to t \to W(\to l\nu) b$ reaction [2]. In contrast, the CMS Collaboration establishes that $Br(t \to c\gamma) < 1.7 \times 10^{-3}$ through $pp \to qg \to t\gamma \to W(\to l\nu) b\gamma$ reaction, being the most stringent limit [3].

2. The extension model

We start from the most general renormalizable Lagrangian, which includes flavor violation mediated by a new neutral massive gauge boson $Z'$. This comes from any extended Lagrangian model or grand unification theories [1, 4], and can be written as follows:

$$L_{NC} = \sum_{i,j} \left[ \bar{f}_i \gamma^\alpha (\Omega_{L,i,f_i} P_L + \Omega_{R,i,f_i} P_R) f_j + \bar{f}_j \gamma^\alpha (\Omega_{L,i,f_i}^* P_L + \Omega_{R,i,f_i}^* P_R) f_i \right] Z'_\alpha$$

where $f_i$ is any fermion of the SM, $Z'_\alpha$ is the neutral gauge boson predicted by several extensions of the SM and $P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$ are the chiral projectors. The $\Omega_{L,R,q_i,j}$ parameters represent the strength of the $Z'_{q_i,j}$ coupling, where $q_i$ is any SM quark. The Lagrangian mentioned above includes couplings that conserve and violate flavor mediated by the $Z'$ boson. The flavor-conserving couplings, $Q_{L,R}^{f_i}$ [4, 5], are related with the $\Omega$ parameters as follows: $\Omega_{L,R,f_i} = -g_2 Q_{L,R}^{f_i}$ and $\Omega_{R,f_i} = -g_2 Q_{R}^{f_i}$, where $g_2$ is the gauge coupling of the $Z'$ boson. For the various extended models we are interested in, the gauge couplings of $Z'$s are of the form $g_2 = \sqrt{\frac{5}{3}} \sin \theta_W g_1 \lambda_g$, where $g_1 = g/\cos \theta_W$ and $\lambda_g$ depends on the symmetry breaking pattern, being of $O(1)$ [5]. In the sequential $Z$ model, the gauge couplings fulfill $g_2 = g_1$. It should also be mentioned that $g$ is the weak coupling constant and $\theta_W$ is the Weinberg angle.

3. $t \to cg$ and $t \to c\gamma$ processes

For the analysis of $t \to cg$ and $t \to c\gamma$ it is necessary to known the Feynman rules involved. The contributions of the vertices that violate flavor and those that respect it can be extracted from the renormalizable Lagrangian given in Eq. (1). Specifically, the Feynman rules associated with the couplings $Z'tc$ and $Z'tt$ are given as $\gamma^\alpha (\Omega_{Ltc} P_L + \Omega_{Rtc} P_R)$ and $-g_2 (Q_{L}^{f_i} P_L + Q_{R}^{f_i} P_R)$, respectively. In the rest of the paper we will assume pure vector couplings (i.e. $\Omega_{Ltc} = \Omega_{tc}$ and $\Omega_{Rtc} = \Omega_{tc}$). The contribution of the $Z'tc$ vertex to the $t \to cg$ and $t \to c\gamma$ decays is computed by using the Feynman diagrams shown in Fig. 1. After applying the Passarino-Veltman reduction scheme, the total amplitude of these processes takes the following form: the total amplitude of

![Figure 1. Feynman diagrams contributing to the $t \to cg, c\gamma$ decays.](image-url)
$t \rightarrow cg$ decay is given by

$$M(t \rightarrow cg) = \frac{igg_2}{64\pi^2m_t} \bar{u}(p_j)\sigma^{\mu\nu}q_\nu e_\mu(q) \left[ F_1(Q_L^i - Q_R^i)(\Omega_{Ltc} - \Omega_{Rtc}) + F_2(Q_L^i\Omega_{Ltc} + Q_R^i\Omega_{Rtc}) \right. \left. + \left( F_1(Q_L^i - Q_R^i)(\Omega_{Ltc} + \Omega_{Rtc}) + F_2(Q_L^i\Omega_{Ltc} - Q_R^i\Omega_{Rtc}) \right) \gamma^5 \right] (t^a)_{kl} u(p_i),$$

(2)

where $(t^a)_{kl} = (\lambda^a/2)_{kl}$, $\lambda^a$ are Gell-Mann matrices, $g_s$ is the strong coupling constant and $\epsilon^a(q)$ is the gluon polarization vector. In contrast, the total amplitude for the $t \rightarrow c\gamma$ decay can be written as

$$M(t \rightarrow c\gamma) = \frac{iegg_2}{64\pi^2m_t} \bar{u}(p_j)\sigma^{\mu\nu}q_\nu e_\mu(q) \left[ F_1(Q_L^i - Q_R^i)(\Omega_{Ltc} - \Omega_{Rtc}) + F_2(Q_L^i\Omega_{Ltc} + Q_R^i\Omega_{Rtc}) \right. \left. + \left( F_1(Q_L^i - Q_R^i)(\Omega_{Ltc} + \Omega_{Rtc}) + F_2(Q_L^i\Omega_{Ltc} - Q_R^i\Omega_{Rtc}) \right) \gamma^5 \right] u(p_i),$$

(3)

where $e$ is the electric charge of the electron, $Q_u = 2/3$ and $\epsilon_\mu(q)$ is the photon polarization vector. The form factors $F_1$ and $F_2$ are explicitly given as

$$F_1 = \frac{m_i^2}{m^2_{Z'}} - 6 \left( B_0(0, m_i^2, m_{Z'}^2) - B_0(m_i^2, m_i^2, m_{Z'}^2) \right),$$

(4)

$$F_2 = 2 \left[ 1 + 2 \left( C_0(m_i^2, 0, 0, m_i^2, m_{Z'}^2, m^2_i) + \frac{m_i^2}{m_i^2} \left( B_0(0, m_i^2, m_{Z'}^2) - B_0(m_i^2, m_i^2, m_{Z'}^2) \right) \right) \right],$$

(5)

where $C_0(m_i^2, 0, 0, m_i^2, m_{Z'}^2, m_i^2)$, $B_0(0, m_i^2, m_{Z'}^2)$ and $B_0(m_i^2, m_i^2, m_{Z'}^2)$ are Passarino-Veltman scalar functions. The amplitudes given in Eqs. (2) and (3) are free of ultraviolet divergences because the $B_0$ functions appear subtracting each other and respect gauge invariance.

4. Results and conclusions

Since our main goal is the numerical estimation of the branching ratios for the $t \rightarrow cg$ and $t \rightarrow c\gamma$ processes, we start from the definition of the decay width [6] and we found that it is given as

$$\Gamma(t \rightarrow cV) = \frac{1}{16\pi m_t} |M(t \rightarrow cV)|^2$$

(6)

where $m_t$ is the top quark mass and $V = g, \gamma$. Based on this definition and squaring the amplitude, we can obtain the branching ratio associated with each process of our study

$$Br(t \rightarrow c\gamma) = \frac{\alpha g^2 Q_u^2}{4096\pi^3} \left[ (|F_1(Q_L^i - Q_R^i)|^2 + |F_2(Q_L^i - Q_R^i)|^2)^2 |\Omega_{tc}|^2 m_i \Gamma_t \right],$$

(7)

$$Br(t \rightarrow cg) = \frac{\alpha g^2 C_F}{4096\pi^3} \left[ (|F_1(Q_L^i - Q_R^i)|^2 + |F_2(Q_L^i - Q_R^i)|^2)^2 |\Omega_{tc}|^2 m_i \Gamma_t \right],$$

(8)

where $C_F = \frac{4}{3}$. Here $\alpha_s = \frac{g^2}{4\pi}$ and $\alpha = \frac{e^2}{4\pi}$ are the coupling constants of the strong and electromagnetic interactions, respectively. Since we only try to estimate the strength of flavor changing neutral currents (FCNC), it is assumed that $\alpha_s = 0.12$. 

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In this work we use the LoopTools package for the numerical evaluation of the branching ratios \[ \text{Br}(t \to cg) \] (\[ \text{Br}(t \to c \gamma) \]) as a function of the \[ m_{Z'} \] boson mass. The value of \( \Omega_{tc} \) was set at \( 9.25 \times 10^{-2} \), which is consistent with the estimate obtained for the \( Z'tc \) coupling in a previous work [8]. In both graphs we can see that as the \( Z' \) boson mass grows, the branching ratio of both processes decreases. For the mass interval \( 2.5 \text{ TeV} < m_{Z'} < 3.5 \text{ TeV} \), it can be clearly appreciated that in the \( t \to cg \) and \( t \to c \gamma \) processes induced by FCNC, \( \text{Br}(t \to cg) \sim 10^{-11} \) and \( \text{Br}(t \to c \gamma) \sim 10^{-13} \), respectively, which is one order of magnitude above the SM predictions [9]. The explored region of the \( Z' \) boson mass is between \( 2.5 \text{ TeV} < m_{Z'} < 6 \text{ TeV} \), which is consistent with the experimental limits on the \( Z' \) boson mass reported by the experimental collaborations ATLAS and CMS [10]. We stress that if two-loop SM contributions were considered, they are expected to be suppressed regarding the one-loop SM contributions, since these dominant contributions are very suppressed because the GIM mechanism, so the new physics contribution should be dominant.

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