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# Higgs mediated flavor-violating transitions of the top quark

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Abstract. Flavor violating  $tu_i H$  vertex induces top quark couplings  $tc\gamma$  and  $tu_i\gamma\gamma$  ( $u_i = u, c$ ) at the one-loop level, in the effective Yukawa sector through dimension six  $SU_L(2) \times U_Y(1)$ -invariant operators. The  $t \to cH$  and  $t \to c\gamma\gamma$  decays can reach branching ratios about  $5 \times 10^{-3}$  and  $10^{-4}$ , respectively. As for tc production, it is found that, due to the presence of a resonant effect in the convoluted cross section  $\sigma(e^+e^- \to \gamma\gamma \to t\bar{c} + \bar{t}c)$ , about  $(0.5 - 2.7) \times 10^3 tc$  events may be produced at the ILC for  $m_H \sim m_t$ .

#### 1. Introduction

The fact that the top quark is the heaviest elementary particle known suggests that it would be quite sensitive to new physics effects. Although very suppressed in the SM, the flavor violating  $t \to u_i V$  decays can have sizable branching ratios in many well motivated of its extensions. On the other hand, it is expected that new physics effects on top quark physics can be observed in both LHC and ILC colliders. In this work it is intended to study the rare top quark decays  $t \to u_i H$ ,  $t \to u_i \gamma$ , and  $t \to u_i \gamma \gamma$ , as well as to investigate the  $\gamma \gamma \to \bar{t} u_i + t \bar{u}_i$  reaction in the context of the ILC operating in the  $\gamma \gamma$  mode, which has shown to be the most efficient mechanism in producing tc events, as the corresponding cross section can be up to 2 orders of magnitude and 1 order of magnitude greater than those associated with the production mechanism in the  $e^+e^-$  and  $e\gamma$  collision modes, respectively [1].

#### **2.** Study of the coupling $f_i f_j H$

We incorporate into the classical action the virtual effects of the heavy degrees by introducing  $SU_L(2) \times U_Y(1)$ -invariant operators of dimension higher than four. To extend the Yukawa sector with dimension-six operators to induce the most general coupling of the Higgs boson to quarks and leptons. A Yukawa sector with these features has the following structure

$$\mathcal{L}_{eff}^{Y} = -Y_{ij}^{q}(\bar{Q}_{i}\Phi_{q}q_{j}) - \frac{\alpha_{ij}^{q}}{\Lambda^{2}}(\Phi^{\dagger}\Phi)(\bar{Q}_{i}\Phi_{q}q_{j}) + H.c.,$$
(1)

where  $Y_{ij}$ ,  $Q_i$ ,  $\Phi_q$  ( $\Phi_q = \Phi$ ,  $\tilde{\Phi}$  for q = d, u respectively and a sum over q is implied),  $d_i$ , and  $u_i$  stand for the usual components of the Yukawa matrix, the left-handed quark doublet, the Higgs doublet, and the right-handed quark singlets of down and up type, respectively. The  $\alpha_{ij}$  numbers are the components of a  $3 \times 3$  general matrix, which parametrize the details of the underlying physics, whereas  $\Lambda$  is the typical scale of these new physics effects. This effective Yukawa sector induces a flavor and CP violating coupling  $f_i f_j H$  of renormalizable type given by

$$\Gamma_{f_i f_j H} = -i(\omega_R^{ij} P_R + \omega_L^{ij} P_L), \qquad (2)$$

where  $\omega_R^{ij} = \frac{gm_i}{2m_W} \delta_{ij} + \Omega_{ij}$  and  $\omega_L^{ij} = \frac{gm_i}{2m_W} \delta_{ij} + \Omega_{ij}^*$ , with  $P_{R,L} = (1 \pm \gamma_5)/2$ . In these expressions,  $\Omega^{(u,d)} = \frac{1}{\sqrt{2}} \left(\frac{v}{\Lambda}\right)^2 V_L^{(u,d)} \alpha^{(u,d)} V_R^{(u,d)\dagger}$ , being  $V_L^{(u,d)}$  and  $V_R^{(u,d)}$  the usual unitary matrices, which correlate gauge states to mass eigenstates [1].



**Figure 1.** Feynman diagrams contributing to the  $t \to c\gamma\gamma$  (a) and  $t \to c\gamma$  (c) decays and to the scattering process  $\gamma\gamma \to tc$  (b).

The  $f_i f_j H$  vertex induces the flavor violating vertices  $f_i f_j \gamma$  and  $f_i f_j \gamma \gamma$  at the one-loop level. The contribution to  $f_i f_j \gamma \gamma$  occurs through two set of Feynman diagrams, each of them giving a finite and gauge invariant contribution. The contribution to  $f_i f_j \gamma \gamma$  occurs through two set of Feynman diagrams, each of them giving a finite and gauge invariant contribution. One of these sets, whose contribution is marginal, include box diagrams, reducible diagrams characterized by the one-loop  $f_i f_j \gamma$  coupling, and reducible diagrams composed by the one-loop  $f_i - f_j$  bilinear coupling. The other set of diagrams, which gives the dominant contribution, is characterized by the SM one-loop  $\gamma \gamma H^*$  coupling, with \* stands for a virtual Higgs. We will study the decays  $t \to u_i \gamma$  and  $t \to u_i \gamma \gamma$ , as well as the scattering process  $\gamma \gamma \to t u_i$  (see Fig. 1).

We are also interested in studying the  $t \rightarrow u_i H$  decay, whose branching ratio can be written as

$$Br(t \to u_i H) = \left(\frac{\Omega_{tu_i}^2}{32\pi}\right) \left(\frac{m_t}{\Gamma_t}\right) \left(1 - \left(\frac{m_H}{m_t}\right)^2\right)^2.$$
(3)



Figure 2. The branching ratios for the  $t \to c\gamma$ , and  $t \to c\gamma\gamma$  decays as a function of the Higgs mass. The thin lines correspond to a Higgs mass in the range 115 GeV  $< m_H < 171.3$  GeV.



Figure 3. The branching ratios for the  $t \to cH$ , and  $H \to \gamma\gamma$  decays as a function of the Higgs mass. The thin lines correspond to a Higgs mass in the range 115 GeV  $< m_H < 171.3$  GeV.

We will consider only the contribution arising from the diagrams characterized by the oneloop  $\gamma\gamma H^*$  coupling, as it dominates. In order to make predictions, some value for the  $\Omega_{tu_i}$  parameter must be assumed. In order to make predictions, some value for the  $\Omega_{tu_i}$  parameter must be assumed. By assuming  $\lambda_{tc} \sim 1$ , branching ratios for the  $t \to cH$  and  $t \to c\gamma$  transitions of the order of  $10^{-4}$  and  $10^{-8}$ , respectively, were found. On the other hand, the branching ratio for the  $t \to c\gamma\gamma$  decay was calculated within the context of the THDM-III, which has the simplest extended Higgs sector that naturally incorporates Higgs mediated flavor changing neutral current at the tree level [1]. It was found that this decays can reach a branching as high as  $10^{-4}$ .

We have found that the best constraint arises from the recently observed  $D^0 - \overline{D^0}$  mixing [1]. Since this observable receives contributions simultaneously from both the tuH and tcH couplings, it is only possible to obtain  $|\Omega_{tc}\Omega_{tu}| < 10^{-3}$ . We will assume that  $\Omega_{tu} = 10^{-1}\Omega_{tc}$ , which implies the bounds  $\Omega_{tc}^2 < 10^{-2}$  and  $\Omega_{tu}^2 < 10^{-4}$ .

We will present results only for those processes involving the quark c, which can be translated to the corresponding transitions involving the quark u simply multiplying by a factor of  $10^{-2}$ . In Fig. 3, the branching ratio for the  $t \to cH$  decay and for the  $H \to \gamma\gamma$  decay are shown as a function of the Higgs mass. We can see that  $Br(t \to cH)$  ranges from  $5 \times 10^{-3}$  to  $5 \times 10^{-4}$  for a Higgs mass in the range 115 GeV  $< m_H < 2m_W$ . On the other hand, from Fig.2 we can see that the branching ratio for the  $t \to c\gamma$  decay is suppressed, as it has a value essentially constant of about of  $5 \times 10^{-8}$ , which however is about 6 orders of magnitude larger than the SM prediction. In contrast, the  $t \to c\gamma\gamma$  decay has a branching ratio which can be as high as  $10^{-4} - 10^{-5}$ . It should be noticed that  $Br(t \to c\gamma\gamma) \sim Br(t \to cH)Br(H \to \gamma\gamma)$ , which is evident from graphs in Fig. 2 [1]. From the amplitude for the  $f_i f_j \gamma \gamma$  coupling, one can construct the unpolarized



Figure 4. The cross section for the  $\gamma\gamma \rightarrow t\bar{c} + \bar{t}c$  processes as a function of the Higgs mass for some values of the c.m.s energy.

cross section of the  $\gamma\gamma \rightarrow \bar{t}c + t\bar{c}$  collision, which in turn defines the cross section of the complete



Figure 5. The cross section for the  $e^+e^- \rightarrow \gamma\gamma \rightarrow t\bar{c} + \bar{t}c$  processes as a function of the Higgs mass for some values of the c.m.s energy

process  $e^+e^- \rightarrow \gamma\gamma \rightarrow \bar{t}c + t\bar{c}$  through the relation [1]

$$\sigma(s) = \int_{(m_c+m_t)/\sqrt{s}}^{y_{max}} dz \, \frac{d\mathcal{L}_{\gamma\gamma}}{dz} \, \hat{\sigma}(\gamma\gamma \to \bar{t}\,c + t\,\bar{c}),\tag{4}$$

where  $z = \sqrt{\hat{s}}/\sqrt{s}$ , being  $\sqrt{s}$  and  $\sqrt{\hat{s}}$  the c.m.s. energies of the  $e^+e^-$  and  $\gamma\gamma$  collisions, respectively. In the above expression  $\frac{d\mathcal{L}_{\gamma\gamma}}{dz}$  represents the photon luminosity [1]. The optimum value for the upper limit in the above integral is  $y_{max} \approx 0.83$ . As in the case of the  $t \to c\gamma\gamma$  decay, we are considering only the contribution given by the diagrams characterized by the SM  $\gamma\gamma H^*$  vertex. Initially, the ILC will operate from a  $\sqrt{s}$  of 200-500 GeV, with a luminosity of 500 fb<sup>-1</sup> within the first years of operation and 1000 fb<sup>-1</sup> during the second phase of operation at 500 GeV.

We will present results for energies in the range 250 GeV  $<\sqrt{s} < 1000$  GeV. In Fig. 5 is shown the pure cross section as a function of the Higgs mass for some values of  $\sqrt{\hat{s}}$  and  $\sqrt{s}$ . As it is shown Fig. 4, the convoluted cross section appears as a function of the Higgs mass for some values of  $\sqrt{\hat{s}}$  and  $\sqrt{s}$ . It can be appreciated a significant enhancement of the convoluted cross section for values of the Higgs mass near the value of the top mass. This peculiar effect, which, as it can be appreciated from the graphic in Fig. 5, is not present in the pure  $\hat{\sigma}(\gamma\gamma \rightarrow t\bar{c} + \bar{t}c)$ cross section (see Fig. 4), has its origin in a resonance that occurs for a Higgs mass near the top mass value [1].

The maximum value of the cross section corresponds to  $m_H = 184$  GeV. The respective number of events is 460, 2720, 2460, 2090, and 1700 if a luminosity of  $1000 \,\mathrm{fb}^{-1}$  is assumed. Our results are 1 order of magnitude lower than those derived within the context of top-colorassisted technicolor models and several orders of magnitude lower than those obtained in the littlest Higgs model [1].

# 3. Conclusions.

We have investigated some phenomenological implications of a flavor violating tcH vertex induced by an extended Yukawa sector that incorporates  $SU_L(2) \times U_Y(1)$ -invariant operators of up to dimension six. By bounding the tcH vertex from the recently observed  $D^0 - \overline{D^0}$  mixing, the  $t \to cH$ ,  $t \to c\gamma$ ,  $t \to c\gamma\gamma$ , and  $\gamma\gamma \to t\bar{c} + \bar{t}c$  processes were predicted. Sizable branching ratios for the  $t \to cH$  and  $t \to c\gamma\gamma$  decays of the order of  $10^{-3}$  and  $10^{-4}$ , respectively, were found. A branching ratio of about  $5 \times 10^{-8}$  for the  $t \to c\gamma$  decays was found, which though it is about 6 orders of magnitude larger than the SM prediction, it is not large enough to be detected. It was found that about of  $(0.5 - 2.7) \times 10^3 tc$  events may be produced for a Higgs boson with  $m_H \sim m_t$ .

# 3.1. Acknowledgments

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# References

[1] J. I. Aranda et al., Phys. Rev. D81, 077701 (2010) and references there in.