DOUBLE FLAVOR VIOLATING TOP QUARK DECAYS IN EFFECTIVE THEORIES

Carmine Pagliarone
Università di Cassino & Istituto Nazionale di Fisica Nucleare Pisa, Italy.
A. Fernández and J. J. Toscano
Benemérita Universidad Autónoma de Puebla, Puebla, Pue., México.

Abstract

The possibility of detecting double flavor violating top quark transitions $t \to u_i \tau \mu$ ($u_i = u, c$) is explored in a model-independent manner, using the effective Lagrangian approach. Low-energy data, on high precision measurements, and current experimental limits are used to constraint the $tu_i H$ and $H \tau \mu$ vertices and then to calculate the branching ratio $\text{BR}(t \to u_i \tau \mu)$. If in the Standard Model $\text{BR}(t \to u_i \tau \mu)$ is of the order of $10^{-13} - 10^{-14}$, higgs-mediated double flavor violating top quark decays can occur with branching ratios ranging from $10^{-3}$ to $10^{-4}$ for $114.4 \text{ GeV}/c^2 < m_H < 2m_W$, that is at the reach of the CERN Large Hadron Collider.

1 Introduction

Despite of the fact that the top quark is the heaviest known particle, with a mass comparable to the electroweak symmetry breaking scale, its dynamical
behavior is rather restrictive. Within the Standard Model (SM), the top quark production cross section is evaluated with an uncertainty that is of the order of $\sim 15\%$ and top quarks are assumed to decay to a $W$ boson and a $b$ quark almost $100\%$ of the time. Due to its exceedingly heavy mass, it is reasonable to expect the top to be more related to new physics than other fermions. Top quark physics may then serve as an important window for probing physics beyond the SM. Although some properties of the top quark have already been examined at the Tevatron\(^1\), a further scrutiny is expected at the CERN Large Hadron Collider (LHC), which will operate as a veritable top quark factory, producing about eight millions of $t\bar{t}$ events per year in its first stage, and hopeful up to about eighteen millions in subsequent years\(^2\). Other relevant studies will be realized in the next generation $e^+e^-$ linear colliders.

2 Effective Lagrangian for the Yukawa sector

In the SM, the Yukawa sector is both CP and flavor conserving. CP and flavor violation can be generated at the tree level if new scalar fields are introduced. Another alternative, which does not contemplate the introduction of new degrees of freedom, consists in incorporating 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. A Yukawa sector with these features has the following structure\(^3\) \(^4\):

\[
\mathcal{L}_{\text{eff}}^Y = -Y^L_{ij} (\bar{L}_i \Phi l_j) - \frac{\alpha^L_{ij}}{\Lambda^2} (\Phi^\dagger \Phi) (\bar{L}_i \Phi l_j) + \text{H.c.} \\
- Y^Q_{ij} (\bar{Q}_i \Phi d_j) - \frac{\alpha^Q_{ij}}{\Lambda^2} (\Phi^\dagger \Phi) (\bar{Q}_i \Phi d_j) + \text{H.c.} \\
- Y^U_{ij} (\bar{Q}_i \Phi u_j) - \frac{\alpha^U_{ij}}{\Lambda^2} (\Phi^\dagger \Phi) (\bar{Q}_i \Phi u_j) + \text{H.c.}
\]

(1)

where $Y_{ij}$, $L_i$, $Q_i$, $\Phi$, $l_i$, $d_i$, and $u_i$ stand for the usual components of the Yukawa matrix, the left–handed lepton doublet, the left–handed quark doublet, the Higgs doublet, the right–handed charged lepton singlet, 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 parameterize the details of the underlying physics, whereas $\Lambda$ is the typical scale of these new physics effects. After spontaneous symmetry breaking, this extended Yukawa sector can be diagonalized as usual via the unitary matrices $V_{l,d,u}^L$ and $V_{l,d,u}^R$, which relate gauge states to mass eigenstates. In the unitary gauge, the diagonalized Lagrangian can be written as follows:

$$L_{\text{eff}}^Y = -\left(1 + \frac{g}{2m_W}H \right) \left(\bar{E} M_l E + \bar{D} M_d D + \bar{U} M_u U \right) - H \left(1 + \frac{g}{4m_W} H \left(3 + \frac{g}{2m_W} H \right) \right) \left(\bar{E} \Omega_l^l P_R E + \bar{D} \Omega_d^d P_R D + \bar{U} \Omega_u^u P_R U + H.c. \right)$$

where $M_a$ ($a = l, d, u$) are the diagonal mass matrix and $\bar{E} = (\bar{e}, \bar{\mu}, \bar{\tau})$, $\bar{D} = (\bar{d}, \bar{s}, \bar{b})$, and $\bar{U} = (\bar{u}, \bar{c}, \bar{t})$ are vectors in the flavor space. In addition, $\Omega^a$ are matrices defined in the flavor space given by

$$\Omega^a = \frac{1}{\sqrt{2}} \left(\frac{v}{\Lambda} \right)^2 V_{L,a}^a V_{R,a}^a$$

The above effective Lagrangian describes the most general coupling of renormalizable type of a scalar field to pairs of fermions. This reproduces the main features of most of extended Yukawa sectors, as the most general version of the two–Higgs doublet model (THDM-III) and multi–Higgs models that comprise additional multiplets of $SU_L(2) \times U_Y(1)$ or scalar representations of larger gauge groups. Our approach also cover more exotic formulations of flavor violation, as the so–called familons models or theories that involves an Abelian flavor symmetry. Results, presented in this paper, are then applicable to a wide variety of models that predict scalar–mediated flavor violation.

### 3 The decay $t \to u_i \tau \mu$

The branching ratio for the 3–body decay $t \to u_i \tau \mu$ is calculated using the general couplings $t \to u_i H$ and $H \to \tau \mu$, obtained using the Effective Lagrangian technique (for further details see):\n
$$\text{Br}(t \to u_i H) = \frac{\Omega_{iu}^2}{32\pi} \left(\frac{m_t}{\Gamma_t} \right) \left(1 - \left(\frac{m_H}{m_t} \right)^2 \right)^2$$

$$\text{Br}(H \to \tau \mu) = \frac{\Omega_{\tau \mu}^2}{4\pi} \left(\frac{m_H}{\Gamma_H} \right) \left(1 - \left(\frac{m_\tau}{m_H} \right)^2 \right)^2$$

These two expressions have been obtained ignoring the $u_i$ and the muon masses. Now, in order to evaluate the branching ratio $\text{Br}(t \to u_i \tau \mu) = \text{Br}(t \to u_i H) \times \text{Br}(H \to \tau \mu)$ we need to calculate the following two terms: $|\Omega_{u_i}^2|$ and $|\Omega_{\tau \mu}^2|$.\n
Figure 2: a) Diagram contributing to the magnetic and electric dipole moments of the $f_i$ fermion; b) diagrams contributing to the $l_i \rightarrow l_j \gamma$ decay.

4 Bounding the $tu_i H$ and $H \tau \mu$ vertices

An estimate of the size of $|\Omega_{tu_i}|^2$ and $|\Omega_{\tau \mu}|^2$ parameters is needed. Although they have been already estimated before, by means of the Cheng–Sher ansatz, or with other similar assumptions, we will resort to the available low–energy data, in order to be more independent from any extra assumption. A constrain on the $|\Omega_{tu_i}|^2$ parameter can be obtained, from the low–energy data, through one–loop or higher order effects. We will examine the contribution to the $tu_i H$ vertex to the proton and neutron magnetic and electric dipole moments (see Figure 2.a). The contribution of the $f_i f_j H$ vertex to the magnetic and electric dipole moments of the $f_i$ fermion have been calculated and the electromagnetic dipoles of $f_i$ can be written as follows:

$$a_i = -\frac{Q_j x_i x_j}{8\pi^2} Re(\Omega_{ij}^2) g(x_j), \quad d_i = -\frac{Q_j x_j}{16\pi^2} \left( \frac{e}{m_H} \right) Im(\Omega_{ij}^2) g(x_j)$$

We now are in position of using low–energy data to bound the $|\Omega_{tu_i}|^2$ and $|\Omega_{\tau \mu}|^2$ parameters.

4.1 Bounds on $|\Omega_{tu_i}|^2$

In order to bound $Re(\Omega_{tu_i}^2)$ we used the available precision measurements on the proton and neutron magnetic dipole moments. We used the experimental uncertainty on the proton magnetic dipole, as it is the most restrictive. Thus, the contribution of the $tu H$ vertex must be less than this uncertainty:

$$|\Delta a_p^{Exp}| < 2.8 \times 10^{-8}$$
Figure 3: a) Behavior of $\Omega_{tu}^2$ b) $\Omega_{t\mu}^2$, as a function of the Higgs mass.

In order to constrain the $\text{Im}(\Omega_{tu}^2)$ term, we used the very stringent experimental limit coming from the neutron electric dipole moment \cite{11}:

$$|d_n| < 2.9 \times 10^{-26} \text{ e.cm.}$$

(8)

The $p$ and $n$ magnetic and electric dipole moments, respectively, are related with those of their elementary constituents through the following expressions:

$$a_p = \frac{2}{3} a_u - \frac{1}{3} a_d - \frac{1}{3} a_s,$$

$$d_n = \frac{4}{3} d_d - \frac{1}{3} d_u$$

(9)

Assuming that the new physics contributions to $a_p$ and $d_n$ arise exclusively from the quark $u$, as in this case $f_j = t$ and assuming, as usual, $m_d \approx m_u \approx m_n/3 \approx m_p/3$ we finally get:

$$|\text{Re}(\Omega_{tu}^2)| < (54\pi^2) \left| \frac{\Delta a_p^{\text{Exp}}}{x_t x_p g(x_t)} \right|,$$

$$|\text{Im}(\Omega_{tu}^2)| < (36\pi^2) \left( \frac{m_H}{e} \right) \left| \frac{\Delta d_n^{\text{Exp}}}{x_t g(x_t)} \right|$$

(10)

As in this case $|\text{Im}(\Omega_{tu}^2)| < |\text{Re}(\Omega_{tu}^2)|$ (as matter of fact for $m_H = 100 \text{ GeV/c}^2$ we have $|\text{Re}(\Omega_{tu}^2)| < 6 \times 10^{-3}$ and $|\text{Im}(\Omega_{tu}^2)| < 10^{-7}$) we can write:

$$|\Omega_{tu}^2|^2 < (54\pi^2) \left| \frac{\Delta a_p^{\text{Exp}}}{x_t x_p g(x_t)} \right|$$

(11)

In Figure 3a, we show the behavior of $|\Omega_{tu}^2|$ as a function of the Higgs mass.

4.2 Bounds on $|\Omega_{t\mu}|^2$

The best experimental limits on the $\mu$ anomalous magnetic moment, and on the electric dipole moment are \cite{10}:

$$|\Delta a_{\mu}^{\text{Exp}}| < 5.4 \times 10^{-10}, \quad |\delta_{\mu}^{\text{Exp}}| < 3.7 \times 10^{-19} \text{ e.cm.}$$

(12)
In this case we obtain:

\[ |\text{Re}(\Omega_{\tau\mu}^2)| < (8\pi^2) \left| \frac{\Delta a_{\mu}^{\text{Exp}}}{x_\tau x_\mu g(x_\tau)} \right|, \quad |\text{Im}(\Omega_{\tau\mu}^2)| < (16\pi^2) \left( \frac{m_H}{e} \right) \left| \frac{\alpha_{\mu}^{\text{Exp}}}{x_\tau g(x_\tau)} \right| \]  

(13)

This time we have \( |\text{Re}(\Omega_{\tau\mu}^2)| < |\text{Im}(\Omega_{\tau\mu}^2)| \) (as matter of fact for \( m_H = 100 \text{ GeV}/c^2 \) we get \( |\text{Re}(\Omega_{\tau\mu}^2)| < 3 \times 10^{-4} \) and \( |\text{Im}(\Omega_{\tau\mu}^2)| < 2 \)). In order to simplify the analysis we will assume that the leptonic Yukawa sector is also CP-conserving, then we can write:

\[ \Omega_{\tau\mu}^2 < (8\pi^2) \left| \frac{\Delta a_{\mu}^{\text{Exp}}}{x_\tau x_\mu g(x_\tau)} \right| \]  

(14)

In Figure 4, we show the behavior of \( \Omega_{\tau\mu}^2 \) as a function of the higgs mass.

5 DFV top quark decays at LHC

We are now able to evaluate the branching ratio for the decay \( t \to u_\tau \tau \mu \) as a function of the higgs mass: \( \text{Br}(t \to u_\tau \tau \mu) = \text{Br}(t \to u_\tau H) \times \text{Br}(H \to \tau \mu) \). The result, given in Figure 4, shows that \( \text{Br}(t \to u_\tau \tau \mu) \) ranges from \( 10^{-3} \) to \( 10^{-4} \) for a higgs mass between 114.4 GeV/c^2 and \( 2m_W \).

LHC will be the ideal machine for investigating the characteristic of the heaviest quark and its role in the SM; with an NLO production cross-section of about 830 pb, 2 top-pair per second are expected and more than 10 million per year at low luminosity conditions of \( 2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1} \). If \( \mathcal{B} \) represents the branching ratio for the higgs mediated double flavor violating top quark decay, \( \mathcal{B} \equiv \text{Br}(t \to u_\tau \tau \mu) \), and if we assume no other significantly accessible decay channels, either
than the SM and the DFV, we will have: \( \text{Br}(t \rightarrow Wb) = 1 - B \). A \( t \bar{t} \) pair can then decays as follows: a) purely SM decays (SM-SM), where both the top quarks decay into \( Wb \) (\( \text{Br}(t \bar{t})_{SM} = (1 - B)^2 \)); b) mixed SM-DFV decays, where one top will decay into \( Wb \) and the other into \( u_i \mu \tau \) (\( \text{Br}(t \bar{t})_{SM-DFV} = 2B(1-B) \)); c) purely DFV decays (DFV-DFV), in this case both the top quarks will decay into \( u_i \mu \tau \) (\( \text{Br}(t \bar{t})_{DFV} = B^2 \)). Because a purely DFV decay is strongly suppressed, we will focus only on SM-DFV top quark decays. As in the channel \( t \bar{t} \rightarrow u_i \mu \tau Wb \) there is no charge correlation between the \( \mu \) and the \( W \), if the \( W \) decays leptonically (\( W \rightarrow \ell \nu \ell \)) it is possible to have both like-sign (LS) and opposite-sign (OS) final states: \( \mu^\pm \ell^\pm \) and \( \mu^\pm \ell^\mp \). On the other hand, the \( \tau \) lepton can decay hadronically with a probability around 65.5 \%, producing a \( \tau \)-jet containing a small number of charged and neutral hadrons. When the momentum of the \( \tau \) is large compared to the mass a very collimated jet is produced. At LHC center of mass energy, for a transverse momentum \( P_T > 50 \text{ GeV/c} \), 90\% of the energy is contained in a cone of radius \( R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.2 \). Hadronic \( \tau \) decays have low charged track multiplicity (one or three prongs) and a relevant fraction of electromagnetic energy deposition in the calorimeters due to photons coming from the decay of neutral pions. In Table 1 we show the expected \( \sigma \times \text{BR} \) for the LS \( t \bar{t} \) decays: \( t \bar{t} \rightarrow \mu^\pm \ell^\pm u_i b \tau_h \nu_f \). We then look for \( t \bar{t} \) final states, containing a tau lepton decaying hadronically (\( \tau_h \)) and two LS leptons: \( t \bar{t} \rightarrow \mu^\pm \ell^\pm u_i b \tau_h \nu_f \). Events are selected requiring the presence of at least two jets (including the \( b \)-jet), a \( \mu \), another lepton (\( e \) or \( \mu \) with the same sign of the first \( \mu \)), one tagged \( \tau \)-jet, one tagged \( b \)-jet and missing transverse energy. The two LS leptons are required to have \( p_T > 20 \text{ GeV/c} \) and \( \eta < 2.4 \). Jets are reconstructed with a cone size of \( R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.5 \), a transverse energy of \( E_T^\text{jet} > 40 \text{ GeV} \) within a fiducial volume of \( |\eta| < 2.4 \). The \( b \)-jets are tagged and required to pass the same kinematic cuts as those applied on the jets. The presence of \( \tau \), in the events, is guaranteed by tagging the \( \tau \)-jets \[^{12}\]. A further cut on the transverse energy of the \( \tau \)-jet, is applied in order to further suppress the background. Using the first 30 fb\(^{-1}\) of data, it will be possible to exclude, at 95 \% C.L., DFV top quark decays mediated by a higgs with a mass up to 160 GeV/c\(^2\).

### 6 Conclusions

In this paper we studied the possibility of detecting double flavor violating top quark decays \( t \rightarrow u_i \mu \tau \) in a model–independent manner using the effective Lagrangian approach. A Yukawa sector that includes all the \( SU_L(2) \times U_Y(1) \)
invariant operators of up to dimension six was proposed and used to construct the most general renormalizable flavor violating $q_i q_j H$ and $H l_i l_j$ vertices. Low-energy data were used to constraint the $t u_i H$ and $H \tau \mu$ couplings and then used to predict the double flavor violating decay $t \rightarrow u_i \tau \mu$. It was found that this decay has a branching ratio of order of $10^{-3} - 10^{-4}$ for $115 \text{ GeV}/c^2 < m_H < 2 m_W$. Considering that LHC will operate as a veritable top quark factory, by using the first 30 fb$^{-1}$ of data it will be possible to exclude, at 95% C.L., DFV top quark decays up to a higgs mass of 160 GeV/c$^2$.

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References

1. F. Abe et al., Phys. Rev. D51, 4623 (1995); Phys. Rev. Lett. 80, 2767 (1998); 80, 2779 (1998); 82, 271 (1999); 80, 2773 (1998); 79, 1992 (1997); 79, 3585 (1997); 80, 5720 (1998); 80, 2525 (1998); S. Abachi et al., ibid. 79, 1197 (1997); 79, 1203 (1997); B. Abbott et al., abid. 80, 2063 (1998); 83, 1908 (1999); Phys. Rev. D58, 052001 (1998).

2. D. Chakraborty, J. Konigsberg, and D. Rainwater, Annu. Rev. Nucl. Part. Sci. 53, 301 (2003).

3. Adriana Cordero–Cid, M. A. Pérez, G. Tavares–Velasco, and J. J. Toscano, Phys. Rev. D70, 074003 (2004).

4. J. L. Díaz–Cruz and J. J. Toscano, Phys. Rev. D62, 116005 (2000).

5. See for instance, J. L. Díaz–Cruz, R. Noriega–Papaqui, and A. Rosado, Phys. Rev. D69, 095002 (2004); Phys. Rev. D71, 015014 (2005).

6. J. L. Feng, T. Moroi, H. Murayam, and E. Schnapka, Phys. Rev. D57, 5875 (1998).

7. I. Dorsner and S. M. Barr, Phys. Rev. D65, 095004 (2002).

8. A. Fernandez, C. Pagliarone, J. Toscano, Higgs mediated Double Flavor Violating top decays in Effective Theories, paper in preparation.

9. T. P. Cheng and M. Sher, Phys. Rev. D35, 3484 (1987).

10. W. M. Yao et al., Jorunal of Physics G33, 1 (2006).

11. The most recent bound on $d_n$ is reported in: C. Baker et al., Phys. Rev. Lett. 97, 131801 (2006).

12. G. Bagliesi, arXiv:0707.0928 [hep-ex].