Top quark rare decays in the standard model and beyond

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Abstract

Theoretical predictions for the top quark rare decays are reviewed within and beyond the standard model. Expectations at the CERN Large Hadron Collider are discussed.

1 Introduction

The production of $10^7 - 10^8$ top quark pairs per year at the CERN Large Hadron Collider (LHC) will allow to probe the top couplings to both known and new particles involved in possible top decay channels different from the main $t \to bW$. Thanks to the large top mass, there are several decays that can be considered, even involving the presence of on-shell heavy vector bosons or heavy new particles in the final states. On a purely statistical basis, one should be able to detect a particular decay channel whenever its branching ratio (B) is larger than about $10^{-6} - 10^{-7}$. In practice, background problems and systematics will lower this potential by a few orders of magnitude, the precise reduction being dependent of course from the particular signature considered. We will see, that the final detection threshold for each channel will not allow the study of many possible final states predicted in the standard model (SM), unless new stronger couplings come into play.

After discussing in section 2 the main top quark rare decay channels predicted by the SM, we review in section 3 the expectations of a large class of possible extensions of the SM, such as the inclusion of a 4^{th} fermion family, the two-Higgs-doublet models, and the minimal supersymmetric standard model (MSSM). Finally, results of the analysis of the LHC potential in the top rare decays field are reported in section 4.

2 Standard Model Decays

In this section, we give an overview of the decay channels of the top quark in the framework of the SM. In the SM the decay $t \to bW$ is by far the dominant one. The top total width is then given by:

$$\Gamma_T \simeq \Gamma(t \to bW) \simeq 0.17 \text{ GeV}|V_{tb}|^2 \frac{m_t^3}{M_W^3} \simeq 1.55\text{GeV}. \tag{1}$$

The rates for other decay channels are predicted to be smaller by a few orders of magnitude in the SM. The second most-likely decays are the Cabibbo-Kobajashi-Maskawa (CKM) non-diagonal decays $t \to sW$ and $t \to dW$. Assuming $|V_{ts}| \simeq 0.04$ and $|V_{td}| \simeq 0.01$, respectively [1], one gets;

$$B(t \to sW) \sim 1.6 \times 10^{-3} \text{ and } B(t \to dW) \sim 1 \times 10^{-4}, \tag{2}$$

in the SM with three families. From now on, $B(t \to \ldots)$ for a generic decay channel, stands for the quantity:

$$B(t \to \ldots) = \frac{\Gamma(t \to \ldots)}{\Gamma(t \to bW)}. \tag{3}$$

The two-body tree-level decay channels are the only ones that LHC could be able to detect in the framework of the SM. The next less-rare processes indeed turn out to have rates not larger than 10^{-6}. At tree level, the decay $t \to bWZ$ (fig. 1) has some peculiar features, since the process occurs near the kinematical threshold ($m_t \sim M_W + M_Z + m_b$). This fact makes crucial the W and Z finite-width effects in the theoretical prediction of the corresponding width. In [2], an estimate of $B(t \to bWZ)$ was given on the basis of the definition:

$$\Gamma(t \to bWZ) \equiv \frac{\Gamma(t \to b\mu\nu_\mu ee)}{B(W \to \mu\nu_\mu)B(Z \to ee)} \tag{4}$$

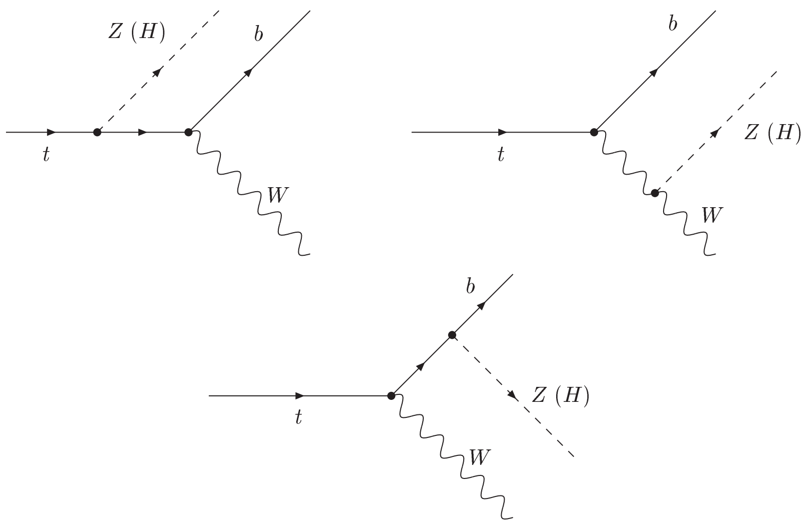

Figure 1: Feynman graphs for the decay $t \to bWZ$ ($t \to bWH$).

involving experimentally well-observable decays. This definition involves 14 diagrams contributing to the $b\mu\nu_\mu ee$ final state in the SM. The estimate for the corresponding branching ratio is:

$$B_{cut}(t \to bWZ) \simeq 6 \times 10^{-7}, \tag{5}$$

for $m_t = 175$ GeV, assuming a minimum cut of $0.8M_Z$ on the ee-pair invariant mass. This cut tries to cope with the contribution of background graphs where the ee pair rises not from a Z boson but from a photon. Recently, in [3], it has been argued that $B(t \to bWZ)$ should be defined by including in the definition in eq. (4) only the three (gauge-invariant) diagrams that correspond to the process where the final state $b\mu\nu_\mu ee$ is truly mediated by a W and a Z. Then one obtains, for $m_t = 175$ GeV:

$$B(t \to bWZ) = B_{res}(t \to bWZ) = 2.1 \times 10^{-6}. \tag{6}$$

Such an increase in $B(t \to bWZ)$ is partly due to the negative interference effects with the graphs where a photon replaces the Z boson (which are present in the previous estimate of the quantity), and partly to the absence of any kinematical cut (which for the resonant graphs is not needed).
One could also find less ambiguous definitions for $B(t \to bWZ)$ than the one involved in eq. (4). For instance, the new definition:

$$\tilde{\Gamma}(t \to bWZ) \equiv \frac{\Gamma(t \to b\mu\nu_\mu\nu_e\nu_e)}{B(W \to \mu\nu_\mu)B(Z \to \nu_e\nu_e)} \tag{7}$$

would not require any kinematical cut, would involve a negligible background, and would give for $B(t \to bWZ)$ the same result as in eq.(6). Of course, the signature $b\mu\nu_\mu\nu_e\nu_e$ would not be practical from an experimental point of view, also because of the tiny rates involved in this decay channel.
Then, the authors in [3] agree that an experimental measurement of the decay rate of $t \to bWZ$ should go through the definition in eq. (4), where the final state $b\mu\nu_\mu ee$ includes all the possible backgrounds. They confirm the result in eq. (5) as an experimental *effective* quantity.

If the Higgs boson is light enough, one could also have the decay $t \to bWH$ (fig. 1), although the present limits on m_H strongly suppress its rate. For $m_H \gtrsim 100$ GeV, one gets [2]:

$$B(t \to bWH) \lesssim 7 \times 10^{-8}. \tag{8}$$

Finally, the decay $t \to cWW$ is very much suppressed by a GIM factor $\frac{m_b^2}{M_W^2}$ in the amplitude. One than gets [4]:

$$B(t \to cWW) \sim 10^{-13}. \tag{9}$$

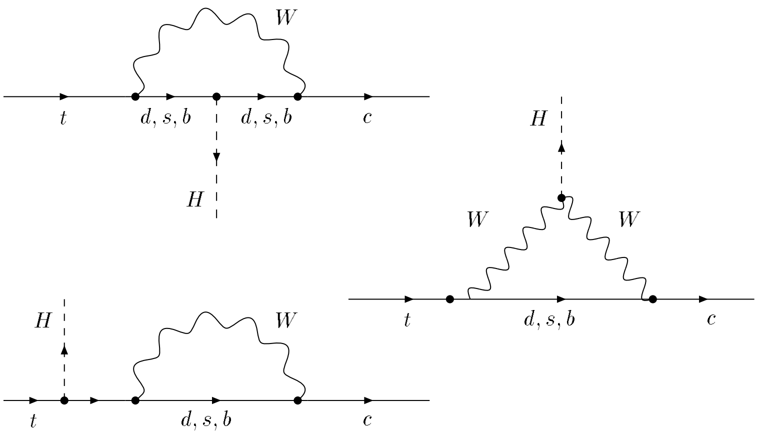

Figure 2: Feynman graphs for the decay $t \to cH$ in the unitary gauge ($m_c = 0$ is assumed).

One can also consider the radiative three-body decays $t \to bWg$ and $t \to bW\gamma$. These channels suffer from infrared divergences, and the evaluation of their rate requires a full detector simulation, including for instance the effects of the detector resolution and the jet isolation algorithm. In an idealized situation where the rate is computed in the t rest frame with a minimum cut of 10 GeV on the gluon or photon energies, one finds [5]:

$$
\begin{aligned}
B(t \to bWg) &\simeq 0.3, & (10)\\
B(t \to bW\gamma) &\simeq 3.5 \times 10^{-3}. & (11)
\end{aligned}
$$

The FCNC decays $t \to cg$, $t \to c\gamma$ and $t \to cZ$ occur at one loop, and are also GIM suppressed by a factor $\frac{m_b^2}{M_W^2}$ in the amplitude. Hence, the corresponding rates are very small [6]:

$$
\begin{aligned}
B(t \to cg) &\simeq 5 \times 10^{-11} & (12)\\
B(t \to c\gamma) &\simeq 5 \times 10^{-13} & (13)\\
B(t \to cZ) &\simeq 1.3 \times 10^{-13} & (14)
\end{aligned}
$$

For a light Higgs boson, one can consider also the FCNC decay $t \to cH$ (fig. 2). A previous evaluation of its rates [6] has now been corrected. For $m_H \simeq 100$ (160) GeV, one gets then [7, 8]:

$$
B(t \to cH) \simeq 0.9 \times 10^{-13} \;\; (4 \times 10^{-15}). \tag{15}
$$

We conclude this section, by presenting in table 1 a summary of the expected decay rates for the main top decay channels in the SM.

3 Beyond the Standard Model (BSM) decays

The fact that a measurement of the top width is not available and the branching ratio $B(t \to bW)$ is a model dependent quantity makes the present experimental constraints on the top BSM decays quite weak. Hence, the large value of m_t allows to consider the possibility of t decays into new massive states with branching fraction of order $B(t \to bW)$. Apart from the production of new final states with large branching fractions, we will see that new physics could also give rise to a considerable increase in the rates of many decay channels that in the SM framework are under the threshold of observability.

channel	B_{SM}
bW	1
sW	$1.6 \cdot 10^{-3}$
dW	$\sim 10^{-4}$
bWg	0.3 ($E_g > 10$ GeV)
$bW\gamma$	$3.5 \cdot 10^{-3}$ ($E_\gamma > 10$ GeV)
bWZ	$2 \cdot 10^{-6}$
cW^+W^-	$\sim 10^{-13}$
bW^+H	$< 10^{-7}$
qg	$5 \cdot 10^{-11}$
$q\gamma$	$5 \cdot 10^{-13}$
qZ	$1.3 \cdot 10^{-13}$
cH	$< 10^{-13}$

Table 1: Branching ratios for the main SM top decay channels.

3.1 4^{th} fermion family

Extending the SM with a 4^{th} fermion family can alter considerably a few t decay channels. First of all, when adding a 4^{th} family to the CKM matrix the present constraints on the $|V_{tq}|$ elements are considerably relaxed. In particular, $|V_{ts}|$ and $|V_{td}|$ can grow up to about 0.5 and 0.1, respectively [1]. Correspondingly, assuming $|V_{tb}| \sim 1$ for the sake of normalization, one can have up to :

$$B_4(t \to sW) \sim 0.25 \;\text{ and }\; B_4(t \to dW) \sim 0.01, \tag{16}$$

to be confronted with the SM expectations in eq. (2).

The presence of a 4^{th} fermion family could also show up in the t direct decay into a heavy b' quark with a relatively small mass ($m_{b'} \sim 100$ GeV) [9]. This decay would contribute to the $t \to cWW$ channel. The corresponding rate would be:

$$\mathrm{B}(t \to W^+ b'(\to W^- c)) \sim 10^{-3}\;(10^{-7}) \quad \text{at} \quad m_{b'} = 100\;(300)\;\text{ GeV}, \tag{17}$$

to be confronted with the SM prediction in eq. (9).

3.2 Two Higgs Doublet models (2HDM's)

The possibility that the electroweak symmetry breaking involves more than one Higgs doublet is well motivated theoretically. In particular, three classes of two Higgs doublet models have been examined in connection with rare top decays, called model I, II and III. The first two are characterized by an *ad hoc* discrete symmetry which forbid tree-level FCNC [10], that are strongly constrained in the lightest quarks sector. In model I and model II, the up-type quarks and down-type quarks couple to the same scalar doublet and to two different doublets, respectively (the Higgs sector of the MSSM is an example of model II). In model III [11, 12], the above discrete symmetry is dropped and tree-level FCNC are allowed. In particular, a tree-level coupling tcH is predicted with a coupling constant $\lesssim \frac{\sqrt{m_t m_c}}{v}$ (where v is the Higgs vacuum expectation value).

Since enlarging the Higgs sector automatically implies the presence of charged Higgs bosons in the spectrum, one major prediction of these new frameworks is the decay $t \to bH^+$, with possibly competitive rates with $B(t \to bW)$ for $m_{H^+} \lesssim 170$ GeV. In the MSSM, one has $B(t \to bH^+) \sim 1$, both at small and large values of $\tan\beta$. If $m_H < m_t - m_b$, one expects $H^+ \to \tau^+\nu$ (favored for large $\tan\beta$) and/or $H^+ \to c\bar{s}$ (favored for small $\tan\beta$) to be the dominant decays. Hence, for $\tan\beta > 1$ and $H^+ \to \tau^+\nu$ dominant, one can look for the channel $t \to bH^+$ by studying a possible excess in the τ lepton signature from the t pair production [13]. On the other hand, if $\tan\beta < 2$ and $m_H > 130$ GeV, the large mass (or coupling) of the t-quark causes $\mathrm{B}(H^+ \to t^*\bar{b} \to W^+ b\bar{b})$ to exceed $\mathrm{B}(H^+ \to c\bar{s})$ (see [14] for details). As a consequence, new interesting signatures at LHC like leptons plus multi-jet channels with four b-tags, coming from the gluon-gluon fusion process $gg \to t\bar{b}H^-$, followed by the $H^- \to \bar{t}b$ decay, have been studied [15]. These processes could provide a viable signature over a limited but interesting range of the parameter space. One should recall however that both $B(t \to bH^+)$ and $B(H^+ \to W^+ b\bar{b})$ are very sensitive to higher-order corrections, which are highly model dependent [16, 17].

In model III, the tree-level FCNC decay $t \to ch$ can occur with branching ratios up to 10^{-2} [12]. In [18], the rate for the channel $t \to ch \to cWW(cZZ)$ has been studied. Accordingly, $B(t \to cWW)$ can be enhanced by several orders of magnitude with respect to its SM value. In particular, for an on-shell decay with $2M_W \lesssim m_h \lesssim m_t$, one can have up to $B(t \to cWW) \sim 10^{-4}$ from this source. The same process was considered in a wider range of models, where the decay $t \to cWW$ can occur not only through a scalar exchange but also through a fermion or vector exchange [9]. In this framework, the fermion exchange too could lead to detectable rates for $t \to cWW$, as in eq. (17).

In 2HDM's, the prediction for the FCNC decays $t \to cg$, $t \to c\gamma$ and $t \to cZ$ can also be altered. While in models I and II the corresponding branching fractions can not anyway approach the detectability threshold [6], in model III values up to $B(t \to cg) \simeq 10^{-5}$, $B(t \to c\gamma) \simeq 10^{-7}$ and $B(t \to cZ) \simeq 10^{-6}$ are predicted [19].

By further extending the 2HDM's sector and including Higgs triplets, one can give rise to a vertex HWZ at tree level in a consistent way [20]. Accordingly, the $t \to bWZ$ decay can be mediated by a charged Higgs (coupled with m_t) that can enhance the corresponding branching fraction up to $B(t \to bWZ) \sim 10^{-2}$. Large enhancements can also be expected in similar models for the channels $t \to sWZ$ and $t \to dWZ$.

3.3 Minimal Supersymmetric Standard Model (MSSM)

Supersymmetry could affect the t decays in different ways [here, we assume the MSSM framework [21], with (or without, when specified) R parity conservation].

First of all, two-body decays into squarks and gauginos, such as $t \to \tilde{t}_1 \tilde{g}$, $t \to \tilde{b}_1 \tilde{\chi}_1^+$, $t \to \tilde{t}_1 \tilde{\chi}_1^0$, could have branching ratios of order $B(t \to bW)$, if allowed by the phase space (see, i.e., [22] for references). QCD corrections to the channel $t \to \tilde{t}_1 \tilde{g}$ have been computed in [23] and found to increase its width up to values even larger than $\Gamma(t \to bW)$. Three-body t decays in supersymmetric particles were surveyed in [22].

The presence of light top and bottom squarks, charginos and neutralinos in the MSSM spectrum could also give rise to a CP asymmetry of the order 10^{-3} in the partial widths for the decays $t \to bW^+$ and $\bar{t} \to \bar{b}W^-$ [24].

Explicit R-parity violating interactions [25] could provide new flavor-changing t decays, both at tree-level (as in the channels $t \to \tilde{\tau}b$ and $t \to \tau b \tilde{\chi}_1^0$ [26]) and at one loop (as in $t \to c\tilde{\nu}$ [27]), with observable rates. For instance, $B(t \to c\tilde{\nu}) \sim 10^{-4} - 10^{-3}$ in particularly favorable cases.

Another sector where supersymmetric particles could produce crucial changes concerns the one-loop FCNC decays $t \to cg$, $t \to c\gamma$, $t \to cZ$ and $t \to cH$, which in the SM are unobservally small. In the MSSM with universal soft breaking the situation is not much affected, while, by relaxing the universality with a large flavor mixing between the 2^{nd} and 3^{rd} family only, one can reach values such as [28, 29]:

$$
\begin{aligned}
B_{MSSM}(t \to cg) &\sim 10^{-6} && (18)\\
B_{MSSM}(t \to c\gamma) &\sim 10^{-8} && (19)\\
B_{MSSM}(t \to cZ) &\sim 10^{-8}, && (20)
\end{aligned}
$$

which anyhow are still not observable. The introduction of B-violating couplings in broken R-parity models could on the other hand give large enhancements [30], and make some of these channels observable. The corresponding upper limits on branching ratios get then:

$$
\begin{aligned}
B_{\not{R}}(t \to cg) &\sim 10^{-3} && (21)\\
B_{\not{R}}(t \to c\gamma) &\sim 10^{-5} && (22)\\
B_{\not{R}}(t \to cZ) &\sim 10^{-4}. && (23)
\end{aligned}
$$

A particularly promising channel is the FCNC decay $t \to ch$ in the framework of MSSM, where $h = h^0, H^0, A^0$ is any of the supersymmetric neutral Higgs bosons [31]. By including the leading MSSM contributions to these decays (including gluino-mediated FCNC couplings), one could approach the detectability threshold, especially in the case of the light CP-even Higgs boson, for which one can get up to:

$$B_{MSSM}(t \to ch^0) \sim 10^{-4}. \tag{24}$$

4 LHC potential for top rare decays

An extensive analysis of the LHC potential for detecting top rare decays has been performed by both the LHC experiments ATLAS and CMS [32]. In the framework of the SM, the top rare decays (that is any channel different from $t \to qW$) turn out to be definitely below the threshold for an experimental analysis at LHC. On the other hand, LHC experiments will be able to probe quite a few predictions of possible extensions of the SM.

An extended Higgs sector will be looked for through the tree-level decay $t \to bH^+$. ATLAS estimates its sensitivity to this channel in the MSSM, through an excess in the tau lepton signal, to be around $\mathrm{B}(t \to H^+ b) = 3\%$ (that is almost 4 times better than what expected from Run 2 at the Tevatron). This would allow to probe all values of $m_{H^\pm}$ below $m_t - 20$ GeV over most of the $\tan\beta$ range. For low $\tan\beta$, the complementary decay mode $H^\pm \to cs$ has been considered. In the mass range $110 < H^\pm < 130$ GeV, the $H^\pm$ peak can be reconstructed and separated from the dominant $W \to jj$ background.
For CMS, using the tau excess signature, the expected 5σ discovery range for 10 fb^{-1} in the MSSM $(m_A, \tan\beta)$ parameter space is $m_A < 110$ GeV, for all $\tan\beta$ values, and somewhat extended ($m_A \lesssim$ 140), for $\tan\beta \lesssim 2$.
Other interesting signatures like $H^\pm \to hW^*$, $H^\pm \to AW^*$ and $H^\pm \to bt^* \to bbW$ are very promising in particular parameter ranges, but have not yet been thoroughly investigated.

ATLAS has studied its sensitivity to the radiative decay $t \to WbZ$. This has been found to be at most of the order 10^{-4}, that is insufficient for the study of a SM signal ($\sim 10^{-6}$), but possibly useful for exploring the predictions of some extended Higgs-sector model, for which $\mathrm{B}(t \to WqZ) \lesssim 10^{-2}$. On the other hand, the radiative Higgs decay $t \to WbH$ seems out of the reach of LHC in any realistic model.

The LHC reach for the FCNC decays $t \to qZ$, $t \to q\gamma$ and $t \to qg$ has also been thoroughly investigated. Apart from the $t \to qg$, which is completely overwhelmed by the hadronic background, both ATLAS and CMS have a sensitivity of about 2×10^{-4} to the $t \to qZ$ channel, while the CMS reach for the $t \to q\gamma$ channel is about 3.4×10^{-5}, that is slightly better than the ATLAS sensitivity (1.0×10^{-4}), assuming an integrated luminosity of 100 fb^{-1}. These thresholds are too high to test the predictions of the models reviewed here. On the other hand, they could be largely sufficient to detect some manifestation of possible FCNC anomalous couplings in the top sector [32].

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