FCNC top decays into Higgs bosons in the MSSM

Jaume GUASCH
Grup de Física Teòrica
and
Institut de Física d’Altes Energies
Universitat Autònoma de Barcelona
08193 Bellaterra (Barcelona), Catalonia, Spain

Abstract

We compute the partial width of the FCNC top quark decay $t \rightarrow c h$ in the framework of the Minimal Supersymmetric Standard Model, where $h \equiv h^0, H^0, A^0$ is any of the neutral Higgs of the MSSM. We include the SUSY electroweak, Higgs, and SUSY-QCD contributions. Our results substantially improve previous estimations on the subject, and we find that there is a possibility that they can be measured at LHC.

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1 Introduction

We perform the computation of the Flavour Changing Neutral Current (FCNC) decay of the top quark into a charm quark and a neutral Higgs particle in the framework of the Minimal Supersymmetric Standard Model (MSSM), \( t \to c h \) where \( h \) is any of the neutral Higgs particles of the MSSM, namely the light or heavy CP-even ("scalar") Higgs bosons \( h^0, H^0 \), or the CP-odd ("pseudoscalar") Higgs \( A^0 \). We compute the contributions from the SUSY electroweak, Higgs, and SUSY-QCD sectors, in a particle mass model motivated by model building and Renormalization Group Equations (RGE). However, we neither restrict ourselves to a spectrum of any SUSY-GUT model (such as SUGRA) –which would constrain the masses in a narrow range−, nor to a generic, phenomenological motivated, spectrum –which would have too many parameters to play with.

There exist some computations of FCNC top quark decays, both in the SM and in the MSSM\[3, 4, 5\]. There has been some work concerning the decay channel into gauge bosons \( t \to c V \), \( V \equiv \gamma, Z, g \), see for example Ref.[4] for some works on the subject. The conclusion of these works is that the branching ratio of this decay is at most \( 10^{-5} \), maybe a bit larger in the gluon channel. However, to our knowledge, there are not so many works on the FCNC decay of the top quark into Higgs in the MSSM\[5\], and they are not so complete as in the case of the gauge bosons. For example in [5] it is concluded that the branching ratio for the decay channel \( t \to c h \) in the MSSM is at most of \( 10^{-9} \), for the SUSY electroweak contributions, and \( 10^{-5} \), for the SUSY-QCD contributions. However we think that the work of [5] is not complete. They do not include effects of the Higgs particles in the loops, and they do not take into account the \( \tilde{q}_L \tilde{q}_R h \) vertices, so they miss the potentially large contributions coming from the trilinear soft-SUSY-breaking terms \( A_{t,b} \), and from the higgsino mass parameter \( \mu \). We find that a full treatment of the SUSY-QCD contributions may greatly enhance the FCNC width by some orders of magnitude. Therefore, a more general, and more rigorous, computation of the decay \( t \to c h \) is mandatory\[6\].

In section 2 we make a summary of the technics of the computation, in sections 3 and 4 we present our results for the SUSY electroweak and the SUSY-QCD contributions to the decay width \( t \to c h \) respectively, and finally we present the conclusions.

2 Relevant lagrangians and form factors

The computation of FCNC processes at one loop, unlike other calculations, does not involve renormalization of parameters, or wave functions, so one is left only with the computation of the different diagrams that contribute to the process. The generic one loop diagrams contributing to the decay under study are in fig. 1. The vertex diagram \( V \) follows after a straightforward calculation. As for the diagrams \( S_t \) and \( S_c \) we define a mixed self-energy,

\[
\Sigma_{tc}(k) \equiv \bar{k} \Sigma_L(k^2) P_L + \bar{k} \Sigma_R(k^2) P_R + m_t \left( \Sigma_{Ls}(k^2) P_L + \Sigma_{Rs}(k^2) P_R \right)
\]

–where the \( m_t \) factor multiplying the scalar part is arbitrary, put there only to maintain the same units between the different \( \Sigma_i \)–, and compute the effects of \( \Sigma_i \) to the amplitude.

\[^2\text{We use a widely known notation}\[5, 6\]; see Refs.\[5, 6\] for further details and conventions.\]
We compute the different contributions to $V$, $S_t$ and $S_c$ and define an “effective” vertex

$$-iT \equiv -i g \bar{u}_c(p) (F_L P_L + F_R P_R) u_t(k).$$

(2)

We have taken into account all three generations of quarks and squarks, and have performed the usual checks of the computation, in particular that the form factors $F_L$ and $F_R$ are free of divergences before adding up the three quark generations, both analytically and numerically in the implementation of the code.

After squaring the matrix element (2), and multiplying by the phase space factor, we can compute the decay width, and define the ratio

$$B(t \to c h) \equiv \frac{\Gamma(t \to c h)}{\Gamma(t \to bW^+)}$$

which will be the main object under study. This ratio is not the total branching fraction of this decay mode, as there are many other channels that should be added up to the denominator of (3) in the MSSM, such as the two and three body decays of the top quark into SUSY particles, and also the decay channel $t \to H^+ b[2, 7]$. For the mass spectrum used in the numerical analysis (see sections 3 and 4) the former are phase space closed, whereas the latter could have a large branching ratio.

We would like to single out two pieces of the interaction lagrangian, namely the ones involving higgsino-sbottom-charm and Higgs-bottom-charm

$$\mathcal{L}_{h\tilde{b}c} = -g V_{cb} \bar{c} \left( R_{1a} \lambda_c P_L + R_{2a} \lambda_b P_R \right) \chi^+ \tilde{b}_a$$

$$\mathcal{L}_{H b c} = \frac{g}{\sqrt{2}M_W} V_{cb} \bar{c} \left( m_c \cot \beta P_L + m_b \tan \beta P_R \right) b H^+,$$

(4)

where $V_{cb}$ is the CKM matrix element, and $\lambda_{c,b}$ are the charm and bottom Yukawa couplings. Looking at these two pieces of the lagrangian one can get an estimation of the relative importance of the different form factors (2) (see section 3).

3 SUSY-EW contributions

For the electroweak contributions to the decay channel $t \to c h$ we work in the so called Super-CKM basis, that is, we take the simplification that the squark mass matrix diagonalizes as the quark mass matrix, so that FCNC processes appear at one loop through the charged sector (charged Higgs and charginos) with the same mixing matrix elements as in the Standard Model (the CKM matrix). We introduce, as usual, the left-right mass matrix mixing elements between squarks$[2]$: $m_q \left( A_q - \mu \{ \tan \beta, \cot \beta \} \right)$.

We have taken into account the contributions from charginos ($\chi^+_i$) and down type squarks ($\tilde{d}_\alpha$, $\alpha = 1, 2, \ldots, 6 \equiv d_1, d_2, \ldots, b_2$, the mass eigenstates down squarks), and from charged Higgs and Goldstone bosons ($H^+, G^+$) and down type quarks ($d, s, b$). We have not included the diagrams with gauge bosons ($W^+$) as the largest contributions will come from the Yukawa couplings of the top and (at large $\tan \beta$) bottom quarks. However, the leading terms from longitudinal $W^+$ are included through the inclusion of Goldstone bosons.

3We refer again to [2] for conventions and notation.
The input parameters chosen to illustrate the results in figs. 2-3 are:

\begin{align}
\tan \beta &= 35 \\
\mu &= -100 \text{ GeV} \\
M &= 150 \text{ GeV} \\
M_{A^0} &= 60 \text{ GeV} \\
m_{\tilde{t}_1} &= 150 \text{ GeV} \\
m_{\tilde{b}_1} &= m_{\tilde{q}} = 200 \text{ GeV} \\
A_t = A_q &= 300 \text{ GeV} \\
A_b &= -300 \text{ GeV}
\end{align}

where \(m_{\tilde{t}_1}, m_{\tilde{b}_1}\) are the lightest \(\tilde{t}\) and \(\tilde{b}\) mass, and all the masses are above present experimental bounds\[3]-[10], though the mass of the pseudoscalar Higgs \((M_{A^0})\) is in the edge of present LEP bounds\[9], and it is possibly excluded by the last analyses on the charged Higgs mass\[7, 10, 11, 12]. However, this light Higgs mass is not essential in the results, as can be seen in fig. 3 (d). We have chosen a SUSY mass spectrum around 200 GeV, which is not too light, so the results will not be artificially optimized. We have also checked all through the numerical analysis that other bounds on experimental parameters (such as \(\delta\rho\)) are fulfilled.

In fig. 2 we have plotted the different form factors of (2) as a function of \(\tan \beta\) for the channel with the lightest scalar Higgs \((h^0)\). We can see that the contributions from the Higgs sector and the contributions from the chargino sector are of the same order. It turns out that they can be either of the same sign, or of opposite sign. The chosen negative value for \(A_b\) is to make the two contributions of the same sign. It is also clear that in both cases \(F_R \gg F_L\). This can be easily understood by looking at the interaction lagrangians involving higgsino-sbottom-charm and Higgs-bottom-charm (4) where we can see that in both of them the contribution to the right-handed form factor will be enhanced by the Yukawa coupling of the bottom quark, compared with the charm Yukawa coupling that will contribute to the left-handed form factor. On the other hand we have checked that the inclusion of the first two generations of quarks and squarks only has an effect of a few percent on the total result.

In fig. 3 we can see the evolution of the ratio (3) with various parameters of the MSSM, by taking into account only the electroweak contributions. The growing of the width with \(\tan \beta\) (fig. 3 (a)) shows that the bottom Yukawa coupling plays a central role in these contributions. The evolution with the trilinear coupling \(A_b\) and the higgsino mass parameter \(\mu\) –the two parameters that appear in the trilinear coupling \(\tilde{b}_L \tilde{b}_R h^\pm\) displayed in figs. 3 (b) and (c) shows that this parameters can enhance the width some orders of magnitude. We have artificially let \(A_b\) grow up to large scales (that are not allowed if one wants that squarks do not develop vacuum expectation values) in order to emphasize the dependence on \(A_b\). The various spikes in these figures reflect the points where the form factors change sign, whereas the shaded region in fig. 3 (c) reflects the exclusion region of \(\mu\) by present LEP bounds on the chargino mass.

In all these figures the ratio (3) is smaller for the heaviest scalar Higgs \((H^0)\) because with the parameters (5) the CP-even Higgs mixing angle \(\alpha\) is near \(-\pi/2\), so making the couplings of \(H^0\) with down quarks and squarks much weaker, but in fig. 3 (d) it can be seen that when the pseudoscalar Higgs mass grows (and this shifts \(\alpha\) far away from \(-\pi/2\)) the two scalar Higgs change roles.
We conclude that the typical value of the ratio (3), at large \(\tan\beta \leq 50\) and for a SUSY spectrum around 200 GeV, is
\[
B_{\text{SUSY-EW}}(t \to c\,h) \simeq 10^{-7}.
\]

This is an improvement of the previous results[5], specially in the \(A^0\) channel, by 2 orders of magnitude.

4 SUSY-QCD contributions

The gluino-mediated supersymmetric strong interactions in the MSSM can also produce FCNC processes. This occurs when the squark mass matrix does not diagonalize with the same matrix as the one for the quarks. We introduce then intergenerational mass terms for the squarks, but in order to prevent the number of parameters from being too large, we have allowed (symmetric) mixing mass terms only for the left-handed squarks. This simplification is often used in the MSSM, and is justified by RGE analysis[13].

The mixing terms are introduced through the parameters \(\delta_{ij}\) defined as
\[
(M^2_{LL})_{ij} = m^2_{ij} \equiv \delta_{ij} m_i m_j,
\]
where \(m_i\) is the mass of the left-handed \(i\) squark, and \(m^2_{ij}\) is the mixing mass matrix element between the generations \(i\) and \(j\). These parameters are constrained by low energy data on FCNC[14]. The bounds have been computed using some approximations, so they must be taken as order of magnitude limits. We use the following bounds on the \(\delta\) parameters[14]
\[
\begin{align*}
|\delta_{12}| &< 0.1 \sqrt{m_{\tilde{u}} m_{\tilde{c}}}/500 \text{ GeV} \\
|\delta_{13}| &< 0.098 \sqrt{m_{\tilde{t}} m_{\tilde{c}}}/500 \text{ GeV} \\
|\delta_{23}| &< 8.2 \, m_{\tilde{c}} m_{\tilde{t}}/(500 \text{ GeV})^2.
\end{align*}
\]

We compute the contributions to diagrams of fig. 1 with gluinos \((\tilde{g})\) and up squarks \((\tilde{u}_\alpha, \alpha = 1, 2, \ldots, 6)\). We use the same input parameters as in the electroweak contributions (5), except for the \(\mu\) parameter, namely
\[
\begin{align*}
\mu & = -200 \text{ GeV} \\
m_{\tilde{g}} & = 150 \text{ GeV} \\
\delta & = \begin{pmatrix} 0 & 0.03 & 0.03 \\ 0 & 0 & 0.6 \\ 0 & 0.6 & 0 \end{pmatrix}.
\end{align*}
\]

A comment is in order for the present set of inputs: we have introduced in (3) the lightest stop mass as an input, and this stop is mostly \(\tilde{t}_R\). However, in this new parametrization we introduce this mass as the lightest \(\tilde{u}_\alpha\) mass, which will be mostly a \(\tilde{t}_R\). On the other hand, we use a larger absolute value for the \(\mu\) parameter to enhance the ratio (3).

Again the largest contribution comes from the right-handed form factor of (2), but this is only because we have chosen not to introduce mixing between right-handed squarks.
We have plotted the evolution of the ratio (3) with some parameters of the MSSM in fig. 4. As can be easily guessed, the most important parameter for these contributions is the mixing mass parameter between the 2nd and 3rd generation of left-handed squarks, the less restricted one of the three (eq. (8)). In fig. 4 (a) it is shown that changing $\delta_{23}$ by 3 orders of magnitude, the ratio (3) can increase by 7 orders of magnitude! We can see in fig. 4 (b) that the $\mu$ parameter also plays an important role, like in the electroweak contributions (fig. 3 (c)), and for the same reasons, bringing the ratio (3) up to values of $10^{-4}$. Notice that the central region of $|\mu| < \sim 90$ GeV is excluded by present LEP bounds on the chargino mass.

The evolution with the gluino mass (fig. 4 (c)) is asymptotically quite stable, showing a slow decoupling. Finally in fig. 4 (d) we have plotted the evolution with the pseudoscalar Higgs mass, it is also quite stable, until near the kinematic limit for $A^0$ and $H^0$.

We conclude that the typical value of the SUSY-QCD contributions to (3), with a SUSY spectrum around 200 GeV, is

$$B^\text{SUSY-QCD}(t \rightarrow c h) \simeq \mathcal{O}(10^{-5}) \ ,$$

but in favourable regions of the parameter space (i.e. large $\mu$, or relatively light gluino) it can easily reach values of $10^{-4}$. This is 1-2 orders of magnitude larger from the previous estimate[5].

5 Conclusions

We have computed the SUSY-electroweak, Higgs, and SUSY-QCD contributions to the FCNC top quark decay $t \rightarrow c h$ ($h = h^0, H^0, A^0$) in the MSSM, using a mass spectrum motivated, but not fully restricted, by model building and Renormalization Group Equations.

We have found that with a SUSY mass spectrum around 200 GeV, which is well above present bounds[8, 9, 10], the different contributions to this decay are typically of the order

$$B^\text{SUSY-EW}(t \rightarrow c h) \simeq 10^{-7}$$

$$B^\text{SUSY-QCD}(t \rightarrow c h) \simeq 10^{-5} - 10^{-4} \ .$$

The difference of at least two orders of magnitude between the two contributions makes worthless to compute the interference between the two contributions, but if the limits on $\delta_{23}$ (eq. (8)) improve, it should be necessary to make the full computation.

The results (11) are an improvement of the previous results[8], specially in the $A^0$ channel, thanks to the inclusion of the $\tilde{q}_L \tilde{q}_R h$ vertex.

It would probably be difficult that this decay can be measured either at the Tevatron, or at the NLC, but there exists a possibility for LHC. As an example to assess the discovery reach of this accelerators the FCNC top quark decays into a vector boson are

$$\text{LHC} : \ B(t \rightarrow c V) > 5 \times 10^{-5}$$

$$\text{NLC} : \ B(t \rightarrow c V) > 10^{-3} - 10^{-4} \ ,$$

where the lack of sensitivity of NLC is due to the lower luminosity. So, if the discovery reach for FCNC Higgs processes are not very different from that of the gauge bosons,
there is a possibility to measure this decay channel at LHC even if SUSY particles are not seen at LEP II.

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**Figure Captions**

**Fig. 1** Generic one loop Feynman Diagrams contributing to $t \to c h$.

**Fig. 2** Different form factors (2) for the channel $t \to c h^0$ as a function of $\tan \beta$, with the typical set of inputs of eq.(5).

**Fig. 3** Evolution of the ratio (3) with (a) $\tan \beta$, (b) the trilinear coupling $A_b$, (c) the higgsino mass parameter $\mu$, and (d) the pseudoscalar Higgs mass $M_{A^0}$, the rest of inputs are given in eq.(5).

**Fig. 4** Evolution of the ratio (3) with (a) the mixing parameter between the 2nd and 3rd squark generations $\delta_{23}$, (b) the higgsino mass parameter $\mu$, (c) the gluino mass $m_{\tilde{g}}$, and (d) the pseudoscalar Higgs mass $M_{A^0}$, the rest of inputs are given in eqs.(5) and (9).
Fig. 1

Fig. 2
Fig. 3
Fig. 4