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Top quark decays into neutral Higgs bosons and gluon in the MSSM[1]

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ABSTRACT

Flavour changing neutral decays of the top quark are known to be extremely suppressed in the SM. This is especially so for the top quark decay into the SM Higgs boson, whose rate is less than 10^{-13}. However, it turns out that the decay modes $t \to c\,h$, with $h \equiv h^0, H^0, A^0$ any of the MSSM neutral Higgs bosons, can be much more gifted. In particular, the rate into the lightest CP-even Higgs boson h^0 – which is an accessible decay mode across the whole MSSM parameter space – is generally higher than the decay into glue, $t \to c\,g$, even though the latter can also be considerably augmented in the MSSM. Our general conclusion is that the Higgs channel $t \to c\,h^0$ can be the "gold-plated" top quark FCNC decay mode in the MSSM with rates that can reach 10^{-4}, i.e. already at the visible level for both LHC and LC.

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1 Introduction

At the tree-level there are no FCNC processes in the SM, and at one-loop they are induced by charged-current interactions, which are GIM-suppressed. In particular, FCNC decays of the top quark into gauge bosons ($t \to c\, V$; $V \equiv \gamma, Z, g$) are very unlikely, with maximum rates of order 10^{-12} for the photon, slightly above 10^{-13} for the Z-boson, and at most 10^{-10} for the gluon channel [1, 2]. Even more dramatic is the situation with the top quark decay into the SM Higgs boson, $t \to c\, H_{SM}$, which has recently been recognized to be much more disfavored than originally thought [1]: $BR(t \to c\, H_{SM}) = 1 \cdot 10^{-13} - 4 \cdot 10^{-15}$ ($M_Z \leq M_H \leq 2\, M_W$) [3]. This rate is far out of the range to be covered by any presently conceivable high luminosity machine. On the other hand, the highest SM rate, namely that of $t \to c\, g$, is still 5 orders of magnitude below the feasible experimental possibilities at the LHC. All in all detection of FCNC decays of the top quark at visible levels (viz. $BR(t \to c\, X) \gtrsim 10^{-5} - 10^{-4}$) by any of the future high luminosity colliders round the corner (especially LHC and LC) seems doomed to failure in the absence of new physics.

Thus the possibility of large enhancements of some FCNC rates up to visible levels, particularly within the context of general two-Higgs-doublet models (2HDM) and especially in the Minimal Supersymmetric Standard Model (MSSM) [4], should be very welcome. In the LHC, for example, the production of top quark pairs will be very high: $\sigma(t\bar{t}) = 800\ pb$ – roughly two orders of magnitude larger than that of the Tevatron II at $\sqrt{s} = 2\, TeV$. In the so-called low-luminosity phase ($10^{33}\, cm^{-2}s^{-1}$) of the LHC one expects ten million $t\,\bar{t}$-pairs per year [5]. And this number will be augmented by one order of magnitude in the high-luminosity phase ($10^{34}\, cm^{-2}s^{-1}$). As for a future e^+e^- linear collider running at e.g. $\sqrt{s} = 500\ GeV$, one has a smaller cross-section $\sigma(t\bar{t}) = 650\ fb$ but a higher luminosity factor ranging from $5 \times 10^{33}\, cm^{-2}s^{-1}$ to $5 \times 10^{34}\, cm^{-2}s^{-1}$ and of course a much cleaner environment [6]. Thus, with datasets from LHC and LC increasing to several $100\, fb^{-1}$/year in the high-luminosity phase, one should be able to collect enough statistics (perhaps some few hundred to few thousand events) from the combined output of these machines enabling us to perform an efficient study of rare top quark decays beyond the SM. A detailed presentation of this work is given in Ref.[7].

2 Relevant decays and Lagrangians in the MSSM

The Higgs channels in the MSSM are especially promising. They comprise the top quark decays into the two CP-even ("scalar") states and the CP-odd ("pseudoscalar") state of the Higgs sector of the MSSM [4],

$$t \to c\, h \qquad (h = h^0, H^0, A^0). \tag{1}$$

Worth emphasizing is the fact that in the MSSM (in contrast to the SM or the unconstrained 2HDM) at least one of these decays (viz. $t \to c\, h^0$) is *always* possible, for in the MSSM there is an upper bound on the mass of the lightest CP-even Higgs boson, $M_{h^0} \lesssim 135\, GeV$ [8], which is below the top quark mass. Moreover, for a sufficiently light pseudoscalar mass, $M_{A^0} < m_t$, all three decays (1) are in principle possible, if the SUSY masses are not that high so as to induce too large positive corrections to M_{H^0}. Preliminary studies of the decays (1) were presented in [9], but they did not include the one-loop Higgs mass relations and moreover they missed some of the most relevant effects.

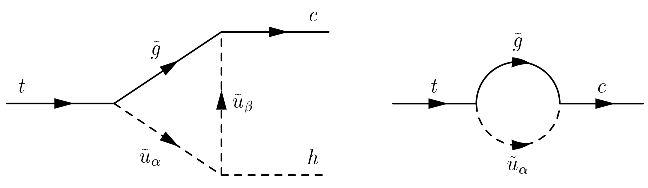

Figure 1: One-loop SUSY-QCD diagrams for the decay $t \to c\,h$: **(a)** vertex diagram, **(b)** mixed $t-c$ self-energy. $\tilde{u}_{\{\alpha,\beta\}}$ stand for mass-eigenstate up-type squarks of any generation.

We report here also on the MSSM rate of the most favored FCNC top quark decay in the SM, namely the top decay into glue

$$t \to c\,g\,. \tag{2}$$

This channel has been extensively studied in the literature, both in the SM [1, 2] and in the MSSM [10, 11]. However, we include a simultaneous numerical analysis of it in order to use it as a fiducial mode with which to better assess the size of our results on the Higgs channels (1). As for the remaining FCNC decay modes, namely $t \to c\,(\gamma, Z)$, they have also been evaluated in the MSSM, but in spite of some enhancements the general conclusion is that they are hopeless [10, 12].

The basic interactions responsible for the enhancements lie both in the QCD sector and in the electroweak (EW) sector of the MSSM. The SUSY-QCD interactions are described by the following Lagrangian, in the mass-eigenstate basis:

$$\begin{aligned}
\mathcal{L}_{\rm SUSY-QCD} &= -\frac{g_s}{\sqrt{2}}\,\bar{\psi}^{\tilde{g}}_c\,[R^*_{5\alpha}\,P_L - R^*_{6\alpha}\,P_R]\,\tilde{q}^*_{\alpha,i}\,\lambda^c_{ij}\,t_j \\
&- \frac{g_s}{\sqrt{2}}\,\bar{\psi}^{\tilde{g}}_c\,[R^*_{3\alpha}\,P_L - R^*_{4\alpha}\,P_R]\,\tilde{q}^*_{\alpha,i}\,\lambda^c_{ij}\,c_j \\
&- \frac{g_s}{\sqrt{2}}\,\bar{\psi}^{\tilde{g}}_c\,[R^*_{1\alpha}\,P_L - R^*_{2\alpha}\,P_R]\,\tilde{q}^*_{\alpha,i}\,\lambda^c_{ij}\,u_j + \text{ h.c. }.
\end{aligned} \tag{3}$$

$\psi^{\tilde{g}}_c$ stands for the gluino spinor, λ^c are the $SU(3)_c$ Gell-Mann matrices and $P_{L,R}$ the chiral projector operators. The 6×6 rotation matrices $R^{(q)}$ are needed to diagonalize the squark mass matrices in (flavor)$\times$(chiral) space as follows (notation as in [7]):

$$\begin{aligned}
\tilde{q}'_\alpha &= \sum_\beta R^{(q)}_{\alpha\beta}\tilde{q}_\beta\ , \\
R^{(q)\dagger}\mathcal{M}^2_{\tilde{q}}R &= \mathcal{M}^2_{\tilde{q}D} = {\rm diag}\{m^2_{\tilde{q}_1},\dots,m^2_{\tilde{q}_6}\}\ \ (q\equiv u,\,d)\ ,
\end{aligned} \tag{4}$$

where $\mathcal{M}^2_{(\tilde{u},\tilde{d})}$ is the square mass matrix for squarks in the EW basis ($\tilde{q}'_\alpha$), with indices $\alpha = 1,2,3,\dots,6 \equiv \tilde{u}_L,\tilde{u}_R,\tilde{c}_L,\dots,\tilde{t}_R$ for up-type squarks, and a similar assignment for down-type squarks. The intergenerational mixing terms leading to gluino-mediated FCNC couplings lie in the off-diagonal entries of the mass matrices. However, in order to prevent the number of parameters from being too large, we have allowed (symmetric) mixing mass terms only for the left-handed (LH) squarks. This simplification is often used in the MSSM

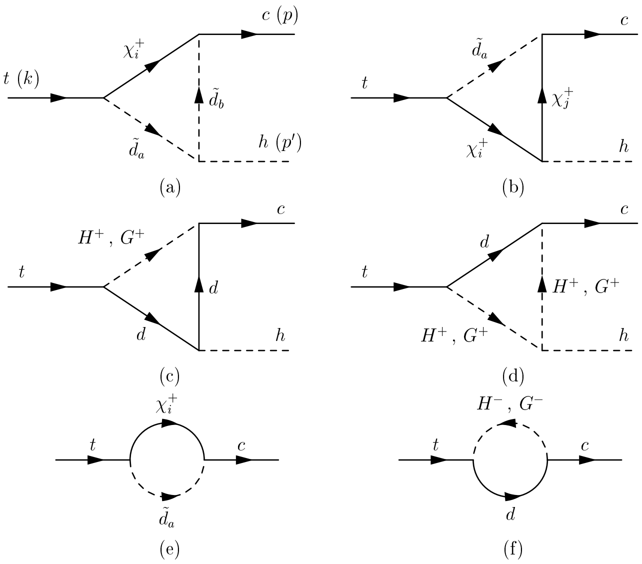

Figure 2: One-loop SUSY-EW diagrams for the decay $t \to c\, h$ ($h = h^0, H^0, A^0$). Here d ($\tilde{d}_{\{a,b\}}$) represent mass-eigenstate down type quarks (squarks) of any generation.

and it is justified by Renormalization Group (RG) analysis [13]. Following this practice, we introduce flavor-mixing coefficients δ_{ij} in the LL block of the 6×6 squark mass matrix (namely the one involving only LH fields of any flavor) as follows:

$$(M^2_{LL})_{ij} = m^2_{ij} \equiv \delta_{ij}\, m_i\, m_j \quad (i \neq j) \ , \tag{5}$$

where m_i is the mass of the left-handed ith squark, and m^2_{ij} is the mixing mass matrix element between generations i and j. Therefore, if the coefficients δ_{ij} are non-vanishing, for some $i \neq j$, then the structure of the diagonalizing matrices $R^{(q)}$ defined above must necessarily lead to gluino-mediated tree-level FCNC between quarks and squarks in the SUSY-QCD Lagrangian (3). This scenario can be generalized by further introducing FCNC interactions on the right-handed (RH) block of the mass matrix, but this hypothesis entails an unnatural departure from the RG expectations and moreover it is not necessary to achieve the visible rates [7].

On the other hand, the leading EW interactions appear through the possibility of large Yukawa couplings (normalized with respect to the $SU(2)_L$ gauge coupling):

$$\lambda_u \equiv \frac{h_u}{g} = \frac{m_u}{\sqrt{2}\, M_W\, \sin\beta} \quad , \quad \lambda_d \equiv \frac{h_d}{g} = \frac{m_d}{\sqrt{2}\, M_W\, \cos\beta} \ . \tag{6}$$

For the computation of the EW effects we work in the approximation that the squark mass matrices diagonalize whith the same matrix elements than the quarks, the standard CKM-matrix. Although we will not spell out here the structure of the various relevant interactions in the EW sector, let us for the sake of illustration to quote the interaction Lagrangian involving charginos, quarks and squarks in the mass-eigenstate basis (notation as in [14]):

$$\mathcal{L}_{u\,\tilde{d}\,\chi^+} = -g \sum_{\substack{d=d,s,b \\ u=u,c,t}} V_{ud}\, \tilde{d}^*_a\, \bar{\psi}^+_i \left(A^{(d,u)}_{+ai}\, P_L + A^{(d,u)}_{-ai}\, P_R \right) u + \text{ h.c.} \ , \tag{7}$$

V_{ud} is the standard CKM-matrix element, and the coupling matrices are defined as

$$A_{+ai}^{(d,u)} = R_{1a}^{(d)*} V_{i1}^{*} - \lambda_d \, R_{2a}^{(d)*} V_{i2}^{*} \ , \ A_{-ai}^{(d,u)} = -R_{1a}^{(d)*} \lambda_u U_{i2} \ , \tag{8}$$

with V_{ij} and U_{ij} the rotation matrices of the chargino sector [14]. Here λ_u, λ_d are the up-like and down-like Yukawa couplings (6). Its significance is determined by the value of the parameter $\tan\beta = v_2/v_1$ [4]. At large $\tan\beta$ one expects that the EW interactions may play here a significant role as in the case of top quark decays into charged Higgs [15]. From these interaction Lagrangians, the Feynman diagrams responsible for the FCNC decays (1) can be depicted in Fig.1 (SUSY-QCD effects) and Fig. 2 (SUSY-EW). One may draw similar diagrams for the decay (2).

3 Numerical Analysis and Discussion

We use the fiducial ratios

$$B(t \to c\, h) \equiv \frac{\Gamma(t \to c\, h)}{\Gamma(t \to b\, W^+)} \ , \ B(t \to c\, g) \equiv \frac{\Gamma(t \to c\, g)}{\Gamma(t \to b\, W^+)} \tag{9}$$

to carry out our numerical analysis.

These ratios are not the total branching fractions $BR(t \to c\, X)$ for the FCNC decay modes under study ($X = h, g$), as there are many other channels that should be added up to the denominator of (9) in the MSSM, if kinematically allowed. However, for better comparison with previous analyses of FCNC top quark decays, the ratios (9) should suffice to assess the experimental viability of the FCNC decays under consideration.

After an exhaustive scanning of the MSSM parameter space we find the following results [7]. The most important source of FCNC enhancement comes from the SUSY-QCD sector, whose numerical effect hinges on the values of the flavour-mixing coefficients δ_{ij} in eq.(5). The present experimental bounds on these quantities depend on the value of the squark masses and read as follows [16]:

$$\begin{aligned} |\delta_{12}| &< .1\, \sqrt{m_{\tilde{u}}\, m_{\tilde{c}}}/500\, GeV \ , \\ |\delta_{13}| &< .098\, \sqrt{m_{\tilde{u}}\, m_{\tilde{t}}}/500\, GeV \ , \\ |\delta_{23}| &< 8.2\, m_{\tilde{c}}\, m_{\tilde{t}}/(500\, GeV)^2 \ . \end{aligned} \tag{10}$$

In using these bounds we make use of $SU(2)$ gauge invariance to transfer the experimental information known from the down-quark sector (for example from $BR(b \to s\, \gamma)$, where the bound on δ_{23} is obtained) to the up-quark sector.

With a SUSY mass spectrum of a few hundred GeV, we find that the different contributions to the Higgs channels are typically of the order

$$\begin{aligned} B^{\rm SUSY-EW}(t \to c\, h) &\simeq 10^{-8} \ , \\ B^{\rm SUSY-QCD}(t \to c\, h) &\simeq 10^{-5} \ . \end{aligned} \tag{11}$$

However, by stretching out a bit more the range of parameters one can reach (for some of the decays)

$$\begin{aligned} B^{\rm SUSY-EW}(t \to c\, h) &\simeq 1 \times 10^{-6} \ , \\ B^{\rm SUSY-QCD}(t \to c\, h) &\simeq 5 \times 10^{-4}. \end{aligned} \tag{12}$$

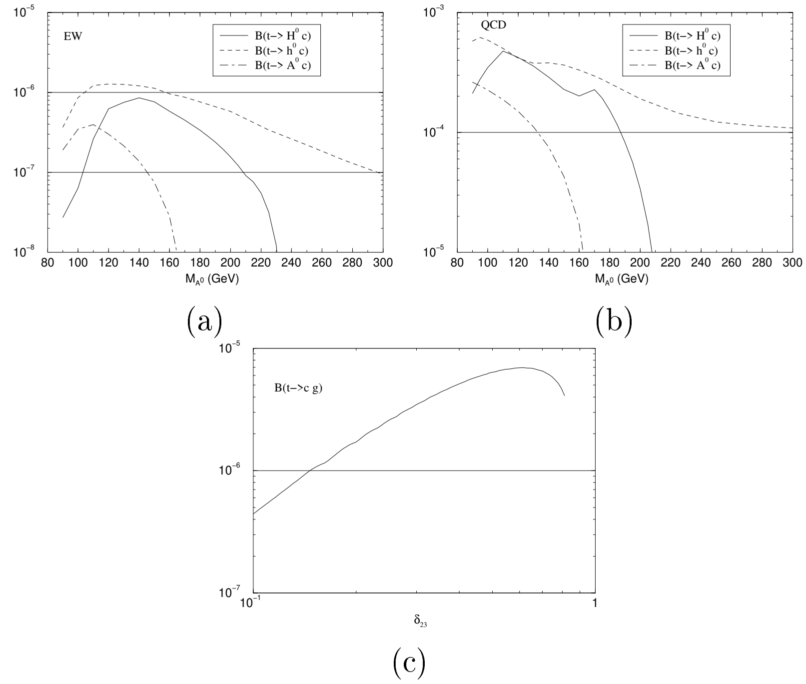

Figure 3: **(a)** Maximum value of $B(t \to c\,h)$, obtained by taking into account only the SUSY-EW contributions, as a function of M_{A^0} ; **(b)** as in (a) but taking into account only the SUSY-QCD contributions; and **(c)** maximum value of $B(t \to c\,g)$ as a function of the intergenerational mixing parameter δ_{23} in the LH sector. In all cases the scanning for the rest of parameters of the MSSM has been performed within the phenomenologically allowed region.

The difference of at least two orders of magnitude between the SUSY-EW and SUSY-QCD contributions makes unnecessary to compute the interference terms between the two sets of amplitudes.

We have obtained the maximum rates (12) from a general search in the MSSM parameter space within the $1\,TeV$ mass region and respecting the experimental constraints, in particular the relations (10). In Fig. 3 we present the maximum values that can be reached by $B(t \to c\,X)$ for each of the processes presented. In Figs. 3a and 3b we show the maximized $B(t \to c\,h)$ as a function of the pseudoscalar Higgs boson mass by taking into account only the SUSY-EW contributions and the SUSY-QCD contributions respectively. Perhaps the most noticeable result is that the decay into the lightest MSSM Higgs boson $(t \to c\,h^0)$ is the one that can be maximally enhanced and reaching values of order $B(t \to c\,h^0) \sim 10^{-4}$ that stay fairly stable all over the parameter space. The reason for this dominance is that the decay $t \to c\,h^0$ is the one which is more sensitive to the trilinear coupling A_t, a parameter whose natural range reaches up to about $1\,TeV$.

We have also studied the optimal FCNC rates of the gluon channel in the MSSM. In Fig. 3c we have plotted the maximum value of $B(t \to c\,g)$ as a function of δ_{23} after scanning for the rest of the MSSM mass parameters within the $1\,TeV$ range. Under the RG-based assumption of only mixing in the LH sector, one has $B^{\rm SUSY-QCD}(t \to c\,g) \lesssim 10^{-5}$. Our results on this channel are compatible with the recent analysis of Ref. [10] in contrast to that of Ref. [11].

To assess the discovery reach of the FCNC top quark decays in the next generation of accelerators we take as a guide the estimations that have been made for gauge boson final estates [17]. Using the information mentioned in Sect. 1 and assuming that all the FCNC decays $t \to c\,X$ $(X = V, h)$ can be treated similarly, we roughly estimate the following sensitivities for 100 fb^{-1} of integrated luminosity:

$$\begin{aligned} \textbf{LHC}: B(t \to c\,X) &\gtrsim 5 \times 10^{-5} \\ \textbf{LC}: B(t \to c\,X) &\gtrsim 5 \times 10^{-4} \\ \textbf{TEV33}: B(t \to c\,X) &\gtrsim 5 \times 10^{-3}\ . \end{aligned} \tag{13}$$

Therefore, LHC seems to be the most suitable collider where to test this kind of phenomena. The LC is limited by statistics (due to much smaller top quark cross-section) but in compensation every collected event is clear-cut. So this machine could eventually be of much help, especially if we take into account that it could deliver 500 fb^{-1} per year [6]. The situation with the Tevatron, however, is much more gloomy, since the required FCNC rates of $\sim 10^{-3}$ cannot be attained unless we artificially search in some remote (unnatural) corner of the parameter space.

To conclude, the FCNC decays of the top quark are such rare events in the SM (especially the top quark decay into the Higgs boson) that their observation at detectable levels should be interpreted as an extremely robust indication of new physics. The effective tagging of FCNC top quark decays in the major accelerators round the corner could well be a first step into discovering SUSY. From our analysis we find the following MSSM maximum rates for the most favorable modes:

$$5 \times 10^{-6} \lesssim B(t \to c\,g)_{\max} < B(t \to c\,h^0)_{\max} \lesssim 5 \times 10^{-4}. \tag{14}$$

In both decays the dominant effects come from SUSY-QCD. However, it should not be undervalued the fact that the maximum electroweak rates for $t \to c\,h$ can reach the 10^{-6} level, i.e. on the verge of being detectable.

Acknowledgments

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