KA-TP-1-2001
UAB-FT-506
January 2001
hep-ph/0101294

FCNC top quark decays beyond the Standard Model

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Flavor Changing Neutral Current decays of the top quark within the strict context of the Standard Model are known to be extremely rare. In fact, they are hopelessly undetectable at the Tevatron, LHC and LC in any of their scheduled upgradings. Therefore, if a few of these events eventually show up in the future we will have certainly discovered new physics. We argue that this could well be the case for the LHC and the LC both within the Minimal Supersymmetric Standard Model (MSSM) and in a general two-Higgs-doublet model (2HDM), especially if we look for FCNC top quark decays into Higgs bosons.

Invited talk presented at the

5th International Symposium on Radiative Corrections
(RADCOR–2000)
Carmel CA, USA, 11–15 September, 2000

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[*]Supported in part by CICYT under project No. AEN99-0766.

[†]Supported by the European Union under contract No. HPMF-CT-1999-00150.

[‡]Supported in part by the Direcció General de Recerca de la Generalitat de Catalunya and by CICYT under project No. AEN99-0766.

1 Introduction

At the tree-level there are no Flavor Changing Neutral Current (FCNC) processes in the Standard Model (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 ($BR(t \to c\,\gamma,\ Z) \sim 10^{-13}$ and $BR(t \to c\,g) \sim 10^{-11}$) [1]. These are much smaller than the FCNC rates of a typical low-energy meson decay, e.g. $B(b \to s\,\gamma) \sim 10^{-4}$. The reason is simple: for FCNC top quark decays in the SM, the loop amplitudes are controlled by down-type quarks, mainly by the bottom quark. Therefore, the scale of the loop amplitudes is set by m_b^2 and the partial widths are of order

$$\Gamma(t \to V\,c) \sim |V_{tb}^* V_{bc}|^2 \alpha\, G_F^2\, m_t\, m_b^4\, F \sim |V_{bc}|^2 \alpha_{em}^2 \alpha\, m_t \left(\frac{m_b}{M_W}\right)^4 F, \tag{1}$$

where α is α_{em} for $V = \gamma, Z$ and α_s for $V = g$. The factor $F \sim (1 - m_V^2/m_t^2)^2$ results, upon neglecting m_c, from phase space and polarization sums. The fourth power mass ratio, in parenthesis in eq. (1), stems from the GIM mechanism and is responsible for the ultralarge suppression beyond naive expectations based on pure dimensional analysis, power counting and CKM matrix elements. From that simple formula, the approximate orders of magnitude mentioned above ensue immediately.

Even more dramatic is the situation with the top quark decay into the SM Higgs boson, $t \to c\,H_{SM}$: $BR(t \to c\,H_{SM}) \sim 10^{-13} - 10^{-15}$ ($m_t = 175\,GeV;\ M_Z \leq M_H \leq 2\ M_W$) [2]. This extremely tiny rate is far out of the range to be covered by any presently conceivable high luminosity machine. On the other hand, the highest FCNC top quark rate in the SM, namely that of the gluon channel $t \to c\,g$, is still 6 orders of magnitude below the feasible experimental possibilities at the LHC. All in all the detection of FCNC decays of the top quark at visible levels (viz. $BR(t \to c\,X) > 10^{-5}$) by the high luminosity colliders round the corner seems doomed to failure in the absence of new physics. Unfortunately, although the FCNC decay modes into electroweak gauge bosons $V_{ew} = \gamma, Z$ may be enhanced a few orders of magnitude, it proves to be insufficient to raise the meager SM rates mentioned before up to detectable limits, and this is true both in the 2HDM – where $BR(t \to V_{ew}\,c) < 10^{-6}$ [1] – and in the MSSM – where $BR(t \to V_{ew}\,c) < 10^{-7}$ [3]. In this respect it is a lucky fact that these bad news need not to apply to the gluon channel, which could be barely visible ($BR(t \to g\,c) \lesssim 10^{-5}$) both in the MSSM [4,5] and in the general 2HDM [1]. But, most significant of all, they may not apply to the non-SM Higgs boson channels $t \to (h^0, H^0, A^0) + c$ either. As we shall show, these Higgs decay channels of the top quark could lie above the visible threshold for a parameter choice made in perfectly sound regions of parameter space.

A systematic discussion of these "gifted" Higgs channels has been made in Ref. [5] for the MSSM and more recently in Ref. [6] for the general 2HDM. Here we will present the results in the 2HDM and the MSSM, and make a close comparison between them. We believe that this study is necessary, not only to assess what are the chances to see traces of new physics in the new colliders but also to clear up the nature of the virtual effects; in particular to disentangle whether the origin of the hypothetically detected FCNC decays of the top quark is ultimately triggered by SUSY or by some alternative renormalizable extension of the SM such as the 2HDM or generalizations thereof. Of course the alleged signs of new physics could be searched for directly through particle tagging, if the new particles were not too heavy. However, even if accessible, the corresponding signatures could be far from transparent. In contrast, the indirect approach based on the FCNC processes has the advantage that one deals all the time with the dynamics of the top quark. Thus by studying potentially new features beyond the well-known SM properties of this quark one can hopefully uncover the existence of the underlying new interactions [7].

2 Relevant fields and interactions

We will mainly focus our interest on the loop induced FCNC decays

$$t \to c\, h \quad (h = h^0, H^0, A^0)\,, \tag{2}$$

in which any of the three possible neutral Higgs bosons from a general 2HDM can be in the final state. However, as a reference we shall compare throughout our analysis the Higgs channels with the more conventional gluon channel $t \to c\, g$.

Although other quarks could participate in the final state of these processes, their contribution is negligible. The lowest order diagrams entering these decays are one-loop diagrams in which Higgs, quarks, gauge and Goldstone bosons – in the Feynman gauge – circulate around. In the MSSM also the SUSY-parters of the above fields, namely squarks and charginos, circulate in the loops. In addition there exists the possibility that the squark-squared-mass-matrix is not simultaneously diagonal to the quark-mass-matrix. In this latter case there exist tree-level FCNC couplings in the interactions quark-squark-gluino and quark-squark-neutralino. This possibility is not unnatural. If one computes the evolution of the squark-squared-mass-matrix using the Renormalization Group Equations, assuming alignment at a certain scale (e.g. a supposed Unification Scale), one finds that non-diagonal terms for the squark-left–squark-left entries are generated [8]. We have computed the MSSM decay widths under two different approximations: in the first one we assume alignment, and the only induced FCNC are generated through the charged sector of the model with the same mixing matrix as in the SM – the CKM-matrix; in the second approach we give up the alignment hypothesis, and assume a free – though restricted by experiment [9]– squark-mass-matrix and compute the SUSY-QCD induced FCNC partial decay widths, which are the leading ones under this approximation.

Here we follow the standard notation [10], namely h^0, H^0 are CP-even Higgs bosons and A^0 is a CP-odd one. When the quark mass matrices are diagonalized in non-minimal extensions of the Higgs sector of the SM, the Yukawa couplings do not in general become simultaneously diagonalized, so that one would expect Higgs mediated FCNC's at the tree-level. These are of course unwanted, since they would lead to large FCNC processes in light quark phenomenology, which are stringently restricted by experiment. One has two canonical choices to get rid of them, called Type I 2HDM and Type II 2HDM [10]. The Higgs sector of the MSSM is that of a Type II 2HDM, with restrictions between the parameters due to the SUSY constraints.

When analyzing the 2HDM I, II cases we will use the following set of free parameters:

$$(m_{h^0}, m_{H^0}, m_{A^0}, m_{H^\pm}, \tan\alpha, \tan\beta)\,, \tag{3}$$

where $m_{H^\pm}$ is the mass of the charged Higgs companions $H^\pm$, $\tan\alpha$ defines the mixing angle α in the diagonalization of the CP-even sector, and $\tan\beta$ gives the mixing angle β in the CP-odd sector. The latter is a key parameter in our analysis. It is given by the quotient of the vacuum expectation values (VEV's) of the two Higgs doublets $\Phi_{2,1}$, viz. $\tan\beta = v_2/v_1$ [10]. The most general (Type I or Type II) 2HDM Higgs potential subject to hermiticity, $SU(2)\times U(1)$ and gauge invariance involves six scalar operators with six free (real) coefficients $\lambda_i\,(i = 1, ..., 6)$ and the two VEV's [10]. We will furthermore assume that $\lambda_5 = \lambda_6$ in the general 2HDM Higgs potential [6]. The alternative set (3) is just a (more physical) reformulation of this fact after diagonalization of the mass matrices and imposing the aforementioned set of constraints. The constraints imposed by SUSY reduce the number of free parameters in eq. (3) to two, which we take to be $(m_{A^0}, \tan\beta)$, since the radiative corrections to the rest of parameters (3) are large we make use of the one-loop expressions to compute them [11][1].

The two canonical types of 2HDM's only differ in the couplings to fermions but they share the rest of Feynman rules. Of particular relevance are the rules for the trilinear Higgs vertices in the 2HDM case, which depend on the Higgs boson mass differences and can be enhanced for large and small $\tan\beta$ – see Ref. [6]. In the MSSM, however, the mass differences are correlated and one can further simplify their form to a combination of trigonometric functions of α and β, using the relations between the parameters (3) – see Ref. [10]. We refrain from giving here the interaction Lagrangian [5,6,10,13].

Both in the generic 2HDM II and in the MSSM, the Feynman rules for the lightest CP-even Higgs, h^0, go over to the SM Higgs boson ones in the limit $\sin(\beta-\alpha) \to 1$. In the particular case of the MSSM, this limit is equivalent to $m_{A^0} \to \infty$. Moreover, in the MSSM one has $m_{h^0} \lesssim 135\,GeV$ [12] whereas in the general Type II model there

[1]The two-loop corrections to the Higgs sector of the MSSM have also recently become available [12]. Their effect, however, cannot significantly modify our one-loop results.

is no upper bound on m_{h^0}, and by the same token the corresponding lower bound is considerably less stringent – see Ref. [6].

Since we shall perform our calculation in the on-shell scheme, we understand that the physical inputs are given by the electromagnetic coupling and the physical masses of all the particles. It should be clear that, as there are no tree-level FCNC decays of the top quark, there is no need to introduce counterterms for the physical inputs. In fact, the calculation is carried out in lowest order with respect to the effective tch and tcg couplings and so the sum of all the one-loop diagrams (as well as of certain subsets of them) should be finite in a renormalizable theory, and indeed it is.

From the interaction Lagrangians and Feynman rules it is straightforward to compute the loop induced FCNC rates for the decays (2) and $t \to c\ g$ [5,6]. We shall refrain from listing the lengthy analytical formulae. The computation in the MSSM was reported in great detail in Ref. [5], and the one in the 2HDM [6] is very similar. Therefore, we will limit ourselves to exhibit the final numerical results. The fiducial ratio on which we will apply our numerical computation is the following:

$$B^j(t \to h + c) = \frac{\Gamma^j(t \to h + c)}{\Gamma(t \to W^+ + b) + \Gamma^j(t \to H^+ + b)}\ , \tag{4}$$

for each Type $j = I, II$ of 2HDM and the MSSM and for each neutral Higgs boson $h = h^0,\ H^0,\ A^0$. While this ratio is not the total branching fraction, it is enough for most practical purposes and it is useful in order to compare with previous results in the literature. We define the fiducial branching ratio for $t \to g + c$ in a similar way.

We have performed a fully-fledged independent analytical and numerical calculation of $\Gamma^j(t \to g + c)$ at one-loop in the context of 2HDM I, II and the MSSM. Where there is overlapping, we have checked the numerical results of Ref. [1][2].

Charged Higgs bosons from Type II models are subject to an indirect bound from the experimental measurement by CLEO of the branching fraction $BR(B \to X_s\gamma)$ [14]. From the various analysis in the literature one finds $m_{H^\pm} > (165 - 200)\,GeV$ for virtually any $\tan\beta \gtrsim 1$ [15,16]. This bound does not apply to Type I models. Therefore, in principle the top quark decay $t \to H^+ + b$ is still possible in 2HDM I; but also in 2HDM II, if $m_{H^\pm}$ lies near the lowest end of the previous bound, and in this case that decay can contribute to the denominator of eq. (4). In SUSY models this limit does not apply provided $\mu A_t < 0$ – see e.g. [17].

3 $t \to ch$ and $t \to cg$ in the MSSM

Under the alignment hypothesis FCNC's are generated at the one-loop level through the charged interactions of quarks with Higgs bosons and squarks with charginos, that

[2] In Ref. [1] $B(t \to g + c)$ is defined without including the charged Higgs channel contribution in the fiducial branching ratio. The agreement is achieved, however, only if it is included.

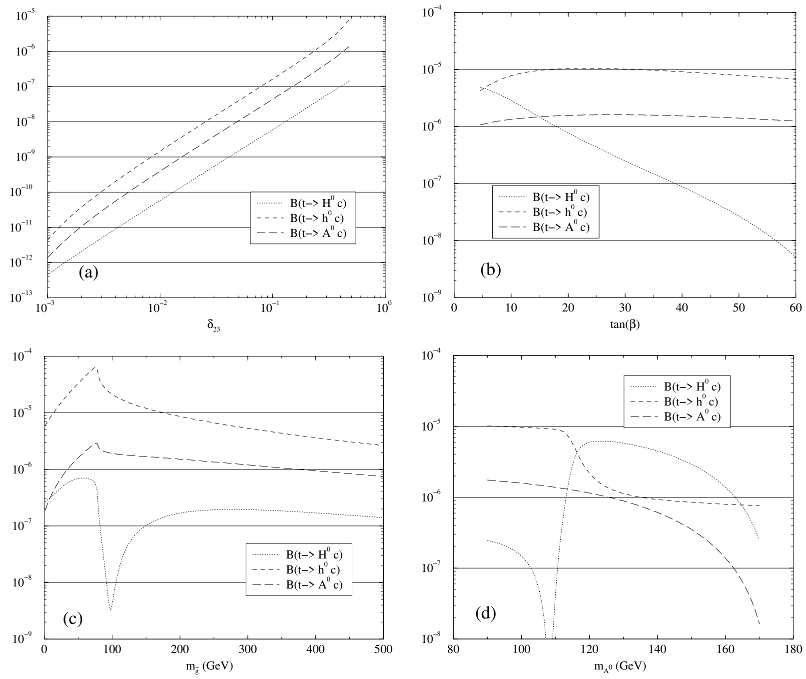

Figure 1: Evolution of the SUSY-QCD contributions to the ratio (4) with **(a)** the mixing parameter δ_{23} between the 2nd and 3rd squark generations; **(b)** $\tan\beta$; **(c)** the gluino mass $m_{\tilde{g}}$; and **(d)** the pseudoscalar Higgs mass M_{A^0}. The rest of inputs are given in eq. (6)

is, they are of electroweak (EW) nature. In this case the largest rates are driven by the trilinear scalar coupling $\tilde{d}_a\tilde{d}_b h$, although the down-type-quark loops contributions are non-negligible. As a consequence the largest FCNC decay rates are obtained at large $\tan\beta$.

Giving up alignment the leading FCNC rates are driven by means of the SUSY-QCD tree-level vertex $u_a\tilde{u}_b\tilde{g}$ for $a \neq b$. The mixing terms between generations are encoded in the parameter

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

where $(M_{LL}^2)_{ij}$ is the non-diagonal squared-mass-matrix element between the ith and jth generations, and m_i is the mass parameter of the ith generation. Low energy experiments are used to give upper bounds to the δ_{ij}, but, whereas the mixing between the 1st and 2nd generation are strongly restricted, the one between the 2nd and the 3rd turns out to be basically free [9], and this is the one which has a greatest impact in the process under study. We assume that inter-generational mixing only exists between the left-handed squarks, since this is the most natural scenario [8]. A detailed analysis showed that the presence of mixing in the right-handed squark sector does not lead to a significant increase of the computed branching ratios [4,5].

Since the EW contributions lie about two orders of magnitude below the SUSY-QCD ones [5], we will concentrate in the latter ones. In Fig. 1 we present the fiducial ratio (4) as a function of the most important parameters: the mixing parameter between the 2nd and the 3rd generation δ_{23}, eq. (5); the gluino mass $m_{\tilde{g}}$; $\tan\beta$; and the mass of the pseudoscalar Higgs m_{A^0}. The set of reference parameters used is:

$$\begin{array}{c} \tan\beta = 35\,,\ m_{A^0} = 100GeV\,,\ \mu = -200GeV\,,\ A_t = A_q = -A_b = 300GeV\,, \\ m_{\tilde{t}_1} = 150GeV\,,\ m_{\tilde{q}} \simeq 200GeV\,,\ m_{\tilde{g}} = 180GeV\,,\ \delta_{12} = \delta_{13} = 0.03\,,\ \delta_{23} = 0.5\,. \\ m_t = 175\,GeV\,,\ \ m_b = 5\,GeV\,,\ \ \alpha_s(m_t) = 0.11\,,\ \ V_{cb} = 0.040\,, \end{array} \qquad (6)$$

and the remaining ones are as in [18].

As anticipated, the most important parameter is δ_{23}. In Fig. 1a we see that an increase in three orders of magnitude on δ_{23} corresponds to a change in six orders of magnitude on $B(t \to ch)$, a fact that can be traced down to the quadratic dependence of the latter on δ_{23}. The dependence on $\tan\beta$ is rather mild since it enters the amplitude through the $\tilde{u}_\alpha\tilde{u}_\beta h$ coupling as $1/\tan\beta$, and also indirectly through the determination of the squark masses. For the chosen set of parameters (6) it has a non-negligible impact on the H^0 channel (Fig. 1b). Although all Feynman diagrams proceed through gluino exchange, the gluino mass turns out not to be a critical quantity. In Fig. 1c we see that the decoupling of the gluino is slow, a fact observed also in other Higgs bosons observables related to the top quark [13]. This fact can be traced back to the presence of chirality-changing couplings, which imply a corresponding gluino mass-insertion in the amplitude. Finally in Fig. 1d we see that the smallest value for the H^0 branching ratio is not due to the smaller phase space available, but to the value of the couplings. In fact $B(t \to cH^0)$ grows with m_{A^0} (and thus with m_{H^0}), until it dies out near the phase space kinematical limit.

In Fig. 2 we display the theoretical prediction for $B(t \to cg)$ as a function of the gluino mass and δ_{23}, assuming $m_{H^\pm} > m_t$. The values for the ratio are below that of the neutral Higgs bosons channels, but still some orders of magnitude above the SM expected value for experimentally allowed values of $m_{\tilde{g}} > 180GeV$. Again the branching ratio grows quadratically with the mixing parameter δ_{23} (Fig. 2a). In contrast with the Higgs bosons channels (Fig. 1c), the gluon channel $B(t \to cg)$ shows a fast decoupling with the gluino mass (Fig. 2b).

In Fig. 3 we present the maximum rates for $B(t \to ch)$ and $B(t \to cg)$ – eq. (4) – in the MSSM. We have made a comprehensive scan of the MSSM parameter space, taking into account present constraints from experiment. 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 $B^{\rm MSSM}(t \to c\,h^0) \sim 10^{-4}$ that stay fairly stable all over the parameter space. The FCNC top quark decay into the lightest Higgs scalar can have an observable ratio in a large portion of the

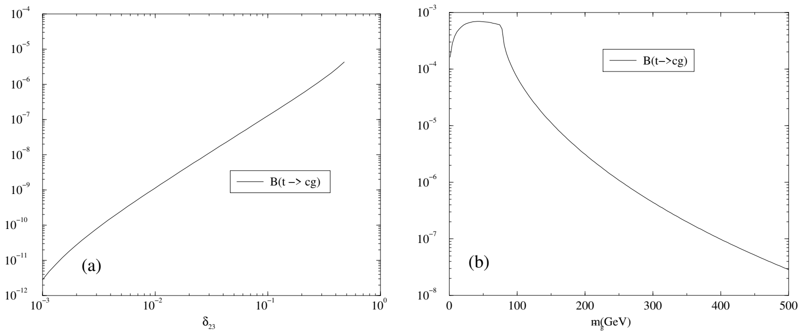

Figure 2: Evolution of the SUSY-QCD effects on $B(t \to c\,g)$ as a function of **(a)** the mixing parameter δ_{23}, and **(b)** the gluino mass $m_{\tilde{g}}$.

parameter space, and in particular for almost all the range of Higgs boson masses. Needless to say, not all of the maxima can be simultaneously attained as they are obtained for different values of the parameters. The maximum FCNC rate of the gluon channel in the MSSM reads (Fig. 3b) $B^{\rm MSSM}(t \to c\,g) \lesssim 10^{-5}$, but it never really reaches the critical value 10^{-5}, which can be considered as the visible threshold for the next generation of colliders (see Sec. 5).

4 $t \to ch$ and $t \to cg$ in the general 2HDM

In the 2HDM case a highly relevant parameter is $\tan\beta$, which must be restricted to the approximate range

$$0.1 < \tan\beta \lesssim 60 \tag{7}$$

in perturbation theory. It is to be expected from the various couplings involved in the processes under consideration that the low $\tan\beta$ region could be relevant for both the Type I and Type II 2HDM's. In contrast, the high $\tan\beta$ region is only potentially important for the Type II. However, the eventually relevant regions of parameter space are also determined by the value of the mixing angle α, as we shall see below.

Of course there are several restrictions that must be respected by our numerical analysis. First, the one-loop corrections to the ρ-parameter from the 2HDM sector cannot deviate from the reference SM contribution in more than one per mil [18]: $|\delta\rho^{2HDM}| \leqslant 0.001$. From the analytical expression for $\delta\rho$ in the general 2HDM we have introduced this numerical condition in our codes.

For both models we have imposed the condition that the (absolute value) of the trilinear Higgs self-couplings do not exceed the maximum unitarity limit tolerated for the SM trilinear coupling: $|\lambda_{HHH}| \leqslant \left|\lambda^{(SM)}_{HHH}(m_H = 1\,TeV)\right| = 3\,g\,(1\,TeV)^2/(2\,M_W)$.

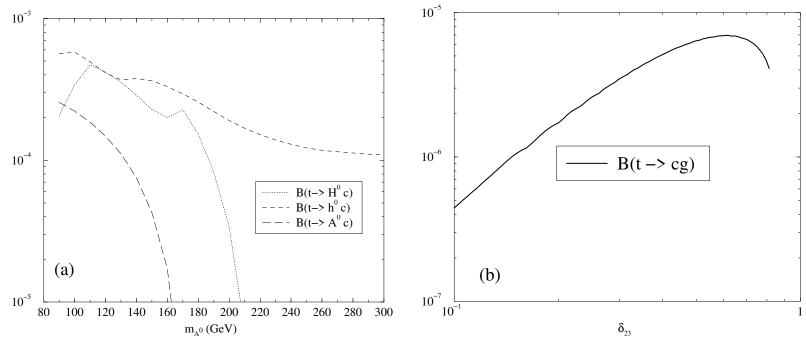

Figure 3: Maximum value of $B(t \to c\,h)$ in the MSSM, obtained by taking into account only the SUSY-QCD contributions, as a function of m_{A^0}; **(b)** maximum value of $B(t \to c\,g)$ as a function of the intergenerational mixing parameter δ_{23} in the LH sector. In all cases the scanning for the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

In the MSSM case it was not necessary to impose this restriction because the Higgs self-couplings are purely gauge. As for the $\delta\rho$ constraint in the MSSM, we have checked that it is satisfied. It is in the 2HDM case that one has to keep an eye very seriously on $\delta\rho$ because it grows with the Higgs boson mass squared differences, whereas in the MSSM the mass differences are much more tamed in all sectors of the theory.

The combined set of independent conditions turns out to be quite effective in narrowing down the permitted region in the parameter space, as can be seen in Figs. 4-7 where we plot the fiducial FCNC rate (4) and the corresponding one for the gluon channel versus the parameters (3). The cuts in some of these curves just reflect the fact that at least one of these conditions is not fulfilled.

After scanning the parameter space, we see in Figs. 4-5 that the 2HDM I (resp. 2HDM II) prefers low values (resp. high values) of $\tan\alpha$ and $\tan\beta$ for a given channel, e.g. $t \to h^0\,c$. Therefore, the following choice of mixing angles will be made to optimize the presentation of our numerical results:

$$\text{2HDM I}: \;\tan\alpha = \tan\beta = 1/4 \;\;;\;\; \text{2HDM II}: \;\tan\alpha = \tan\beta = 50\,. \qquad (8)$$

We point out that, for the same values of the masses, one obtains the same maximal FCNC rates for the alternative channel $t \to H^0\,c$ provided one just substitutes $\alpha \to \pi/2 - \alpha$. Equation (8) defines the eventually relevant regions of parameter space and, as mentioned above, depend on the values of the mixing angles α and β, namely $\beta \simeq \alpha \simeq 0$ for Type I and $\beta \simeq \alpha \simeq \pi/2$ for Type II. Despite naive expectations, and due to the structure of the Yukawa couplings of Type II models, there is a cancellation of the contributions in the low $\tan\beta$ end. This is in contrast to Type I models where

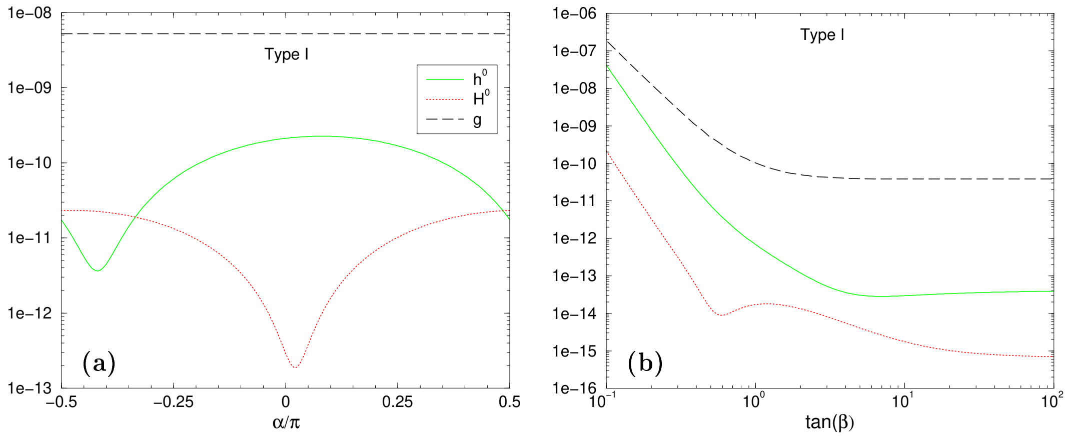

Figure 4: Evolution of the FCNC top quark fiducial ratio (4) – and the corresponding one for $B(t \to g + c)$ – in Type I 2HDM versus: **(a)** the mixing angle α in the CP-even Higgs sector, in units of π; **(b)** $\tan\beta$. The values of the fixed parameters are as in eqs. (8) and (9).

the maximal ratios occur. So the most favoured region of Type II models definitely is the high $\tan\beta$ one.

Due to the $\alpha \to \pi/2 - \alpha$ symmetry of the maximal rates for the CP-even Higgs channels, it is enough to concentrate the numerical analysis on one of them, but one has to keep in mind that the other channel yields the same rate in another region of parameter space. Whenever a mass has to be fixed, we choose conservatively the following values for both models:

$$m_{h^0} = 100\,GeV\,, \;\; m_{H^0} = 150\,GeV\,, \;\; m_{A^0} = m_{H^\pm} = 180\,GeV\,. \tag{9}$$

The variation of the results with respect to the masses is studied in Figs. 6-7. In particular, in Fig. 6 we can see the (scanty) rate of the channel $t \to A^0\, c$ when it is kinematically allowed. This is easily understood as it is the only one that does not have trilinear couplings with the other Higgs particles. While it does have trilinear couplings involving Goldstone bosons, these are not enhanced. The crucial role played by the trilinear Higgs self-couplings in our analysis cannot be underestimated as they can be enhanced by playing around with both (large or small) $\tan\beta$ *and* also with the mass splittings among Higgses. This feature is particularly clear in Fig. 6a where the rate of the channel $t \to h^0\, c$ is dramatically increased at large m_{A^0}, for fixed values of the other parameters and preserving our list of constraints.

From Figs. 4a and 4b it is pretty clear that the possibility to see FCNC decays of the top quark into Type I Higgs bosons is plainly hopeless even in the most favorable regions of parameter space – the lowest (allowed) $\tan\beta$ end. In fact, the highest rates remain neatly down 10^{-6}, and therefore they are (at least) one order of magnitude

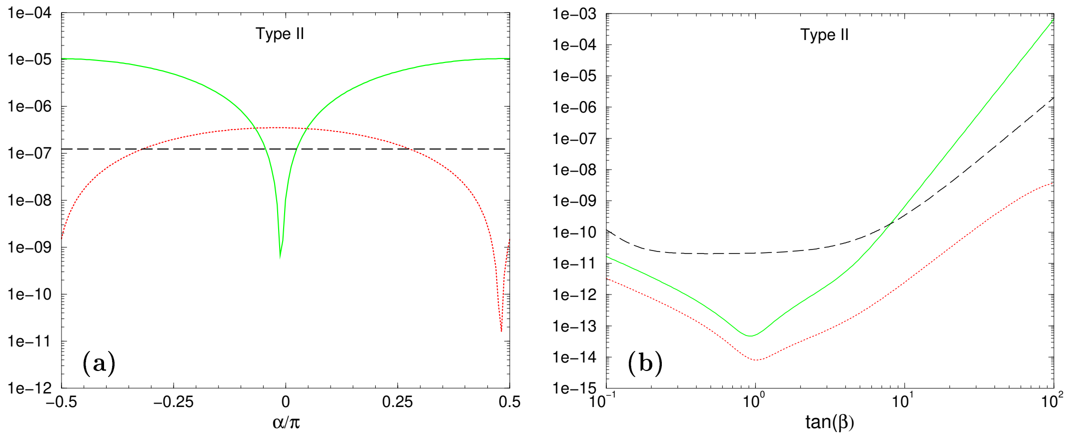

Figure 5: As in Fig. 4, but for the 2HDM II. The plot in (b) continues above the bound in eq. (7) just to better show the general trend.

below the threshold sensibility of the best high luminosity top quark factory in the foreseeable future (see Section 5).

Fortunately, the meager situation just described does not replicate for Type II Higgs bosons. For, as shown in Figs. 5a and 5b, the highest potential rates are of order 10^{-4}, and so there is hope for being visible. In this case the most favorable region of parameter space is the high $\tan\beta$ end in eq. (7). Remarkably, there is no need of risking values over and around 100 to obtain the desired rates. But it certainly requires to resort to models whose hallmark is a large value of $\tan\beta$ of order or above $m_t/m_b \gtrsim 35$. As for the dependence of the FCNC rates on the various Higgs boson masses (Cf. Figs. 6-7) we see that for large m_{A^0} the decay $t \to h^0\, c$ can be greatly enhanced as compared to $t \to g\, c$. We also note (from the combined use of Figs. 5b, 6a and 6b) that in the narrow range where $t \to H^+\, b$ could still be open in the 2HDM II, the rate of $t \to h^0\, c$ becomes the more visible the larger and larger is $\tan\beta$ and m_{A^0}. Indeed, in this region one may even overshoot the 10^{-4} level without exceeding the upper bound (7) while also keeping under control the remaining constraints. Finally, the evolution of the rate (4) and $B(t \to g + c)$ with respect to the two CP-even Higgs boson masses is shown in Figs. 7a and 7b.

5 Discussion and conclusions

In the near and middle future, with the upgrades of the Tevatron (Run II, TeV33), the advent of the LHC, and the construction of an e^+e^- linear collider (LC), new results on top quark physics, and possibly also on Higgs physics, will be obtained. With datasets from LHC and LC increasing to several $100 fb^{-1}$/year in the high-

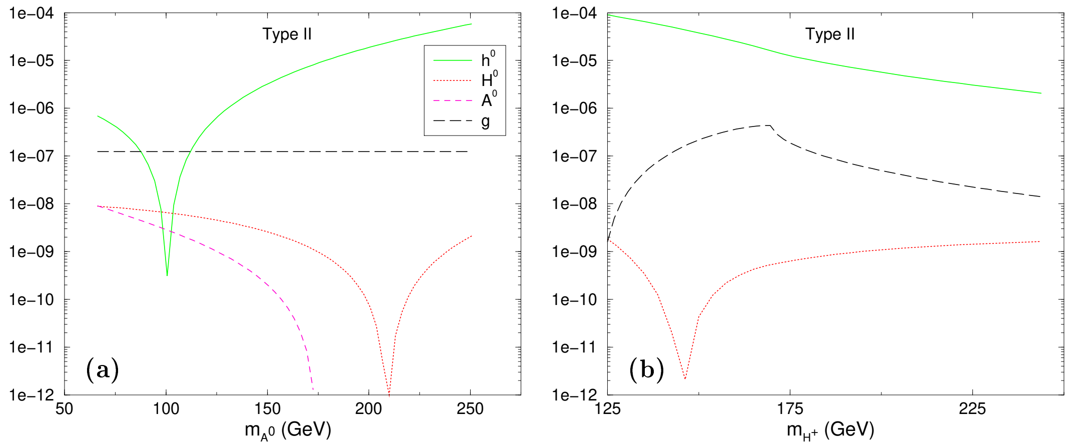

Figure 6: Evolution of the FCNC top quark fiducial ratios (4) – and the corresponding one for $B(t \to g + c)$ – in Type II 2HDM versus: **(a)** the CP-odd Higgs boson mass m_{A^0}; **(b)** the charged Higgs boson mass $m_{H^\pm}$. The values of the fixed parameters are as in eqs. (8) and (9). The plot in (b) starts below the bound $m_{H^\pm} > 165\,GeV$ mentioned in the text to better show the general trend.

luminosity phase, one should be able to pile up an enormous wealth of statistics on top quark decays. Therefore, these machines should be very useful to analyze rare decays of the top quark, viz. decays whose branching fractions are extremely small ($\lesssim 10^{-5}$).

The sensitivities to FCNC top quark decays for $100\,fb^{-1}$ of integrated luminosity in the relevant colliders are estimated to be [19]:

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

This estimation has been confirmed by a full signal-background analysis for the hadron colliders and also for the LC in the case of gauge boson decays [20]. From these experimental expectations and our numerical results it becomes patent that whilst the Tevatron will remain essentially blind to this kind of physics, the LHC and the LC will have a significant potential to observe FCNC decays of the top quark beyond the SM. Above all there is a possibility to pin down top quark decays into neutral Higgs particles, eq. (2), within the framework of the general 2HDM II provided $\tan\beta \gtrsim m_t/m_b \sim 35$, and within the MSSM provided δ_{23}–eq. (5)– is large. The maximum rates are of order 10^{-4} in both models and correspond to the two CP-even scalars. In the MSSM the lightest Higgs boson is highlighted all over the m_{A^0} range. This conclusion is remarkable from the practical (quantitative) point of view, and also qualitatively because the top quark decay into the SM Higgs particle is the less favorable top quark FCNC rate in the SM. On the other hand, we deem practically hopeless to see FCNC

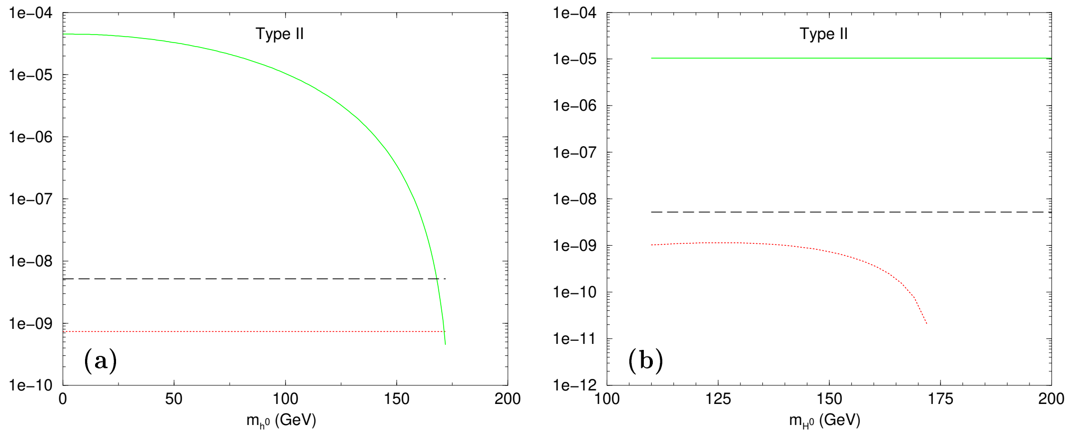

Figure 7: As in Fig. 6, but plotting versus: **(a)** the lightest CP-even Higgs boson mass m_{h^0}; **(b)** the heaviest CP-even Higgs boson mass m_{H^0}.

decays of the top quark in a general 2HDM I for which the maximum rates are of order 10^{-7}. This order of magnitude cannot be enhanced unless one allows $\tan\beta \ll 0.1$, but the latter possibility is unrealistic because perturbation theory breaks down and therefore one cannot make any prediction within our approach.

We have made a parallel numerical analysis of the gluon channel $t \to c\ g$. We confirm that this is another potentially important FCNC mode of the top quark in extensions of the SM [1,4–6] but, unfortunately, it still falls a bit too short to be detectable. The maximum rates for this channel lie below 10^{-6} in the 2HDM I (for $\tan\beta > 0.1$) and in the 2HDM II (for $\tan\beta < 60$), and below 10^{-5} for the MSSM, and so it will be hard to deal with it even at the LHC.

We are thus led to the conclusion that the Higgs channels (2), more specifically the CP-even ones, give the highest potential rates for top quark FCNC decays in a general 2HDM II and the MSSM. Most significant of all: they are *the only* FCNC decay modes of the top quark, within the simplest renormalizable extensions of the SM, that have a real chance to be seen in the next generation of high energy, high luminosity, colliders.

Although the 2HDM II and the MSSM show similar behaviour, there exist some conspicuous differences on which we wish to elaborate a bit in what follows. First, in the general 2HDM II the two channels $t \to (h^0, H^0)\ c$ give the same maximum rates, provided we look at different (disjoint) regions of the parameter space. The $t \to A^0\ c$ channel is, as mentioned, negligible with respect to the CP-even modes. Hereafter we will discard this FCNC top quark decay mode from our discussions within the 2HDM context. On the other hand, in the MSSM there is a most distinguished channel, viz. $t \to h^0\ c$, which can be high-powered by the SUSY stuff all over the parameter space. In this framework the mixing angle α becomes stuck once $\tan\beta$ and the rest of the independent parameters are given, and so there is no possibility to reconvert the couplings between h^0 and H^0 as in the 2HDM. Still, we must emphasize that in the MSSM the other two decays $t \to H^0\ c$ and $t \to A^0\ c$ can be competitive with $t \to h^0\ c$ in certain portions of parameter space. For example, $t \to H^0\ c$ becomes competitive when the pseudoscalar mass is in the range $110\,GeV < m_{A^0} \lesssim 170\,GeV$ –Cf. Fig. 1d. The possibility of having more than one FCNC decay (2) near the visible level is a feature which is virtually impossible in the 2HDM II. Second, the reason why $t \to h^0\ c$ in the MSSM is so especial is that it is the only FCNC top quark decay (2) which is always kinematically open throughout the whole MSSM parameter space, while in the 2HDM all of the decays (2) could be, in the worst possible situation, dead closed. Nevertheless, this is not the most likely situation in view of the fact that all hints from high precision electroweak data seem to recommend the existence of (at least) one relatively light Higgs boson [21,22]. This is certainly an additional motivation for our work, as it leads us to believe that in all possible (renormalizable) frameworks beyond the SM, and not only in SUSY, we should expect that at least one FCNC decay channel (2) could be accessible. Third, the main origin of the maximum FCNC rates in the MSSM traces back to the tree-level FCNC couplings of the gluino [5]. These are strong couplings, and moreover they are very weakly restrained by experiment. In the absence of such gluino couplings, or perhaps by further experimental constraining of them in the future, the FCNC rates in the MSSM would boil down to just the EW contributions, to wit, those induced by charginos, squarks and also from SUSY Higgses. The associated SUSY-EW rate is of order 10^{-6} at most [5], and therefore it is barely visible, most likely hopeless even for the LHC. In contrast, in the general 2HDM the origin of the contributions is purely EW and the maximum rates are two orders of magnitude higher than the full SUSY-EW effects in the MSSM. It means that we could find ourselves in the following situation. Suppose that the FCNC couplings of the gluino get severely restrained in the future and that we come to observe a few FCNC decays of the top quark into Higgs bosons, perhaps at the LHC and/or the LC. Then we would immediately conclude that these Higgs bosons could not be SUSY-MSSM, whilst they could perhaps be CP-even members of a 2HDM II. Fourth, the gluino effects are basically insensitive to $\tan\beta$, implying that the maximum MSSM rates are achieved equally well for low, intermediate or high values of $\tan\beta$, whereas the maximum 2HDM II rates (comparable to the MSSM ones) are attained only for high $\tan\beta$.

The last point brings about the question of whether it would be possible to discern between different models if these decays are detected. The answer is, most likely yes. There are many possibilities and corresponding strategies, but we will limit ourselves to point out some of them. For example, let us consider the type of signatures involved in the tagging of the Higgs channels. In the favorite FCNC region (8) of the 2HDM II, the combined decay $t \to h\ c \to cb\bar{b}$ is possible only for h^0 or for H^0, but not for both – Cf. Fig. 5a – whereas in the MSSM, h^0 together with H^0, are highlighted for $110\,GeV < m_{A^0} < m_t$, with no preferred $\tan\beta$ value. And similarly, $t \to A^0\ c$ is also non-negligible for $m_{A^0} \lesssim 120\,GeV$ –Cf. Fig. 1d. Then the process $t \to h\ c \to c b\bar{b}$ gives rise to high p_T charm-quark jets and a recoiling $b\bar{b}$ pair with large invariant mass. It follows that if more than one distinctive signature of this kind would be observed, the origin of the hypothetical Higgs particles could not probably be traced back to a 2HDM II.

One might worry that in the case of h^0 and H^0 they could also (in principle) decay into electroweak gauge boson pairs $h^0, H^0 \to V_{ew}\overline{V}_{ew}$, which in some cases could be kinematically possible. But this is not so in practice for the 2HDM II [6]. Again, at variance with this situation, in the MSSM case $H^0 \to V_{ew}\overline{V}_{ew}$ is perfectly possible – not so $h^0 \to V_{ew}\overline{V}_{ew}$ due to the aforementioned upper bound on m_{h^0} – because $\tan\beta$ has no preferred value in the most favorable MSSM decay region of $t \to H^0\ c$. Therefore, detection of a high p_T charm-quark jet against a $V_{ew}\overline{V}_{ew}$ pair of large invariant mass could only be advantageous in the MSSM, not in the 2HDM. Similarly, for $\tan\beta \gtrsim 1$ the decay $H^0 \to h^0\ h^0$ (with real or virtual h^0) is competitive in the MSSM in a region where the parent FCNC top quark decay is also sizeable. Again this is impossible in the 2HDM II and therefore it can be used to distinguish the two (SUSY and non-SUSY) Higgs frames.

Finally, even if we place ourselves in the high $\tan\beta$ region both for the MSSM and the 2HDM II, then the two frameworks could still possibly be separated provided that two Higgs masses were known, perhaps one or both of them being determined from the tagged Higgs decays themselves, eq. (2). Suppose that $\tan\beta$ is numerically known (from other processes or from some favorable fit to precision data), then the full spectrum of MSSM Higgs bosons would be approximately determined (at the tree level) by only knowing one Higgs mass, a fact that could be used to check whether the other measured Higgs mass becomes correctly predicted. Of course, the radiative corrections to the MSSM Higgs mass relations can be important at high $\tan\beta$ [12], but these could be taken into account from the approximate knowledge of the relevant sparticle masses obtained from the best fits available to the precision measurements within the MSSM. If there were significant departures between the predicted mass for the other Higgs and the measured one, we would probably suspect that the tagged FCNC decays into Higgs bosons should correspond to a non-supersymmetric 2HDM II.

At the end of the day we see that even though the maximum FCNC rates for the MSSM and the 2HDM II are both of order 10^{-4} – and therefore potentially visible – at some point on the road it should be possible to disentangle the nature of the Higgs model behind the FCNC decays of the top quark. Needless to say, if all the recent fuss at CERN [21] about the possible detection of a Higgs boson would eventually be confirmed in the future (e.g. by the LHC), this could still be interpreted as the discovery of one neutral member of an extended Higgs model.

We emphasize our most essential conclusions in a nutshell: i) Detection of FCNC top quark decay channels into a neutral Higgs boson would be a blazing signal of physics beyond the SM; ii) There is a real chance for seeing rare events of that sort both in generic Type II 2HDM's and in the MSSM. The maximum rates for the leading FCNC processes (2) and $t \to c\, g$ in the 2HDM II (resp. in the MSSM) satisfy the relations

$$BR(t \to g\, c) < 10^{-6}(10^{-5}) < BR(t \to h\, c) \sim 10^{-4}\,, \tag{11}$$

where it is understood that h is h^0 or H^0, but not both, in the 2HDM II; whereas h is most likely h^0, but it could also be H^0 and A^0, in the MSSM ; iii) Detection of more than one Higgs channel would greatly help to unravel the type of underlying Higgs model.

The pathway to seeing new physics through FCNC decays of the top quark is thus potentially open. It is now an experimental challenge to accomplish this program using the high luminosity super-colliders round the corner.

Acknowledgments

One of the authors (J.S) would like to thank H. Haber and T. Junk for helpful discussions. J.G. thanks S. Peñaranda for suggestions.

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