Single top-quark production by direct supersymmetric flavor-changing neutral-current interactions at the LHC

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Production of (electrically neutral) heavy-quark pairs, such as $t\bar{c}$ and $\bar{t}c$, is extremely suppressed in the SM. In supersymmetric (SUSY) theories, such as the MSSM, the number of these events can be significantly enhanced thanks (mainly) to the FCNC couplings of gluinos. We compute the efficiency of this mechanism for FCNC production of heavy quarks at the LHC. We find that $\sigma(pp \to t\bar{c} + \bar{t}c)$ can reach 1 pb, and therefore one can expect up to 10^5 events per $100\,\mathrm{fb}^{-1}$ of integrated luminosity (with no counterpart in the SM). Their detection would be instant evidence of new physics, and could be a strong indication of underlying SUSY dynamics.

1. Introduction

Flavor-changing neutral-current (FCNC) interactions of top quarks are among the most promising processes to deal with as a probe of new physics. This is so because that kind of processes are (in contrast to low-energy meson FCNC physics) extremely suppressed in the SM. For instance, while radiative B-meson decays have branching ratios of order $B(b \to s\gamma) \sim 10^{-4}$, typical FCNC top-quark decays, such as $t \to Zc$ and $t \to gc$, have SM branching ratios of order of at most 10^{-13} and 10^{-11} respectively [1], which in practice are impossible to measure. And among these FCNC processes the rarest ones in the SM are those involving the top quark and the Higgs boson, e.g. $B(t \to H_{\rm SM}\, c) \sim 10^{-14}$ [2] and the crossed one $B(H_{\rm SM} \to t\,\bar{c}) \sim 10^{-13}$-$10^{-16}$ (depending on the Higgs mass) [3]. Fortunately, when one considers the impact of new physics (e.g. Supersymmetry or generalized Higgs sectors) the situation may change dramatically. Indeed, as first emphasized in the detailed work of [4], the FCNC processes involving top quarks and Higgs bosons may constitute a prominent door to SUSY physics in high-luminosity colliders. In that work it was found that, in contradistinction to the SM case, the top-quark decays into MSSM Higgs bosons $h = h^0, H^0, A^0$ [5] can be the most favored FCNC top decays of all, with branching ratios that can reach the level of $B(b \to s\gamma)$. This is not possible (without fine-tuning) for the FCNC top quark decays into gauge bosons in the MSSM, which stay typically two orders of magnitude below [6]. Similarly, the maximal MSSM Higgs boson FCNC rates into top-quark final states, e.g. $H^0, A^0 \to t\bar{c} + \bar{t}c$, can be of order 10^{-4} [7], which suggests that these decays could be a source of a sizeable number of FCNC events $t\bar{c}$ and $\bar{t}c$ in a high-luminosity collider. Actually, a detailed calculation of the number of these events at the LHC has recently been reported in [8] and confirmed this expectation, to wit: a few thousand FCNC events per $100\,\mathrm{fb}^{-1}$ of integrated luminosity are possible. Furthermore, a number of works have stressed the importance of this kind of FCNC processes in more general two-Higgs-doublet models (2HDM) [3, 9], including some effects that could appear in multiple

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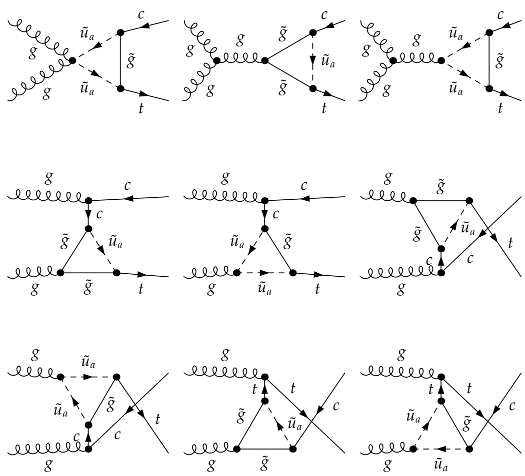

Figure 1. Feynman diagrams contributing to the production of $t\bar{c}$ final states at the LHC through loops of gluinos and squarks. Only a small sample of them is shown. The FCNC interactions take place at the vertices $\tilde{g} - \tilde{q}_i - q_j$ (with $i, j = c, t$), which are proportional to δ_{23}.

Higgs models [10]. Finally, let us also mention the possibility of enhanced FCNC top-quark effects in top-color assisted technicolor models [11]. A general, model-independent, parametrization of new FCNC effects is presented in [12].

Interestingly enough, there also exists the possibility to produce $t\bar{c}$ and $\bar{t}c$ final states without Higgs bosons or any other intervening particle. In this work we will show that the FCNC gluino interactions in the MSSM can actually be the most efficient mechanism for direct FCNC production of top quarks.

2. FCNC interactions in the MSSM

The flavor structure of the MSSM involves fermion and sfermion mass matrices, and in general the diagonalization of the first flavor structure does not guarantee the diagonalization of the second. For example, the requirement of $SU(2)_L$ invariance means that the top-left-squark mass matrix cannot be simultaneously diagonal to the bottom-left-squark mass matrix, and therefore these two matrices cannot be in general simultaneously diagonal with the top-quark and bottom-quark mass matrices. Even if we would arrange this to be so, the radiative corrections (e.g. from the charged currents) would destroy this arrangement. This is a sign that one cannot consistently demand the absence of flavor-mixing interactions in the MSSM. Indeed, even if we would "align" the parameters at a high energy GUT scale, the RG running down the electroweak scale would missalign the mass matrices [13]. As a well-known example, let us recall that the top-squark decay into charm quark and neutralino ($\tilde{t} \to c\,\chi^0$) is UV-divergent in the MSSM, unless we allow for FCNC interaction terms in the classical Lagrangian that can absorb these infinities [14]. Therefore, in general, in the MSSM we expect terms of the form gluino–quark–squark or neutralino–fermion–sfermion, with the quark and squark having the same charge but belonging to different flavors. In this work we will concentrate only on the first type of terms, which are expected to be dominant. A detailed Lagrangian describing these generalized SUSY–QCD interactions mediated by gluinos can be found, e.g. in [4]. The relevant parameters are the flavor-mixing coefficients δ_{ij}. In contrast to previous studies [15], we will allow them only in the LL part of the 6×6 sfermion mass matrices in flavor-chirality space [4]. This assumption is not only for simplicity, but also because it is suggested by RG arguments [13]. Thus, if $M_{\rm LL}$ is the LL block of a sfermion mass matrix, we define δ_{ij} $(i \neq j)$ as follows: $(M_{\rm LL})_{ij} = \delta_{ij}\,\tilde{m}_i\,\tilde{m}_j$, where $\tilde{m}_i$ is the soft SUSY-breaking mass parameter corresponding to the LH squark of ith flavor [4]. We will be mostly interested in the parameter δ_{23}, because it is the one relating the second and third generations (therefore involving the top quark physics). δ_{23} is the less restricted one from the phenomenological point of view. This is because the phenomenological bounds on the various δ_{ij} (cf. [16]) are obtained from the low-energy FCNC processes. These involve mainly the first and second generations. Thus δ_{23} is an essentially free parameter within, say, the natural interval $0 < \delta_{23} < 1$.

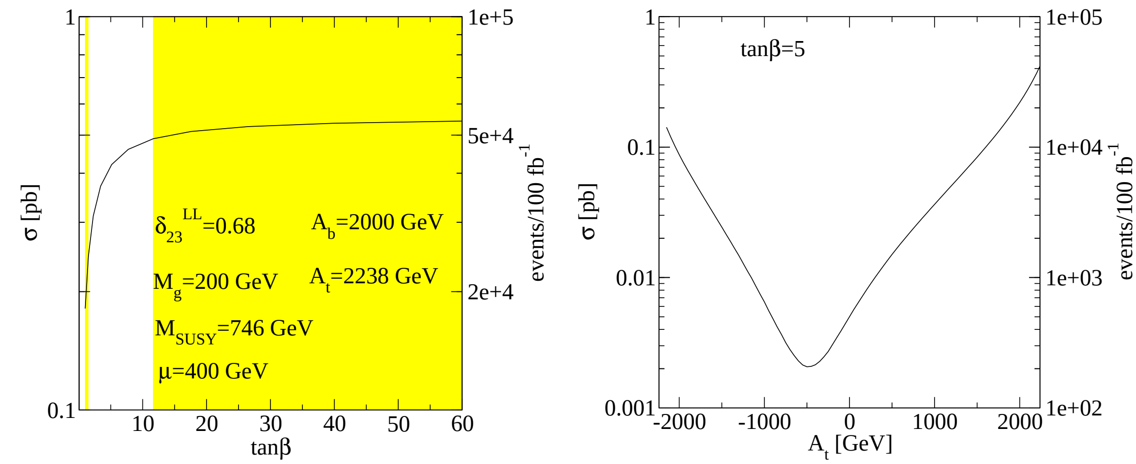

Figure 2. σ_{tc} (in pb), Eq.(1), and number of events per $100\,\mathrm{fb}^{-1}$ of integrated luminosity at the LHC, as a function of $\tan\beta$ and A_t for the given parameters. The shaded region is excluded by $B_{\rm exp}(b \to s\gamma)$.

Actually we have two such parameters, $\delta_{23}^{(t)}$ and $\delta_{23}^{(b)}$, for the up-type and down-type LL squark mass matrices respectively. The former enters the process under study whereas the latter enters $B(b \to s\gamma)$. We will use this observable to restrict our predictions on $t\bar{c} + \bar{t}c$ production.

3. Single top-quark production from gluino FCNC interactions in the MSSM

In Fig. 1 we show some of the diagrams involved in the direct production of the FCNC $t\bar{c}$ final states. We have performed the calculation of the full one-loop SUSY–QCD cross-section $\sigma_{tc} \equiv \sigma(pp \to t\bar{c})$ using standard algebraic and numerical packages for this kind of computations [17]. (Of course $\sigma(pp \to t\bar{c}+\bar{t}c) = 2\,\sigma_{tc}$.) The complete formulae are very cumbersome, so to simplify the discussion it will be sufficient to quote the general form of the cross-section:

$$\sigma_{tc} \sim \left(\delta_{23}^{(t)LL}\right)^2 \, \frac{m_t^2 (A_t - \mu/\tan\beta)^2}{M_{\rm SUSY}^4} \, \frac{1}{m_{\tilde{g}}^2} \, . \qquad (1)$$

Here A_t is the trilinear top-quark coupling, μ the higgsino mass parameter and $M_{\rm SUSY}$ stands for the overall scale of the squark masses – see (3) below. The gluino mass is denoted by $m_{\tilde{g}}$. The superscript in $\delta_{23}^{(t)\rm LL}$ is to emphasize that we consider only the contributions from the LL block of the (top-squark) mass matrix. We have performed the computation of the above cross-section together with the branching ratio $B(b \to s\gamma)$ in the MSSM, because only in this way can we be sure that the region of the parameter space that we employ to compute σ_{tc} does respect the experimental bounds on $B(b \to s\gamma)$. Specifically, we take $B_{\rm exp}(b \to s\gamma) = (2.1\text{-}4.5) \times 10^{-4}$ at the 3σ level [18]. Again, to ease the discussion, it suffices to quote the MSSM formula for the branching ratio as follows [8]:

$$B(b \to s\gamma) \sim \left(\delta_{23}^{(b)\rm LL}\right)^2 \, \frac{m_b^2 (A_b - \mu\tan\beta)^2}{M_{\rm SUSY}^4} \, . \qquad (2)$$

Notice that $\delta_{23}^{(b)\rm LL}$ from the down-quark mass matrix is related to the parameter $\delta_{23}^{(t)\rm LL}$ in (1) (from the up-quark mass matrix) because the two LL blocks of these matrices are precisely related by the CKM rotation matrix K as follows: $(\mathcal{M}_{\tilde{u}}^2)_{LL} = K\,(\mathcal{M}_{\tilde{d}}^2)_{LL}\,K^\dagger$ [16].

4. Numerical analysis

In Figs. 2 and 3 we present the main results of our numerical analysis. We see that σ_{tc} is very

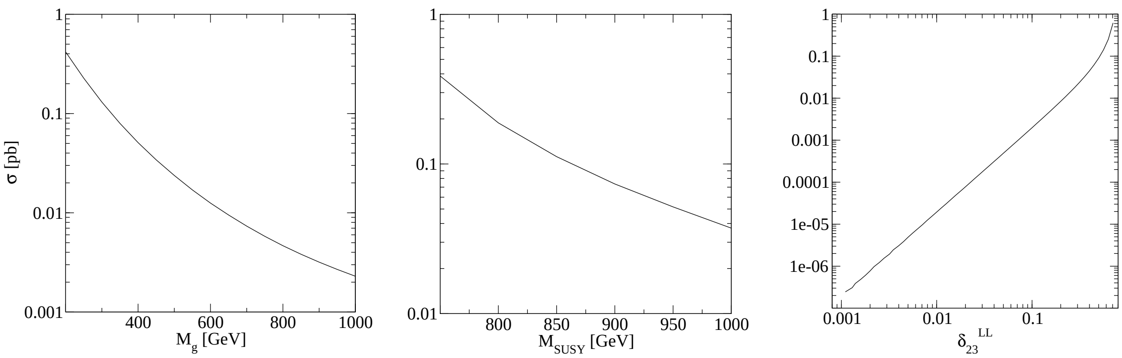

Figure 3. As in Fig. 2, but for σ_{tc} as a function of $m_{\tilde{g}}$, $M_{\rm SUSY}$ and $\delta_{23}^{\rm LL}$, respectively.

sensitive to A_t and that it decreases with M_{SUSY}, but mainly with $m_{\tilde{g}}$. As expected, it increases with $\delta_{23}^{\rm LL} \equiv \delta_{23}^{(t){\rm LL}}$, but it does not reach the maximum range of this parameter. At the maximum of σ_{tc}, it prefers $\delta_{23}^{\rm LL} = 0.68$, as we shall see below. The reason stems from the correlation of this maximum with the $B(b \to s\gamma)$ observable. At the maximum, the cross-section for $t\bar{c}+\bar{t}c$ production lies around $2\sigma_{tc} \simeq 1\,{\rm pb}$, if we allow for relatively light gluino masses $m_{\tilde{g}} = 200$ GeV (see Fig. 3). For higher $m_{\tilde{g}}$ the cross-section falls down fast; at $m_{\tilde{g}} = 500$ GeV it is already 10 times smaller. The total number of events per $100\,{\rm fb}^{-1}$ lies between 10^4-10^5 for this range of gluino masses. The fixed values of the parameters in these plots lie near the values that provide the maximum of the FCNC cross-section. The dependence on μ is not shown, but we note that σ_{tc} decreases by $\sim 40\%$ in the allowed range $\mu = 200$-800 GeV. Values of $\mu > 800$ GeV are forbidden by $B_{\rm exp}(b \to s\gamma)$. Large negative μ is also excluded by the experimental bound we take for the lightest squark mass, $m_{\tilde{q}_1} \lesssim 150$ GeV; too small $|\mu| \lesssim 200$ GeV is ruled out by the chargino mass bound $m_{\chi_1^\pm} \le 90$ GeV. The approximate maximum of σ_{tc} in parameter space has been computed using an analytical procedure. Let us briefly summarize the method. Define $\delta_{33}^{\rm LR} = m_t(A_t - \mu/\tan\beta)/M_{\rm SUSY}^2$, which is involved in (1). Then the lines of constant σ_{tc} are hyperbolas in the $\delta_{33}^{\rm LR} - \delta_{23}^{\rm LL}$ plane. Next consider the up-type squark mass matrix in the following approximation (in particular, only the 2nd and 3rd squark families are considered):

$$\mathcal{M}_{\tilde{q}}^2 = M_{\rm SUSY}^2 \left(\begin{array}{c|ccc} & c_{\rm L} & t_{\rm L} & t_{\rm R} \\ \hline c_{\rm L} & 1 & \delta_{23}^{\rm LL} & 0 \\ t_{\rm L} & \delta_{23}^{\rm LL} & 1 & \delta_{33}^{\rm LR} \\ t_{\rm R} & 0 & \delta_{33}^{\rm LR} & 1 \end{array} \right) . \qquad (3)$$

Upon diagonalization it is easy to see that the allowed squark masses should lie inside the circle $\left(\delta_{23}^{LL}\right)^2 + \left(\delta_{33}^{LR}\right)^2 = R^2$ whose radius is $R = 1 - m_{\tilde{q}_1}^2/M_{SUSY}^2$. Notice that R increases with M_{SUSY}, but we impose the (approximate) constraint $|A_t| < 3\,M_{SUSY}$ to avoid color-breaking minima. This puts a bound on δ_{33}^{LR}. Finally, looking for the point in the straight line $\delta_{33}^{LR} = \delta_{23}^{LL}$ where the outermost hyperbola $\sigma_{tc} =$ const. is tangent to the circle of radius R in the $\delta_{33}^{\rm LR}$-$\delta_{23}^{\rm LL}$ plane, we find the approximate maximum at

$$\delta_{23}^{LL} = \frac{\sqrt{2}}{1 + \left[1 + \frac{2}{9}\, m_{\tilde{q}_1}^2/{m_t}^2\right]^{1/2}} \simeq 0.68\,. \qquad (4)$$

This is the result quoted before. The residual parameters of the maximum easily follow. A previous analysis of this process [15] did not make a systematic study of the parameter space and did not take into account the important restrictions imposed by $b \to s\gamma$ for $\tan\beta > 10$ (cf. Fig. 2). That reference missed the bulk of the contribution and tended to emphasize that the main effects stem from the LR sector of the full mass matrix $\mathcal{M}_{\tilde{q}}^2$, namely from δ_{ij}^{LR} $(i \neq j)$. In contrast, we have proved that it suffices to consider the LL sector, which is the only one that is well motivated by renormalization group arguments [13].

Finally, we note that $t\bar{c}$ final states can also be produced at one-loop by the charged-current interactions within the SM. We have computed this one-loop cross-section at the LHC, with the result $\sigma^{\rm SM}(pp \to t\bar{c} + \bar{t}c) = 7.2 \times 10^{-4}\,{\rm fb}$. It amounts to less than one event in the entire lifetime of the LHC. So it is pretty obvious that only the presence of new physics could be an explanation for these events, if they are ever detected.

5. Discussion and conclusions

We have computed the full one-loop SUSY–QCD cross-section for the production of single top-quark states $t\bar{c} + \bar{t}c$ at the LHC. We have shown that this direct production mechanism is substantially more efficient (typically a factor of 100) than the production and subsequent FCNC decay [8] of the heavy MSSM Higgs bosons ($H^0, A^0 \to t\bar{c} + \bar{t}c$). It is important to emphasize that, if the mass generation mechanism is associated to a fundamental Higgs sector, then the detection of a significant number of $t\bar{c} + \bar{t}c$ states could be interpreted as a distinctive SUSY signature. The reason for this is that in an unconstrained 2HDM (types I and II), these FCNC events cannot be produced at comparable rates. There is no direct production mechanism in this case (at one-loop), and therefore a significant $t\bar{c} + \bar{t}c$ signature could only come from Higgs-boson decays whose efficiency, though, was shown to be comparatively much smaller [3], namely only a few hundred events could be expected versus 10^5 events that can be achieved by direct production in the MSSM. Given the robust signal carried by the single top-quark in the final state, these FCNC processes could be a very helpful tool to complement the search for SUSY physics at the LHC collider. Before closing we point out that there are also direct SUSY–EW (electroweak) loop diagrams (complementing the SUSY–QCD ones in Fig. 1), which could be important in certain regions of the MSSM parameter space. The corresponding analysis of these SUSY–EW effects will be presented elsewhere.

Note added. After the present work was first submitted, we noticed the recent reference [19] which addresses the same subject.

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