Impact of SUSY-QCD corrections on top quark decay distributions

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Abstract:
We compute the supersymmetric QCD corrections to the decay distribution of polarized top quarks for the semileptonic decay mode $t(↑) \rightarrow bl^+\nu_l$. As a byproduct, we reinvestigate the SUSY-QCD corrections to the total decay width $\Gamma(t \rightarrow W^+b)$ and resolve a discrepancy between two previous results in the literature.

Keywords: top quarks, supersymmetry, radiative corrections

*supported by a Heisenberg fellowship of D.F.G.
1 Introduction

The dynamics of top quark production and decay will be studied in detail at the Tevatron and LHC hadron colliders. Moreover, a possible future linear $e^+e^-$ collider will allow for precision studies of top quarks, in particular in the threshold region \([1]\). Precise experimental data will be matched by accurate theoretical predictions, which are possible since non-perturbative effects in top quark decays are cut off by the large decay width $\Gamma \approx 1.5 \text{ GeV}$. Such investigations may well yield hints to physics beyond the Standard Model, since production and decay of top quarks involve very high energy scales. In particular, virtual effects of supersymmetric particles may affect top quark production and its decay profile \([2]\). Supersymmetric electroweak \([3]\) and strong \([4, 5]\) quantum corrections to the total top quark decay width $\Gamma(t \to W^+b)$ have been calculated already some time ago. In this article we extend those calculations by considering the SUSY-QCD corrections to the fully differential decay distribution of polarized top quarks for the semileptonic decay mode. From this distribution we can easily derive as a special case the SUSY-QCD corrections to the total decay width and compare our result to two conflicting previous calculations \([4, 5]\).

Our letter is organized as follows: In section 2 we discuss the calculation of the SUSY-QCD correction to the differential decay distribution for $t(\uparrow) \to bl\nu$ and to the total top quark width. In section 3 we perform a numerical analysis of our results in terms of sbottom and gluino masses, taking into account mixing in the stop sector. Section 4 contains our conclusions.

2 Analytic results

The virtual supersymmetric corrections to the $tW^+b$ vertex to order $\alpha_s$ are determined by the following SUSY-QCD interaction Lagrangian (where we suppress colour and spinor indices of the (s)quark fields and $q = t, b$):

$$
L_{\tilde{g}\tilde{q}q} = \sqrt{2} g_s T^a \tilde{q} [P_L \tilde{g}_a \tilde{q}_R - P_R \tilde{g}_a \tilde{q}_L] + h.c.,
$$

where $\tilde{g}_a$ are the Majorana gluino fields, $T^a = \lambda^a / 2$ with the Gell-Mann matrices $\lambda^a$, and $\{\tilde{q}_L, \tilde{q}_R\}$ are the weak-eigenstate squarks that are associated to the chiral components $P_{L,R} = \frac{1}{2} (1 \mp \gamma_5) q$ of the quarks. The squark mass eigenstates are related to these weak eigenstates through a rotation:

$$
\begin{pmatrix}
\tilde{q}_1 \\
\tilde{q}_2
\end{pmatrix} =
\begin{pmatrix}
\cos \theta_{\tilde{q}} & \sin \theta_{\tilde{q}} \\
-\sin \theta_{\tilde{q}} & \cos \theta_{\tilde{q}}
\end{pmatrix}
\begin{pmatrix}
\tilde{q}_L \\
\tilde{q}_R
\end{pmatrix} \equiv R_{\tilde{q}}.
$$
Furthermore, we need the contribution of the squarks to the charged current interaction, which is given in the mass basis \( \{ \tilde{q}_1, \tilde{q}_2 \} \) by:

\[
\mathcal{L}_{cc} = -\frac{ie}{\sqrt{2}\sin\theta_W} \sum_{i,j} \left[ R_{i1}^{\tilde{q}} \tilde{R}_{j1}^{\tilde{q}} \bar{\tilde{b}}_i W_{\mu j}^{\tilde{q}+} \right] + h.c. \tag{3}
\]

Consider now an initial state consisting of top quarks at rest with polarization \( \mathbf{P} \). For the semileptonic decay

\[
t(p_t) \to b(p_b) + l^+(p_l) + \nu_l(p_{\nu}), \tag{4}
\]

the renormalized amplitude including the SUSY-QCD corrections can be written in terms of four formfactors (we neglect lepton masses and the mixing between generations):

\[
iT_{fi} = \left( -\frac{ie}{\sqrt{2}\sin\theta_W} \right)^2 \frac{(-ig_{\mu\nu})}{(p_t - p_b)^2 - m_W^2 + i\Gamma_W m_W} \bar{u}(p_b) \gamma^\mu P_L \left[ 1 + F_L + \frac{1}{2} (\delta Z_L^t + \delta Z_L^b) \right] + \gamma^\mu P_R F_R + \frac{\bar{P}_L^\mu (P_L H_L + P_R H_R)}{m_t} \right] u(p_l)
\]

(5)

In (5), \( Z_L^{t,b} = 1 + \delta Z_L^{t,b} \) denotes the renormalization constant for the top (bottom) quark field, which we fix by imposing on-shell renormalization conditions. This is equivalent to the method used in [5], where only one renormalization constant for the \((t,b)\) doublet is used. In that case an on-shell condition can only be fulfilled by one field, inducing a finite wave-function renormalization for the other. Accordingly, we find

\[
\frac{1}{2} (\delta Z_L^t + \delta Z_L^b) = \delta Z_L - \frac{1}{2} \tilde{\Pi}_t (m_t^2), \tag{6}
\]

where \( \delta Z_L \) and \( \tilde{\Pi}_t (m_t^2) \) are given explicitly in Eqs. (6)-(10) of ref. [5]. The form factors in Eq. (5) are defined in complete analogy to the corresponding ones in Eq. (3) of [5], except for a relative factor \( m_W/m_t \) in the definition of \( H_{LR} \). We find complete agreement for all formfactors. They are listed explicitly in Eq. (11) of [5] for arbitrary squark mixing angles and masses. Therefore we do not write them down here but only remark that in the limit of vanishing \( b \)-quark mass and no squark mixing the formfactors \( F_R \) and \( H_L \) are equal to zero.

The phase space \( R_3 \) of the final state of reaction (4) may be parametrized by two scaled energies and two angles:

\[
dR_3 = \frac{m_t^2}{32(2\pi)^4} dx_b dx_l dx_P d^2\chi d\cos\theta, \tag{7}
\]

where \( x_b = 2E_b/m_t \), \( x_l = 2E_l/m_t \). The four-momenta and the polarization of the top quark are explicitly parametrized in the top quark rest frame as follows:
\[ p_l = E_l(1,0,0,1), \]
\[ p_b = E_b(1,0,\beta \sin \theta_{lb}, \beta \cos \theta_{lb}), \]
\[ p_\nu = p_l - p_b - p_l, \]
\[ P = |P|(0, \sin \theta \sin \chi, \sin \theta \cos \chi, \cos \theta), \]

(8)

where
\[ \beta = \sqrt{1 - 4z_b/x_b^2}, \quad \cos \theta_{lb} = \frac{x_l x_b - 2(x_l + x_b - 1) + 2z_b}{x_l x_b \beta} \]

(9)

with the scaled mass square of the bottom quark \( z_b = m_b^2/m_t^2 \). The differential decay rate is given by
\[ d\Gamma = \frac{1}{2m_t N_C} \sum |T_{fi}|^2 dR_3, \]

(10)

where the sum is taken over the colour and spins of the final state. The fully differential distribution for reaction (4) reads at tree level:
\[ \frac{d\Gamma^0_{lep}}{dx_l dx_b d\chi d\cos \theta} = c \frac{x_l(1-x_l-z_b)}{(1-x_b+z_b-\xi)^2 + \eta^2 \xi^2} (1 + |P| \cos \theta), \]

(11)

where
\[ c = \frac{e^4 m_t}{128(2\pi)^4 \sin^4 \theta_W}, \]

(12)

with
\[ \xi = \frac{m_W^2}{m_t^2}, \quad \eta = \frac{\Gamma_W}{m_W}. \]

(13)

Our result for the SUSY-QCD corrections to the semileptonic decay distribution reads:
\[ \frac{d\Gamma^{\text{SUSY-QCD}}_{lep}}{dx_l dx_b d\chi d\cos \theta} \]
\[ = c \frac{x_l(1-x_l-z_b)}{(1-x_b+z_b-\xi)^2 + \eta^2 \xi^2} \times \{ (1 + |P| \cos \theta) \Re f_1 + |P| \sin \theta [\cos \chi \Re f_2 + \sin \chi \Im f_2] \}. \]

(14)

with
\[ f_1 = 2F_L + 8Z_L' + 8Z_B' - 2\sqrt{z_b} \frac{1-x_b+z_b}{x_l(1-x_l-z_b)} F_R \]
\[ + \left[ 1 - (1-x_b+z_b) \frac{1-x_l}{x_l(1-x_l-z_b)} \right] [H_R + \sqrt{z_b} H_L], \]

(15)

\[ f_2 = -\frac{x_l \beta \sin \theta_{lb}}{2(1-x_l-z_b)} [(1-x_l) H_R + \sqrt{z_b}(H_L + 2F_R)]. \]

(16)
The function Im$f_2$ can only be nonzero if $m_t$ is larger than $m_{\tilde{g}} + m_{\tilde{t}}^{\text{light}}$, where $m_{\tilde{t}}^{\text{light}}$ denotes the mass of the light stop. We will not discuss this case in the following.

The SUSY-QCD correction to the total decay rate $\Gamma(t \rightarrow W^+b)$ can be easily obtained from (14) in the following way: The narrow width approximation is applied, i.e., one makes the replacement

$$\frac{1}{((p_{t} - p_{b})^2 - m_W^2)^2 + m_W^2 \Gamma_W^2} \rightarrow \frac{\pi}{m_W \Gamma_W} \delta((p_{t} - p_{b})^2 - m_W^2).$$

(17)

In particular, this fixes the scaled $b$-quark energy to $x_b = 1 - \xi + z_b$. The three remaining integrations are easily performed. Finally, one has to divide out the branching ratio for the semileptonic decay of the $W$, which is achieved by replacing $\Gamma_W$ in (17) by $\Gamma(W^+ \rightarrow bl^+\nu_l) = G_F m_W^3 / (6\sqrt{2}\pi)$ with $G_F = e^2 / (4\sqrt{2}m_W^2 \sin^2 \theta_W)$. The result is:

$$\Gamma^1 \equiv \Gamma^0 + \Gamma^{\text{SUSY-QCD}} = \Gamma_0 \left[1 + 2\text{Re} F_L + \text{Re} \delta Z^b_L + \text{Re} \delta Z^b_L + 2 \frac{G_1}{G_0} \text{Re} F_R + 2 \frac{G_2}{G_0} \text{Re} H_L + 2 \frac{G_3}{G_0} \text{Re} H_R \right],$$

(18)

where the Born decay $\Gamma_0$ rate is given by

$$\Gamma_0 = \frac{m_t^3 G_F}{8\sqrt{2}\pi} \left[(1 - \xi + z_b)^2 - 4z_b\right]^{1/2} G_0$$

(19)

and

$$G_0 = (1 - \xi)(1 + 2\xi) + z_b(z_b + \xi - 2),$$

$$G_1 = -2\xi \sqrt{z_b},$$

$$G_2 = \frac{\sqrt{z_b}}{2} \left[(1 - \xi)^2 + z_b(z_b - 2\xi - 2)\right],$$

$$G_3 = \frac{1}{\sqrt{z_b}} G_2.$$

(20)

Our result for the total decay rate disagrees with the corresponding result given in Eq. (15) of [5]. The disagreement appears to be due to an error that occurred in deriving $G_{2,3}$ from the standard matrix elements $M_{2,3}$ given in Eq. (13) of [5]. The result in [5] can be corrected by interchanging $G_2 \leftrightarrow G_3$ (or, equivalently, $H_L \leftrightarrow H_R$). In an earlier work [4], the supersymmetric QCD contributions to the top quark width have been computed for the special case of degenerate SUSY masses and $m_b = 0$. We performed a numerical comparison with Figures 2 and 3 of [4] and find complete agreement when using the same input parameters.
3 Numerical analysis

In this section we discuss the impact of the SUSY-QCD corrections on the total top quark decay width, on the energy spectra of the charged lepton, and on observables sensitive to the top quark polarization.

We start by considering the relative correction

\[
\delta \tilde{g} = \frac{\Gamma^1 - \Gamma^0}{\Gamma^0}
\]

to the total decay rate. As mentioned above, this quantity has been studied in the literature before with two different results. Our calculation confirms the earlier result [4]. The effects of the mixing of the chiral components of stop and sbottom have been considered only in [5]. Therefore it seems worthwhile to reconsider the quantity \(\delta \tilde{g}\).

The stop and sbottom mass matrices can be expressed in terms of MSSM parameters as follows:

\[
M_t^2 = \begin{pmatrix}
M_{\tilde{Q}}^2 + m_t^2 + m_{\tilde{Z}}^2 (\frac{1}{2} - Q_t s_W^2) \cos 2\beta & m_t (A_t - \mu \cot \beta) \\
m_t (A_t - \mu \cot \beta) & M_{\tilde{U}}^2 + m_t^2 + m_{\tilde{Z}}^2 Q_t s_w^2 \cos 2\beta
\end{pmatrix},
\]

\[
M_b^2 = \begin{pmatrix}
M_{\tilde{Q}}^2 + m_b^2 - m_{\tilde{Z}}^2 (\frac{1}{2} + Q_b s_W^2) \cos 2\beta & m_b (A_b - \mu \tan \beta) \\
m_b (A_b - \mu \tan \beta) & M_{\tilde{D}}^2 + m_b^2 + m_{\tilde{Z}}^2 Q_b s_w^2 \cos 2\beta
\end{pmatrix},
\]

where \(M_{\tilde{Q}}, M_{\tilde{U}}, M_{\tilde{D}}\) are the soft SUSY-breaking parameters for the squark doublet \(\tilde{q}_L\) and the squark singlets \(\tilde{t}_R\) and \(\tilde{b}_R\), respectively. Further, \(A_t, b\) are the stop and sbottom soft SUSY-breaking trilinear couplings, and \(\mu\) is the SUSY-preserving bilinear Higgs coupling.

The ratio of the two Higgs vacuum expectation values is given by \(\tan \beta\), \(Q_t = 2/3\) and \(Q_b = -1/3\) denote the electric charges of \(t\) and \(b\), and \(s_W = \sin \theta_W\). The squared physical masses of the stops and sbottoms are the eigenvalues of the above matrices. In order to keep the numerical discussion tractable, we make the following simplifying assumptions: We neglect mixing in the sbottom sector. This is certainly justified if \(\tan \beta\) is not too large. In any case \(\tan \beta\) only enters through the mass matrices. If sbottom mixing is neglected, the dependence on \(\tan \beta\) is very weak [5] and we set \(\tan \beta = 1\) for all following results. Further, we set \(M_{\tilde{Q}} = M_{\tilde{D}}\) and neglect the bottom quark mass in the mass matrices. Under these assumptions the sbottom mass matrix is diagonal with degenerate mass eigenvalues, \(M_b^2 = \text{diag}(m_b^2, m_b^2)\). Note that using degenerate sbottom masses close to the experimental lower mass limit maximizes the impact of the SUSY-QCD corrections. The stop mass matrix simplifies under the above assumptions to

\[
M_t^2 = \begin{pmatrix}
m_t^2 + m_{\tilde{t}}^2 & m_t M_{LR} \\
m_t M_{LR} & M_{\tilde{U}}^2 + m_t^2
\end{pmatrix},
\]
Figure 1: SUSY-QCD correction $\delta_{\tilde{g}}$ as a function of the gluino mass for different sbottom masses and no mixing: $m_{\tilde{b}}$ = 80 GeV (a), 120 GeV (b), 160 GeV (c) and 200 GeV (d).

with $M_{LR} = A_t - \mu$. Maximal mixing ($\theta_{\tilde{t}} = \frac{\pi}{4}$ and $M_{LR} \neq 0$) corresponds to $M_{\tilde{U}}^2 = m_{\tilde{b}}^2$. The latter relation will also be assumed for $M_{LR} = 0$, leading to the following stop mass eigenvalues:

$$m_{\tilde{t}_{1,2}} = \sqrt{m_{\tilde{b}}^2 + m_t^2 \pm m_t M_{LR}}.$$ (24)

Fig. 1 shows $\delta_{\tilde{g}}$ for $M_{LR} = 0$ as a function of the gluino mass for different values of $m_{\tilde{b}}$. The SUSY-QCD corrections are negative and of the order of several permill for gluino masses larger than 100 GeV. Even for very small gluino masses the SUSY-QCD corrections are at most $\sim ( -1 ) \%$. Our Fig. 1 corresponds exactly to Fig. 2a of [5]. In particular, we use $m_t = 174$ GeV and $\alpha_s(m_t) = 0.11$. (For the bottom quark mass we use $m_b = 4.75$ GeV.) We find about 30% to 40% smaller SUSY-QCD effects than the authors of [5] and can exactly reproduce their curves if we, just for this purpose, substitute $H_L \leftrightarrow H_R$.

The effect of mixing is studied in Figs. 2a,b, where we plot $\delta_{\tilde{g}}$ as a function of the mixing parameter $M_{LR}$ for different sbottom and gluino masses. For $M_{LR} = 200$ GeV, $m_{\tilde{g}} = 150$ GeV and $m_{\tilde{b}} = 100$ GeV (which implies $m_{\tilde{t}}^{\text{light}} = 74$ GeV), the SUSY-QCD corrections reduce the total top quark decay width by about 2%. Larger squark and/or gluino masses lead to smaller SUSY-QCD corrections. Note that the squark masses we use are compatible with bounds obtained in a recent ALEPH analysis [7]. For the gluino mass, experi-

\footnote{Note that by fixing $\theta_{\tilde{t}} = \frac{\pi}{4}$ the light stop can be either $\tilde{t}_1$ or $\tilde{t}_2$ depending on the sign of $M_{LR}$.}
mental lower mass limits are typically higher than 200 GeV (see, e.g. [8, 9]), but these limits only apply within the minimal supergravity model.

![Graphs showing SUSY-QCD correction δg as a function of the mixing parameter M_{LR} for m_{\tilde{b}} = 100 GeV (a) and m_{\tilde{b}} = 120 GeV (b). The full curve is for m_{\tilde{g}} = 150 GeV, the dashed curve for m_{\tilde{g}} = 200 GeV.]

Figure 2: SUSY-QCD correction δg as a function of the mixing parameter M_{LR} for m_{\tilde{b}} = 100 GeV (a) and m_{\tilde{b}} = 120 GeV (b). The full curve is for m_{\tilde{g}} = 150 GeV, the dashed curve for m_{\tilde{g}} = 200 GeV.

We now turn to the discussion of the fully differential leptonic decay distribution, Eq. (14). In Fig. 3a we plot the charged lepton energy spectrum $d\Gamma_{\text{lep}}/dx_l$ and in Fig. 3b the relative SUSY-QCD correction

$$
\delta_{\text{lep}}(x_l) = \left( \frac{d\Gamma^0_{\text{lep}}}{dx_l} \right)^{-1} \left[ \frac{d\Gamma^1_{\text{lep}}}{dx_l} - \frac{d\Gamma^0_{\text{lep}}}{dx_l} \right].
$$

In the narrow width approximation for the W boson we have

$$
\delta_{\text{lep}}(x_l) = \text{Re } f_1.
$$

We consider here the case of maximal mixing with $M_{LR} = 200$ GeV and masses $m_{\tilde{b}} = 100$ GeV and $m_{\tilde{g}} = 150$ GeV. In this case $\delta_{\text{lep}}(x_l)$ reaches values of $-2.7\%$ close to the sharp drop of the energy spectrum at $x_l \approx 0.2$. As can be seen in Fig. 3b, the narrow width approximation for the W propagator works well in almost the whole kinematic range for $x_l$ which is allowed within this approximation.

A sample of highly polarized top quarks (which can be produced at a linear collider with polarized beams operating close to the $t\bar{t}$ production threshold) would allow for additional
Figure 3: SUSY-QCD corrections to the charged lepton energy spectrum: (a) shows $d\Gamma_{\text{lep}}/dx_l$ in GeV in leading order (dashed line) and including the SUSY-QCD corrections (full line), (b) shows the relative correction $\delta_{\text{lep}}(x_l)$ in percent. The dashed curve in (b) shows $\delta_{\text{lep}}(x_l)$ using the narrow width approximation for the $W$ propagator. All curves are for $m_\tilde{b} = 100$ GeV, $m_\tilde{g} = 150$ GeV, and $M_{LR} = 200$ GeV.

tests of the top quark decay profile. A well-known characteristic of semileptonic decays of polarized top quarks is the factorization of the double differential cross section

$$\frac{d\Gamma_{\text{lep}}}{dx_l d\cos \theta} = f(x_l)(1 + |P| \cos \theta),$$

which holds true not only at the Born level, but also to high accuracy including QCD radiative corrections [6]. This means in particular that the charged lepton is the perfect analyser of the top quark spin, i.e. the distribution $(\Gamma)^{-1}d\Gamma/d\cos \theta$ has maximal slope $|P|$ up to permill QCD corrections. As exhibited by Eq. (27), SUSY-QCD corrections respect the factorization (27) exactly. This means that the normalized distribution $1/\Gamma d\Gamma/d\cos \theta$ is not affected by the SUSY-QCD corrections.

The general decay distribution (24) contains a further term for nonzero top quark polarization, which is determined by the function $\text{Re } f_2$. This term may be accessed by considering the azimuthal asymmetry

$$\delta_{\chi}(x_l) = \left( \frac{d\Gamma_{\text{lep}}^0}{dx_l} \right)^{-1} \left[ \int_0^{\pi/2} + \int_{3\pi/2}^{2\pi} - \int_{\pi/2}^{3\pi/2} \right] d\chi \frac{d\Gamma_{\text{lep}}^{\text{SUSY-QCD}}}{dx_l d\chi}.$$
Figure 4: Azimuthal asymmetry $\delta_{\chi}(x_l)$ for $|P| = 1$ and the same choice of mass parameters as in Figs. 3a,b. The dashed line shows $\delta_{\chi}(x_l)$ in the narrow width approximation.

Note that $\delta_{\chi}(x_l)$ is zero in leading order. In the narrow width approximation,

$$\delta_{\chi}(x_l) = \frac{|P|}{2} \text{Re} \ f_2.$$  \hspace{1cm} (29)

Fig. 4 shows $\delta_{\chi}(x_l)$ for the same choice of mass parameters that have been used in Figs. 3a,b and for maximal top quark polarization $|P| = 1$. The asymmetry is negative and of the order of a permill.

4 Conclusions

The results of our analysis of the SUSY-QCD corrections to the decay $t(\uparrow) \rightarrow b l \nu$ may be summarized as follows:

1. The total decay width of the top quark is reduced by a few permill (no mixing) up to several percent (maximal mixing in the stop sector, sbottom masses around 100 GeV and gluino masses in the range 150 to 200 GeV). A conflict between two previous calculations \cite{4,5} has been resolved in favour of the earlier work \cite{4}.

2. The SUSY-QCD corrections to the energy spectrum of the charged lepton reach values of almost $-3\%$ for maximal mixing.

3. Observables that are sensitive to the top quark polarization are hardly affected by the SUSY-QCD corrections: The tree level factorization of $d\Gamma_{lep}/(dx_l d \cos \theta)$, cf. Eq. \cite{27}, is respected, and the azimuthal asymmetry \cite{28} induced at one-loop is tiny.
Acknowledgments

We would like to thank W. Bernreuther, A. Freitas, and D. Stöckinger for comments on the manuscript.

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