HEAVY CHARGED HIGGS BOSON DECAYING INTO TOP QUARK IN THE MSSM

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ABSTRACT

Observing a heavy charged Higgs boson produced in the near future at the Tevatron or at the LHC would be instant evidence of physics beyond the Standard Model. Whether such a Higgs boson would be supersymmetric or not it could only be decided after accurate prediction of its properties. Here we compute the decay width of the dominant decay of such a boson, namely $H^+ \rightarrow t \bar{b}$, including the leading electroweak corrections originating from large Yukawa couplings within the MSSM. These electroweak effects turn out to be of comparable size to the $\mathcal{O}(\alpha_s)$ QCD corrections in relevant portions of the MSSM parameter space. Our analysis incorporates the stringent low-energy constraints imposed by radiative $B$-meson decays.
The Minimal Supersymmetric extension of the Standard Model (MSSM) remains nowadays as the only tenable Quantum Field Theory of the strong and the electroweak interactions beyond the SM that is able to keep pace with the SM ability to (consistently) accommodate all known high precision measurements. Moreover, the MSSM offers a starting point for a successful Grand Unified framework where a radiatively stable low-energy Higgs sector can survive. All in all it is well justified, we believe, to keep alive all efforts on all fronts trying to discover a supersymmetric particle. The next Tevatron run, and of course also the advent of the LHC, should offer us a gold-plated scenario for testing real, or at least virtual, manifestations of SUSY, if this symmetry has anything to do at all with the origin of the electroweak scale. A crucial part of the task aimed to understand the origin of this scale is to unveil the nature of the spontaneous symmetry-breaking mechanism and its likely connection to a fundamental Higgs sector.

Thus, the less exotic – and in this sense the most easily identifiable – hint of SUSY physics would perhaps be the finding of a non-standard Higgs particle. It is well-known that the MSSM predicts the existence of two charged Higgs pseudoscalar bosons, $H^\pm$, one neutral CP-odd boson, $A^0$, and two neutral CP-even states, $h^0$ and $H^0$ ($M_{h^0} < M_{H^0}$). In the absence of direct sparticle detection, and because of the similar phenomenological properties of the lightest neutral boson $h^0$ and the SM Higgs boson, the experimentum crucis for the MSSM could just be the discovery of a heavy charged Higgs particle with accurate measurement and prediction of its properties, namely at a level of quantum effects – i.e. effects capable of revealing the details of the underlying supersymmetric dynamics. In connection to this possibility, we wish to show here that vestiges of virtual SUSY physics in the decay $H^+ \rightarrow t \bar{b}$ can be large enough for even a hadron machine producing a heavy charged Higgs boson to be sensitive to them.

As already emphasized in Ref. [3], the $H^\pm t \bar{b}$-vertex responsible for the decay under consideration could be at the root of the Higgs production mechanism itself. For, one expects that e.g. $H^+$ (similarly for $H^-$) can be generously produced in hadron machines through $t \bar{b}$-fusion: $gg \rightarrow H^+ t \bar{b}$ (Fig. 1a) as well as from charged Higgs bremsstrahlung off top and bottom quarks [4]: $q \bar{q} \rightarrow H^+ t \bar{b}$ (Fig. 1b). While the first mechanism is to be dominant at the LHC, the second one could still give a chance to Tevatron, where Drell-Yan production of $t \bar{t}$ and $b \bar{b}$ are the primary processes. In both cases one relies on the possibility of enhanced Yukawa couplings of the charged Higgs boson with top and bottom quarks:

$$\lambda_t \equiv \frac{h_t}{g} = \frac{m_t}{\sqrt{2} M_W \sin \beta}, \quad \lambda_b \equiv \frac{h_b}{g} = \frac{m_b}{\sqrt{2} M_W \cos \beta}. \quad (1)$$

The process in Fig. 1b is not necessarily too suppressed against the ordinary two-body mode $qq' \rightarrow W^* \rightarrow t \bar{b}$ as this amplitude is purely electroweak, i.e. of $O(\alpha_W)$, whereas the

\footnote{For recent comprehensive reviews of Higgs physics in the SM and MSSM, see e.g. Ref. [2].}
former involves a three-body final state, but in compensation it is of order $\mathcal{O}(\alpha_s \lambda_b \sqrt{\alpha_W})$; and so at large $\tan \beta$ (where $\lambda_b > 1$) it may well afford a contribution of comparable size. A preliminary supersymmetric treatment of $H^+ \to t \bar{b}$ was put forward in Ref. [3] (see also [4]), where the $\mathcal{O}(\alpha_s)$ QCD effects were evaluated in the MSSM. However, to our knowledge, a thorough study within the MSSM including the complete electroweak contributions from the Higgs boson sector (with both $\lambda_t$ and $\lambda_b$ nonvanishing), together with the host of sfermions and chargino-neutralinos, is not available in the literature. And this missing information can be essential for several reasons. First, because the SUSY electroweak (SUSY-EW) corrections could be enhanced due to the intervention of supersymmetric top quark and bottom quark Yukawa couplings of the type (1). Second, because for large gluino (and especially for large sbottom) masses the SUSY-QCD corrections would no longer be that dominant, and yet potentially important supersymmetric electroweak effects – mainly sensitive to stop and chargino exchanges – could still be alive. However, these very same SUSY parameters are relevant to the low-energy physics of the radiative $\bar{B}^0$-decays ($b \to s \gamma$). Therefore, the severe constraints imposed by this process cannot be ignored for the study of the charged Higgs decay, and so we have taken them explicitly into account. We have used – and checked – the LO formula (see the extensive literature [5] for details):

$$BR(b \to s \gamma) \simeq BR(b \to c \nu \bar{\nu}) \frac{(6 \alpha_{\text{em}}/\pi) \left( \eta^{16/23} A_\gamma + C \right)^2}{I \left( m_c/m_b \right) \left[ 1 - \frac{2}{3\pi} \alpha_{\text{em}}(m_b) f_{\text{QCD}}(m_c/m_b) \right]}$$

where

$$A_\gamma = A_{\text{SM}} + A_{H^-} + A_{\chi^- \tilde{q}}$$

is the sum of the SM, charged Higgs and chargino-squark amplitudes, respectively. Although the NLO QCD corrections to the SM ($W$-mediated) and charged Higgs mediated amplitudes are already available (see e.g. Refs. [6, 7]), still a $\sim 30\%$ uncertainty (similar to the LO result in the SM) ought to be anticipated for the unknown MSSM contributions at the NLO.

A crucial issue concerning the SUSY-EW corrections is the renormalization of $\tan \beta$. This parameter enters the lowest-order decay rate of $H^+ \to t \bar{b}$ as follows:

$$\Gamma_0 = \left( \frac{3 G_F M_H^2}{4 \pi \sqrt{2}} \right) \lambda^{1/2}(1, x^2, y^2) \left[ (1 - x^2 - y^2) (x^2 \cot^2 \beta + y^2 \tan^2 \beta) - 4 x^2 y^2 \right]$$

2For the ordinary QCD and standard $\mathcal{O}(\alpha_W m_t^2/M_W^2)$ corrections (in the $\lambda_b = 0$ approximation) to that decay in a generic two-Higgs-doublet model (2HDM), see Ref. [3] and references therein.

3The SUSY-QCD and SUSY-EW corrections to the neutral Higgs boson decays into quarks have been addressed in Ref. [3].
with \( \lambda(1, x^2, y^2) = [1 - (x + y)^2][1 - (x - y)^2] \), and \( x = m_t^2/M_W^2 \), \( y = m_b^2/M_H^2 \); \( M_H \) being the mass of \( H^\pm \). We shall follow the procedure devised in Ref. [1] where \( \tan \beta \) is defined by means of the \( \tau \)-lepton decay of \( H^\pm \):

\[
\Gamma(H^+ \to \tau^+ \nu_\tau) = \frac{\alpha m_\tau^2 M_H}{8 M_W^2 s_W^2} \tan^2 \beta = \frac{G_F m_\tau^2 M_H}{4 \pi \sqrt{2}} \tan^2 \beta (1 - \Delta r^{MSSM});
\]

\( \Delta r^{MSSM} \) is analyzed in [12]. This definition generates a counterterm

\[
\frac{\delta \tan \beta}{\tan \beta} = \frac{1}{2} \left( \frac{\delta M_W^2}{M_W^2} - \frac{\delta g^2}{g^2} \right) - \frac{1}{2} \delta Z_H + \cot \beta \delta Z_{HW} + \Delta_r.
\]

\( \Delta_r \) above stands for the complete set of MSSM one-loop effects on the \( \tau \)-lepton decay of \( H^\pm \); \( \delta Z_H \) and \( \delta Z_{HW} \) stand respectively for the charged Higgs and mixed \( H - W \) wave-function renormalization factors; and the remaining counterterms \( \delta g^2 \) and \( \delta M_W \) are the standard ones [13]. We would like to emphasize that the definition of \( \tan \beta \) given above allows to renormalize the \( H^\pm t b \)-vertex in perhaps the most convenient way to deal with our main process \( H^+ \to t \bar{b} \). Indeed, from the practical point of view, we recall the excellent methods for \( \tau \)-identification developed by the Tevatron collaborations, which have recently been used by CDF to study the crossed decay \( t \to H^+ b (\to \tau^+ \nu_\tau b) \) [14]. These techniques should prove very helpful to pin \( \tan \beta \) down from experiment.

The general structure of the on-shell renormalized one-loop form factors in the MSSM is similar to that in Refs. [3, 11] and hence we shall refrain from exhibiting cumbersome analytical details [15]. Even though we shall explore the evolution of our results as a function of the charged Higgs mass in the LHC range, for the numerical analysis we wish to single out the Tevatron accessible window

\[
m_t \lesssim M_H \lesssim 300 \text{ GeV}.
\]

This window is especially significant in that the CLEO measurements [16] of \( BR(b \to s \gamma) \) forbid most of this domain within the context of a generic 2HDM. However, within the MSSM the mass interval (7) is perfectly consistent with eq.(2) provided that relatively light stop and charginos \( (\lesssim 200 \text{ GeV}) \) occur [1]. We recall that for lighter chargino and stops \( (\lesssim 100 \text{ GeV}) \) supersymmetric charged Higgs bosons may exist in the kinematical window enabling the aforementioned top quark decay \( t \to H^+ b \) [11, 17].

In Figs. 2-5 we display in a nutshell our results for a representative choice of parameters within the present framework[1]. While in Figs. 2-3 we have carefully determined a region of the supersymmetric parameter space compatible with the \( b \to s \gamma \) measurements, in

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4 Although the inclusion of the NLO effects on the charged Higgs corrected amplitude may considerably shift the range (7) up to higher values of \( M_H \) [10], the NLO corrections on the SUSY amplitudes have not been computed, and so as in the LO case they might well contribute to compensate the Higgs counterpart.

5 See Ref. [15] for an exhaustive numerical analysis in the MSSM parameter space.
Figs. 4-5 we exhibit the evolution of the quantum corrections as a function of the most significant parameters. To this end it will be useful to define the quantity

$$
\delta = \frac{\Gamma(H^+ \to t \bar{b}) - \Gamma_0(H^+ \to t \bar{b})}{\Gamma_0(H^+ \to t \bar{b})},
$$

which gives the correction with respect to the tree-level width (4). The MSSM correction (8) includes the full QCD yield (both from gluon and gluinos) at $\mathcal{O}(\alpha_s)$ plus all the leading MSSM electroweak effects driven by the Yukawa couplings (1).

Let us now elaborate a bit on the relevant region of the MSSM parameter space that we have determined from the analysis of eq.(2). This region (Cf. Figs. 2-3) has been obtained in accordance with the CLEO data [16] on radiative $\bar{B}^0$ decays at $2\sigma$. Our set of independent MSSM inputs and remaining constraints is as in [3, 11]; in particular, we have imposed that non-SM contributions to the $\rho$-parameter be tempered by the relation

$$
\delta \rho_{\text{new}} \leq 0.003.
$$

Moreover, we have checked that the known necessary conditions for the non-existence of colour-breaking minima [18] are fulfilled. For definiteness, where $M_H$ has to be fixed, we have chosen the value $M_H = 250\, GeV$ within the range (7), though we shall explicitly show the evolution of our results with $M_H$. As for the dependence on the QCD renormalization scale $\mu_{\text{QCD}}$, following Ref. [16] we have entertained a variation of it in the segment $m_b/2 \leq \mu_{\text{QCD}} \leq 2m_b$ ($m_b = 5\, GeV$) and made allowance for an additional 10% theoretical uncertainty. On the whole this amounts to a $\gtrsim 30\%$ indeterminacy in the MSSM prediction. Even so, the constraint from $b \to s\gamma$ in combination with the others does project out a quite definite domain of the supersymmetric parameter space. For example, in Fig. 2a we determine the allowed (shaded) region in the $(\mu, A_t)$-plane for fixed values of the other parameters.

The information from Fig. 2a is indeed relevant since, as it is apparent in the plot, the trilinear coupling $A_t$ (a hot parameter modulating the SUSY-EW corrections) becomes strongly correlated with the higgsino mixing parameter $\mu$, especially for low $\mu$. The central vertical band around $\mu = 0$ is excluded by our (conservative) requirement that charginos should be heavier than $100 GeV$. For $\mu < 0$, we find $A_t > 0$ in the permitted region by $\bar{B}^0$ decays; conversely, for $\mu > 0$, we find $A_t < 0$. Similarly, in Fig. 2b we plot the proper area in the $(\tan \beta, A_t)$-plane and we see that there exists a sizeable solution in the large $\tan \beta$ regime where to compute $\Gamma(H^+ \to t \bar{b})$. There is of course a low $\tan \beta$ solution, too, but in practice we shall only explore the large $\tan \beta$ option. This is because the MSSM corrections (8) other than the ordinary QCD corrections are not significant at low $\tan \beta$ (unless $\tan \beta < 1$, which is not so appealing from the theoretical point of view) and thus in that circumstance the potential SUSY nature of $H^\pm$ could not be disentangled from
the measurement of its top quark decay mode. In the large \( \tan \beta \) subdomain relevant to our Higgs decay, namely

\[ 20 \lesssim \tan \beta \lesssim 50, \tag{10} \]

the bottom quark Yukawa coupling, \( \lambda_b \), is comparable to the top quark Yukawa coupling, \( \lambda^\top \). In Fig. 3 we describe the correlation with the lightest sbottom and stop masses, \( m_{\tilde{b}_1} \) and \( m_{\tilde{t}_1} \). Specifically, in Figs. 3a and 3b we project the \( b \rightarrow s \gamma \) constraint onto the \((m_{\tilde{b}_1}, A_t)\) and \((m_{\tilde{t}_1}, A_t)\) planes, respectively. From the first one it is patent that there exists an essentially unlimited spectrum of heavy sbottom masses compatible with any stop trilinear coupling in the range \( 500 \text{ GeV} < A_t < 1 \text{ TeV} \) and without violating the \( \delta \rho \) condition (9) – represented by the contour line hanging from above in Fig. 3a. This situation is different from that in Fig. 3b where there is a rather compact domain of proper \( m_{\tilde{t}_1} \) values for each \( A_t \). We emphasize that, contrary to the more commonly known result that holds at low \( \tan \beta \), namely that the lightest stop allowed by radiative \( B \)-meson decays ought to be reachable at LEP 200, at high \( \tan \beta \) the permissible values for \( m_{\tilde{t}_1} \) are, instead, shifted away of the LEP 200 possibilities. As a matter of fact, the whole spectrum of sparticle masses that we use (including charginos) is unreachable by LEP 200.

We are now ready to restrict our analysis of \( H^+ \rightarrow t \bar{b} \) within the appropriate domain pinpointed in Figs. 2-3. We set out by looking at the branching ratio of \( H^+ \rightarrow \tau^+ \nu_\tau \) (Cf. Fig. 4). Even though the partial width of this process does not get renormalized (as it is used to define \( \tan \beta \)), its branching ratio is seen to be very much sensitive to the MSSM corrections to \( \Gamma(H^+ \rightarrow t \bar{b}) \). For large \( \tan \beta \) as in eq.(11), \( BR(H^+ \rightarrow \tau^+ \nu_\tau) \) may achieve rather high values (10 – 50%) for Higgs masses in the interval (3), and it never decreases below the 5 – 10\% level in the whole range. Therefore, a handle for \( \tan \beta \) measurement is always available from the Higgs \( \tau \)-channel and so also an opportunity for discovering quantum SUSY signatures on \( \Gamma(H^+ \rightarrow t \bar{b}) \). As for the other \( H^\pm \)-decays, we note that the potentially important mode \( H^+ \rightarrow \tilde{t}_i \tilde{b}_j \) does not play any role in our case since (for reasons to be clear below) we are mainly led to consider bottom-squarks heavier than the charged Higgs. Moreover, the \( H^+ \rightarrow W^+ h^0 \) decay which is sizeable enough at low \( \tan \beta \) becomes extremely depleted at high \( \tan \beta \). Finally, the decays into charginos and neutralinos, \( H^+ \rightarrow \chi^+_i \chi^0_\alpha \), are not \( \tan \beta \)-enhanced and remain negligible. Thus at the end of the day we do find an scenario where \( H^+ \rightarrow t \bar{b} \) and \( H^+ \rightarrow \tau^+ \nu_\tau \) can be deemed as the only relevant decay modes.

In order to assess the impact of the electroweak effects, we demonstrate that a typical set of inputs can be chosen such that the SUSY-QCD and SUSY-EW outputs are of comparable size. In Figs. 5a and 5b we display \( \delta \), eq.(8), as a function respectively of

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\[ \text{Theoretically, high values of } \tan \beta \text{ as in eq.(11) are well-motivated in the arena of widely different types of SUSY Yukawa coupling unification models.} \]
\( \mu < 0 \) and \( \tan \beta \) for fixed values of the other parameters (within the \( b \to s \gamma \) allowed region). Remarkably, in spite of the fact that all sparticle masses are beyond the scope of LEP 200 the corrections are fairly large. We have individually plot the SUSY-EW, SUSY-QCD, standard QCD and total MSSM effects. The Higgs-Goldstone boson corrections (which we have computed in the Feynman gauge) are isolated only in Fig. 5b just to make clear that they add up non-trivially to a very tiny value in the whole range \([1,1]\), and only in the small corner \( \tan \beta < 1 \) they can be of some significance.

In Figs. 5c-5d we render the various corrections \([3]\) as a function of the relevant squark masses. For \( m_{\tilde{b}_1} \approx 200 GeV \) we observe (Cf. Fig. 5c) that the SUSY-EW contribution is non-negligible (\( \delta_{\text{SUSY-EW}} \approx +20\% \)) but the SUSY-QCD loops induced by squarks and gluinos are by far the leading SUSY effects (\( \delta_{\text{SUSY-QCD}} > 50\% \)) - the standard QCD correction staying invariable over \(-20\% \) and the standard EW correction (not shown) being negligible. In contrast, for larger and larger \( m_{\tilde{b}_1} > 300 GeV \), say \( m_{\tilde{b}_1} = 400 \) or \( 500 GeV \), and fixed stop mass at a moderate value \( m_{\tilde{t}_1} = 150 GeV \), the SUSY-EW output is longly sustained whereas the SUSY-QCD one steadily goes down. However, the total SUSY pay-off adds up to about \(+40\% \) and the net MSSM yield still reaches a level around \(+20\% \), i.e. of equal value but opposite in sign to the conventional QCD result. This would certainly entail a qualitatively distinct quantum signature.

We stress that the main parameter to decouple the SUSY-QCD correction is the lightest sbottom mass, rather than the the gluino mass \([3]\). For this reason, since we wished to probe the regions of parameter space where these electroweak effects are important, the direct SUSY decay \( H^+ \to \tilde{t}_i \tilde{b}_j \) mentioned above is blocked up kinematically and plays no role in our analysis. On the other hand, the SUSY-EW output is basically controlled by the lightest stop mass, as it is plain in Fig. 5d, where we vary it in a range past the LEP 200 threshold.

We have also checked that in the alternative \( \mu > 0, A_t < 0 \) scenario (also admissible according to Fig. 2a), the SUSY-QCD correction is negative but it is largely cancelled by the SUSY-EW part, which stays positive, so that the total \( \delta_{\text{MSSM}} \) is negative and larger (in absolute value) than the standard QCD correction. Finally, coming back to Fig. 4 we remark that if we take the standard QCD-corrected branching ratio (central curve in that figure) as a fiducial quantity, rather than the corresponding tree-level result, then \( BR(H^+ \to \tau^+ \nu_\tau) \) undergoes an effective MSSM correction of order \( \pm (40 \text{ } \text{ } 50\%) \). The sign of this effect is given by the sign of \( \mu \). In practice, \( BR(H^+ \to \tau^+ \nu_\tau) \) should be directly measurable from the cross-section for \( \tau \)-production \([14]\).

To summarize, supersymmetric quantum effects on the decay width of \( H^+ \to t \bar{b} \) could be sizeable enough to seriously compete with the ordinary QCD corrections. Furthermore, our computation shows that these effects are compatible with CLEO data from
low-energy $B$-meson phenomenology. The present study completes preliminary super-
symmetric treatments where only the SUSY-QCD corrections were calculated\cite{3,5} within
the ($b \rightarrow s \gamma$)-unconstrained MSSM parameter space. Here we have evaluated for the first

time the leading SUSY-EW effects and combined them with the SUSY-QCD ones both
within the domain of compatibility with $b \rightarrow s \gamma$. As a result, we confirm that also in
the constrained case the SUSY-QCD effects are generally very important\cite{3}. However,
we have exemplified an scenario with sparticle masses above the LEP 200 discovery range
where the SUSY electroweak corrections triggered by large Yukawa couplings can be
comparable to the SUSY-QCD effects. In this context the total SUSY correction remains
fairly large --around $+(30 - 50)\%$-- with a $\sim 50\%$ component from electroweak super-
symmetric origin. This situation occurs for i) large tan $\beta$ ($> 20$), ii) huge sbottom masses
($> 300$ GeV) and iii) relatively light stop and charginos ($100 - 200$ GeV). If the charged
Higgs mass lies in the intermediate window (\cite{3}), a chance is still left for Tevatron to pro-
duce a charged Higgs heavier than the top quark by means of “charged Higgsstrahlung”
off top and bottom quarks. Should, however, a heavier $H^\pm$ exist outside the window (\cite{3}),
the LHC could continue the searching task mainly from gluon-gluon fusion where again
$H^\pm$ is produced in association with the top quark. The upshot is that the whole range
of charged Higgs masses up to about $1$ TeV could be probed and, within the present
renormalization framework, its potential supersymmetric nature be unravelled through
a measurement of $\Gamma(H^+ \rightarrow t \bar{b})$ with a modest precision of $\sim 20\%$. Alternatively, one
could look for indirect SUSY quantum effects on the branching ratio of $H^+ \rightarrow \tau^+ \nu_{\tau}$ by
measuring this observable to within a similar degree of precision.

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**Figure Captions**

- **Fig.1** Typical charged-Higgs production mechanisms at hadron colliders: (a) $H^+$ production through $t\bar{b}$-fusion; and (b) through charged Higgs bremsstrahlung off top and bottom quarks.

- **Fig.2** Domains of the MSSM parameter space allowed by $b \rightarrow s\gamma$ at 2σ level and the theoretical constraints explained in the text, for given values of the other parameters. (a) Permitted region in the $(\mu, A_t)$-plane; (b) In the $(\tan\beta, A_t)$ plane. The proper domains are the shaded ones.

- **Fig.3** (a) As in Fig.2, but in the $(m_{\tilde{b}_1}, A_t)$-plane; (b) As before, but in $(m_{\tilde{t}_1}, A_t)$-plane. Remaining inputs as in Fig. 2.

- **Fig.4** The branching ratio of $H^+ \rightarrow \tau^+ \nu_\tau$ for positive and negative values of $\mu$ and $A_t$ allowed by eq.(2), as a function of the charged Higgs mass; $A$ is a common value for the trilinear couplings. The central curve includes the standard QCD effects only.

- **Fig.5** (a) The SUSY-EW, SUSY-QCD, standard QCD and full MSSM contributions to $\delta$, eq.(3), as a function of $\mu$; (b) As in (a), but as a function of $\tan \beta$. Also shown in (b) is the Higgs contribution, $\delta_{\text{Higgs}}$; (c) As in (a), but as a function of $m_{\tilde{b}_1}$; (d) As a function of $m_{\tilde{t}_1}$. Remaining inputs as in Fig. 4.
Fig. 1
\[ \tan \beta = 30 \]
\[ M = 175 \text{ GeV} \]
\[ M_H = 250 \text{ GeV} \]
\[ m_{\tilde{t}} = 150 \text{ GeV} \]
\[ m_{\tilde{b}} = 500 \text{ GeV} \]
\[ m_{\tilde{u}} = 1 \text{ TeV} \]

(a)

(b)

\( \mu = -200 \text{ GeV} \)

Fig. 2
$\tan\beta = 30$
$M = 175 \text{ GeV}$
$m_{t_1} = 150 \text{ GeV}$
$m_{g_1} = 400 \text{ GeV}$
$m_{u_1} = m_{\nu} = 1 \text{ TeV}$

$\mu = 200 \text{ GeV}$
$m_{b_1} = 300 \text{ GeV}$

$A = -200 \text{ GeV}$
$m_{b_1} = 500 \text{ GeV}$

$A = 600 \text{ GeV}$

Fig. 4
\( M_H = 250 \text{ GeV} \)
\( m_{\tilde{b}_1} = 500 \text{ GeV} \)
\( A = 600 \text{ GeV} \)

\( \delta \)

\( \mu \) (GeV)

\( \tan \beta \)

\( m_{\tilde{b}_1} \) (GeV)

\( m_{\tilde{t}_1} \) (GeV)

Fig. 5