

Quantum SUSY signatures in low and high energy processes

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Abstract. In the search for phenomenological evidence of supersymmetry through the indirect method of quantum signatures, it is useful to seek correlations of the non-standard quantum effects in low and high energy processes, such as those involving on one hand the properties of the B -mesons and on the other hand the physics of the top quark and of the Higgs bosons. There are regions of the MSSM parameter space where the potential quantum SUSY signatures in the two energy regimes are strongly interwoven and therefore the eventual detection of these correlated quantum effects would strongly point towards the existence of underlying supersymmetric dynamics.

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Supersymmetry (SUSY) is perhaps the only known framework beyond the standard model (SM) which is capable of extending non-trivially the quantum field theoretical structure of the conventional strong and electroweak interactions while keeping all the necessary ingredients insuring internal consistency, such as gauge invariance and renormalizability. A major goal of SUSY is to produce a unified theory of all the interactions, including gravity. At present, the simplest and most popular realization of this idea, namely the minimal supersymmetric standard model (MSSM), is being thoroughly scrutinized by experiment and it has successfully passed all the tests up to now. In particular, the global fit analyses to a huge number of indirect precision data within the MSSM are comparable to those in the SM [1]. In view of the fact that supersymmetric particles must be quite heavy, one naturally looks for 'quantum signatures' of the new physics by means of the indirect method of high precision measurements.

In this talk we wish to stress the possibility of seeing large virtual effects of SUSY through the correlation of the quantum effects in the low and high energy domains. Thus on the one hand at high energies we have above all the physics of the top quark and the potential existence of the Higgs bosons. Indeed, one expects that a first hint of Higgs activity, if ever, should appear in concomitance with the detailed studies of top quark phenomenology. On the other hand, in the low energy domain, B -meson physics could be a serious competitor to high energy processes in the search for extensions of the SM. Not in vain the restrictions placed by radiative B^0 decays $B^0 \rightarrow X_s \gamma$, i.e.

$$b \rightarrow s \gamma \tag{1}$$

on the global fit analyses [1] to indirect precision electroweak data have played a significant role. In the absence of SUSY, the CLEO data alone [2] on the decay (1) is able

to preclude general type II two-Higgs-doublet models (2HDM's) involving typical charged Higgs masses $M_{H^\pm} \lesssim 250$ GeV [3], thus barring the possibility of the non-standard top quark decay $t \rightarrow H^+ b$. Still we should point out that the inclusion of the ALEPH data [4], with a larger central value, would not completely close this channel. In any case a bound on the charged Higgs mass is there and stems from the fact that charged Higgs bosons of $\mathcal{O}(100)$ GeV interfere constructively with the SM amplitude of the decay (1) and render a final value of $BR(b \rightarrow s\gamma)$ exceedingly high. This situation can be remedied in the MSSM, where there may be a compensating contribution from relatively light charginos and stops which tend to cancel the Higgs effects. Thus, we see that from B -meson physics a door is open within the MSSM context for the non-SM top quark decay $t \rightarrow H^+ b$ [5] which could compete with the SM mode $t \rightarrow W^+ b$. Moreover, Higgs exchange may also play a role in semileptonic B -meson decays, especially into τ -leptons,

$$b \rightarrow c\tau^-\bar{\nu}_\tau, \quad (2)$$

where charged Higgs exchange could significantly modify the SM expectations. Remarkably enough, the MSSM quantum corrections to B -meson decay processes (1)–(2) on the one hand, and to the top quark decays

$$\begin{aligned} t &\rightarrow W^+ b, \\ t &\rightarrow H^+ b, \end{aligned} \quad (3)$$

and the τ -lepton charged Higgs decay

$$H^+ \rightarrow \tau^+ \nu_\tau \quad (4)$$

on the other, can be correlated in certain regions of parameter space; e.g. they could be both maximized in the same domain. This would be a dramatic example of low and high energy correlations that could be a clue to the discovery of 'virtual SUSY'.

Ultimately, the potential connection between the quantum effects in the two energy regimes stems from the role played by the Yukawa sector. Within the SM the physics of the top quark is intimately connected with that of the Higgs sector through the Yukawa couplings. However, if this is true in the SM, the more it should be in the MSSM where both the Higgs and the top quark sectors are virtually 'doubled' with respect to the SM. As a consequence, the Yukawa coupling sector is richer in the supersymmetric model than in the standard one. This could greatly modify the phenomenology already at the level of quantum effects on electroweak observables. As a matter of fact in the MSSM the bottom-quark Yukawa coupling may counterbalance the smallness of the bottom mass at the expense of a large value of $\tan\beta$ – the ratio v_2/v_1 of the vacuum expectation values of the two Higgs doublets – the upshot being that the top-quark and bottom-quark Yukawa couplings in the superpotential

$$h_t = \frac{gm_t}{\sqrt{2}M_W \sin\beta}, \quad h_b = \frac{gm_b}{\sqrt{2}M_W \cos\beta}, \quad (5)$$

can be of the same order of magnitude, perhaps even showing up in 'inverse' hierarchy: $h_t < h_b$ for $\tan\beta > m_t/m_b$. Notice that due to the perturbative bound $\tan\beta \lesssim 60$ one never reaches a situation where $h_t \ll h_b$. In a sense $h_t \sim h_b$ could be judged as a natural relation in the MSSM. Thus from the practical point of view, one should not dismiss the

possibility that the bottom-quark Yukawa coupling could play a momentous role in the phenomenology of B -meson decays and top quark decay and production, to the extent of drastically changing standard expectations on the observables associated to them, such as decay widths and cross-sections.

Needless to say, direct top quark decays into SUSY particles are in principle possible as well, both as 2-body and 3-body final states. Among the 2-body channels carrying an explicit SUSY signature, the following two-body modes stand out:

$$\begin{aligned}
 \text{(i)} \quad & t \rightarrow \tilde{t}_i \chi_\alpha^0, \\
 \text{(ii)} \quad & t \rightarrow \tilde{b}_i \chi_\alpha^+, \\
 \text{(iii)} \quad & t \rightarrow \tilde{t}_i \tilde{g}.
 \end{aligned}
 \tag{6}$$

Therein, \tilde{t}_i , \tilde{b}_i , χ_α^+ , χ_α^0 , \tilde{g} ($i = 1, 2$; $\alpha = 1, 2, \dots, 4$) denote stop, sbottom, chargino, neutralino and gluino sparticles, respectively. (Decay (iii) assumes that a light gluino window is still open, although admittedly it is almost ruled out at present.) Also quite a few three-body decays are possible and have been studied in detail [6]. Here, however, we assume that sparticles are heavy enough that the above direct top SUSY decays are forbidden. We are thus mainly concerned with the SM decay and the charged Higgs decay of the top quark. In fact, while the decays (3) are not necessarily MSSM processes, we wish to study whether hints of SUSY can be recognized out of them from pure supersymmetric quantum effects.

In the following we display the numerical results accounting for the potential supersymmetric effects underlying the low and high energy decays (2)–(4) and comment on the possibility of seeing correlated SUSY quantum corrections in low and high energy processes. We perform the analysis of quantum effects in the on-shell G_F -scheme, which is characterized by the set of inputs $(G_F, M_W, M_Z, m_f, M_{SUSY}, \dots)$, and we use the process (4) to define (and renormalize) $\tan \beta$ [5]. The supersymmetric strong (SUSY-QCD) and the supersymmetric electroweak (SUSY-EW) one-loop vertex diagrams for the charged Higgs decay of the top quark, $t \rightarrow H^+ b$, are displayed in figure 1. The bottom mass corrections in figure 2, as well as the corresponding τ -lepton mass counterterms associated to our definition of $\tan \beta$, turn out to be very important. The corresponding diagrams for the standard top quark decay, $t \rightarrow W^+ b$, are obtained by just replacing H^+ with W^+ in figure 1, but the mass counterterms of figure 2 play no role since in this case

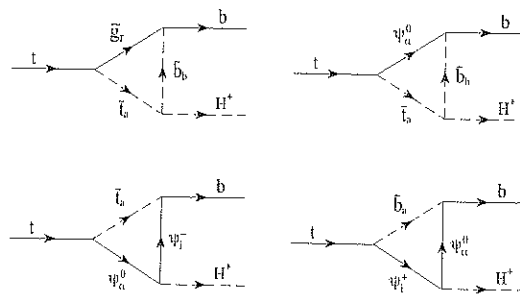


Figure 1. SUSY-QCD and SUSY-EW one-loop vertices for $t \rightarrow H^+ b$. The Ψ 's are chargino and neutralino unphysical mass-eigenstates related to the physical mass-eigenstates (χ 's) as explained in ref. [6].

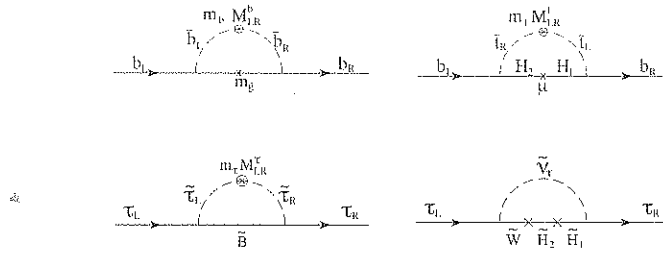


Figure 2. Relevant bottom and τ -lepton mass counterterms for $t \rightarrow H^+b$ and $H^+ \rightarrow \tau^+\nu_\tau$. Here $M_{LR}^{b,\tau} = A_{b,\tau} - \mu \tan \beta$, and $M_{LR}^t = A_t - \mu \cot \beta$, with μ the higgsino mass parameter and the A 's the corresponding trilinear couplings.

there is no need to renormalize $\tan \beta$. Both decay processes (3) are well understood in the MSSM [5, 7]. Here we shall mainly report on $t \rightarrow H^+b$ because the standard top quark decay gives a small yield. In fact, in the on-shell G_F -scheme the quantum corrections to the standard decay $t \rightarrow W^+b$ are negative and of the order of a few per cent (except in some unlikely cases). Therefore, they approximately cancel out against the positive SM contributions of the same order of magnitude leaving the ordinary QCD effects ($\simeq -10\%$) as the net MSSM corrections (cf. figure 3a). Hence no significant imprint of underlying SUSY dynamics is left in $\Gamma(t \rightarrow W^+b)$ and in this way we are naturally led to examine closer the charged Higgs decay of the top quark. To be sure, $t \rightarrow H^+b$ has been object of many studies in the past (cf. [5] and references therein), mainly within the context of 2HDM's, and it is being thoroughly searched in recent analyses at the Tevatron [8]. Notwithstanding, no systematic treatment of the MSSM quantum effects existed in the literature until very recently [5].

To appraise the relative importance of the various types of MSSM effects on $\Gamma(t \rightarrow H^+b)$, in figures 3b–3d we provide plots for the correction to the partial width as a function of $\tan \beta$, the lightest sbottom mass ($m_{\tilde{b}_1}$) and the gluino mass ($m_{\tilde{g}}$) reflecting also the various individual contributions. Specifically, we show in these figures:

- (i) The supersymmetric electroweak contribution from genuine (R -odd) sparticles (denoted $\delta_{\text{SUSY-EW}}$), i.e. from sfermions (squarks and sleptons), charginos and neutralinos;
- (ii) The electroweak contribution from non-supersymmetric (R -even) particles (δ_{EW}). It is composed of two distinct types of effects, namely, those from Higgs and Goldstone bosons (collectively called ‘Higgs’ contribution, and denoted δ_{Higgs}) plus the leading SM effects from conventional fermions (δ_{SM}):

$$\delta_{\text{EW}} = \delta_{\text{Higgs}} + \delta_{\text{SM}}. \tag{7}$$

The remaining non-supersymmetric electroweak effects are subleading and are neglected.

- (iii) The strong supersymmetric contribution (denoted by $\delta_{\text{SUSY-QCD}}$) from squarks and gluinos;
- (iv) The strong contribution from conventional quarks and gluons (labelled δ_{QCD}); and
- (v) The total MSSM contribution, δ_{MSSM} , namely, the net sum of all the previous contributions:

$$\delta_{\text{MSSM}} = \delta_{\text{SUSY-EW}} + \delta_{\text{EW}} + \delta_{\text{SUSY-QCD}} + \delta_{\text{QCD}}. \tag{8}$$

Quantum SUSY signatures

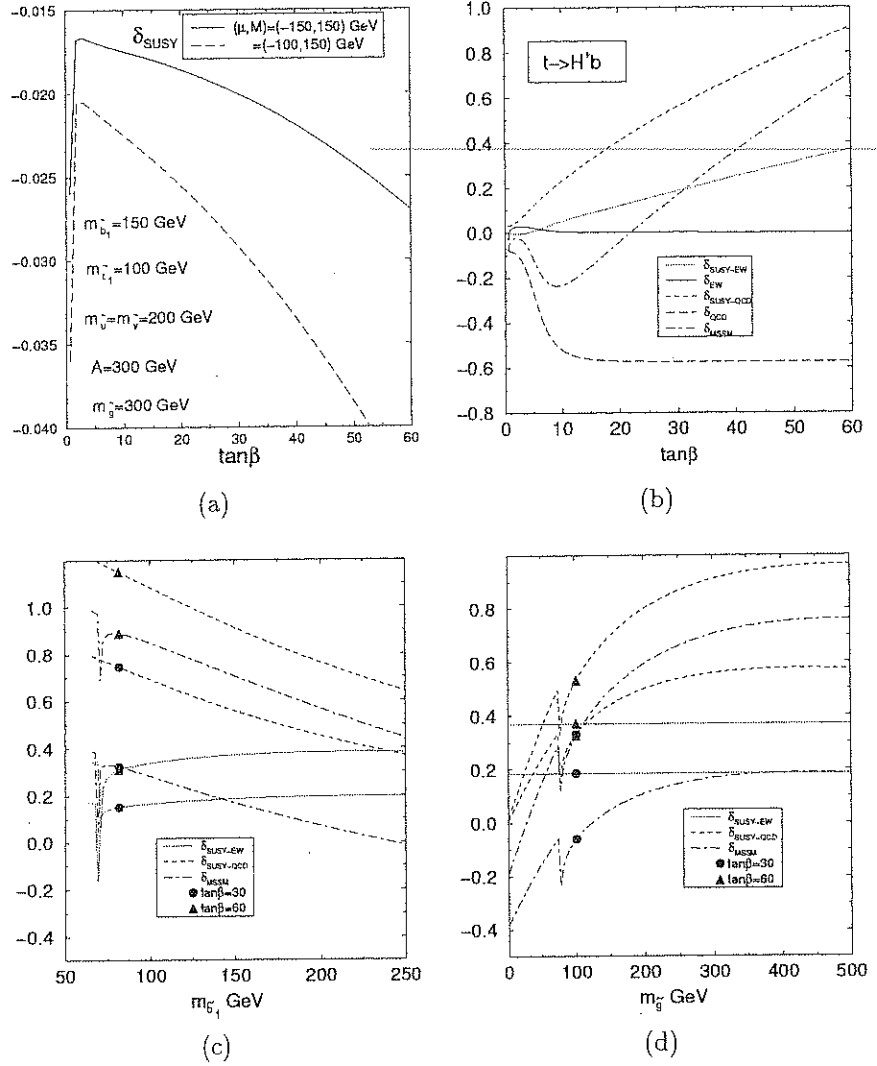


Figure 3. (a) The total (electroweak and strong) SUSY correction to $\Gamma(t \rightarrow W^+ b)$ for given sets of parameters. Notation as in ref. [5]. (b) The SUSY-EW, SUSY-QCD, standard QCD and full MSSM corrections to $\Gamma(t \rightarrow H^+ b)$ as a function of $\tan\beta$; (c) As in (b), but as a function of the lightest sbottom mass; (d) As in (b), but as a function of the gluino mass.

We remark in figure 3d the local maximum in the gluino contribution. Only for super-heavy gluinos $m_{\tilde{g}} \gg 1$ TeV the effect eventually decouples.

We may easily understand the reason why $t \rightarrow W^+ b$ cannot generate comparably large quantum SUSY signatures as $t \rightarrow H^+ b$. The counterterm configuration associated to vertices involving gauge bosons and conventional fermions does not involve the term $\delta m_b/m_b$ (cf. figure 2) – which grows linearly with $\tan\beta$ – so that one cannot expect similar

enhancements. Therefore, the SUSY-QCD corrections to $t \rightarrow W^+b$ are not foreseen to be particularly significant in this case, but just of order $\alpha_s(m_t)/4\pi$. This is borne out by the numerical analysis in figure 3a. The only hope for gauge boson interactions with top and bottom quarks to develop sizeable radiative corrections is to appeal to large non-oblique corrections triggered by the Yukawa terms (5). However, even in this circumstance the results are rather disappointing. For, at large $\tan\beta \geq m_t/m_b$, the bottom quark Yukawa coupling (the only relevant one in these conditions) gives a contribution of order

$$\frac{\alpha_W m_b^2 \tan^2 \beta}{4\pi M_W^2} \gtrsim \frac{\alpha_W m_t^2}{4\pi M_W^2}, \quad (9)$$

which is numerically very close to the strong contribution $\alpha_s(m_t)/4\pi$. In contrast, the typical SUSY-QCD effect is of order

$$C_F \frac{\alpha_s}{4\pi} \tan \beta, \quad (10)$$

($C_F = 4/3$ being a colour factor) in the limit where there is no large hierarchy between the sparticle masses. The ratio between (10) and (9) reads

$$C_F \left(\frac{\alpha_s}{\alpha_W} \right) \left(\frac{M_W}{m_t} \right)^2 \tan \beta = \mathcal{O}(1) \tan \beta. \quad (11)$$

Consequently, in the entire high $\tan\beta$ regime the SUSY-QCD effects on the tbH^\pm -vertex are expected to be a factor of order $\tan\beta$ larger than the SUSY-QCD and Yukawa coupling effects on tbW^\pm .

As a practical application of the previous analysis of SUSY quantum effects on $t \rightarrow H^+b$, let us consider the implications derived from the non-observation of an excess of τ -events from H^\pm decays (4) at the Tevatron. Our definition of $\tan\beta$ from the vertex associated to the decay (4) allows to renormalize the tbH^\pm -vertex in perhaps the most convenient way to deal with $t \rightarrow H^+b$. Indeed, from the practical point of view, we should recall the excellent methods for τ -identification developed by the Tevatron collaborations and recently used by CDF to study the permitted region in the $(\tan\beta, M_H)$ -plane [8]. However, we wish to show that this analysis may undergo dramatic changes when we incorporate the MSSM quantum effects [9]. Although CDF utilizes inclusive τ -lepton tagging, for our purposes it will suffice to focus on the exclusive final state (l, τ) , with l a light lepton, as a means for detecting an excess of τ -events [10]. To be precise, we are interested in the $t\bar{t}$ cross-section leading to the decay sequences $t\bar{t} \rightarrow H^+b, W^-\bar{b}$ and $H^+ \rightarrow \tau^+\nu_\tau, W^- \rightarrow l\bar{\nu}_l$, and vice versa. The relevant quantity can be easily derived from the measured value of the canonical cross-section $\sigma_{t\bar{t}}$ for the standard channel $t \rightarrow bl\nu_l, \bar{t} \rightarrow b\bar{q}q'$, after inserting appropriate branching fractions, namely [9]

$$\sigma_{t\bar{t}} = \left[\frac{4}{81} \epsilon_1 + \frac{4 \Gamma(t \rightarrow Hb)}{9 \Gamma(t \rightarrow Wb)} \epsilon_2 \right] \sigma_{t\bar{t}}. \quad (12)$$

The first term in the bracket comes from the SM top quark decay, and for the second term we assume (at high $\tan\beta$) 100% branching fraction of H^+ into τ -lepton, as explained before. Finally, ϵ_i are detector efficiency factors. Thus, in most of the phase space available for top decay the bulk of the cross-section (12) is provided by the contribution

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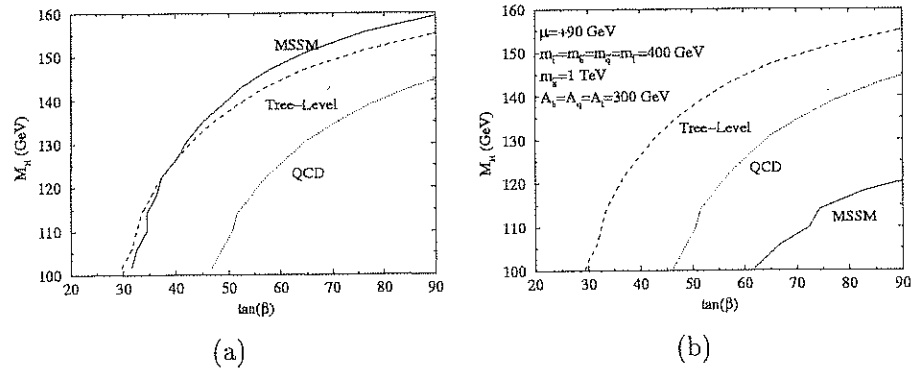


Figure 4. (a) The 95% C.L. exclusion plot in the $(\tan\beta, M_H)$ -plane for $\mu < 0$. Shown are the tree-level (dashed), QCD-corrected (dotted) and fully MSSM-corrected (continuous) contour lines. The excluded region in each case is the one lying below these curves. The set of parameters is as in figure 3; (b) As in (a), but for a $\mu > 0$ scenario characterized by a heavier SUSY spectrum.

of $\Gamma(t \rightarrow H^+ b)$. Consequently, the observable (12) should be highly sensitive to MSSM quantum effects.

In figures. 4a and 4b we derive the (95% C.L.) excluded regions for $\mu < 0$ and $\mu > 0$, respectively. (In the $\mu > 0$ case we choose a heavier SUSY spectrum in order that the correction remains perturbative.) [9]. We point out that the numerical results in figures 4a–4d include the restrictions on the MSSM parameter space placed by the radiative B -meson decay, eq. (1). From inspection of these figures it can hardly be overemphasized that the MSSM quantum effects on the CDF analysis [8] can be dramatic. In particular, while for $\mu < 0$ the MSSM-corrected curve is significantly more restrictive than the QCD-corrected one [10], for $\mu > 0$ the bound essentially disappears from the perturbative region ($\tan\beta \lesssim 60$).

We conclude the high energy analysis by pointing out the recent work of ref. [11]. Using Tevatron data in the $b\bar{b}\tau^+\tau^-$ channel these authors improve the bound in the $(\tan\beta, M_H)$ -space. Nonetheless this calculation was performed only at the tree-level and hence it could undergo significant MSSM radiative corrections. The potentially large effects not included in that paper stem from the production mechanism of the CP-odd Higgs boson A^0 (through $b\bar{b}$ -fusion) before it decays into $\tau^+\tau^-$ pairs. Indeed, the $b\bar{b}A^0$ vertex is known [12] to develop important MSSM corrections in the relevant regions of the $(\tan\beta, M_H)$ -plane purportedly ‘excluded’ by the tree-level analysis of ref. [11]. Therefore, a detailed re-examination of the excluded region at the quantum level is in order within the context of the MSSM before jumping into conclusions.

On the other hand, moving now into the low energy domain, semileptonic B -meson decays can also reveal themselves as an invaluable probe for new physics. In the specific case of the inclusive semi-tauonic B -meson decays, $B^- \rightarrow \tau^- \bar{\nu}_\tau X$ (cf. eq. (2)) one defines the following ratio

$$R = \frac{\Gamma(B^- \rightarrow \tau^- \bar{\nu}_\tau X)}{\Gamma(B^- \rightarrow l^- \bar{\nu}_l X)}, \quad (13)$$

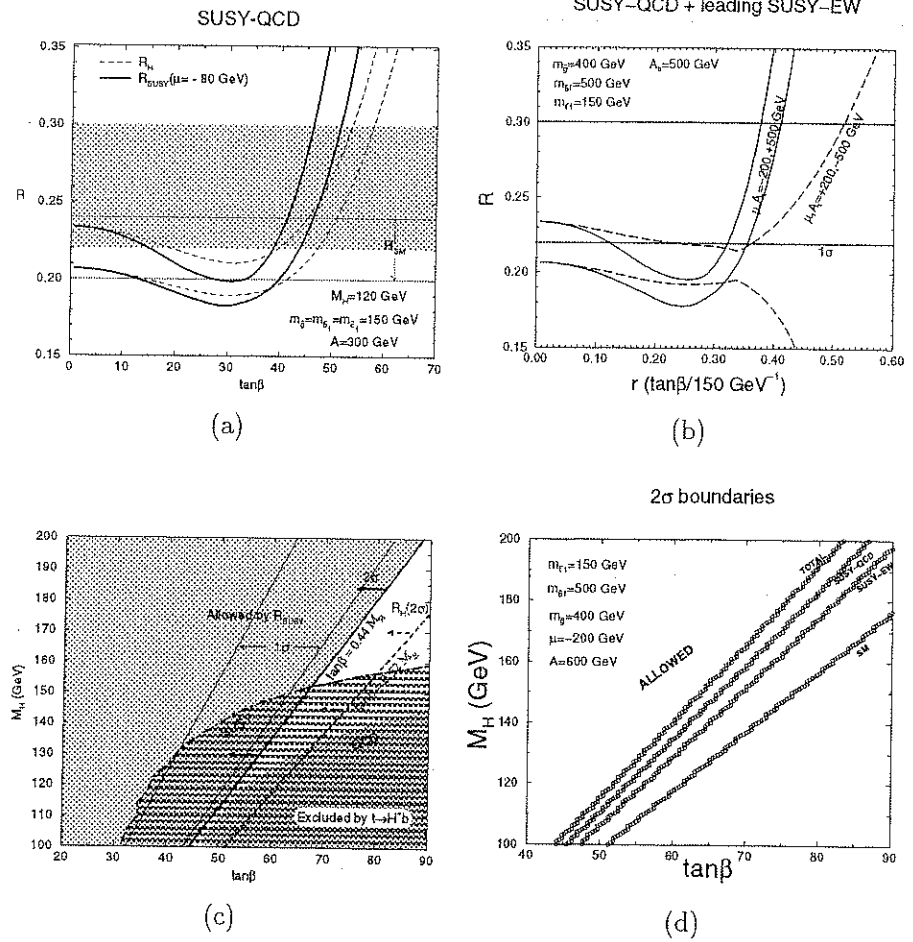


Figure 5. (a) The SUSY-QCD corrected ratio R_{SUSY} , eq. (16), as a function of $\tan\beta$ and for fixed $\mu < 0$. Also shown are the SM result, R_{SM} , (dotted band) and the Higgs-corrected result without SUSY effects, R_H . The shaded band is the experimental measurement at the 1σ level; (b) Similar to (a) but for two cases $\mu < 0$ and $\mu > 0$ and including the leading SUSY-EW effects; (c) The allowed region in the $(\tan\beta, M_H)$ plane for $\mu < 0$; (d) As in (c), but showing the differences of the R_{SUSY} -excluded area after including the leading SUSY-EW effects in that ratio.

where $l = e, \mu$ is a light lepton. In figures 5a-d we derive the bounds obtained on the $(R, \tan\beta)$ and $(\tan\beta, M_H)$ planes from the SUSY corrected ratio (13). The observable (13) is sensitive to two basic parameters of generic 2HDM's, namely $\tan\beta$ and the (charged) Higgs mass, $M_H \equiv M_{H^\pm}$. For type II 2HDM's (as in the MSSM case) the following upper bound at 1σ (respectively 2σ) is claimed in the literature [13]:

$$\tan\beta < 0.49(0.52)(M_H/\text{GeV}). \tag{14}$$

The bound (14) also hinges on the transition from the free quark model decay amplitude

to the meson decay amplitude. In practice this is handled within the heavy quark expansion formalism [13]. Now, of course our point is whether that bound is significantly modified within the context of the MSSM, in particular after including the gluino mediated short-distance corrections. This analysis has been carried out in ref. [14]. Here the new ingredient is that we also include the leading SUSY–EW effects induced by large higgsino-squark-quark Yukawa couplings, again of the type (5). We find the following impact of the SUSY effects on the physics of the semi-tauonic inclusive B -meson decays within the framework of the MSSM. For $\mu > 0$, there could be no $\tan \beta - M_H$ bound at all (figure 5b). However, for the most likely case $\mu < 0$ (figures 5a, b, c, d), the SUSY effects further restrict the allowed region in the $(\tan \beta, M_H)$ -plane as compared to eq. (14). The shaded region in figure 5c limited by the bold solid line is allowed at 2σ level by the ratio (13) after including SUSY–QCD effects. The narrow subarea between the thin solid lines is permitted at 1σ level only. The 2σ region allowed without including SUSY–QCD corrections is indicated by R_H , and the one excluded by $t \rightarrow H^+b$ (without SUSY effects) is also shown. Using the present day sparticle mass limits and the LEP input data on B -meson decays we have at the 1σ (2σ) level [14]:

$$\tan \beta < 0.40(0.43)(M_H/\text{GeV}). \quad (15)$$

While in figures 5a and 5c we consider only the SUSY–QCD corrections to the ratio (13), in figures 5b and 5d we have also included the leading SUSY–EW effects, which amount to an additional 5–10% strengthening of the bound (15).

Summarizing, from the analysis of the potential SUSY quantum effects on the semi-tauonic decays and top quark decays, a correlation seems to emerge, namely at large $\tan \beta$ the SUSY imprint on the corresponding low energy and high energy processes are both maximized. The effect is fairly large, at the level of 20% or larger. For top decays into charged Higgs, it can be of order 50%. We have also found that at present the information on $(\tan \beta, M_H)$ as collected from B -meson decays is more restrictive than the one from top quark decays in certain regions of parameter space, namely those which are phase-space inaccessible to top quark decay. However, in the phase-space accessible region, the data from top quark physics is more restrictive. Clearly, knowledge from both low energy and high energy data can be very useful to better pinpoint in the future the physical boundaries of the MSSM parameter space. Alternatively, if the two approaches would converge to a given portion of that parameter space, one could claim strong indirect evidence of SUSY.

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