SUPERSYMMETRIC QUANTUM EFFECTS ON THE
HADRONIC WIDTH OF A HEAVY CHARGED HIGGS
BOSON IN THE MSSM

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ABSTRACT

We discuss the QCD and leading electroweak corrections to the hadronic width of the charged Higgs boson of the MSSM. In our renormalization framework, \( \tan \beta \) is defined through \( \Gamma(H^+ \rightarrow \tau^+ \nu_\tau) \). We show that a measurement of the hadronic width of \( H^\pm \) and/or of the branching ratio of its \( \tau \)-decay mode with a modest precision of \( \sim 20\% \) could be sufficient to unravel the supersymmetric nature of \( H^\pm \) in full consistency with the low-energy data from radiative \( B \)-meson decays.

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The discovery of a heavy top quark at the Tevatron constituted, paradoxically as it may sound, both a reassuring confirmation of a long-standing prediction of the Standard Model (SM) of the electroweak interactions and at the same time the consolidation of an old and intriguing suspicion, namely, that the SM cannot be the last word in elementary particle physics. What are, however, the potential paradigms of new physics at our disposal? There are a few good candidates. Notwithstanding, at present 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 \cite{1} is the Minimal Supersymmetric Standard Model MSSM \cite{2}. This fact alone, if we bare in mind the vast amount of high precision data available both from low-energy and high-energy physics, should justify (we believe) all efforts to search for SUSY in present day particle accelerators. Moreover, the MSSM offers a starting point for a successful Grand Unified framework \cite{3} where a radiatively stable low-energy Higgs sector can survive.

Within the SM the physics of the top quark is intimately connected with that of the Higgs sector through the Yukawa couplings. One expects that a first hint of Higgs physics, if ever, should appear in concomitance with the detailed studies of top quark phenomenology. 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 of 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

\[
h_t = \frac{g m_t}{\sqrt{2} M_W \sin \beta}, \quad h_b = \frac{g m_b}{\sqrt{2} M_W \cos \beta},
\]  

(1)
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 \( h_t << h_b \). In a sense \( h_t \sim h_b \) could be judged as a natural relation in the MSSM. On the phenomenological side, one should not dismiss the possibility that the bottom-quark Yukawa coupling could play a momentous role in the physics of the top quark and of the Higgs bosons \cite{4}, to the extend of drastically changing standard expectations on the observables associated to them, such as decay widths and cross-sections.

It is well-known \cite{5} 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 this talk we wish to emphasize the possibility of seeing large quantum SUSY signatures in the physics of the MSSM Higgs boson decays; specifically, we shall concentrate on the potential supersymmetric quantum effects on the decays of the charged Higgs boson of the MSSM as a means to unveil its hypothetical SUSY nature.

For a heavy charged Higgs boson, the main fermionic decay channel is the top quark decay mode $H^+ \to t \bar{b}$, whose partial width is essentially the full hadronic width of $H^+$. In fact, the other two standard fermionic decay modes are $H^+ \to c \bar{s}$ and $H^+ \to \tau^+ \nu_\tau$. However, for any charged Higgs mass $M_H$ and $\tan \beta > 2$, the branching ratio of the former decay is negligibly small, whereas that of the latter is subdominant but not negligible (see later on). The bare interaction Lagrangian describing the $H^+ t \bar{b}$-vertex in the MSSM reads as follows \[3\]:

$$\mathcal{L}_{Htb} = \frac{g V_{tb}}{\sqrt{2} M_W} H^+ \bar{t} \left[ m_t \cot \beta P_L + m_b \tan \beta P_R \right] b + \text{h.c.}, \quad (2)$$

where $P_{L,R} = 1/2(1 \mp \gamma_5)$ are the chiral projector operators and $V_{tb}$ is the CKM matrix element – henceforth we set $V_{tb} = 1$. The corresponding counterterm Lagrangian follows right away after re-expressing everything in terms of renormalized parameters and fields in the standard electroweak on-shell scheme \[4\]. It takes on the form:

$$\delta \mathcal{L}_{Htb} = \frac{g}{\sqrt{2} M_W} H^+ \bar{t} \left[ \delta C_L m_t \cot \beta P_L + \delta C_R m_b \tan \beta P_R \right] b + \text{h.c.}, \quad (3)$$

with

$$\delta C_L = \frac{\delta m_t}{m_t} - \frac{\delta v}{v} + \frac{1}{2} \delta Z_{H^+} + \frac{1}{2} \delta Z_L^b + \frac{1}{2} \delta Z_R^t - \delta \tan \beta + \delta Z_{HW} \tan \beta,$$

$$\delta C_R = \frac{\delta m_b}{m_b} - \frac{\delta v}{v} + \frac{1}{2} \delta Z_{H^+} + \frac{1}{2} \delta Z_L^t + \frac{1}{2} \delta Z_R^b + \delta \tan \beta - \delta Z_{HW} \cot \beta.$$

Here $\delta v$ is the counterterm for $v = \sqrt{v_1^2 + v_2^2} = \sqrt{2} M_W/g$; $\delta Z_H$ and $\delta Z_{HW}$ stand respectively for the charged Higgs and mixed $H - W$ wave-function renormalization factors. The remaining are standard wave-function and mass renormalization counterterms for the fermion external lines \[3\].

We remark the counterterm $\delta \tan \beta$, which is fixed here by the renormalization condition that the parameter $\tan \beta$ is inputed from the tree-level expression for $\Gamma(H^+ \to \tau^+ \nu_\tau)$ either in the $\alpha$ or in the $G_F$ schemes \[4\]. From this it follows that \[8\]

$$\frac{\delta \tan \beta}{\tan \beta} = \frac{1}{2} \left( \frac{\delta M_{H^0}^2}{M_{H^0}^2} - \frac{\delta y^2}{g^2} \right) - \frac{1}{2} \delta Z_H + \cot \beta \delta Z_{HW} + \Delta_{\tau}, \quad (5)$$

One could also define $\tan \beta$ through the $\tau$-decay of the CP-odd Higgs boson, $A^0 \to \tau^+ \tau^-$, and then compute quantum corrections to $\Gamma(H^+ \to \tau^+ \nu_\tau)$ \[7\]. Conversely, in the framework of the present paper we could compute one-loop effects on the partial width of $A^0 \to \tau^+ \tau^-$. 

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\[3\] Page dimensions: 612.0x792.0

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and so the various one-loop diagrams for $H^+ \rightarrow t\bar{b}$ can be parametrized in terms of two form factors $F_L, F_R$ and the remaining counterterms:

$$i \Lambda = \frac{ig}{\sqrt{2} M_W} \left[ m_t \cot \beta (1 + \Lambda_L) P_L + m_b \tan \beta (1 + \Lambda_R) P_R \right], \quad (6)$$

where

$$\Lambda_L = F_L + \frac{\delta m_t}{m_t} + \frac{1}{2} \delta Z^b_L + \frac{1}{2} \delta Z^t_L - \Delta_r$$

$$- \frac{\delta v^2}{v^2} + \delta Z_{H^+} + (\tan \beta - \cot \beta) \delta Z_{HW},$$

$$\Lambda_R = F_R + \frac{\delta m_b}{m_b} + \frac{1}{2} \delta Z^t_L + \frac{1}{2} \delta Z^b_R + \Delta_r. \quad (7)$$

In these equations, $\Delta_r$ involves the complete set of MSSM one-loop effects on the $\tau$-lepton decay width of $H^\pm$.

The basic free parameters of our analysis, in the electroweak sector, are contained in the stop and sbottom mass matrices:

$$\mathcal{M}^2_t = \begin{pmatrix} m^2_{tL} + m_t^2 + \cos 2\beta (\frac{1}{2} - \frac{2}{3} s_W^2) M^2_Z & m_t M^t_{LR} \\ m_t M^t_{LR} & M^2_{tR} + \frac{m_t^2}{2} + \frac{2}{3} \cos 2\beta s^2_W M^2_Z \end{pmatrix} \quad (8)$$

$$\mathcal{M}^2_b = \begin{pmatrix} m^2_{bL} + m_b^2 + \cos 2\beta (-\frac{1}{2} + \frac{1}{3} s_W^2) M^2_Z & m_b M^b_{LR} \\ m_b M^b_{LR} & M^2_{bR} + \frac{m_b^2}{2} - \frac{1}{3} \cos 2\beta s^2_W M^2_Z \end{pmatrix} \quad (9)$$

with

$$M^t_{LR} = A_t - \mu \cot \beta, \quad M^b_{LR} = A_b - \mu \tan \beta, \quad (10)$$

$\mu$ being the SUSY Higgs mass parameter in the superpotential. The $A_{t,b}$ are the trilinear soft SUSY-breaking parameters and the $M_{\tilde{q}_{L,R}}$ are soft SUSY-breaking masses. By $SU(2)_L$-gauge invariance we must have $M^t_{tL} = M^b_{bL}$, whereas $M^t_{tR}, M^b_{bR}$ are in general independent parameters. We denote by $m_{\tilde{t}_i}$ and $m_{\tilde{b}_i}$ the lightest stop and sbottom mass eigenvalues. In the strong supersymmetric gaugino sector, the basic parameter is the gluino mass, $m_{\tilde{g}}$. 

Figure 1: SUSY-QCD and SUSY-EW one-loop vertices for $H^+ \rightarrow t\bar{b}$. 

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Figure 2: One-loop vertices from the Higgs sector of the MSSM for $H^+ \rightarrow t \bar{b}$.

Figure 3: Leading SUSY-QCD (a) and SUSY-EW (b) contributions to $\delta m_b/m_b$ in the electroweak-eigenstate basis. The $\tilde{H}_i$ ($i = 1, 2$) are the charged higgsinos.

The one-loop vertices contributing to the above on-shell form factors in the MSSM are displayed in Figs. 1 and 2. Specifically, in Fig. 1 we show the SUSY-QCD contributions from gluinos $\tilde{g}_r$ ($r = 1, \ldots, 8$) and bottom- and top-squarks $\tilde{b}_a, \tilde{t}_b$ ($a, b = 1, 2$). Also shown are the leading supersymmetric electroweak effects (SUSY-EW) driven by the Yukawa couplings ($\Pi$); the latter effects consist of the genuine (R-odd) SUSY contributions from chargino-neutralinos $\Psi^\pm_i, \Psi^0_\alpha$ ($i = 1, 2; \alpha = 1, \ldots, 4$) and bottom- and top-squarks. On the other hand in Fig. 2 we detail the various Higgs and Goldstone boson graphs – which we compute in the Feynman gauge.

As we said, the three-point functions in Figs. 1 and 2 are renormalized Green functions, so that appropriate counterterms for all the fermionic and Higgs wave-function external lines are already included. In particular, in Fig. 3 we single out the (finite) leading parts of the bottom quark supersymmetric self-energy loops. They feed the form factor $\Lambda_R$ in
eq.(7) through the bottom mass counterterm and are numerically very relevant:

\[
\left( \frac{\delta m_b}{m_b} \right) \simeq -\frac{2\alpha_s(m_t)}{3\pi} m_{\tilde{g}} \mu \tan \beta I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{b}}) \\
- \frac{h_t^2}{16\pi^2} \mu \tan \beta A_t I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu),
\]

(11)

where

\[
I(m_1, m_2, m_3) = \frac{m_1^2 m_2^2 \ln \frac{m_1^2}{m_2^2} + m_2^2 m_3^2 \ln \frac{m_2^2}{m_3^2} + m_1^2 m_3^2 \ln \frac{m_1^2}{m_3^2}}{(m_1^2 - m_2^2)(m_2^2 - m_3^2)(m_1^2 - m_3^2)}. 
\]

(12)

For the numerical analysis we wish to single out the Tevatron accessible window for the charged Higgs mass

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

(13)

This window is especially significant in that the CLEO measurements [9] of \( BR(b \to s \gamma) \) forbid most of this domain within the context of a generic two-Higgs-doublet model (2HDM). In contrast, within the MSSM the mass interval (13) is perfectly consistent [10] with the \( b \to s \gamma \)-allowed region. At this point it may be wise to make the following remark. Although the inclusion of the NLO effects on the charged Higgs corrected amplitude may considerably shift [11] the range (13) up to higher values of \( M_H \), within the strict

![Figure 4: The branching ratio of \( H^+ \to \tau^+ \nu_\tau \) as a function of the charged Higgs mass for fixed values of the other parameters; \( A \) is a common value for the trilinear couplings. The central curve includes the standard QCD effects only.](image-url)
2HDM, the NLO corrections on the SUSY amplitudes have not been computed, and so as in the LO case they could also contribute to compensate the Higgs counterpart. We recall that for light charginos and stops ($\lesssim 100\, GeV$) the CLEO data on $b \rightarrow s \gamma$ allow [12] supersymmetric charged Higgs bosons to exist in the kinematical window enabling the top quark decay $t \rightarrow H^+ b$ [13], which is crossed to the one under consideration.

In the following we present some of the results of the numerical analysis [10]. It was already shown [14] that SUSY-QCD effects decrease significantly with increasing sbottom masses. Even so, for $m_{\tilde{b}_1}$ of a few hundred GeV (e.g. $100 - 200\, GeV$) they remain important. Here we wish to concentrate on a region of the MSSM parameter space where the only relevant charged Higgs boson decays are $H^+ \rightarrow t \bar{b}$ and $H^+ \rightarrow \tau^+ \nu_\tau$. An scenario like this is possible if the squarks are sufficiently heavy that the direct SUSY Higgs decays into top and sbottom squarks, namely $H^+ \rightarrow \tilde{t}_i \bar{b}_j$ [13], are not possible. Moreover, the $H^+ \rightarrow W^+ h^0$ decay which is sizeable enough at low $\tan \beta$ it becomes extremely depleted [14] 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. In practice we may effectively set up the desired scenario if we assume that the sbottoms are rather heavy (i.e. typically $m_{\tilde{b}_1} \geq 300\, GeV$). It is known [10] that this assumption is compatible with the MSSM analysis of $b \rightarrow s \gamma$ at large $\tan \beta$. Therefore, we expect that the SUSY-QCD effects will be somewhat depressed, but now the question is whether this withdrawal of the gluino-squark corrections could be compensated by the SUSY-EW contributions triggered by the Yukawa couplings.

In Fig. 4 we confirm that $BR(H^+ \rightarrow \tau^+ \nu_\tau)$ at high $\tan \beta$ is quite large in the Higgs mass interval [13] and that it never decreases below $5 - 10\%$ in the whole mass range up to about $1\, TeV$. Hence this process can safely be used to input $\tan \beta$ from experiment and in this way we are ready to study the evolution of the quantum corrections to the original decay $H^+ \rightarrow t \bar{b}$ as a function of the most significant parameters. These are shown in Figs. 5a-5d. The corrections are defined in terms of the quantity

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

which traces the size of the effect with respect to the tree-level width. The MSSM correction [14] includes the full QCD yield (both from gluons [16] and gluinos [14]) at $O(\alpha_s)$ plus all the leading MSSM electroweak effects [10] driven by the Yukawa couplings [7].

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.(14), as a function respectively of $\mu < 0$ and $\tan \beta$ for fixed values of the other parameters (within the $b \rightarrow s \gamma$ allowed region). Remarkably, in spite of the fact that all sparticle masses are beyond the scope of
Figure 5: (a) The SUSY-EW, SUSY-QCD, standard QCD and full MSSM contributions, eq.(14), 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.
LEP 200 the corrections are fairly large. We have individually plotted the SUSY-EW, SUSY-QCD, standard QCD and total MSSM effects. The Higgs-Goldstone boson corrections are isolated only in Fig. 5b just to make clear that they add up non-trivially to a very tiny value in the whole large tan $\beta$ range, and that only in the small corner tan $\beta < 1$ they can be significant. We point out that for general (non-SUSY) 2HDM’s, the Higgs sector may give a more relevant contribution, whose origin stems not only from the top quark Yukawas [17], but also from the bottom quark sector [18].

In Figs. 5c-5d we render the various corrections (14) as a function of the relevant squark masses. For $m_{\tilde{b}_1} < 200 \text{GeV}$ we observe (Cf. Fig. 5c) that the SUSY-EW contribution is non-negligible ($\delta_{\text{SUSY-EW}} \simeq +20\%$) 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 $m_{\tilde{b}_1} > 300 \text{GeV}$, say $m_{\tilde{b}_1} = 400$ or $500 \text{GeV}$, and fixed stop mass at a moderate value $m_{\tilde{t}_1} = 150 \text{GeV}$, 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. in this case being of equal value but opposite in sign to the conventional QCD result. A qualitatively distinct and quantitatively sizeable quantum signature like that could not be missed!

From another point of view, the virtual SUSY effects on $\Gamma(H^+ \to t \bar{b})$ could also be pinned down indirectly from the renormalization effect on the branching ratio of the $\tau$-mode $H^+ \to \tau^+ \nu_\tau$. Indeed, returning to Fig. 4 and taking the standard QCD-corrected branching ratio of the $\tau$-lepton decay mode of $H^+$ (central curve in that figure) as a fiducial quantity, we see that $BR(H^+ \to \tau^+ \nu_\tau)$ undergoes an effective MSSM renormalization of order $\pm(40 - 50)\%$. The sign of this correction is given by the sign of $\mu$. In practice this could be a good alternative method to experimentally tag this effect, for the observable $BR(H^+ \to \tau^+ \nu_\tau)$ should be directly measurable from the cross-section for $\tau$-production at e.g. the Tevatron and the LHC.

In summary, the SUSY contributions to the hadronic width $\Gamma(H^+ \to t \bar{b})$ could be quite large, namely of the order of several ten percent. These results have been obtained within the domain of experimental compatibility of the MSSM with $b \to s \gamma$. In general the leading supersymmetric contribution stems from the SUSY-QCD sector. However, we have produced a scenario where the SUSY-EW could be equally important. The upshot is that the whole range of charged Higgs masses up to about $1 \text{TeV}$ could be probed and, within the present renormalization framework, its potential supersymmetric nature be unravelled through a measurement of $\Gamma(H^+ \to t \bar{b})$ 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. At the end of the day we have found that the physics of the combined decays $H^+ \rightarrow t\bar{b}$ and $H^+ \rightarrow \tau^+ \nu_{\tau}$ could be the ideal environment where to target our search for large non-SM quantum effects that would strongly hint at the SUSY nature of the charged Higgs.

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