MSSM AND Z WIDTH: IMPLICATIONS ON TOP QUARK AND HIGGS PHYSICS

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ABSTRACT

We discuss the one-loop quantum corrections to the top quark width and to the hadronic widths of the Higgs bosons of the MSSM, and emphasize the results obtained in particular regions of the MSSM parameter space which have been proposed to alleviate the anomalies observed in the decay modes of the $Z$ into $b\bar{b}$ and $c\bar{c}$. We find that the corrections can be large and should be visible through the measurement of the top quark production cross-sections in future experiments at the Tevatron and at the LHC.

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Lately we have been witnesses to a flood of experimental information potentially challenging the predictions of the SM to an unprecedented level. We are referring to the recent scrutinies of high precision electroweak data on $Z$-boson observables \cite{1}, where the “anomalies” in the ratios $R_b$ and $R_c$, far from disappearing, apparently have consolidated their status in the context of the SM. On the face of it, one is tempted to believe that physics might be taking a definite trend beyond the SM. There is in the literature a fairly big amount of early as well as of very recent SUSY work on $R_b$ \cite{2,3} showing that the discrepancies can be significantly weakened. The fact that the anomalies in $R_b$ and $R_c$—and perhaps also in $\alpha_s(M_Z^2)$ \cite{4}—can be simultaneously minimized \cite{5} after including supersymmetric quantum effects on the $Z$-boson partial widths is a remarkable feature of the Minimal Supersymmetric Standard Model (MSSM) which should not be understated.

In view of the new wave of SUSY potentialities, it is natural to study the possible consequences that the particular subspace of MSSM parameters singled out by the $Z$ observables may have in other areas of Particle Physics. As shown in Refs.\cite{2,3}, one privileged piece of parameter space, call it Region I, is characterized by a large value of $\tan \beta (\sim m_t/m_b)$ in conjunction with a moderate value of both the CP-odd Higgs and the lightest chargino mass around 60 GeV. In Refs.\cite{6}-\cite{7} we studied the impact of Region I of the MSSM parameter space on the top-quark width. The result for the standard decay $t \rightarrow W^+b$ is that the overall (electroweak plus strong) SUSY corrections can be relatively large ($\gtrsim 10\%$) in some cases, but in general the SUSY corrections to $t \rightarrow H^+b$ are larger and in contradistinction to the former case remain sizeable even for all sparticle masses well above 100 GeV. Another relevant region (Region II) is characterized by a large value of the CP-odd Higgs mass, $M_{A^0}$, namely of a few hundred GeV, and by a relatively light chargino and stop of 60 GeV. Here we encounter what we dubbed the “tangential solution” to the $R_b$ anomaly (see Fig.4 of Ref.\cite{3}); in the light of the present data on $R_b$ \cite{1} it is no longer a strict “solution”, though it is certainly much better than the SM prediction, for it only differs $-1.5 \sigma$ from the central value of $R_b^{\text{exp}} = 0.2211 \pm 0.0016$, in comparison to the more severe $-3.4 \sigma$ discrepancy afflicting the SM prediction. In Region II the harmful (negative) effects on $R_b$ from heavy higgses are restrained since $\tan \beta$ is assumed to lie in the intermediate interval $2 \lesssim \tan \beta \lesssim 20$ (see Fig.3 of Ref.\cite{3}), so that the aforementioned “tangential solution” becomes optimized and is entirely due to genuine (R-odd) supersymmetric particles. We remark that although Region I is more efficient to mitigate the $R_b$ anomaly, its scope is limited to $M_{A^0} < 70 \text{ GeV}$ (equivalently, $M_{H^+} \lesssim 100 \text{ GeV}$). In contrast, the “tangential solution” in Region II extends the range of $M_{A^0}$ (and therefore that of $M_{H^+}$) from about 100 GeV up to about $1 \text{ TeV}$. Finally, we may envision another situation (Region III) where the $R_b$ anomaly can also be alleviated by pure supersymmetric quantum effects, namely, it is characterized by the same sparticle
spectrum as in Region II together with very small values of $\tan\beta$ ($\lesssim 0.7$) and very large (effectively decoupled) $M_{H^\pm} > 1\,\text{TeV}$. This solution lies in the far left edge of Fig.4 of Ref.[3] but it is not explicitly exhibited there. Since for our purposes we are not interested in a too heavy MSSM Higgs spectrum, we shall not dwell on Region III any further.

From the foregoing considerations, we see that the state of the art in $Z$-boson anomalies is such that present-day quantum physics of $Z$-boson observables still tolerates both the “light” ($M_{A^0} < m_t$) and heavy ($M_{A^0} > m_t$) kinematical domains of MSSM Higgs boson masses. (Of course, the CP-even mass remains always relatively light, $M_{h^0} \lesssim 130\,\text{GeV}$.) Notwithstanding, these domains are qualitatively very different. Whereas in Region I the charged Higgs decay of the top quark, $t \rightarrow H^+ b$, is the relevant process to deal with [7], in Region II $M_{H^+}$ can be sufficiently large to prompt the top-quark decay of a supersymmetric charged Higgs boson, $H^+ \rightarrow t b$. In view of the possible existence of Region II compatible with $Z$-boson data, in the present note we shall be concerned with the bearing of SUSY physics on that decay, perhaps one of the most important decay modes to search for at the LHC and also in the next generation of Tevatron experiments. The study of the quantum effects on $H^+ \rightarrow t b$ could be the clue to unravel the potential supersymmetric nature of the charged Higgs.

Furthermore, should the physical domain of the MSSM parameter space turn out to fall in Regions I or II, then we shall see that the hadronic widths $\Gamma(A^0, h^0, H^0) \rightarrow q\bar{q}$ of the neutral Higgs bosons of the MSSM must, too, incorporate important virtual SUSY signatures to look for which can be extracted from measured quantities by subtracting the corresponding conventional QCD corrections [3]. In our analysis we will neglect those decays leading to light $q\bar{q}$ final states since their branching ratios are very small. Thus, for the lightest neutral Higgs, $h^0$, we will concentrate on just the decay $h^0 \rightarrow b\bar{b}$ (which can take place only in Region I), whereas for $A^0, H^0$ we shall consider the channels $A^0, H^0 \rightarrow b\bar{b}$ and $A^0, H^0 \rightarrow t\bar{t}$ (involving Regions I/II and II, respectively) with the understanding that the $t\bar{t}$ modes are dominant, if available (i.e. if $M_{A^0} > 2m_t$).

The basic free parameters of our analysis concerning the electroweak sector are contained in the stop and sbottom mass matrices ($q = t, b$):

$$
\mathcal{M}_q^2 = \begin{pmatrix}
M_{\tilde{q}L}^2 + m_q^2 + \cos 2\beta (T_q^3 - Q_q) \sin^2 \theta_W M_Z^2 \\
m_q M_{LR}^q M_{\tilde{q}R}^q + m_q^2 + Q_q \cos 2\beta \sin^2 \theta_W M_Z^2
\end{pmatrix},
$$

with

$$
M_{LR}^{\{t,b\}} = A_{\{t,b\}} - \mu \{\cot \beta, \tan \beta\},
$$

$\mu$ being the SUSY Higgs mixing 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 $M_{\tilde{t}L} = M_{\tilde{b}L}$, whereas $M_{\tilde{t}R}$, $M_{\tilde{b}R}$ are in general
independent parameters. In the strong supersymmetric sector, the basic parameter is the gluino mass, \(m_{\tilde{g}}\). For the sake of simplicity in the presentation, we shall treat the sbottom mass matrix by freezing the sbottom mixing parameter at \(M_{LR}^b = 0\) and assuming equal eigenvalues: \(m_{\tilde{b}_1} = m_{\tilde{b}_2} \equiv m_{\tilde{b}}\). As far as the stop mass matrix is concerned it is generally non-diagonal (\(M_{LR}^t \neq 0\)) and the stop masses are different, with the convention \(m_{\tilde{t}_2} > m_{\tilde{t}_1}\).

For the full SUSY corrections to \(t \to W^+ b\) and \(t \to H^+ b\) we refer the reader to the detailed Refs. \([6, 7, 9]\). Here we limit ourselves to report on the conventional QCD and SUSY-QCD contributions to the decays \(\Gamma(H^+ \to tb)\) and \(\Gamma(A^0, h^0, H^0) \to q\bar{q}\). Indeed, the strong corrections mediated by quarks, gluons and their SUSY partners (squarks and gluinos, respectively) are expected to be the leading corrections to these decays in the MSSM. (The analysis of the larger and far more complex body of SUSY-electroweak corrections to these modes, namely the corrections mediated by squarks, sleptons, chargino-neutralinos and the Higgs bosons themselves, is given in Refs. \([9, 10]\).)

To compute the one-loop SUSY-QCD corrections to \(\Gamma \equiv \Gamma(H^+ \to t \bar{b})\) in the MSSM, we shall adopt the on-shell renormalization scheme \([11]\) where the fine structure constant, \(\alpha\), and the masses of the gauge bosons, fermions and scalars are the renormalized parameters: \((\alpha, M_W, M_Z, M_{H^0}, m_f, M_{SUSY}, ...)\). The interaction Lagrangian describing the \(H^+ tb\)-vertex in the MSSM reads as follows:

\[
\mathcal{L}_{Htb} = \frac{g V_{tb}}{2M_W} H^+ \bar{t} [a^+_L(t) P_L + a^+_R(b) P_R] b + \text{h.c.},
\]

where \(P_{L,R} = 1/2(1 \mp \gamma_5)\) are the chiral projector operators and \(V_{tb} = 1\)– and

\[
a^+_L(t) = \sqrt{2} m_t \cot \beta, \quad a^+_R(b) = \sqrt{2} m_b \tan \beta.
\]

Similarly, the interaction Lagrangian describing the various neutral Higgs decays \(\Phi^i \to q \bar{q}\) \((\Phi^1 \equiv A^0, \Phi^2 \equiv h^0, \Phi^3 \equiv H^0)\) at tree-level in the MSSM reads as follows:

\[
\mathcal{L}_{\Phi qq} = \frac{g}{2M_W} \Phi^i \bar{q} \left[a^i_L(q) P_L + a^i_R(q) P_R\right] q.
\]

We shall focus on top and bottom quarks \((q = t, b)\). In a condensed and self-explaining notation we have defined

\[
\begin{align*}
    a^1_R(t, b) &= -a^1_L(t, b) = m_q(i \cot \beta, i \tan \beta), \\
    a^2_R(t, b) &= a^2_L(t, b) = m_q(-c_\alpha/s_\beta, s_\alpha/c_\beta), \\
    a^3_R(t, b) &= a^3_L(t, b) = m_q(-s_\alpha/s_\beta, -c_\alpha/c_\beta),
\end{align*}
\]

with \(c_\alpha \equiv \cos \alpha, s_\beta \equiv \sin \beta\) etc. (Angles \(\alpha\) and \(\beta\) are related in the usual manner as prescribed by the MSSM \([12]\).)
The one-loop corrected amplitudes for all the decays above have the generic form 
\( \langle i \rangle = +1, 2, 3 \):
\[
iO^i = \frac{ig}{2M_W} \left[ a^i_L(q) \left( 1 + O^i_L(q) \right) PL + a^i_R(q') \left( 1 + O^i_R(q') \right) PR \right].
\] (7)
The renormalized form factors read
\[
O^i_L(q) = K^i_L(q) + \frac{\delta m_q}{m_q} + \frac{1}{2} \delta Z^q_L + \frac{1}{2} \delta Z^q_R,
\]
\[
O^i_R(q') = K^i_R(q') + \frac{\delta m_{q'}}{m_{q'}} + \frac{1}{2} \delta Z^{q'}_L + \frac{1}{2} \delta Z^{q'}_R
\] (8)
where the \( K^i_{L,R} \) stand for the 3-point function contributions, and the remaining terms include the mass and wave-function renormalization in the on-shell scheme (see the similar analysis of Ref.[7]).

After explicit computation of the various loop diagrams, the results are conveniently casted in terms of the relative correction with respect to the corresponding tree-level width, \( \Gamma_0 \):
\[
\delta = \frac{\Gamma - \Gamma_0}{\Gamma_0}.
\] (9)
A crucial parameter entering the loop contributions is \( \tan \beta \). In supersymmetric theories, like the MSSM, the spectrum of higgses and of Yukawa couplings is richer than in the SM and, in such a framework, the bottom-quark Yukawa coupling may counterbalance the smalness of the bottom mass at the expense of a large value of \( \tan \beta \), the upshot being that the top-quark and bottom-quark Yukawa couplings in the superpotential read
\[
h_t = \frac{g m_t}{\sqrt{2} M_W \sin \beta}, \quad h_b = \frac{g m_b}{\sqrt{2} M_W \cos \beta}.
\] (10)
Thus, since the perturbative domain of these Yukawa couplings is \( 0.5 < \tan \beta \lesssim 70 \), there is room enough for both \( h_t \) and \( h_b \) being larger than the gauge coupling, \( g \), and even comparable to one another (for \( \tan \beta = m_t/m_b \approx 35 \)). This is so in Region I where \( \tan \beta \) is very large, and is also partly the case in Region II where \( \tan \beta \) can be moderately high.

In Fig.1a we plot the width of \( H^+ \rightarrow t \bar{b} \) versus \( \tan \beta \) after including SUSY-QCD effects and compare it with the corresponding tree-level width, \( \Gamma_0 (H^+ \rightarrow t \bar{b}) \), as well as with the partial widths of two alternative (non-hadronic) modes. We have fixed \( m_t = 180 \text{GeV} \), \( M_{H^+} = 250 \text{GeV} = M_{tR} \), the squark masses \( m_{t_R} = 60 \text{GeV} \), \( m_{b} = 150 \text{GeV} \), and the gluino mass \( m_{g} = 200 \text{GeV} \). It is patent that the corrections can be very large in the high \( \tan \beta \) regime. This can be further appreciated in Fig.1b, where we plot both the SUSY-QCD (\( \delta_g \)) and the conventional QCD (\( \delta_g \)) corrections (9) against \( M_{H^+} \). It is seen that in the very relevant region \( M_{H^+} \leq 500 \text{GeV} \) and depending on the actual value of \( \tan \beta \), the SUSY-QCD effects can be comparable or even be dominant over the standard QCD corrections. Since \( \delta_g \) can have either sign (opposite to the sign of \( \mu \)), the total
QCD correction in the MSSM, $\delta g + \delta \tilde{g}$, could be much smaller than what would be naively expected within the context of conventional quantum chromodynamics. Alternatively, $\delta g + \delta \tilde{g}$ could be extremely large near the $t\bar{b}$ threshold, suggesting that in this case higher orders should be taken into account.

The analysis of $\delta \tilde{g}$ and $\delta g$ (or $-\delta g$) for the neutral Higgs decay modes is exhibited in Figs.1c-1d. We have fixed the same values for the squark masses, gluino mass and mixing parameters as in the previous figures. The shaded areas in Fig.1c signal the differences between the corrections obtained using the tree-level and the one-loop Higgs mass relations. Although $\delta g$ for neutral higgses is strictly independent of $\tan\beta$, for fixed Higgs masses, the indirect dependence is due to the evolution of the MSSM Higgs masses $M_{h^0}, M_{H^0}$ as a function of $M_{A^0}$ since this evolution does depend on $\tan\beta$. In Regions I and II we see from Fig.1c that the decays $h^0 \rightarrow b\bar{b}$ and $A^0 \rightarrow b\bar{b}$ receive negative standard QCD corrections of about $-35\%$. For $M_{A^0} \gtrsim 100\, GeV$, the standard QCD correction to $h^0 \rightarrow b\bar{b}$ remains saturated at that value since the mass $M_{h^0}$ also saturates at its maximum value, whereas the modes $A^0, H^0 \rightarrow b\bar{b}$ obtain increasing negative corrections. In contrast, $A^0 \rightarrow t\bar{t}$ and $H^0 \rightarrow t\bar{t}$, receive positive standard QCD corrections (in this case we have plotted $-\delta \tilde{g}$ in Fig.1d), which are of order $40-50\%$ near the threshold. It is clear from Figs. 1c-1d that in many cases the SUSY effects are important since they can be of the same order as the standard QCD corrections. As a matter of fact, there are situations where $|\delta \tilde{g}| > |\delta g|$, with the possibility of the SUSY effects either reinforcing the standard QCD corrections or cancelling them out, perhaps to the extend of reversing their sign! Obviously, this feature could be used to differentiate SUSY and non-SUSY neutral higgses produced in the colliders.

In summary, we have found that $t \rightarrow H^+ b$ or $H^+ \rightarrow t\bar{b}$ and/or $A^0, H^0 \rightarrow b\bar{b}, t\bar{t}$ could be the ideal experimental environment where to study the nature of the spontaneously symmetry breaking mechanism. It could even be the right place where to target our long and unsuccessful search for large, and slowly decoupling, quantum supersymmetric effects. In this respect it should be stressed the fact that the typical size of our corrections is maintained even for all sparticle masses well above the LEP 200 discovery range. Fortunately, the next generation of experiments at the Tevatron and the future high precision experiments at the LHC may well acquire the ability to test the kind of effects considered here \[13\]. In fact, since the leading Higgs production vertices are the same as the hadronic Higgs decay vertices that we have been dealing with in the present work, we expect that $t$ and $t\bar{t}$ can be copiously produced in association with MSSM Higgs particles in Regions I and II (where the SUSY Yukawa couplings $h_t$ and $h_b$ are enhanced). Moreover, in these regions the large SUSY corrections reported here automatically translate into sizeable effects on the cross-sections, a fact which may constitute a distinctive imprint of SUSY.
Figure 1: (a) The SUSY-QCD corrected and uncorrected width $\Gamma(H^+ \rightarrow t\bar{b})$ as a function of $\tan\beta$ (remaining parameters given on the text) as compared to two alternative (non-hadronic) decays; (b) The SUSY-QCD ($\delta_{g\sim}$) and QCD ($\delta_g$) corrections to $\Gamma(H^+ \rightarrow t\bar{b})$ versus $M_{H^+}$; (c)-(d) As in (b), but for the hadronic widths of the neutral MSSM higgses as a function of $M_{A^0}$.
As a final remark, we emphasize that the vigorous quantum effects (∼ 50%) potentially underlying the dynamics of the MSSM higgses are in stark contrast to the milder SUSY radiative effects (few per mil!) expected in the physics of gauge bosons [3]. Needless to say, the excellence of the latters over the formers lies in the high precision techniques achieved by the Z experiments at LEP, which might enable us to resolve the small SUSY corrections and perhaps confirm that they are responsible for the anomalies observed in the Z width. Be as it may, our analysis suggests that Higgs physics at the colliders might well take its turn in the near future and eventually provide the most straightforward handle to “virtual” Supersymmetry.

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