IMPLICATIONS ON THE SUPERSYMMETRIC HIGGS SECTOR FROM TOP QUARK DECAYS AT THE TEVATRON

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ABSTRACT

From the τ-lepton analysis of the charged Higgs decay of the top quark at the Tevatron, \( t \to H^+ b \to \tau^+ \nu_\tau b \), it is possible to set rather stringent bounds on the \((\tan \beta, M_{H^\pm})\)-plane, if one assumes that \( H^\pm \) is a charged member of a generic two-Higgs-doublet model. However, if we consider the possibility that \( H^\pm \) is supersymmetric, then we find that the allowed region in the \((\tan \beta, M_{H^\pm})\)-plane can be significantly modified by the MSSM quantum corrections. Throughout our analysis we correlate the top quark results with the limits imposed by radiative and semileptonic \( B \)-meson decays. Remarkably, one can envision situations in the MSSM parameter space where \( H^\pm \) completely eludes those bounds, i.e. a charged Higgs with a mass below the top quark mass could coexist with essentially any value of \( \tan \beta \).
The Minimal Supersymmetric Standard Model (MSSM) \[1\] is a most tantalizing candidate to extend the quantum field theoretical structure of the Standard Model (SM) of the strong and electroweak interactions while keeping all the necessary ingredients insuring internal consistency, such as gauge invariance and renormalizability. Furthermore, supersymmetric theories are the only tenable theoretical framework for aiming at an unified theory of all interactions including gravity. In spite of the fact that the sparticles themselves have so far escaped detection, SUSY has always eschewed experimental refutation; well on the contrary, it persists since its inception (roughly a quarter of century ago!) as a challenging proposal for physics beyond the SM. For one thing the MSSM remains consistent with all known high precision data at a level comparable to the SM \[2, 3\], a feature which is unparalleled by any alternative paradigm of the basic particle interactions of nature.

In this note we address the possibility of seeing indirect effects of SUSY through the interplay between top quark and Higgs boson physics. A particularly distinctive part of the field content of the MSSM is the Higgs sector, which is extended to contain two doublet scalar fields leading to five physical states, namely two charged Higgs pseudoscalar bosons, $H^\pm$, one neutral CP-odd boson, $A^0$, and two neutral CP-even Higgs states, $h^0$ and $H^0$ ($M_{h^0} < M_{H^0}$) \[4\]. Probing this extended Higgs sector can be very useful to search for SUSY, due to the special constraints imposed by the underlying symmetry. In this respect, much work has been done mainly for the neutral Higgs bosons \[4\], and especially in connection with the lightest CP-even state, $h^0$, which could mimic the SM Higgs boson in the allowed mass range $M_{h^0} \lesssim 130 GeV$ — i.e. the one obtained after including the MSSM quantum corrections \[4\]. Thus, in principle, finding a heavy ($> 130 GeV$) neutral Higgs scalar with similar couplings as the SM Higgs boson would be a natural disprove of the MSSM. Nonetheless, even if such a state were the first one to be found, it would be far from clear whether it fully behaved as a SM Higgs boson, at least not before a lot of precision data were collected on the new particle. On the other hand, if a charged Higgs boson, $H^\pm$, happened to exist, its identification should in principle be easier (if it were light enough) and it would constitute an undeniable sign of physics beyond the SM. However, also in this case its nature would not be immediately apparent. For, in the absence of other Higgs bosons (for example, the neutral ones of the MSSM), we could not clearly distinguish whether we would be dealing with a SUSY charged Higgs or e.g. with some charged member of a generic two-Higgs-doublet model (2HDM).

Along this vein the CDF Collaboration at the Tevatron has carried out direct searches for charged Higgs production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8 TeV$ \[6, 7\]. In these studies one is concerned with the final configurations $t\bar{t} \rightarrow H^+ H^- b\bar{b}, W^+ H^- b\bar{b}, H^+ W^- b\bar{b}$. The latter would differ from that of the standard model, $t\bar{t} \rightarrow W^+ W^- b\bar{b}$, by an excess of states.
with one (or two) \( \tau \)-lepton “jets” (i.e. usually tagged in the hadronic decay mode) and two \( b \)-quarks and large missing transverse energy associated to the decays \( H^+ \rightarrow \tau^+ \nu_\tau \) and/or \( H^- \rightarrow \tau^- \bar{\nu}_\tau \). To grasp a hint of the relative importance of these events, notice the following rates (where for illustration purposes we have just kept the relevant Yukawa couplings):

\[
\frac{\Gamma^{(0)}(t \rightarrow H^+ b)}{\Gamma^{(0)}(t \rightarrow W^+ b)} = \left( 1 - \frac{M_H^2}{m_t^2} \right)^2 \frac{m_t^2 \tan^2 \beta + \cot^2 \beta}{\left( 1 - \frac{M_W^2}{m_t^2} \right)^2 \left( 1 + 2 \frac{M_W^2}{m_t^2} \right)}^2, \tag{1}
\]

and (at large tan \( \beta \))

\[
\frac{\Gamma^{(0)}(H^+ \rightarrow \tau^+ \nu_\tau)}{\Gamma^{(0)}(H^+ \rightarrow cs)} = \frac{1}{3} \left( \frac{m_\tau}{m_c} \right)^2 \frac{\tan^2 \beta}{(m_s^2/m_c^2) \tan^2 \beta + \cot^2 \beta} \rightarrow \frac{1}{3} \left( \frac{m_\tau}{m_s} \right)^2 > 10. \tag{2}
\]

We see from eq.(1) that if \( M_H \) (the mass of \( H^\pm \)) is not too close to the phase space limit, then there are two regimes, namely a low and a high tan \( \beta \) regime, where the partial width of the unconventional top quark decay becomes sizeable as compared to the standard decay \( t \rightarrow W^+ b \). Nevertheless we shall focus only on the high tan \( \beta \) regime as it is this case that is correlated with the Higgs maximum rate into the \( \tau \)-mode versus the hadronic mode (Cf. eq.(2)). Clearly, the identification of the charged Higgs decay of the top quark could be a matter of observing a departure from the universality prediction for all the lepton channels through the measurement of an excess of inclusive (hadronic) \( \tau \)-events. However, from the non-observation of any \( \tau \)-lepton surplus, one may determine an exclusion region in the \((\tan \beta, M_H)\)-plane \[3\]-\[8\] for any (Type II) 2HDM \[4\] – tan \( \beta \) being the usual ratio of the two VEV’s after SSB. The region highlighted in this plane consists of a sharply edged area forbidding too high values of tan \( \beta \) in correlation with \( M_H \). In the relevant SUSY region \( M_H > 100 \text{ GeV} \) (see below) the most recent analysis would imply that values in the range tan \( \beta \gtrsim 40 \) would be excluded \[7\].

Now, an important point that we wish to make hereafter is that the above branching ratios for this analysis could be significantly modified by the SUSY quantum corrections. In fact, whereas the supersymmetric effects are known to be generally small for the standard top quark decay \( t \rightarrow W^+ b \) (Cf. Ref. \[11\]), this is not necessarily so for the unconventional mode \( t \rightarrow H^+ b \) \[10, 11\].

In spite of its foreseeable importance, the impact of the SUSY quantum corrections on the dynamics of \( t \rightarrow H^+ b \) was not included in any of the aforementioned analysis \[3\]-\[8\]. And this is especially significant in a decay like \( t \rightarrow H^+ b \) whose sole existence could, in a sense, already be an indirect sign of SUSY. For, as is well-known, the CLEO data \[13\] on the radiative decays \( \bar{B}^0 \rightarrow X_s \gamma \) (viz. \( b \rightarrow s \gamma \)) set a rather stringent lower bound on the

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\footnote{See Ref. \[12\] for a review and a comparative study.}
mass of any charged Higgs scalar belonging to a generic $2HDM$, to wit: $M_H > 240 GeV$. Therefore, with only the $W^\pm$ and $H^\pm$ electroweak corrections, the charged Higgs mass is forced to lie in a range where the decay $t \to H^+ b$ becomes kinematically blocked up. Of course, this is so because the virtual Higgs effects go in the same direction as the SM contribution. Fortunately, this situation can be remedied in the MSSM where the complete formula for the $b \to s \gamma$ branching ratio reads (see the extensive literature [14] for details):

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

with

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

being the sum of the SM, charged Higgs and chargino-squark amplitudes, respectively. (The contributions from the neutralino and gluino amplitudes are in this case generally smaller as they enter through FCNC.) Now, the important feature here is that the unwanted charged Higgs effects could to a large extent be compensated for by the chargino-stop contributions. And in this case a relatively light charged Higgs particle would perfectly be allowed in the MSSM for the decay $t \to H^+ b$ to occur.

In our renormalization framework, we use $H^+ \to \tau^+ \nu_\tau$ to define the parameter $\tan \beta$ through

$$\Gamma(H^+ \to \tau^+ \nu_\tau) = \frac{\alpha e m^2 \tan^2 \beta}{8 m^2 W^2 s_W^2} = \frac{G_F m^2}{4\pi \sqrt{2}} \tan^2 \beta (1 - \Delta r_{MSSM}).$$

This generates a counterterm [11]

$$\frac{\delta \tan \beta}{\tan \beta} = \frac{1}{2} \left(\frac{\delta m^2_W}{m^2_W} - \frac{\delta g^2}{g^2}\right) = -\frac{1}{2} \delta Z_{H^\pm} + \cot \beta \delta Z_{HW} + \Delta r,$$

which allows to renormalize the $t b H^+$-vertex in perhaps the most convenient way to deal with our physical process $t \to H^+ b \to \tau^+ \nu_\tau b$. Apart from the full set of electroweak and strong corrections from the roster of SUSY particles (squarks, gluinos, chargino-neutralinos and higgses), we of course include the standard QCD correction with the running $b$-quark mass evaluated at the top quark mass scale [15]. $\Delta r$ above involves the complete MSSM effects on $H^+ \to \tau^+ \nu_\tau$.

The results are presented in Figs.1-4. We point out that in the present work we have locked together the MSSM parameter space regions for the two decays $b \to s \gamma$ and $t \to H^+ b$ in order to find compatible solutions. In doing so we have used the full structure involved in eqs. (3),(4). Notice that recently the NLO QCD effects in the SM
amplitude have been computed and the total error has diminished from roughly 30% to 15% (including the error in $m_b/m_c$) \[16\].

In Fig.1 we determine the permitted region in the $(\tan \beta, A_t)$-plane in accordance with the CLEO data on radiative $B^0$ decays at $2\sigma$. For fixed $\mu < 0$, we find that $A_t \mu < 0$ in the allowed region. This piece of information could be important since, as it is patent in that figure, the trilinear coupling $A_t$ – entering the SUSY electroweak corrections – becomes strongly correlated with $\tan \beta$. This correlation depends slightly upon the value of the charged Higgs mass, $M_H$, and it is built-in for the rest of the plots (Figs.2-4). From the SM result mentioned above, we have made allowance for an uncertainty of order 30% stemming from the non-computed NLO corrections within the MSSM.

For definiteness, and to ease comparison with the non-supersymmetric results, we will normalize our analysis with respect to Ref.\[8\]. Here the $(l, \tau)$-channel, with $l$ a light lepton, is used to search for an excess of $\tau$-events. This should suffice to illustrate the potential impact of the MSSM effects on this kind of physics. To be precise, we are interested in the $t \bar{t}$ cross-section for the $(l, \tau)$-channel, $\sigma_{tr}$, i.e. for the final states caused by 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 $t \rightarrow b l \nu_l, \bar{t} \rightarrow b q q'$, after inserting appropriate branching fractions, namely

$$\sigma_{tr} = \left[ \frac{4}{81} \epsilon_1 + \frac{4}{9} \frac{\Gamma(t \rightarrow H b)}{\Gamma(t \rightarrow W b)} \epsilon_2 \right] \sigma_{t\bar{t}}, \quad (7)$$

where the first term in the bracket comes from the SM decay, and for the second term we assume (at high $\tan \beta$) 100% branching fraction of $H^+$ into $\tau$-lepton, as explained before. Finally, $\epsilon_i$ are detector efficiency factors\[8\]. Notice that the use of the measured value of $\sigma_{t\bar{t}}$\[17\], instead of the predicted value within the standard NLO QCD approach\[18\], allows a model-independent treatment of the result. In this respect, we note that there could be MSSM effects on the standard mechanisms for $t \bar{t}$ production\[19\] (viz. Drell-Yan $q \bar{q}$ annihilation and gluon-gluon fusion) as well as corrections in the subsequent top quark decays\[19\].

Therefore, proceeding in this way the bulk of the MSSM pay-off stems from the $t \rightarrow H^+ b$ contribution in eq.(7). Specifically, in Fig. 2 we determine, as a function of $\tan \beta$ and for a given Higgs mass and fixed set of SUSY parameters, the cross-section for the $(l, \tau)$ final state. There we show the tree-level ($\sigma_0$), QCD-corrected ($\sigma_{QCD}$) and fully MSSM-corrected ($\sigma_{MSSM}$) results. Of course, $\sigma_{MSSM}$ includes both the SUSY-QCD and standard QCD effects, plus the MSSM electroweak corrections. Note that the QCD curve is similar to the one in Ref.\[8\], but as it is also patent the full MSSM curve is quite

\[\text{2There is, however, a small difference due to the fact that we use the top quark scale, instead of the}$$
different from the QCD one: in fact, the two curves lie mostly on opposite sides with respect to the tree-level curve!.

The horizontal line in Fig. 2 gives the cross-section for the number of events expected in the \((l, \tau)\)-configuration at the 95% C.L. after correcting for the detector efficiencies. Hence the crossover points of the three curves with this line determine (at 95% C.L.) the maximum allowed value of \(\tan \beta\) for the given set of parameters. It is plain that the MSSM curve crosses that line much earlier than the QCD curve, so that the \(\tan \beta\) bound is significantly tighter than in the non-supersymmetric case. Notice that for this particular set of parameters the MSSM and tree-level curves turn out to meet the horizontal line at about the same point, which means that the SUSY effects fully counterbalance the standard QCD correction. We remark that this feature may occur for negative values of the higgsino mixing parameter (in Fig.2, \(\mu = -90 \text{ GeV}\)). The situation with \(\mu > 0\) is different and it will be discussed below.

In Fig. 3 we present our results in the \((\tan \beta, M_H)\)-plane, by iterating the procedure followed in Fig. 2 for \(\mu < 0\) and for charged Higgs masses comprised in the relevant kinematical range \(100 \text{ GeV} < M_H < m_t\). Here the lower bound follows from the LEP constraint \(M_{A_0} > 60 \text{ GeV}\) and the SUSY Higgs mass relations\(^3\). We also show the three exclusion curves for the tree-level, QCD and MSSM corrected cross-sections. The excluded region in each case is the one below the curves. By simple inspection of Fig. 3, it can hardly be overemphasized that the MSSM quantum effects can be dramatic. Thus e.g. while for \(M_H = 100 \text{ GeV}\) the maximum allowed value of \(\tan \beta\) is about 46 according to the QCD contour, it is only about 30 according to the MSSM contour. We have also checked that, after all, the modulation of the latter by the \(b \to s \gamma\) constraint is not too significant even when including the 30% uncertainty mentioned above. For, it turns out that although the branching ratio for the \(b \to s \gamma\) decay severely limits the set of possible values of \(A_t\) for each \(\tan \beta\) (Cf. Fig. 1), the corresponding impact on \(t \to H^+ b\) is really minor. This is due in part to the fact that the supersymmetric electroweak corrections are not the dominant component in \(t \to H^+ b\), and also in part to the observed stabilization of its contribution within the region of parameter space allowed by \(b \to s \gamma\).

The above picture may undergo a significant qualitative change when we move to the \(\mu > 0\) scenario. This can be appraised in Fig. 4, where we plot the excluded region in the \((\tan \beta, M_H)\)-plane again for the same cases as before. Although not shown, we have also determined the portion of the \((\tan \beta, A_t)\)-plane permitted by \(b \to s \gamma\) for \(\mu > 0\) (implying that \(A_t < 0\)), and checked that also in this case the influence on our top quark mass scale, to compute the QCD corrections.

\(^3\)In the absence of these theoretical relations, we recall that the LEP absolute bound on direct charged Higgs boson searches is much lower, viz. \(M_H > 44 \text{ GeV}\)\(^2\).
analysis is not dramatic. The point with the $\mu > 0$ scenario is that the MSSM curve is, in contradistinction to the $\mu < 0$ case, the less restrictive one. As a matter of fact it is even less restrictive than the original CDF curve for the inclusive $\tau$ channel! (Cf. Ref.\[6\]). The reason is the following: for $\mu > 0$, the SUSY corrections have the same (negative) sign as the standard QCD corrections and, therefore, the cross-section for the $\tau$-lepton signal becomes extremely depleted. In Fig.4 we have chosen a heavier SUSY spectrum than in the previous figures in order to keep the total correction within the limits of perturbation theory. We see that for squark masses of several hundred GeV and a gluino mass of 1 TeV the excluded area can be enforced to withdraw to a corner of parameter space. However, in this corner one cannot be precise any more since further reduction would make also the Higgs sector nonperturbative (see below). Hence the conclusion emerging for the case $\mu > 0$ is quite remarkable, to wit: relatively light ($\gtrsim 100 - 120$ GeV) charged Higgs masses within the kinematical range of $t \to H^+ b$ could be allowed for essentially any admissible value of $\tan \beta$ within perturbation theory (i.e. $\tan \beta < 60 - 70$). In other words, within this scenario one could not disprove the existence of relatively light supersymmetric charged higgses by the current methods of $\tau$-lepton analysis at the Tevatron\[4\].

It is also interesting to compare our results with the bounds obtained from semileptonic and semitauonic $B$-meson decays. In Ref.\[22\] the excluded region in the ($\tan \beta, M_{H^\pm}$)-plane is computed for a general $2HDM$ whereas in Ref.\[23\] the corresponding MSSM analysis is performed and it is also confronted with the (uncorrected) top quark decay exclusion region. However, in the presence of the corrected results, we may compare Fig.2 of the present work with Fig.3 of Ref.\[23\] (both for $\mu < 0$). We realize that the supersymmetric results on the top quark decay greatly improve the bound from semitauonic $B$ decays across the crucial region defined by $30 \lesssim \tan \beta \lesssim 65$ and Higgs masses ranging between $100 - 150$ GeV. Even though for $\tan \beta > 65$ the semitauonic $B$-meson decays are more restrictive, it should be pointed out that this range is already ruled out on sound theoretical grounds, namely by the breakdown of perturbation theory; for instance, the top quark Yukawa coupling with the CP-odd Higgs boson $A^0$ would become $g m_b \tan \beta/2 M_W > 1$. On the other hand, the $\mu > 0$ region is not so favoured by $B$-meson decays, but it is still compatible with experimental data at the 1$\sigma$ level for $\tan \beta \lesssim 40 \[23\].

In summary, from the the study of the quantum effects on the top quark decay channel into charged Higgs particles we arrive at the conclusion that the recently presented $\tau$-lepton analyses by the CDF Collaboration at Fermilab are in general model-dependent and could be significantly altered by potentially underlying new physics. In particular, since in the absence of new interactions the results from radiative $B$-meson decays generally

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\[4\]Thus the criticism put forward in Ref.\[8\] against the large $\tan \beta$ approach\[21\] to the – nowadays residual – $R_b$ anomaly would be unfounded in this case.
preclude the existence of charged Higgs bosons below the top quark mass, it is reasonable to link the existence of the decay $t \rightarrow H^+ b$ to the viability of the leading candidate for physics beyond the SM, viz. the MSSM. In this framework we find that, depending on the sign of the higgsino mixing parameter, $\mu$, the recent $\tau$-lepton exclusion plots in $(\tan \beta, M_H)$-space presented by CDF could either be further strengthened or on the contrary be greatly weakened. This dual situation could only be decided from additional experimental information unambiguously favouring a given sign of $\mu$ in other physical processes. We remark that although for brevity sake we have presented our numerical analysis for a given choice of the MSSM parameters, we have checked that our conclusions hold basically unaltered in ample regions of parameter space involving typical sparticle masses of a few hundred GeV \cite{24}. While the details of the exclusion plot in $(\tan \beta, M_H)$-space may depend on the particular channel used to tag a potential excess of $\tau$-leptons, all of these plots (and of course also the one from the inclusive measurement) should undergo significant changes. Finally, it is clear that similar considerations apply to experiments of the same nature being planned for the future at the LHC. Thereby a general conclusion seems to consolidate \cite{12}: In contrast to gauge boson observables, the MSSM quantum effects on Higgs boson physics can be rather large and should not be ignored in future searches at the Tevatron and at the LHC.

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**Figure Captions**

- **Fig.1** The allowed region (shaded area) in the \((A_t, \tan \beta)\)-plane by the \(b \to s \gamma\) decay within the framework of the MSSM, and for a given set of inputs. Here the most relevant SUSY parameters are: the gaugino-higgsino mass parameters \(M\) and \(\mu\), the lightest stop and sbottom masses \(m_{\tilde{t}_1, \tilde{b}_1}\), the trilinear couplings \(A_t, A_b\), and the gluino mass \(m_{\tilde{g}}\). The corresponding parameters for the other squark and slepton generations are also given, and the Higgs mass is fixed at \(M_H = 120\, GeV\).

- **Fig.2** The cross-section for the \((\tau, l)\)-channel (in fb) for the tree-level \((\sigma_0)\), QCD-corrected \((\sigma_{QCD})\) and fully MSSM-corrected \((\sigma_{MSSM})\) cases, for the same parameters as in Fig.1. The horizontal line gives the 95% C.L. cross-section for the observation of the \((\tau, l)\) final state.

- **Fig.3** 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 Fig.1, with \(A_t\) within the allowed region.

- **Fig.4** As in Fig.3, but for a \(\mu > 0\) scenario characterized by a heavier SUSY spectrum.
\[
\tan(\beta)
\]

\begin{align*}
M_H &= 120 \text{ GeV} \\
\mu &= -90 \text{ GeV} \\
M &= 150 \text{ GeV}, \ m_\tau &= 300 \text{ GeV} \\
m_{\tilde{t}} &= 100 \text{ GeV} \\
m_{\tilde{b}} &= 150 \text{ GeV} \\
A_b &= 300 \text{ GeV} \\
m_q &= m_t = 400 \text{ GeV} \\
A_q &= A_t = 300 \text{ GeV}
\end{align*}

Fig. 1

Fig. 2
\[ \tan(\beta) \]

Fig. 3

\[ M_H \text{ (GeV)} \]

\[ \mu = +90 \text{ GeV} \]
\[ m_t = m_b = m_q = m_{\tau} = 400 \text{ GeV} \]
\[ m_{\tilde{g}} = 1 \text{ TeV} \]
\[ A_b = A_q = A_{\tilde{l}} = 300 \text{ GeV} \]

Fig. 4