Supersymmetric effects on heavy charged Higgs boson production in hadron colliders

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The production of a heavy supersymmetric charged Higgs boson ($M_{H^\pm} \geq 200 \text{ GeV}$) at the Tevatron and at the LHC is studied. We include the leading one-loop quantum effects within the MSSM in the relevant high tan$\beta$ region. Whereas the chances for the Tevatron are limited, and critically depend on the size of the unknown NLO QCD effects, at the LHC the discovery range is more comfortable and may extend the reach above $M_{H^\pm} = 1 \text{ TeV}$.

1. Introduction

The experimental accuracy reached by the electroweak precision observables in particle accelerators allows to test the Standard Model (SM) at the quantum level within an accuracy better than one per mil. Although precision observables at LEP have played an important role in this respect, a new generation of experiments at the Tevatron (II), LHC and a future Linear Collider (LC) will be necessary to find out the ultimate nature of the spontaneous symmetry breaking mechanism. When extending the Higgs sector, we mainly focus on two-Higgs-doublet models (2HDM), and most particularly on the Type II ones –like that of the the Minimal Supersymmetric Standard Model (MSSM) \cite{1}. The fact that the Higgs bosons of the MSSM (and their SUSY counterparts) couple most preferentially to heavy quarks suggests that the physics of the top and bottom quarks is the natural arena where to try to get a hint of the existence of SUSY Higgs particles. In this paper we report on the production of a heavy charged Higgs boson in association with the top and bottom quarks at the Tevatron and LHC energies within the MSSM. The mass of the charged Higgs is assumed $M_{H^\pm} \gtrsim 200 \text{ GeV}$, and so it cannot come from the decay of a top quark. While the detection of a charged Higgs boson would still leave a lot of questions unanswered, it would immediately offer (in contrast to the detection of a neutral one) indisputable evidence of physics beyond the SM. The basic production processes under consideration are

\begin{equation}
pp \to H^+ \bar{t}b + X \quad \text{Tevatron (LHC).}
\end{equation}

There are many other processes for charged Higgs production, which have been studied in the literature \cite{2}, such as: i) one-loop gluon fusion ($gg \to H^+ H^-$); ii) tree-level pair production in bottom quark scattering ($b \bar{b} \to H^+ H^-$), iii) associated production with $W^\pm$: $b \bar{b} \to W^\pm H^\mp$ (tree-level), $gg \to W^\pm H^\mp$ (one-loop), iv) Drell-Yan type production ($q \bar{q} \to V \to H^+ H^-$). However, in all these cases the production cross-section is smaller than for (1) if we restrict ourselves to high values of $\tan\beta$ ($> 20$). Although process (1) has been
studied previously [2,3], the inclusion of the leading quantum SUSY effects was missing and turns out to be very important, as first hinted in [4] and further elaborated in [5].

2. Leading order Cross-section in QCD

At the parton level, the reaction (1) proceeds through three channels: i) $q\bar{q}$-annihilation for light quarks

$$q\bar{q} \rightarrow H^+\bar{b}$$

(2)

where $q = u, d$ (the $s$ contribution can be safely neglected), a channel only relevant for the Tevatron; ii) $gg$-fusion

$$gg \rightarrow H^+\bar{b}$$

(3)

which is dominant at the LHC, but it can also be important at the Tevatron for increasing $H^+$ masses; and finally there is the iii) bottom-gluon 2-body channel

$$bg \rightarrow H^+\bar{t}$$

(4)

We will compute the cross-section for the charged Higgs boson production process (1) at the leading order (LO) in QCD, namely at $O(\alpha_S^2)$. However, the QCD corrections at the next-to-leading order (NLO) or $O(\alpha_S^3)$ could be important. Although a dedicated calculation of these higher order effects for the process under consideration is not available, let us mention that the corresponding calculation for the related process in the Standard Model, $p\bar{p}(pp) \rightarrow H t\bar{t} + X$, is available and shows that the NLO effects lead to a non-trivial QCD $K$-factor which is typically smaller than one at the Tevatron, and up to 1.4 at the LHC [6]. On the other hand, partial calculations of the QCD corrections to the process (1) at the NLO have appeared. For example, in Ref. [7] the standard NLO QCD corrections to the subprocess (2) at the LHC are computed, obtaining a large $K$-factor between $\sim 1.6$ and $\sim 1.8$ for $\tan\beta \lesssim 20$. Taking into account these considerations, a large $K$-factor for the full process (1) coming from the standard QCD corrections (e.g. $K_{QCD}^{QCD} \simeq 1.5$) is not ruled out. However, in the absence of a complete calculation of these QCD effects, in what follows we present our results at the leading order and will parametrize our ignorance of the complete NLO effects in terms of a $K$-factor, which will be assumed different from one only for the Tevatron, where the size of the cross-section is hardly the necessary for a viable study. On the other hand, for the LHC the cross-section, being typically three orders of magnitude larger, can afford a QCD $K$-factor of one.

Once a PDF for $b$-quarks is used, there is some amount of overlap between $bg$- and $gg$-initiated amplitudes, which has to be removed [8]. The overlap arises because the $b$-density in the $bg$ amplitude receives contributions from gluon splitting which was already counted in the $gg$ amplitude, so we have to avoid double counting by the subtracting of the gluon splitting term. The net partonic cross-section from the $bg$- and $gg$-initiated subprocesses is

$$\sigma(bg + gg \rightarrow H^+\bar{t} + X)_{\text{net}} = \sigma(g\bar{b} \rightarrow H^+\bar{t}) + \sigma(gg \rightarrow H^+\bar{t}b) - \sigma(g \rightarrow b\bar{b} \otimes g\bar{b} \rightarrow H^+\bar{t}).$$

(5)

Furthermore, for the study of the various differential distributions one has to properly combine the $2 \rightarrow 2$ and $2 \rightarrow 3$ processes mentioned above in order to reproduce not only the total cross-section but also the correct event kinematics. The point is that we know the total amount of double counting but not a priori which part of this value should be subtracted from the $H^+\bar{t}$ process and which part from the $H^+\bar{t}b$ one. We apply here the method proposed in [9] for the analogous process of the single top quark production. According to this method we use the cut on the transverse momenta of the $b$-quark associated with charged Higgs boson production to separate and recombine $gg$- and $bg$-initiated processes.

3. Signal versus background

Concerning the signature, we consider the dominant $t\bar{b}b$ final state for the combined signal process (1). We focus here on the triple $b$-tagging case and consider the situation where one top decays hadronically and the other leptonically (including only electron and muon decay channels) in order to reduce the combinatorics when both
Then we form and keep all top quarks are reconstructed. The branching ratio of $t\bar{t}b\bar{b}$ to $b\bar{b}b\bar{b}e\mu qq'$ is $2/9 \times 2/3 \times 2 = 8/27$.

In order to decide whether a charged Higgs boson cross-section leads to a detectable signal, we have to compute the background rate. The main QCD backgrounds leading to the same $t\bar{t}b\bar{b}$ signature and their respective cross-sections are shown in Table 1. For reconstructing the W-boson mass from lepton and neutrino momenta: $M_{W_1}^{rec} = (p_ℓ + p_ν)^2$. The basic cuts for the leptons (electron or muon) have been chosen as follows:

$$p_\ell^t > 15 \text{ GeV}, \quad |η_\ell| < 2.5, \quad p_T^{miss} > 15 \text{ GeV}; (6)$$

ii) We reconstruct the mass of the second W-boson ($M_{W_2}^{rec}$). The following basic cuts for the jets were chosen for the Tevatron (LHC):

$$p_T^{j,b} > 20 (30) \text{ GeV }, \quad |η_j| < 3, \quad |η_b| < 2. \quad (7)$$

Then we form and keep all $m_{t_1} = M_{W_1}$ and $m_{t_2} = M_{W_2}$ combinations for the first and second top-quarks; iii) In the final step we form the χ function

$$χ^2 = (M_{W_1}^{rec} - M_W)^2 + (M_{W_2}^{rec} - M_W)^2 + (m_{t_1} - m_t)^2 + (m_{t_2} - m_t)^2$$

for all combinations of $b$-jets, jets, lepton and neutrino and choose the combination giving the smallest (best) value of the χ function. After the reconstruction of the $t\bar{t}b\bar{b}$ state one should reconstruct the charged Higgs boson mass for the signal and the continuous $t\bar{b}$ mass for the background. We assume that the $b$-jet with the highest $p_T$ in $t\bar{b}(\bar{b})$ signature comes from the $H^+$ decay. After all cuts are set up we obtained the signal and background efficiencies, $S/B$ ratio and signal significance $S/\sqrt{B}$ – see Tables 4,5 in the second paper of [5] for details. They will be used in the next section after including the SUSY corrections.

For the calculation we use $m_t = 175 \text{ GeV}$, $m_b = 4.6 \text{ GeV}$ and the CTEQ4L set of PDFs [10]. Here $m_t, m_b$ refer to the quark pole masses.

The central value of the (common) factorization and renormalization scale, $µ_R$, for the signal processes has been chosen equal to $M_{H^+}$, whereas that of the background processes to $2m_t$. We have checked the uncertainty of the signal due to variations of $µ_R$ in the interval $M_{H^+}/2 < µ_R < 2M_{H^+}$. We find that individual sub-channels show a stronger dependence than the total cross-section, which varies $δσ ∼ 28\%$ at the Tevatron II and $δσ ∼ 18\%$ at the LHC. We have also compared our CTEQ4 results with the ones obtained with the MRST (central gluon) PDFs [11]. Again, significant deviations appear for some of the individual sub-channels (up to $∼ 50\%$), but they are compensated in the sum, leaving a $5 – 10\%$ thanks to the subtraction procedure in [5].

### 4. Supersymmetric quantum effects

In Figs. 1a, b we find the regions of the $tanβ – M_{H^+}$ plane in which the Tevatron and the LHC can find (or exclude) the existence of the charged Higgs boson. The curves correspond to the various sets of MSSM parameters indicated in Table 2. For the Tevatron we have included a QCD $K$-factor of 1.5, whereas for the LHC we have just set $K = 1$. From these figures it is obvious that the presence of the SUSY corrections alters signif-

|        | $µ$ | $M_2$ | $m_3$ | $m_{t_1}$ | $m_{\tilde{t}_1}$ | $A_t$ | $A_b$ |
|--------|-----|-------|-------|-----------|-------------------|------|------|
| A      | -1000 | 200 | 1000 | 1000 | 1000 | 500 | 500 |
| B      | -200 | 200 | 1000 | 500 | 500 | 500 | 500 |
| C      | 200 | 200 | 1000 | 500 | 500 | -500 | 500 |
| D      | 1000 | 200 | 1000 | 1000 | 1000 | -500 | 500 |

Table 2

Sets of MSSM parameters used in the computation of the SUSY corrections to process (6). All masses and trilinear couplings in GeV.

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σ($qq → t\bar{t}b\bar{b}$) 6.62 fb 0.266 pb  
σ($gg → t\bar{t}b\bar{b}$) 0.676 fb 6.00 pb  
σ($gq → t\bar{t}b$) 1.22 fb 4.33 pb  
Subtr. term 0.72 fb 2.1 pb  

Table 1

The main background processes to the signal (6) at the Tevatron (2nd column) and the LHC (3rd column) under cuts explained in the text. The corresponding subtraction term is also shown.
significant the Higgs boson discovery potential of the hadron colliders. It is also patent the Tevatron could have a chance to find a charged Higgs boson in the intermediate range $M_{H^\pm} < 280$ GeV.

Let us now sketch how the various quantum corrections have been computed. Among the plethora of possible corrections we disregarded virtual supersymmetric effects on the $qqg$ and $ggg$ vertices and on the gluon propagators. We expect those to be of order $(\alpha_S/4\pi) \cdot (s/M_{\text{SUSY}}^2)$ and thus suppressed by a non-enhanced (i.e. $\tan\beta$-independent) MSSM form factor coming from the loop integrals. Therefore, we can neglect these contributions as we are only considering effects of the form $(\alpha_S/4\pi)^n \cdot \tan^n \beta$ at large $\tan\beta$. The cross-section for the signal increases steeply with $\tan\beta$ and becomes highly significant for $\tan\beta > 30$, while it is much smaller for $\tan\beta$ in the low interval $2 - 20$ where the remaining SUSY corrections are of the same order or even dominant, so our approximation is well justified. Similarly, we neglect all those electroweak corrections in vertices and self-energies which are proportional to pure $SU(2)_L \times U(1)_Y$ gauge couplings; in particular, vertices involving electroweak gauge bosons and those involving electroweak gauginos. Furthermore, we have checked that vertices involving Higgs bosons exchange yield a very tiny overall contribution, due to automatic cancellations arranged by the underlying supersymmetry. Finally, there are the strong gluino-squark diagrams and the $\tan\beta$-enhanced higgsino-squark vertices implicit in chargino-neutralino loops. We have extracted the parts of these interactions which are (by far) the more relevant ones at high $\tan\beta$ and confirmed that the remaining contributions are negligible. In practice this means that we may concentrate our analysis on the interval $\tan\beta > 20$ where we can be sure that our approximation does include the bulk of the MSSM corrections while at the same time the cross-section of process \((2)\) starts to be sufficiently large to consider it as an efficient mechanism for charged Higgs boson production. The leading contributions are similar to those found in Ref. \([12]\) for the decay process $t \to H^+ b$, where we also refer for detailed renormalization issues. Recently these dominant effects have been conveniently described through an
effective Lagrangian approach that contains effective couplings absorbing both the leading SUSY contributions and the known part of the QCD corrections [13]. At high tan β the most relevant piece is the effective \( tbH^+ \)-coupling as it carries the leading part of the (appropriately resummed) quantum effects:

\[
\mathcal{L} = \frac{g_{V_{tb}}}{\sqrt{2} M_W} \frac{m_b(\mu_R) \tan \beta}{1 + \Delta m_b} H^+ \tau_L b_R + h.c. \quad (9)
\]

The quantity \( \Delta m_b \) above—see ([12] [13])—contains the bulk of the supersymmetric contributions. Although the leading corrections have been identified, we have computed the full set of one-loop SUSY diagrams for the relevant \( tbH^+ \) vertex, which involve similar diagrams as in the on-shell case [12], but here we have got to account for the off-shell external lines, which is a non-trivial task. The result is that these off-shell corrections amount to a few percent contribution that we have included in our numerical analysis.

Coming back to Figs. 3 and Table 2, let us remark that parameter set B constitutes a typical case for moderately positive corrections. On the other hand set A is over-optimized, and sets C and D give more and more negative corrections. In all cases these corrections decouple very slowly with the gluino mass, for fixed values of the other masses. Furthermore, they exhibit a non-decoupling behavior when all SUSY parameters are scaled up by a common factor [12] [13]. This SUSY non-decoupling behavior [1] is associated to the properties of the quantity \( \Delta m_b \) entering eq.(1). The violation of the decoupling theorem [14] is caused by the dimensionful Higgs-quark-squark coupling, which increases arbitrarily with the SUSY scale. Through this coupling the MSSM Higgs doublet that interacts only with the top quark at the tree-level, effectively couples to the bottom quark at one-loop. Therefore, that interaction cannot be re-absorbed in the parameters of the low-energy Higgs sector after integrating out the sparticle masses. This welcome feature is at the basis of the large radiative corrections found in our study of the charged Higgs production process [1], and it could be responsible for the eventual finding of this scalar boson. These facts were amply exploited in Ref. [15] where the suggestion of the present calculation was first made and the importance of its correlation with the neutral Higgs production processes \( p\bar{p}(pp) \rightarrow h\bar{b}b + X (h = h^0, H^0, A^0) \) was first emphasized. Such effects and correlations could eventually lead to the discovery of SUSY.

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