Prospects for supersymmetric charged Higgs boson discovery at the Tevatron and the LHC

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We investigate the prospects for heavy charged Higgs boson production through the mechanisms $p\bar{p}(pp) \to tbH^{\pm}+X$ at the upgraded Fermilab Tevatron and at the upcoming LHC collider at CERN respectively. We focus on the MSSM case at high values of $\tan\beta \gtrsim m_t/m_b$ and include the leading SUSY quantum corrections. A detailed study is performed for all important production modes and basic background processes for the $t\bar{t}b\bar{b}$ signature. At the upgraded Tevatron a charged Higgs signal is potentially viable in the $220 - 250$ GeV range or excluded at 95 %CL up to 300 GeV. At the LHC, a $H^{\pm}$ of mass up to 800 GeV can be discovered at 5σ or else be excluded up to a mass of ~ 1.5 TeV. The presence of SUSY quantum effects may highly influence the discovery potential in both machines and can typically shift these limits by 200 GeV at the LHC.

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The full experimental confirmation of the Standard Model (SM) is still waiting for the finding of the Higgs boson. Last LEP results, suggesting a light neutral Higgs of about 115 GeV [1], are encouraging, but we will have to wait the news from the upgraded Fermilab Tevatron or from the upcoming Large Hadron Collider at CERN to see this result either confirmed or dismissed. For intermediate masses above the LEP limit and below 180 GeV there is a chance for the Tevatron, but for higher masses up to 1 TeV one needs the LHC. However, even if a neutral Higgs boson is discovered, the principal question will stand immutable at the forefront of Elementary Particle research: is the minimal SM realized in nature or does a model beyond the SM exist with an extended Higgs sector? In most of these extensions, the physical spectrum contains neutral Higgs particles and some of them may mimic the SM one. But in general they also involve charged Higgs bosons, and this introduces an obvious distinctive feature. For example, in the general two-Higgs-doublet model (2HDM) [2] one just adds up another doublet of Higgs scalars and then the spectrum of the model contains three neutral Higgs bosons $h = h^0, H^0, A^0$ and two charged ones $H^{\pm}$. 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. In this Letter we report on the main results from a fully-fledged study of the $H^{\pm}$ production in hadron colliders. We restrict our analysis to the Higgs sector of the Minimal Supersymmetric Standard Model (MSSM), which is beyond doubt the most prominent (Type II) 2HDM [2]. The lengthy details of this work will be presented elsewhere.

The relevant mechanisms on which we will concentrate

$$p\bar{p}(pp) \to tbH^{\pm} + X \quad \text{(Tevatron)(LHC)}\,, \tag{1}$$

are long known to be the leading ones for $H^{\pm}$ production at high $\tan\beta$ [3]. They constitute the charged counterpart of the process $p\bar{p} \to t\bar{t}H+X$ for Higgs boson production in the SM, recently revisited in [4] for the Tevatron, and of $p\bar{p}(pp) \to t\bar{t}h+X$ for neutral MSSM Higgs boson production at the Tevatron and the LHC [5]. While the study of (1) has been further addressed in the literature [6], to the best of our knowledge all the works on this subject– except a first estimation in [7]– do stick to a tree-level computation without SUSY quantum effects, in spite of the fact that some of them explicitly admit that the sort of charged Higgs boson they are dealing with is of the MSSM type. Therefore, they are unavoidably affected by some drawbacks. In the present work we have implemented several additional features which improve in a substantial manner our knowledge on the real capability for the mechanisms (1) to produce a charged Higgs boson or to put limits on its mass within the MSSM. First, we include the leading SUSY radiative corrections (both strong and electroweak) along with an analysis of the off-shell effects. Second, we perform a beyond-the-parton-level simulation of events, which includes the toy-detector simulation, jet fragmentation, and initial and final radiation effects. And yet another new aspect of the present work is the proper kinematical analysis of the $gg \to H^+\bar{t}b$ and $g\bar{b} \to H^+\bar{t}$ subprocesses at the level of differential cross-sections after correctly combining them, using the standard recipe for the total cross-section [9], and a method based on Ref. [10] for the differential one.

A realistic study of charged Higgs boson physics cannot be accomplished without including the information provided by radiative corrections. These are not only potentially large in the computation of the MSSM Higgs boson masses themselves but also in the interaction vertices and self-energies of given processes, particularly in the decay of the top quark into charged Higgs and for the hadronic decays of the MSSM Higgs bosons [11,12]. Supersymmetric quantum effects can also be very impor-

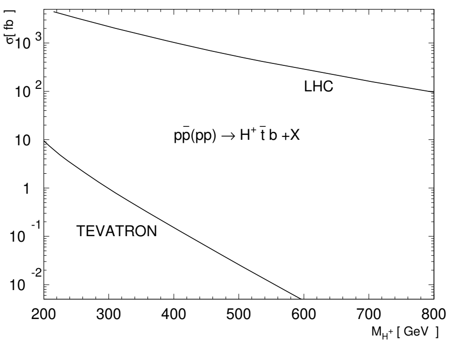

FIG. 1. Tree-level cross-sections (1) versus $M_{H^\pm}$ at the Tevatron Run II (2 TeV) and LHC (14 TeV) for $\tan\beta = 50$.

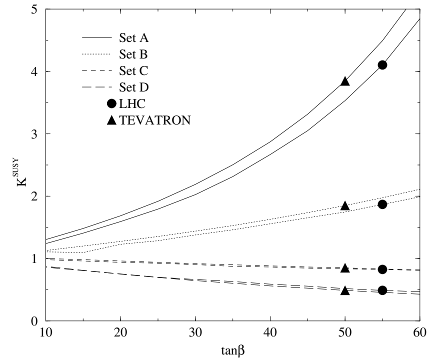

FIG. 2. $K_{SUSY} = \sigma^{\rm SUSY}/\sigma^{\rm tree}$ factor for the signal (1) as a function of $\tan\beta$ for the typical sets of parameters in Table I, at the Tevatron (for $M_{H^\pm} = 250$ GeV) and the LHC (for $M_{H^\pm} = 500$ GeV).

tant for the processes (1). Indeed, in Fig. 1 we present the tree-level signal cross-sections as a function of $M_{H^\pm}$ for the LHC and Tevatron colliders, whereas in Fig. 2 a rich variety of SUSY effects is exhibited, as a function of $\tan\beta$, for the various sets of MSSM parameters indicated in Table I. For the signal the leading corrections can be described through an effective Lagrangian approach [12]

$$\mathcal{L} = \frac{gV_{tb}}{\sqrt{2}\,M_W}\,\frac{\overline{m}_b\,\tan\beta}{1+\Delta m_b}\,H^+\bar{t}_L\,b_R + h.c. \tag{2}$$

where $\overline{m}_b$ is the running bottom mass in the $\overline{MS}$. The previous formula allows to treat the leading SUSY Yukawa coupling effects correctly resummed to all orders [12]. The analytic form of the strong (SUSY-QCD) and electroweak (SUSY-EW) corrections Δm_b in the MSSM is given in Ref. [12]. Although Δm_b is the only correction that contributes at order $(\alpha/4\pi)\,\tan\beta$ $(\alpha = \alpha_S, \alpha_W)$ and thus dominates for large $\tan\beta$, we have also included off-shell SUSY-QCD and SUSY-EW corrections to the $tbH^\pm$ vertex and to the fermion propagators. We have made extensive use of the CompHEP package for the algebraic and numerical calculations [13]. Despite CompHEP is only able (in principle) to deal with tree-level calculations, with the help of Eq. (2) we have managed to add the SUSY corrections to the $tbH^\pm$ vertex and fermion propagators and we have assessed the relevance of the off-shell contributions. To this end we have evaluated the full set of one-loop SUSY diagrams for the relevant tbH^+ vertex. The same set was considered in detail in Ref. [11] for the case where all external particles are on-shell. In the present instance, however, at least one of the quarks in that vertex is off shell. Therefore, we can use the same bunch of diagrams as in the on-shell case but we have to account for the off-shell external lines, which is a non-trivial task. We have studied this issue in detail by expanding the off-shell propagators. First, we have modified CompHEP's Feynman rules to allow for the most general off-shell $\bar{t}bH^+$ vertex; then we have let CompHEP reckon the squared matrix elements and dump the result into REDUCE code. The subsequent numerical computation of the one-loop integrals has been done using the package LoopTools [14]. At this point, we have inserted expressions for the coefficients of the off-shell $\bar{t}bH^+$ vertex that include the one-loop off-shell supersymmetric corrections to the vertex itself and to the off-shell fermion propagators and fermionic external lines. Only half the renormalization of an internal fermion line has to be included, the other half being associated to the gqq vertex. This procedure has allowed us to estimate the relative size of the off-shell effects in the signal cross-section, which never exceeds the few per cent level. The upshot is that the approximation of neglecting vertex and propagator corrections in the cross-section, which may be called "improved Born" approximation, is really justified in the relevant region of parameter space.

	μ	M	$m_{\tilde{g}}$	$m_{\tilde{t}_1}$	$m_{\tilde{b}_1}$	A_t	A_b
Set A	-1000	200	1000	1000	1000	500	500
Set B	-200	200	1000	500	500	500	500
Set C	200	200	1000	500	500	-500	500
Set D	1000	200	1000	1000	1000	-500	500

TABLE I. Typical sets of SUSY parameters used in the computation of the signal cross-section (1) in Fig. 2 (all entries in GeV). Here μ and M are the higgsino and $SU(2)$ gaugino mass parameters, $m_{\tilde{g}}$ is the gluino mass, $m_{\tilde{t}_1}$ and $m_{\tilde{b}_1}$ are the lightest stop and sbottom masses, and A_t, A_b are the top and bottom quark trilinear SUSY-breaking couplings. The $|\delta\rho| < 0.001$ constraint is satisfied. Notation as in Ref. [11].

As for the signal versus background study we have focused on the $t\bar{t}b\bar{b}$ signature corresponding to the $H^+ \to t\bar{b}$ decay channel, which has the biggest branching ratio at high $\tan\beta$. Then we have concentrated on the triple-b tagging case, which gives the best possibility to measure the signal cross-section (1). This is a crucial point, especially for the Tevatron, where the production rate is too small to give any viable signal in the case of four-b tagging. As regards the LHC, a triple-b tagging study allows the signal cross-section to be measured more precisely, even though the signal/background ratio can be better for the four-b tagging case. We notice that the background processes in Table II are in-

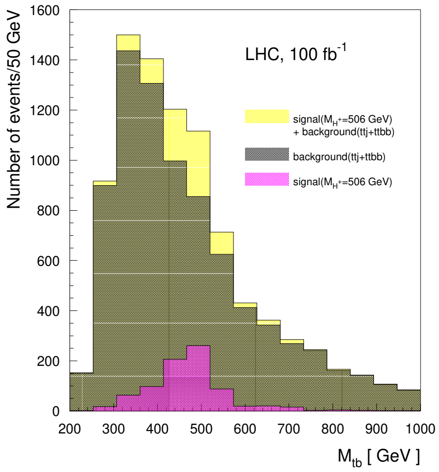

FIG. 3. Reconstructed tb invariant-mass distribution for signal, background and signal plus background events, for $M_{H^\pm} = 500$ GeV, at the LHC.

(a)	$\sigma(qq \to t\bar{t}b\bar{b})$	6.62 fb	0.266 pb
	$\sigma(gg \to t\bar{t}b\bar{b})$	0.676 fb	6.00 pb
	$\sigma(gb \to t\bar{t}b)$	1.22 fb	4.33 pb
	Subtr. term	0.72 fb	2.1 pb
(b)	$\sigma(q\bar{q} \to gt\bar{t})$	1890 fb	21 pb
	$\sigma(gq \to qt\bar{t})$	193 fb	122 pb
	$\sigma(gg \to gt\bar{t})$	262 fb	371 pb

TABLE II. (a) The main background processes to the signal (1) at the Tevatron (2nd column) and the LHC (3rd column) under the cuts explained in the text. The various contributions are shown together with that of the subtraction term [9]; (b) Background from $pp \to t\bar{t}qg$ when the light quark or gluon are misidentified as a b-jet.

sensitive to the leading type of SUSY effects that contribute to (1). To perform a realistic signal and background event simulation we complied with the following procedure. The (tree-level) matrix elements for the signal and background processes have been calculated using the CompHEP package [13]. The next step was the parton-level event simulation, also with the help of CompHEP. Then we automatically linked the parton-level events from CompHEP to the PYTHIA 6.1 Monte Carlo generator and the CompHEP–PYTHIA interface [15]. Therefore we took into account the effects of the final-state radiation, hadronization and string-jet fragmentation using PYTHIA tools. The following resolutions were used for the jet and electron energy smearing: $\Delta E^{had}/E = 0.8/\sqrt{E}$ and $\Delta E^{ele}/E = 0.2/\sqrt{E}$. In our analysis we used the cone algorithm for the jet reconstruction with a cone size $\Delta R = \sqrt{\Delta\varphi^2 + \Delta\eta^2} = 0.7$. The choice of this jet-cone value is related to the crucial role of the final-state radiation (FSR), which strongly smears the shape of the reconstructed charged Higgs boson mass. We have checked that the value of 0.7 minimizes the FSR effects. Now, in order to decide whether a charged Higgs cross-section leads to a detectable signal, we have to compute the background rate. Since the mistagging probability of light quark and gluon jets is expected to be $\lesssim 1\%$ [16], the only significant backgrounds leading to the same $t\bar{t}$ signature are those shown in Table II along with their respective cross-sections. For the $t\bar{t}b\bar{b}$ and $t\bar{t}qg$ processes we have applied the jet separation cut $\Delta_R^{jj} > 0.5 (\Delta_R = \sqrt{\Delta\theta^2 + \Delta\phi^2})$ and the initial cut $p_T^j > 10$ GeV ($p_T^j > 20$ GeV) at the Tevatron (LHC). For the $t\bar{t}j$ process the initial cut $p_T^j > 10$ GeV ($p_T^j > 20$ GeV) was applied at the Tevatron (LHC). To obtain a realistic description of the b-tagging efficiency as a function of b-quark transverse momenta, for the Tevatron we use the projected b-tagging efficiency of the upgraded DØ detector [8] while for the LHC we parameterize numerical results from the CMS collaboration [16]. Efficiencies for both parameterizations are about 60% at the p_T^b saturation value of ~ 100 GeV. We assume that b-jets can be tagged only for pseudorapidity $|\eta_b| \le 2$ by both Tevatron and LHC experiments. Furthermore, we have optimized the reconstruction procedure, the p_T cut on the leading b-jet ($p_T^b > [M_{H^+}/5-15]$GeV) and window cut on the tb-invariant mass around the selected values of M_{H^+} ($|m_{tb} - M_{H^+}| < 5\sqrt{M_{H^+}}$) to achieve the maximal significance of the cross-section signal σ_S (1) versus the background, $\sigma_S/\sqrt{B}$. The typical efficiency at the Tevatron is $5-6\%$ while for LHC it goes down to $1-2\%$. These values include the triple b-tagging, branchings of W-bosons decays (leptonic and hadronic decay modes) and the efficiency of the kinematical cuts and reconstruction of the $t\bar{t}b\bar{b}$ signature. As an example, Figure 3 shows the reconstructed tb invariant-mass distribution for signal and background events at the LHC.

In Fig. 4 we present the discovery and exclusion limits for $H^\pm$ at the Tevatron and the LHC at high $\tan\beta$: It shows the signal cross-section σ_S and the cross-sections which would lead to the 5σ, 3σ and 1.98σ(95% CL) significance. From the intersections of the last three with σ_S we infer the mass ranges which can be discovered or excluded. The tree-level case is also shown, and it is seen to be too small at the Tevatron to place any limit. But when including SUSY effects the situation changes. We take the moderate input set B from Table I. The unknown QCD effects at NLO are estimated by including a K-factor (typically one expects $K \simeq 1.5$ [6]), and we used a bottom quark pole mass $m_b = 4.6$ GeV. For example, for $M_{H^\pm} = 215$ GeV at the Tevatron one would expect 7 signal and about 6 background reconstructed events at $L = 25$ fb^{-1}. At the LHC with $M_{H^\pm} = 500$ GeV we have 1200 and 3800 signal and background events respectively at $L = 100$ fb^{-1}. A canonical $5\,\sigma$ discovery limit around 800 GeV can be obtained at the LHC for the MSSM charged Higgs, or else an exclusion limit at 95% $C.L.$ up to at least 1.2 TeV ($K = 1$). For the Tevatron we can now place a 95% $C.L.$ exclusion limit

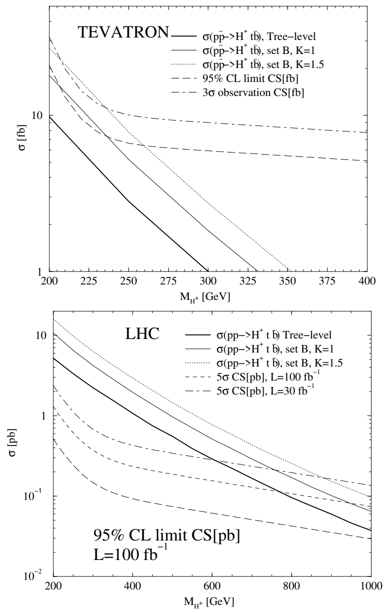

FIG. 4. Discovery and exclusion limits for the charged Higgs boson at the (a) Tevatron and (b) LHC, for $\tan\beta = 50$. Shown are the total cross-sections for: i) the signal (1) at the tree-level, ii) the SUSY corrected signal for the input set B in Table I including QCD factors $K = 1$ and $K = 1.5$, iii) the $3\,\sigma$ (Tevatron) or $5\,\sigma$ (LHC) discovery limits at the integrated luminosities $L = \int \mathcal{L}dt = 30\ fb^{-1}$ and $100\ fb^{-1}$, iv) the 95% CL exclusion limit at $L = 100\ fb^{-1}$.

in the mass range $200 - 250$ GeV, if $K = 1$. However, if the QCD factor is $K \simeq 1.5$ this would open the exciting opportunity to observe the charged Higgs already at the Tevatron with a 3σ significance in the mass range $220 - 250$ GeV!. Moreover, one should notice that b-tagging efficiency could be increased up to $\sim 70\%$ with the use of the 3D vertexing algorithms [4]. For triple b-tagging, this would augment the signal by at least a factor of 2, and so the discovery and the 95% exclusion limits would be extended accordingly. Needless to say, in case of maximal SUSY enhancement (Cf. set A) the exclusion/observation mass range for the charged Higgs boson would be further enlarged.

In summary, we have assessed the possibility to see a SUSY charged Higgs at the Tevatron and the LHC through the mechanisms (1). Our study of the quantum corrections within the MSSM has shown that at high $\tan\beta$ they are dominated by exceptionally important effects that can be absorbed into an effective $tbH^{\pm}$ vertex, and therefore in practice they can be treated as an "improved Born approximation". From a detailed signal versus background study we have shown that the prospects for the signal discovery are viable for the Tevatron (if $M_{H^\pm} \lesssim 250$ GeV) and promising for the LHC (if $M_{H^\pm} \lesssim 1.5$ TeV). In deriving these limits we have demonstrated that the quantum machinery from the MSSM can play a crucial role to increase the signal. In large portions of the parameter space the genuine SUSY corrections could show up as a smoking gun over the tree-level cross-section (after subtracting the conventional QCD effects) with a contribution of the order or larger than the QCD effects themselves. Since both the processes (1) and the SUSY effects are only relevant at high $\tan\beta$, the sole presence of the signal could be a hallmark of the underlying MSSM dynamics. A close comparison with the neutral Higgs boson production processes mentioned above should be, if available, very useful to confirm or dismiss the MSSM nature of the charged and neutral Higgs bosons.

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