Contribution of gluon fusion to the production of charged Higgs bosons at hadron colliders

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We study the production of the charged Higgs boson at future hadron colliders CERN (LHC) through the mechanism of gluon fusion ($gg \to t\bar{b}H^-$). This calculation is a good approximation for the complete allowed range of the charged Higgs boson mass. In particular, for $m_H > m_t + m_b$ our resulting cross section is similar to the one obtained using the mechanism of gluon-b fusion, whereas for $m_t > m_H + m_b$ our results reproduce the resonant behavior due to the decay $t \to H^+ + b$.

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I. INTRODUCTION

The study of the Higgs sector has become one of the most important tests of the standard model (SM) [1]. The minimal SM predicts only one neutral Higgs boson: however, in most extensions, such as the two-Higgs-doublet model [including the supersymmetry (SUSY) case], the scalar spectrum contains also a charged Higgs boson ($H^\pm$), whose detection would be a clear signal of the new physics incorporated in such models. Current data from the CERN e^+e^- collider LEP I excludes charged Higgs bosons with a mass up to about 41 GeV [2], whereas the next stages of LEP will extend the limits to about 90 GeV [3].

The production of charged Higgs bosons has been studied also at hadron colliders [3]. For light values of $m_{H^\pm}$, the decay $t \to H^+ + b$ is the dominant source of charged Higgs bosons, with the top quark being produced by gluon fusion. There are several studies [4] concluding that this decay mode can be detected at the current and future hadron colliders [Fermilab Tevatron and/or CERN Large Hadron Collider (LHC)]. On the other hand, for the mass region $m_{H^\pm} > m_t + m_b$, the production of charged Higgs boson has been studied with the reactions $b + g \to t + H^-$ and $t\bar{b} \to H^+$, using a method of calculation that treats the quarks, b, t as heavy partons [5]. However, it is not known how to detect an $H^\pm$ in this mass range because of the lack of a clear signature since in most models the dominant Higgs boson decay is into $t\bar{b}$, which seems quite difficult to be detectable due to the large QCD backgrounds.

On the other hand, if one is interested in the threshold behavior of the cross section, then neither of the previous calculations are appropriate, since they are valid only in their particular mass range. In the present paper we study the production of a charged Higgs boson through the reaction of gluon fusion, namely $g + g \to t\bar{b} + H^-$, which should give the correct behavior for the complete range of charged Higgs boson masses. Thus, we expect that our calculation will be a better approximation, since it encompasses both of the previous calculations [5].

The organization for the remainder of this paper is as follows. We present in Sec. II the relevant details of the calculation. Section III contains the results for the cross section and comments about the possible decays and signatures that could lead to the detection of $H^\pm$. Finally, Sec. IV contains our conclusions.

II. PRODUCTION OF $H^\pm$ THROUGH GLUON FUSION

The cross section for this reaction will be evaluated with the following assignment of momenta:

$$g(q_1) + g(q_2) \to t(p_1) + \bar{b}(p_2) + H^-(p_3) \ . \qquad (1)$$

The Feynman graphs for this reaction, at the parton level, are shown in Fig. 1. In order to evaluate the amplitude, we shall use the Feynman rules summarized in [3], which discusses two models, denoted as I and II, respectively. For model I the vertex $H^- t\bar{b}$ is given by

$$\frac{ig}{\sqrt{2}m_W}(m_t \cot\beta P_R + m_b \tan\beta P_L) \ , \qquad (2)$$

where $P_{R,L} = (1 \pm \gamma_5)/2$. For model II the corresponding vertex is obtained from Eq. (2) by replacing $\tan\beta \to \cot\beta$ and $\cot\beta \to \tan\beta$.

The cross section is evaluated using an expression for the phase space that helps in order to reproduce in a numerical integration the correct resonant behavior, near the threshold of the decay $t \to b + H^+$. This is done by choosing the invariant mass of the final $b - H^\pm$ pair [$s_{23} = (p_2 + p_3)^2$], as one of the integration variables in the expression for the phase space.

Thus, the cross section at the partonic level has the form

$$d^4\hat{\sigma} = \frac{1}{32(2\pi)^4 s_{23} s}|M|^2 \lambda_1 \lambda_2 ds_{23} d\beta \sin\beta d\beta_1 \sin\beta_1 d\beta_2 \ , \qquad (3)$$

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where s denotes the c.m. energy of the colliding partons (gluons), and the integration limits for s_{23} are

$$(m_{H\pm} + m_b)^2 < s_{23} < (s^{1/2} - m_t)^2 ,$$

whereas all the angles $(\beta, \beta_1, \beta_2)$ range from 0 to π. They are defined as follows: β corresponds to the orientation of $\mathbf{p}_1$ in the c.m. of the protons, and $\beta_{1,2}$ define the orientation of $\mathbf{p}_{2,3}$ in the c.m. of the $b - H^{\pm}$ subsystem. The functions $\lambda_{1,2}$ are given by $\lambda_1 = \lambda^{1/2}(s, m_t^2, s_{23})$, $\lambda_2 = \lambda^{1/2}(s_{23}, m_b^2, m_{H\pm}^2)$, where

$$\lambda(x,y,z) = (x-y-z)^2 - 4yz .$$

The squared amplitude ($|M|^2$) has been evaluated using the program REDUCE. However, we shall not present here its explicit expression, since its form is too long and not particularly illuminating.

The total hadronic cross section is obtained after convoluting with parton distributions: namely,

$$\sigma = \int_{\tau_{\min}}^{1} d\tau \frac{dL}{d\tau} \hat{\sigma}(\tau S) , \qquad (4)$$

where $\tau = s/S$, $\tau_{\min} = (m_t + m_b + m_{H\pm})^2/S$; S denotes the total c.m. energy, and $dL/d\tau$ denotes the gluon-gluon luminosity in the colliding hadrons [6].

We shall present results using the Harriman-Martin-Roberts-Stirling set B [HMRS (B)] distribution functions [7]. One the other hand, only model I will be discussed, since it is the one used in the minimal SUSY SM. Moreover, for low values of tanβ, the results for model II can be easily translated from those of model I.

III. DISCUSSION OF RESULTS

The cross section corresponding to LHC is shown in Fig. 2, as a function of $m_{H^\pm}$, for m_t = 150 GeV, and tanβ = 1, using the distribution functions of HMSR(B) set [7].

The dependence of the cross section on tanβ goes as follows. For model I, the cross section decreases (increases) for moderate large (small) values for tanβ, since in this case the part of the vertex proportional to m_t is suppressed. However, for very large values of tanβ, the contribution proportional to m_b becomes dominant and the

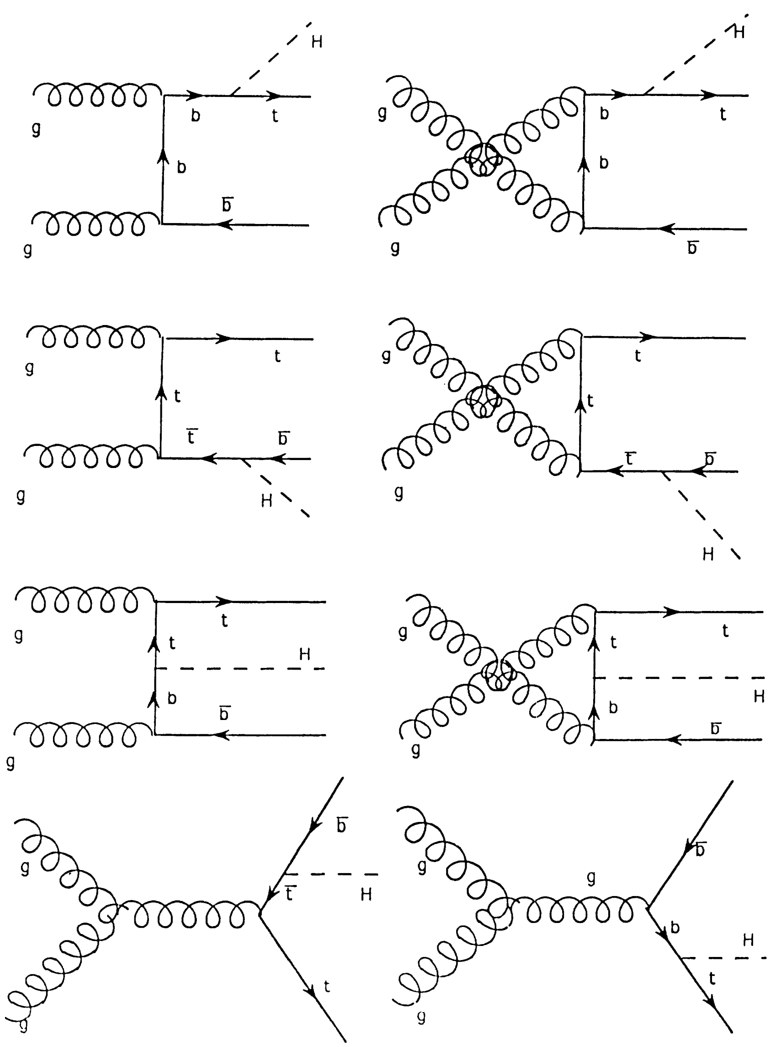

FIG. 1. Feynman graphs for the production of a charged Higgs boson in association with a pair $t\bar{b}$ at hadron colliders.

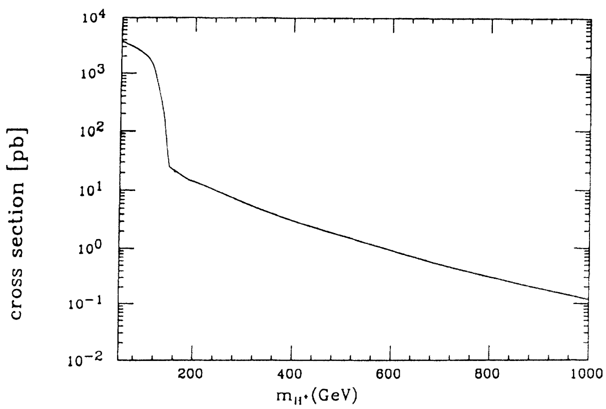

FIG. 2. Cross section for the production of $H^{\pm}$ in association with a pair $t\bar{b}$ at LHC, with HMRS(B) distribution functions, for $m_t = 150$ GeV.

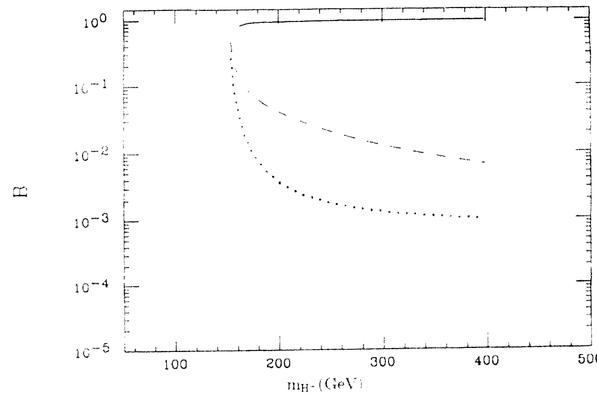

FIG. 3. Branching ratios of $H^{\pm}$ in the SUSY model for $m_t = 150$ GeV, $m_{\tilde{q}} = 500$ GeV, $\tan\beta = 2$. The solid line represents $H^+ \to t\bar{b}$; the dotted line, $H^+ \to \tau^- \nu_\tau$; the dashed line, $H^{\pm} \to W^{\pm} + h^0$.

cross section can reach similar values to the case with $\tan\beta \simeq 1$. On the other hand, for model II the cross section has the opposite behavior.

For the mass range close to the threshold of the decay $t \to b + H^+$, the gluon fusion mechanism gives the dominant contribution to the cross section. On the other hand, for the region $m_t < m_H < 1$ TeV, the gluon fusion reaction should give also a good approximation, as shown in [5].

Our results indicate that the method used in the literature [5] to calculate the cross section to produce charged Higgs bosons at hadron colliders, which includes only the $2 \to 1$ and $2 \to 2$ reactions, is a good approximation, although it has the disadvantage of its inability to reproduce the resonant behavior.

The decay of a Higgs boson into a pair $t\bar{b}$ will be difficult to observe due to the large QCD backgrounds. In order to detect this mode at hadron colliders, a good t/b separation will be required, as it has been remarked in [8]. However, when the charged Higgs boson is produced through gluon fusion, the final state includes also a pair $t + \bar{b}$, which could be used to tag the signal. Previous analysis has focused only in the top quark to tag the signal [8]. However, if it were possible to identify them with good efficiency at hadron colliders, then the b quark could be used also to tag the signal. Nevertheless, in order to determine the detector requirements that could allow the use of the b quark to tag the signal, it is necessary to make a detailed simulation study of the signal and background, which is beyond the scope of this work.[1]

Other decays that could be detected are $H^- \to \tau^- \nu_\tau$ and $H^{\pm} \to W^{\pm} + h^0$, where h^0 is the lightest neutral member of the scalar spectrum. In the minimal SUSY SM, where h^0 is lighter than $H^{\pm}$, both modes become competitive in the mass range $m_t > m_{H^{\pm}} + m_b$. We show in Fig. 3 the branching ratios of $H^{\pm}$ in the minimal SUSY SM.[2]

However, in a general two-Higgs-doublet model the τ mode may be the dominant decay, and it is detectable for the mass range $m_t > m_{H^{\pm}} + m_b$ [3]. Then, one may wonder if the τ mode could be detectable beyond such mass range. However, as Fig. 2 shows, the cross section decreases very fast beyond the threshold, and it does not help in order to allow detection of this mode. Similar conclusions hold for the decay $H^{\pm} \to W^{\pm} + h^0$.

Another possibility is to study the signature from rare decays of the charged Higgs boson, such as the decays into WZ or $E\gamma$. For example, the cross section at the Superconducting Super Collider (SSC) for $m_H = 250$ and $m_t = 150$ GeV is $\sigma = 70$ pb, then with $B(H^{\pm} \to W^{\pm} + \gamma) \simeq 10^{-4}$, and after including a leptonic decay $W^{\pm} \to l^{\pm} + \nu_l$, we end with about 14 events. Although the number of events would seem rather small, it is important to stress the fact that the possible backgrounds are not too large, as it was recognized in [8]. However, in models with elementary scalars the decay modes $H^{\pm} \to W^{\pm} + \gamma/Z$, have very small branching ratios ($\simeq 10^{-6}$) [8], whereas technicolor (TC) models predict larger values [10], but still not detectable.

IV. CONCLUSIONS

In summary, we have calculated the production of a charged Higgs boson using the gluon fusion mechanism, and we find that it could help to detect a possible charged Higgs boson at the LHC. It gives the correct behavior for masses close to the threshold of the decay $t \to H^+ + b$, and the resulting cross section beyond the threshold agrees with the one obtained from b-g fusion ($\simeq 10^2$ pb), which indicates that the use of the b quark as a parton in hadron collisions is a good approximation. However, our calculation includes explicitly an additional b quark in the final state, which could be used to tag the signal, and thus to make feasible the detection of a charged Higgs boson at the future hadron colliders.

[1] After completion of this work, it appeared a paper by Gunion [9], where a study of this type is presented, with the conclusion that it is possible to detect this reaction at LHC.

[2] We use the formulas given in [3] to evaluate the branching ratios.

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