Supersymmetric Higgs Bosons Discovery Potential at Hadron Colliders through $bg$ channel

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\section*{ABSTRACT}

We explore the discovery potential of the supersymmetric Higgs bosons through $bg$ channel at Tevatron and LHC. Compared with the process of $qq' \rightarrow WH$, this channel is more advantageous to finding the supersymmetric Higgs bosons at Tevatron if $\tan\beta$ is larger than ten.

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One of the most important physics goals for future high energy physics is the discovery of
the Higgs boson. Recent direct search in the LEP2 experiments of running at $\sqrt{s} = 183$ Gev
via the $e^+e^- \rightarrow Z^*H$ yields a lower bound of $\sim 89.9$ Gev on the standard model (SM) Higgs
mass [1]. Next year’s running at 192 Gev will explore up to a Higgs boson mass of about
96 Gev [2]. After LEP2 the search for the Higgs particles will be continued at the CERN
Large Hadron Collider (LHC) for Higgs boson masses up to the theoretical upper limit.
Before the LHC comes into operation it is worth considering whether the Higgs boson can
be discovered from the existing hadron collider, the Tevatron. Much study has been made
in the detection of a Higgs boson at the Tevatron [3]. In Ref. [2], it was pointed out that if
the Higgs boson is discovered at LEP2, it should be observed at the Tevatron’s Run II with
CM energy $\sqrt{s} = 2$ Tev and an integrated luminosity $\sim 10 fb^{-1}$, through the production
subprocess $q\bar{q}' \rightarrow WH$, followed by $W \rightarrow \ell\nu$ and $H \rightarrow b\bar{b}$, and if the Higgs boson lies beyond
the reach of LEP2, $m_H \geq (95-100)$ Gev, then a $5-\sigma$ discovery will be possible in the above
production sub-process in a future Run III with an integrated luminosity $30 fb^{-1}$ for masses
up to $m_H \approx 125$ Gev. However, we notice that this channel can’t work for large $\tan \beta$ [5].
Recently, Ref. [6] has studied the Higgs boson discovery potential of the process $gg \rightarrow H$
at Tevatron, and found that the SM-like Higgs boson could be found if its mass lie in the
range of 135 to 180 Gev. In literatures, there are also many works [8] discussing Higgs bosons
discovery abilities with b quarks at hadron colliders. For examples, in the first reference of
Ref. [8], the process $P\bar{P} \rightarrow b\bar{b}HX$, in which the actual physical subprocess of the inclusive
rate of Higgs production associated with bottom quarks is $gg \rightarrow b\bar{b}H$, has been examined.
In this paper we examine the Higgs-bottom association production $p\bar{p} \rightarrow bH(\bar{b}H)X$ in which
the actual physical subprocess is $bg \rightarrow bH$. It is evident that this process is different from
$p\bar{p} \rightarrow b\bar{b}HX$ in tagging only one b quark in our case.

As we know, the distributions of the sea b-quark and gluon grow rapidly for small x
region, when $x < 0.1$, the gluon distribution function is far larger than u quark distribution
function and the same thing occur for sea b quark when $x < 0.01$, so Tevatron and LHC are
good places to examine the bg channel.

It is well-known that the couplings of CP-even neutral Higgs bosons to down-type quarks in supersymmetric (SUSY) models are given by [9]

\[-ig m_D \cos \alpha \over 2 m_w \cos \beta\] for \(H^0 D \bar{D}\)  \\
\[-ig m_D \sin \alpha \over 2 m_w \cos \beta\] for \(h^0 D \bar{D}\). \hspace{1cm} (1,2)

When \(\tan \beta \geq 35\) the couplings of \(H^0, h^0\) to \(b\) quark can be as large as those to \(t\) quark. Therefore, it is possible to discover SUSY Higgs bosons, in particular for large \(\tan \beta\), at Tevatron through the bg channel.

Including radiative corrections, the mixing angle \(\alpha\) in eqs. (1,2) is determined by

\[
tan2\alpha = \frac{\sin^2 \beta (m_A^2 + m_Z^2) - 2 R_{12}}{\cos^2 \beta (m_A^2 - m_Z^2) + R_{22} - R_{11}}, \quad - \frac{\pi}{2} < \alpha \leq 0,
\hspace{1cm} (3)
\]

where \(R_{ij}\) are the radiative corrections to the mass matrix of the neutral Higgs bosons in the \(\{H_1^0, H_2^0\}\) basis and have been given in references [10-11]. An analysis of the couplings of Higgs bosons to vector bosons, up-type and down-type quarks in both large \(\tan \beta\) and large \(m_A\) limits has been performed [12] and some numerical results for \(\tan \beta = 1.5\) and 30 in vanishing mixing case have been given in ref. [13]. For our purpose, we shall concentrate on the general analysis of the couplings of Higgs bosons to down-type quarks, based on the results given in ref. [11]. In order to simplify discussions we assume \(m_Q = m_U = m_D = m_S\) and consider the following three representative cases.

(I) The case \(A_t = A_b = \mu = 0\)

There is no mixing between stops as well as between sbottoms in this case. It should be noted that this case is of only an academical excise (\(\mu = 0\) is ruled out by chargino and neutralino searches at LEP2). The leading corrections come from stop-loop and can be written as

\[R_{11} = R_{12} = 0,\] \hspace{1cm} (4)
\[
R_{22} = \frac{3G_F}{\sqrt{2}\pi^2} \frac{m_t^4}{\sin^2 \beta} \log(1 + \frac{m_S^2}{m_t^2}),
\]

(5)

where terms of order \( \frac{m_S^2}{m_t^2} \) (i=t, b) or \( \frac{m_S^2}{m_t^2} \) have been neglected.

(II) The case \( \mu \neq 0, A_t = A_b = 0 \)

The radiative corrections depend on \( \tan \beta \) strongly. A large mixing between sbottoms happens while the mixing between stops is still small if \( \tan \beta \) is large and \( \mu \) is not too small \footnote{In supergravity models due to the radiative electroweak symmetry breaking mechanism one usually has \( |\mu| \geq M_{1/2} \) at electroweak scale \cite{16} so that the condition is satisfied.}. With \( \mu > 100 \) Gev, \( \tan \beta \geq m_t/m_b \), and in the range of \( m_S \) from 500 Gev to 1 Tev, \( R_{12} \sim R_{11} \sim \) a few thousandth of \( R_{22} \).

(III) The case \( \mu \sim A_t \sim A_b \neq 0 \)

There is a large mixing between stops. The mixing between sbottoms is large if \( \tan \beta \) is large. In this case, for \( \mu > 100 \) Gev and \( \tan \beta \geq m_t/m_b \), the radiative corrections to non-diagonal matrix element, \( R_{12} \), can reach more than ten percents of the radiative corrections to the diagonal matrix element, \( R_{22} \), while the radiative corrections to the another diagonal matrix element, \( R_{11} \), is still far smaller than \( R_{22} \).

We calculate the cross sections of \( bg \rightarrow bh^0 \) and \( bg \rightarrow bH^0 \) in all above three cases for different \( \tan \beta \). Through the paper, \( m_A \) and \( \tan \beta \) are choosen as input parameters. The loop corrected masses of Higgs bosons \( h^0 \) and \( H^0 \) \cite{11} are used in calculations. The numerical results are given in Figs.1-2.

In Fig. 1, we show the cross sections of the processes \( bg \rightarrow bh^0 \) and \( bg \rightarrow bH^0 \) for case (I) assuming \( m_S = 1 \) Tev. From these curves, we can see that in a very wide region of \( m_H \), the cross sections are much larger than that in SM, and can reach dozens of pb at Tevatron and \( 10^3 \) pb at LHC for large \( \tan \beta \), which is due to the enhancement of the couplings of \( h_0 - b - \bar{b} \) and \( H - b - \bar{b} \) compared to the SM case. Compared with the \( q\bar{q}' \rightarrow WH \) channel, the \( bg \rightarrow bH \) channel is more advantageous to searching for SUSY Higgs bosons if \( \tan \beta \) is larger than 10, because for the \( q\bar{q}' \rightarrow WH \) channel the cross sections for the supersymmetric
Higgs bosons are always smaller than the SM case, especially for large $\tan \beta$, which is due to the suppression of $\sin(\beta - \alpha)$ [5], and the cross sections at most reach 1 pb at Tevatron for the interesting mass region of $95 - 125$ Gev. Compared with the gluon-fusion mechanism $gg \to H$ which is the dominant mechanism for neutral Higgs boson productions at LHC for small and moderate values of $\tan \beta$, the $bg \to bH$ channel can compete with it at Tevatron and LHC if $\tan \beta \geq 35$. One can also see from the figure that when the mass of the lightest Higgs boson approaches its upper limit, the cross sections come back to the SM case, which is due to the reason that the couplings of the lightest Higgs boson is the same as the SM case when its mass approaches upper limit.

From our numerical results, we find that the cross sections in the cases (II) and (III) are similar to those in the case (I) in most of range of Higgs masses (below 120 Gev for $h^0$ mass and above 140 Gev for $H^0$ mass), except in a narrow range around 130 Gev where the cross sections in the case (III) are significantly different from those in the case (I). As an examples, in Fig. 2 we show the cross sections of three cases in the narrow mass region at Tevatron. It is evident from the figure that the upper limit of $h^0$ mass for case (III) increases by about two Gev compared to case (I), while much less variations appear for case (II).

We did similar calculations for $m_S = 0.5$ Tev. And results are that the cross sections have little changes while the shift of the upper limit of $h^0$ mass is significant.

Fig. 3 and 4 are devoted to the processes $bg \to bA^0$ and $bg \to tH^−$. Since the coupling of psedoscalar Higgs boson to b quark is proportional $\tan \beta$, the cross sections increase quadratically with the increment of $\tan \beta$ and can reach several dozens pb at Tevatron. We notice that the cross section of the charged Higgs boson for $\tan \beta = 10$ is smaller than those of $\tan \beta = 2$ and 40, which is the consequence of the competitive between the couplings $m_t/\tan \beta$ and $m_b \tan \beta$.

To summarize, as a complementary process of $qq' \to WH$ and $gg \to H$, $bg$ channel could be very important in finding the supersymmetric Higgs bosons at Tevatron and LHC. In particular, it is possible to find the SUSY neutral Higgs bosons at Tevatron via $bg$ channel if $\tan \beta \geq 10$. Anyway, the real Monte Carol simulation including QCD and electro-weak
corrections is needed, and will give the further information for experiments.

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[1] P. McNamara, ICHEP ’98, Vancouver, July 1998.

[2] C. Quigg, FERMILAB-CONF-98/059-T, hep-ph/9802320.

[3] A. Stange, W. Marciano, and S. Willenbrock, Phys. Rev. D49, 1354 (1994); *ibid.* D50, 4491 (1994); S. Kim, S. Kuhlman, and W. Yao, CDF-ANAL-EXOTIC-PUBLIC-3904, Oct. 96; W. Yao, FERMILAB-CONF-96-383-E, Jun. 96; J. Womersley, D0 Note 3227, Apr. 97; S. Parke, FERMILAB-CONF-97/335-T.

[4] T. Han and S. Willenbrock, Phys. Lett. B273, 167 (1990);
J. Ohnemus and W. J. Stirling, Phys. Rev. D47, 2722 (1993);
H. Baer, B. Bailay, and J. F. Owens, Phys. Rev. D47, 2730 (1993);
S. Smith and S. Willenbrock, Phys. Rev. D54, 6696 (1996).

[5] C. S. Li and S. H. Zhu, Phys. Lett. B444, 224 (1998); Q. H. Cao, C. S. Li and S. H. Zhu, hep-ph/9810458.

[6] T. Han, R. J. Zhang, hep-ph/9807424.

[7] H. Georgi, S. Glashow, M. Machacek and D. V. Nanopoulos, Phys. Lett. 40, 692 (1978).

[8] D. Dicus, T. Stelzer, Z. Sullivan and S. Willenbrock, hep-ph/9811492; Z. Kunszt and F. Zwirner, Nucl. Phys. B385, 3 (1992); M. Drees, M. Guchait, and P. Roy, Phys. Rev. Lett. 80,
2047 (1998); Erratum 81, 2394 (1998); M. Carena, S. Mrenna, and C. Wagner, hep-ph/9808312; J. Dai, J. Gunion, and R. Vega, Phys. Lett. B345, 29 (1995); Phys. Lett. B387, 801 (1996); J. Diaz-Cruz, H.-J. He, T. Tait, and C.-P. Yuan, Phys. Rev. Lett. 80, 4641 (1998); C. Balazs, J. Diaz-Cruz, H.-J. He, T. Tait, and C.-P. Yuan, hep-ph/9807349; D. Choudhury, A. Datta, and S. Raychaudhuri, hep-ph/9809552; C. Kao and N. Stepanov, Phys. Rev. D 52, 5025 (1995); V. Barger and C. Kao, Phys. Lett. B424, 69 (1998); J. Diaz-Cruz, H.-J. He, T. Tait, and C.-P. Yuan, Phys. Rev. Lett. 80, 4641 (1998); C. Balazs, J. Diaz-Cruz, H.-J. He, T. Tait, and C.-P. Yuan, hep-ph/9807349; D. Choudhury, A. Datta, and S. Raychaudhuri, hep-ph/9809552; C. Kao and N. Stepanov, Phys. Rev. D 52, 5025 (1995); V. Barger and C. Kao, Phys. Lett. B424, 69 (1998);

[9] J. Gunion, H. Haber, G. Kane and S. Dawson, The Higgs Hunter’s Guide (Addison-Wesley, Reading, MA, 1990).

[10] Y. Okada, M. Yamaguchi and T. Yanagida, Prog. Theor. Phys. 85, 1 (1991); H. Haber and R. Hempfling, Phys. Rev. Lett. 66, 1815 (1991); J. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. B257, 83 (1991).

[11] M Carena, M. Quiros and C. Wagner, Nucl. Phys. B461, 407 (1996).

[12] W. Loinaz and J. Wells, hep-ph/9808287.

[13] H.E. Haber and G.L. Kane, Phys. Rep. 117, 75 (1985); J.F. Gunion and H.E. Haber, Nucl. Phys. B272, 1 (1986).

[14] M. Gluck, E. Reya and A. Vogt, Z. Phys. C53, 127 (1992).

[15] M. Spiral, CERN-TH/97-68 (hep-ph/9705337).

[16] M. Drees and M. M. Nojiri, Nucl. Phys. B369, 54 (1992).
FIG. 1. The total cross sections versus $m_H$ for case (I), where $m_S = 1$ Tev, and the solid and dashed lines represent the results at Tevatron and LHC, and A, B, C and D represent $\tan \beta = 2, 10, 40$ and in the SM, respectively.
FIG. 2. The total cross sections versus $m_H$, where $m_S = 1$ Tev, $\tan \beta = 40$, and the solid, dashed, dotted and dot-dashed lines represent the results for case (I), (II), (III) and in SM, respectively. For case (II), $A_t = A_b = 0$ and $\mu = -500$ Gev; for case (III), $A_t = A_b = \mu = -500$ Gev.
FIG. 3. The total cross sections versus $m_{A_0}$, where the solid and dashed lines represent the results at Tevatron and LHC, respectively, and A, B, C and D represent $\tan \beta = 2, 10, 40$ and in the SM.
FIG. 4. The total cross sections versus $m_{H^-}$, where solid and dashed lines represent the results at Tevatron and LHC, respectively, and A, B and C represent $\tan \beta = 2, 10, 40$, respectively.