Supersymmetric Higgs pair discovery prospects at hadron colliders. †

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Abstract

We study the potential of hadron colliders in the search for the pair production of neutral Higgs bosons in the framework of the Minimal Supersymmetric Standard Model. Using analytical expressions for the relevant amplitudes, we perform a detailed signal and background analysis, working out efficient kinematical cuts for the extraction of the signal. The important role of squark loop contributions to the signal is emphasised. If the signal is sufficiently enhanced by these contributions, it could even be observable at the next run of the upgraded Tevatron collider in the near future. At the LHC the pair production of light and heavy Higgs bosons might be detectable simultaneously.

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1. Introduction

The search for Higgs bosons is one of the most important tasks for experiments at present and future high energy colliders [1]. In particular, the Tevatron will soon start its next collider run with slightly increased beam energy and greatly increased luminosity; a few years later experiments at the LHC will commence taking data.

We study the production of two neutral Higgs bosons in gluon fusion, followed by the decays of both bosons into $b\bar{b}$ pairs. We focus on the final states where both Higgs bosons have (nearly) the same mass, since the resulting kinematical constraint helps to reduce the background. The SM cross section [2] is too small to be useful. However, the scalar sector of the SM suffers from well–known naturalness problems. These can be cured by introducing Supersymmetry. Here we concentrate on the simplest potentially realistic supersymmetric model, the minimal supersymmetric standard model (MSSM). Several effects can greatly enhance the Higgs pair production cross section in the MSSM as compared to the SM:

1) If $\tan\beta \gg 1$, the Yukawa coupling of the $b-$quark is enhanced by a factor $\sim \tan\beta$ compared to its SM value. It thus becomes comparable to the top quark Yukawa coupling for $\tan\beta \sim m_t(m_t)/m_b(m_t) \simeq 60$, which is possible in most realizations of the MSSM. For Higgs boson masses around 100 GeV the squared $b-$loop contribution then exceeds the $t-$loop contribution, which is suppressed by the large mass of the top quark, by a factor ~ 15 [3].

2) For some region of parameter space ($m_A \sim 300$ GeV, $\tan\beta \lesssim 4$) the branching ratio for $H \to hh$ decays is sizable. h pair production through resonant H exchange is then enhanced by a factor $(gM_W/\lambda_t\Gamma_H)^2 \sim 100$ [3].

3) Contributions from loops involving $\tilde{b}$ or $\tilde{t}$ squarks can exceed those from b and t quark loops by more than two orders of magnitude [4]. This enhancement can occur for all values of m_A and $\tan\beta$, but requires a fairly light squark mass eigenstate ($\tilde{t}_1$ or $\tilde{b}_1$), as well as large trilinear Higgs–squark–squark couplings.

2. Monte Carlo Simulation

In order to study the observability of the signal for Higgs pair production in the $4b$ final state, we have written MC generators for complete sets of signal as well as background processes. These generators were designed as new external user processes for the PYTHIA 5.7/JETSET 7.4 package [5], using a special interface.

We used the CompHEP package [6] to generate background events on the parton level.

For both signal and background, the effects of initial and final state radiation, hadronization (in the string model), as well as decay of the $b-$flavored hadrons have been taken into account through the interface with PYTHIA 5.7/JETSET 7.4. ‡

3. Signal and Background Study

We have calculated squark loop contributions to the pair production of two neutral Higgs bosons. If CP is conserved, squark loops contribute only if the two produced Higgs bosons have identical CP quantum numbers. We gave complete analytical expressions that allow the evaluation of these contributions (for details see [4]). The Feynman diagrams contributing to the $gg \to hh$, HH, hH, and AA processes are presented in Fig. 1, while the contributions to the processes $gg \to hA$ and HA are shown in Fig. 2. We take equal soft breaking contributions to diagonal entries of the stop and sbottom mass matrices ($m_{\tilde{t}_L} = m_{\tilde{t}_R} = m_{\tilde{b}_R} \equiv m_{\tilde{q}}$), as well as equal trilinear soft breaking parameters in the stop and sbottom sectors ($A_t = A_b \equiv A_q$). We fix the running masses of the top and bottom quarks to $m_t(m_t) = 165$ GeV and $m_b(m_b) = 4.2$ GeV, respectively. This leaves us with a total of 5 free parameters which determine our signal cross sections: m_A, tanβ, $m_{\tilde{q}}$, A_q and the supersymmetric higgsino mass parameter μ.

This parameter space is subject to experimental constraints [7], especially from the unsuccessful searches for Higgs bosons at LEP. We also demand that the masses of the lighter physical stop and sbottom exceed 90 GeV which follows from squark searches at LEP. We also require that the contribution from stop and sbottom loops to the electroweak $\rho-$parameter satisfies $\delta\rho_{\tilde{t}\tilde{b}} \leq 0.0017$. Finally, we only consider values of A_q and μ in the range $|A_q|$, $|\mu| \leq 3m_{\tilde{q}}$; this is necessary to avoid the breaking of electric charge and color in the absolute minimum of the scalar potential.

There are 6 different channels for producing two neutral Higgs bosons in the MSSM: HH, hh,

‡ For details see [7]

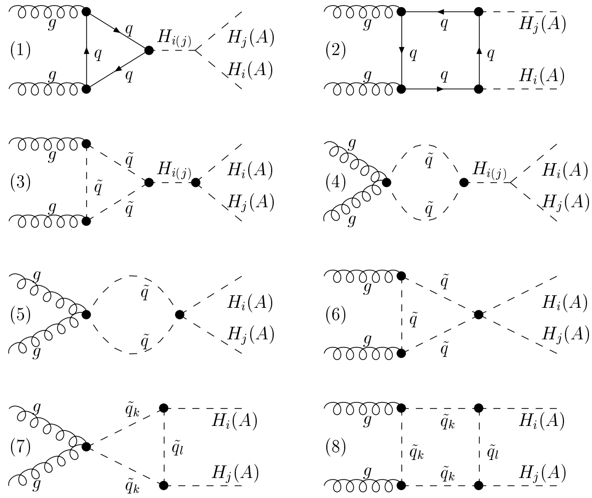

Figure 1. Feynman diagrams for hh, HH, hH, and AA Higgs boson pair production. $H_{i(j)} = h, H$ for $i(j) = 1, 2$ respectively, $\tilde{q}_{k(l)} = \tilde{q}_1, \tilde{q}_2$ for $k(l) = 1, 2$.

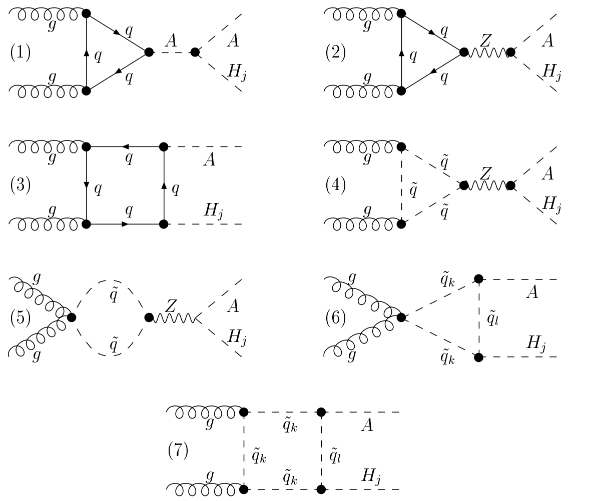

Figure 2. Feynman diagrams for the hA and HA Higgs boson pair production. $H_j = h, H$ for $j = 1, 2$ respectively, $\tilde{q}_{k(l)} = \tilde{q}_1, \tilde{q}_2$ for $k(l) = 1, 2$.

AA, Hh, HA and hA. Often several channels contribute to a given signal even after cuts have been applied, once the experimental resolution has been taken into account. The reason is that often two Higgs bosons are essentially degenerate in mass, especially for high tanβ. In our analysis we have combined contributions from different production channels assuming a Gaussian distribution for the reconstructed Higgs boson mass. We start with the diagonal process (hh, HH or AA production) giving the best signal significance, and then add all other contributions to the "search window" defined below, after resolution smearing has been taken into account. In order to give an idea of the signal rate for negligible squark loop contributions, in Fig. 3 we present contours of constant total signal cross section in fb in the $(m_A, \tan\beta)$ plane.

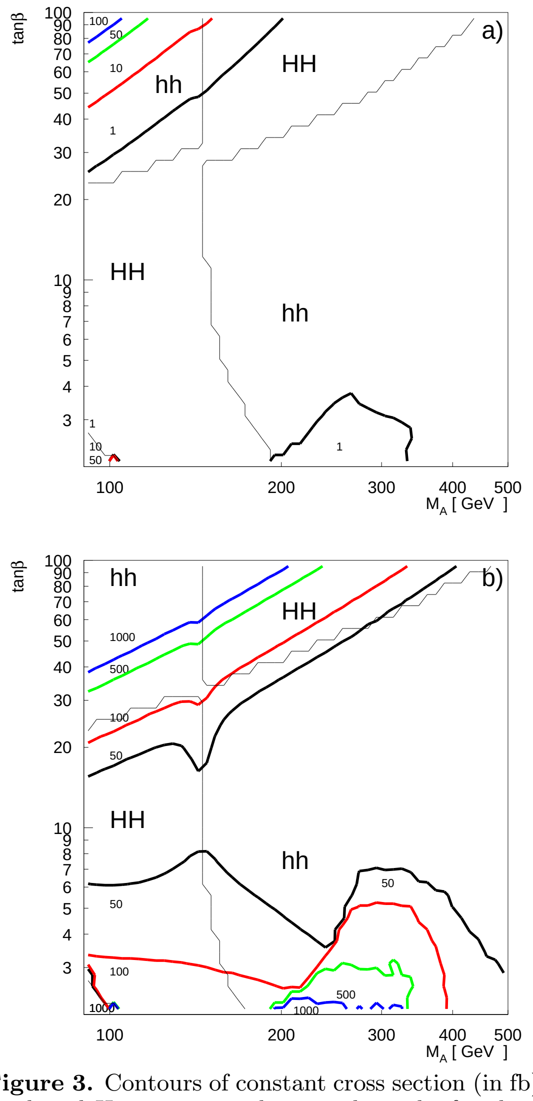

Figure 3. Contours of constant cross section (in fb) for combined Higgs pair production channels, for the case of negligible squark loop contributions for Tevatron a) and the LHC b).

The total cross section is about 200 times higher at the LHC than at the Tevatron. Given an integrated luminosity of 100 fb^{-1}, we expect well over 1,000 Higgs pair events at the LHC for all combinations of m_A and tanβ. In contrast, if squark loop contributions are indeed small, at the Tevatron the raw signal rate is often too small to give a positive signal even at TeV33 (25 fb^{-1}).

In order to decide whether a Higgs pair cross section leads to a detectable signal, we have to compute the background rate. To suppress "fake" backgrounds, we require that all four $b-$jets are tagged as such. The total cross sections for the two main irreducible backgrounds for the basic parton–level acceptance cuts $p_T > 25$ GeV, $\Delta R_{jj} > 0.5$ for Tevtron (LHC) is 1.5 (59) pb for $Zb\bar{b}$ production and 2.6 (330) pb for $b\bar{b}b\bar{b}$ production.

The cross sections for the most important "fake" backgrounds for Tevatron(LHC) are 3.1 (19.1) pb for $Wb\bar{b}$ ($Q = M_{b\bar{b}}$) and 1.6 (164) nb for $jjb\bar{b}$ ($Q = M_{b\bar{b}}$). Since the mis–tag probability of light quark and gluon jets is expected to be $\lesssim 1\%$ [9, 10], after $b-$tagging these "fake" backgrounds are much smaller than the irreducible backgrounds listed above and we therefore ignore them.

One can see that irreducible backgrounds are clearly far larger than the signal. A more elaborate set of cuts is thus necessary.

As already noted, we require all four $b-$jets to be tagged. A realistic description of the $b-$tagging efficiency is therefore very important. In case of the Tevatron, we use the projected $b-$tagging efficiency of the upgraded DØ detector [9] and CMS collaboration [10].

We assume that $b-$jets can be tagged only for pseudorapidity $|\eta_b| \leq 2$ by both Tevatron and LHC experiments.

We constructed the following kinematical variables and respective set of cuts for an efficient extraction of the signal:

1) Reconstructed Higgs boson mass, M_H: we chose the pairing that gives the smallest difference between the invariant masses of the two pairs: $M_H = [M_{b_1b_2} + M_{b_3b_4}]/2$. After resolution smearing, the distribution in M_H for the signal can be described by a Gaussian with width $\sigma \simeq \sqrt{M_H}$ (in GeV units). The search window is defined as: $0.9m_{H,in} - 1.5\sigma \leq M_H \leq 0.9m_{H,in} + 1.5\sigma$.

2) Mass difference between the invariant masses of the two pairs (small for signal): $\Delta M_H = |M_{b_1b_2} - M_{b_3b_4}| \leq 2\sigma$.

3) The angles in the transverse plane between the two jets in each pair should be large while two transverse opening angles therefore tend to be correlated: $\Delta\phi_{b_1,b_2},\ \Delta\phi_{b_3,b_4} > 1,\ \ |\Delta\phi_{b_1,b_2} - \Delta\phi_{b_3,b_4}| < 1$.

4) All four $b-$jets in the signal are fairly hard. We applied cuts on the softest and hardest of these jets, with transverse momenta $p_{T,min}$ and $p_{T,max}$:

$$\text{TEV}: p_{T,min} > M_H/8 + 1.25\sigma;\ p_{T,max} > M_H/8 + 2\sigma.$$

$$\text{LHC}: p_{T,min} > M_H/4;\ p_{T,max} > M_H/4 + 2\sigma.$$

5) The $4b$ invariant mass M_{4b}: the signal distribution for this variable is concentrated around

the invariant mass of the Higgs pair. This quantity has been shown to be useful for disentangling quark and squark loop contributions [4]:
$M_{4b} > 1.9 M_H - 3\sigma$.
The efficiency of these cuts applied plus $4b-$tagging for several input (search) Higgs boson masses is listed in the following Table for the Tevatron and LHC.

The background efficiency refers to the cross section defined through the basic acceptance cuts ($p_T(b) > 25$ GeV for all four b (anti–)quarks, and jet separation $\Delta R_{jj} > 0.5$ for all jet pairs).

TEVATRON:

$m_{H,in}$ [GeV]		120	160	200
$\epsilon_{\rm signal}$ [%]		2.10	2.74	3.30
ϵ_{Zbb} [%]		.187	.0935	.0314
ϵ_{bbbb} [%]		.137	.0318	.0072
$bbbb + Zbb$	# events	8.1	2.1	.5
$bbbb$	for	.9	.4	.1
Zbb	2 fb^{-1}	7.2	1.7	.4
signal [fb] $\cdot Br$	95% c.l.	153	78.4	45.3
signal [fb] $\cdot Br$	5σ	413	229	148
$bbbb + Zbb$	# events	101	26.3	6.6
$bbbb$	for	11.1	5.5	1.9
Zbb	25 fb^{-1}	89.9	20.8	4.7
signal [fb] $\cdot Br(4b)$	95% c.l.	37.4	14.6	7.1
signal [fb] $\cdot Br(4b)$	5σ	76.9	30.0	19.4

LHC:

$m_{H,in}$ [GeV]		120	160	200
$\epsilon_{\rm signal}$ [%]		.34	.90	1.38
ϵ_{Zbb} [%]	$4b$ tag	.0263	.0190	.0081
ϵ_{bbbb} [%]		.0142	.0112	.0071
$bbbb + Zbb$	# events	4900	3863	2419
$bbbb$	for	240	174	73.6
Zbb	100 fb^{-1}	4660	3689	2345
signal [fb] $\cdot Br$	95% c.l.	570	171	70.1
signal [fb] $\cdot Br$	5σ	1426	427	175

Table 1. Signal and background efficiencies and minimal cross sections for a 95% c.l. exclusion limit on, as well as a 5σ discovery of, Higgs boson pair production at the Tevatron and LHC.

This Table also contains results for the minimal total signal cross section times branching ratio needed to exclude Higgs boson pair production at the 95% c.l., as well as the minimal total cross section times branching ratio required to claim a 5σ discovery of Higgs boson pair production in the $4b$ final state. We give these critical cross sections for two values of the integrated luminosity at the Tevatron, characteristic for the upcoming Run II and for the final luminosity at the end of the "TeV33" run, respectively. In case of the LHC, we give results for an integrated luminosity of 100 fb^{-1}, corresponding to one year of data at full luminosity.

Systematic uncertainties are a concern especially at the LHC, where the large signal rate can lead to a very small signal to background ratio if the significance is defined using statistical errors only. We assign an systematic uncertainty of 2% on the background estimate, as obtained by extrapolation from the side bins. We thus require a minimal signal to background ratio of 0.04 for the 95% c.l. exclusion limit, and 0.1 for the 5σ discovery cross section. This requirement in fact fixes the critical cross sections at the LHC for $m_{H,in} \leq 180$ GeV.

4. Potential of Hadron Colliders for Higgs Pair Search

By comparing the results of Table 1 and Fig. 3a, it becomes clear that in the absence of sizable squark loop contributions to the signal cross section, the potential of Tevatron experiments for this search is essentially nil. In contrast, some parts of the $(m_A, \tan\beta)$ plane can be covered at the LHC even if squark loop contributions are negligible. For this pessimistic assumption of negligible squark loop contributions, LHC experiments might discover a 5σ signal if $\tan\beta$ is large ($\gtrsim 50$), and can at least exclude some regions of parameter space where $\tan\beta$ is small ($\lesssim 2.5$).

In order to illustrate the possible importance of squark loop contributions, we performed various Monte Carlo searches of the three–dimensional parameter space ($m_{\tilde{q}}$, A_q, μ). We believe that our procedure should reproduce the maximal cross section to within a factor of two or so.

The results are presented in Fig. 4, which shows the regions that can be probed with 2 and 25 fb^{-1} of data at the Tevatron (a), and with 100 fb^{-1} of data at the LHC (b). We see that now virtually the entire part of the $(m_A, \tan\beta)$ plane will give a $\geq 5\sigma$ signal at the LHC. Moreover, the entire region $m_A \leq 200$ GeV, and most of the region with $m_A \leq 300$ GeV, can be probed at the Tevatron with 25 fb^{-1} of data. Perhaps the most surprising, and encouraging, result is that a substantial region of parameter space will give a $\geq 5\sigma$ signal at the Tevatron already with 2 fb^{-1} of data! This is the first time that such a robust signal for Higgs boson production at the next run of the Tevatron collider has been suggested.

We found that, unlike for the case of negligible squark loop contribution, the most significant signal now always comes from hh production, in some cases augmented by the production of nearly degenerate Higgs bosons (hA and AA production); however, these auxiliary modes contribute much less to the total signal, since squark loop contributions to these modes are absent (for the hA channel) or relatively small (for AA production).

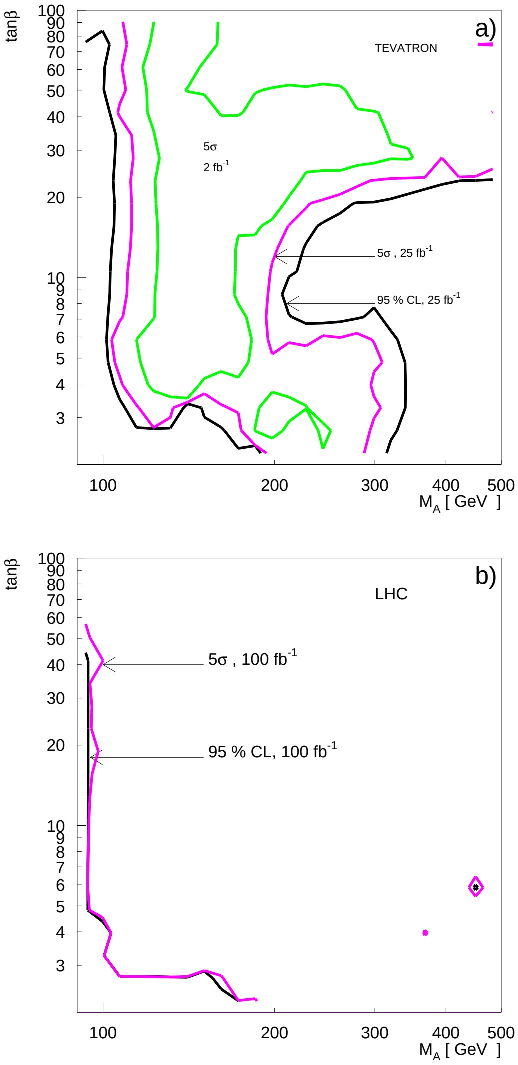

Figure 4. 95% c.l. exclusion and 5σ discovery regions for Higgs pair production at the Tevatron (25 fb^{-1}) (a) and LHC (100 fb^{-1}) (b), for "maximized" squark loop contributions. The light grey contour in (a) shows the region where a $\geq 5\sigma$ signal should be detectable at the Tevatron with just 2 fb^{-1} of data.

5. Summary and Conclusions

The main outcome of this analysis are values of the minimal total signal cross section times branching ratio required for a 5σ observation of the signal, as well as for placing 95% c.l. exclusion limits, at both the Tevatron and the LHC.

In the absence of substantial squark loop contributions, the prospects for Tevatron experiments appear to be dim. LHC experiments can then only probe scenarios with $m_A \lesssim 300$ GeV and either very large or quite small values of tanβ.

On the other hand, if squark loop contributions are nearly maximal, and if it is possible to construct an efficient trigger for events containing 4 $b-$jets with $\langle p_T \rangle \sim 50$ GeV, LHC experiments should find a signal for hh production for practically all allowed combinations of m_A and tanβ; HH production (augmented by nearly degenerate modes) should be visible for most scenarios with $m_H \leq 2m_t$. Moreover, with 25 fb^{-1} of data, Tevatron experiments would be sensitive to most of the region with $m_A < 300$ GeV; if tanβ is large, even scenarios with $m_A > 500$ GeV might be detectable. Our most exciting result is that a significant region of parameter space with $m_A \lesssim 250$ GeV should be accessible already at the next run of the Tevatron collider, which is projected to collect 2 fb^{-1} of data. This seems to be the most robust signal for the production of MSSM Higgs bosons at the Tevatron that has been suggested so far.

Acknowledgments

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References

[1] J. F. Gunion, A. Stange, and S. Willenbrock, hep–ph/9602238.
[2] E. W. N. Glover and J. J. van der Bij, Nucl. Phys. **B309**, 282 (1988).
[3] T. Plehn, M. Spira, and P. M. Zerwas, Nucl. Phys. **B479**, 46 (1996); Erratum: ibid. **B531**, 655 (1998).
[4] A. Belyaev, M. Drees, O. J. P. Éboli, J. K. Mizukoshi and S. F. Novaes, Phys. Rev. **D**60, 075008 (1999).
[5] T. Sjöstrand, Comp. Phys. Comm. **82**, 74 (1994).
[6] E. E. Boos et al., hep-ph/9503280.
[7] A. Belyaev, M. Drees, J.K. Mizukoshi, hep–ph/9909386.
[8] CTEQ collab., H. L. Lai et al., Phys. Rev. **D55**, 1280 (1997), hep–ph/9606399.
[9] Proc. of Supersymmetry/Higgs RUN II workshop, http://fnth37.fnal.gov/susy.html
[10] CMS collab., S. Abdullin et al., hep-ph/9806366