Supersymmetric Higgs pair discovery
prospects at hadron colliders †

A Belyaev 1,2, M Drees 3, O J P ’Eboli 4, J K Mizukoshi 5, and S F Novaes 4

1 CERN Theory Division, CH-1211 Geneva, Switzerland
2 Skobeltsyn Institute for Nuclear Physics, Moscow State University, 119 899, Moscow, Russia
3 Physik Department, TU München, James Franck Str., D–85748 Garching, Germany
4 Instituto de Física Teórica, Universidade Estadual Paulista, Rua Pamplona 145, 01405–900, São Paulo, Brazil.
5 Stanford Linear Accelerator Center, University of Stanford, Stanford, CA 94309, USA

Abstract
We perform a detailed study of 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. 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 each boson 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 with respect to the SM:

1) If \( \tan\beta \gg 1 \), the Yukawa coupling of the \( b \)-quark is enhanced by a factor \( \sim \tan\beta \) with respect to its SM value. It thus becomes comparable to the top quark Yukawa coupling for \( \tan\beta \sim m_t(m_t)/m_b(m_b) \sim 60 \), 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 \( \sim 15 \) [3].

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

3) Contributions from loops involving \( b \) or \( t \) 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 \( (\tilde{t}_1 \text{ or } \tilde{b}_1) \), 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].
We used the CompHEP package \cite{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 \(b\)-flavoured hadrons have been taken into account. (see \cite{7}).

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 \cite{3}). The Feynman diagrams contributing to the \(gg \rightarrow hh, HH, hH, \) and \(AA\) processes are presented in Fig. 1. We take equal soft breaking contributions to diagonal entries of the stop and sbottom mass matrices \((m_{\tilde{t}_L} = m_{\tilde{t}_R} = m_{\tilde{b}_{\tilde{L}}} \equiv m_{\tilde{b}_{\tilde{R}}} )\), as well as equal trilinear soft breaking parameters in the stop and sbottom sectors \((A_t = A_b \equiv A_{\tilde{q}})\). 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: \(m_A, \tan \beta, m_{\tilde{q}}, A_{\tilde{q}}\) and the supersymmetric higgsino mass parameter \(\mu\).

![Figure 1](image1.png)

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 \(k(l) = 1, 2\).

This parameter space is subject to experimental constraints \cite{3}, 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 \(\delta \rho_k \leq 0.0017\). Finally, we only consider values of \(A_{\tilde{q}}\) and \(\mu\) in the range \(|A_{\tilde{q}}|, |\mu| \leq 3 m_{\tilde{q}}\); this is necessary to avoid the breaking of electric charge and colour in the absolute minimum of the scalar potential.

There are 6 different channels for producing two neutral Higgs bosons in the MSSM: \(HH, hh, AA, Hh, HA\) 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 \(\tan \beta\). 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), which gives the best signal significance, and then add all other contributions to the “search window”. In order to give an idea of the signal rate for negligible squark loop contributions, we present in Fig. 2 contours of constant total signal cross section in fb in the \((m_A, \tan \beta)\) plane.

![Figure 2](image2.png)

Figure 2. Contours of constant cross section (in fb) for combined Higgs pair production channels, for the case of negligible squark loop contributions for the 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 \(\tan \beta\). 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 25 fb\(^{-1}\) luminosity.

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 be
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 the Tevatron (LHC) are 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 the Tevatron (LHC) are 3.1 (19.1) pb for $Wb\bar{b}$ ($Q = M_{bb}$) and 1.6 (164) nb for $jjb\bar{b}$ ($Q = M_{bb}$). Since the mis-tag probability of light quark and gluon jets is expected to be $\lesssim 1\%$, 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 and CMS collaboration. 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 cut set 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: $0.9m_{H,\text{in}} - 1.5\sigma \leq M_H \leq 0.9m_{H,\text{in}} + 1.5\sigma$.

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

3) The angles in the transverse plane between the two jets in each pair should be large, while the two transverse opening angles therefore tend to be correlated: $\Delta \phi_{b_1b_2}, \Delta \phi_{b_3b_4} > 1, \ |\Delta \phi_{b_1b_2} - \Delta \phi_{b_3b_4}| < 1$.

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 $p_{T,\text{min}}$ and $p_{T,\text{max}}$: TeV : $p_{T,\text{min}} > M_H / 8 + 1.25\sigma$; $p_{T,\text{max}} > M_H / 8 + 2\sigma$; LHC : $p_{T,\text{min}} > M_H / 4$; $p_{T,\text{max}} > M_H / 4 + 2\sigma$.

5) The 4$b$ invariant mass: 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: $M_{b\bar{b}} > 1.9M_H - 3\sigma$.

The efficiency of these cuts applied plus 4$b$-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:

| $m_{H,\text{in}}$ [GeV] | 120 | 160 | 200 |
|------------------------|-----|-----|-----|
| $\epsilon_{\text{signal}}$ [%] | 2.10 | 2.74 | 3.30 |
| $\epsilon_{Zbb}$ [%] | 1.187 | 0.935 | 0.314 |
| $\epsilon_{b\bar{b}b\bar{b}}$ [%] | 0.137 | 0.0318 | 0.0072 |

### LHC:

| $m_{H,\text{in}}$ [GeV] | 120 | 160 | 200 |
|------------------------|-----|-----|-----|
| $\epsilon_{\text{signal}}$ [%] | 3.4 | 9.0 | 1.38 |
| $\epsilon_{Zbb}$ [%] | 0.0263 | 0.0190 | 0.0081 |
| $\epsilon_{b\bar{b}b\bar{b}}$ [%] | 0.0412 | 0.0112 | 0.0071 |

Table 1. Signal and background efficiencies and minimal cross sections for a 95% c.l. exclusion limit on, as well as a 5$\sigma$ 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 5$\sigma$ discovery of Higgs boson pair production in the 4$b$ 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.

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 a 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 5$\sigma$ discovery cross section. This requirement in fact fixes the critical cross sections at the LHC for $m_{H,\text{in}} \leq 180$ GeV.

### Potential of Hadron Colliders for Higgs Pair Search

By comparing the results of Table 1 and Fig. 2, 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 5\(\sigma\) 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 $(m_{\tilde{q}}, A_{\tilde{q}}, \mu)$. We believe that our procedure should reproduce the maximal cross section to within a factor of 2 or so.

The results are presented in Fig. 3, which shows the region where a $\geq 5\sigma$ signal should be detectable at the Tevatron with just 2 fb$^{-1}$ of data.

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 $m_A \lesssim 200$ GeV, and most of the region with $m_A \lesssim 300$ 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.

5. Summary and Conclusions
The main outcome of this analysis consists in values of the minimal total signal cross section times branching ratio required for a 5\(\sigma\) 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 $\tan \beta$.

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 $\tan \beta$; $HH$ production (augmented by nearly degenerate modes) should be visible for most scenarios with $m_H \lesssim 2m_A$. Moreover, with 25 fb$^{-1}$ of data, Tevatron experiments would be sensitive to most of the region with $m_A < 300$ GeV; if $\tan \beta$ 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.

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