Supersymmetric models with an additional singlet field offer the Higgs boson the possibility to decay to two pseudoscalars, \( a \). If the mass of these pseudoscalars is above the \( b\bar{b} \) threshold, \( a \to b\bar{b} \) is generically the dominant decay mode. The decay \( h \to aa \to b\bar{b}b\bar{b} \) may be seen above backgrounds at the Tevatron if the Higgs production cross section is enhanced relative to that of the standard model.

In this paper we propose exploring such a scenario at the Tevatron. The Higgs boson is dominantly produced singly and subsequently decays via \( h \to aa \to b\bar{b}b\bar{b} \). We calculate the backgrounds to this signal using the multipurpose code MadEvent \([6]\). It is usually assumed, either explicitly or tacitly, that this background overwhelms the signal, and we confirm that this is the case. However, we find that if the signal is sufficiently enhanced, then it emerges from the background. This opens the question of whether there exists models with enhanced Higgs production and with a significant branching ratio for the above decay mode.

We do not restrict our study to one particular model beyond the MSSM but consider the general case, where \( M_h \) varies between 110 and 150 GeV. This approach is motivated by the fact that these extended models include a large region in parameter space with \( M_h \) in this range and with \( M_a \) between zero and 200 GeV \([8]\).

In this mass region, the SM Higgs production cross section at the Tevatron is less than 1 pb, via \( gg \to h \); however, in the MSSM the cross section is much larger for large \( \tan \beta \), with both \( gg \to h \) and \( bb \to h \) contributing \([9]\). It is an open question whether there exist extensions of the MSSM which maintain this large production rate, while at the same time yielding a significant branching ratio for \( h \to aa \to b\bar{b}b\bar{b} \).

Background.—Let us consider the general case of a scalar particle, \( h \), which almost exclusively decays to two lighter pseudoscalars (or scalars), \( a \), followed by the decay to \( b \) quarks.

The dominant background is due to QCD multijet production, with varying combinations of true \( b \) tags and mistagged jets. As we will see, we must require at least three \( b \) tags to have a reasonable signal-to-background ratio, so we have to consider the backgrounds \((j = u, d, s, c, g)\):

- \( pp \to b\bar{b}b\bar{b} \);
- \( pp \to b\bar{b}j \);
- \( pp \to b\bar{b}jj \), where one jet is mistagged;
- \( pp \to bjjj \), where two jets are mistagged;
- \( pp \to jjjj \), where three jets are mistagged.
The CDF and D0 collaborations have performed searches for neutral Higgs bosons produced in association with bottom quarks, followed by \( b \to b \bar{b} \) using a secondary-vertex trigger \([1]\). Guided by their analyses, we chose the cuts listed in Table I. The requirement on the minimum invariant mass of any two jets may not be necessary, but it eliminates many background events and therefore makes the event generation more efficient.

The different background processes sum to an enormous background of 380 nb prior to \( b \) tagging. In order to extract the signal, we must require that three or more jets are tagged. In reality, the tagging efficiency is a \( p_T \) and \( \eta \) dependent function. For simplicity, and to allow others to easily reproduce our results, we approximate the tagging efficiency and the mistag rates by the constant values listed in Table I. This overestimates the actually capabilities of the detectors, but is sufficient for a crude analysis.

Tagging three or more jets, the background drops dramatically to 63 pb. Table II lists the cross sections of the various processes, categorized by the number of \( b \) and \( c \) jets present. We see that \( b\bar{b}jj \) with one mistagged light jet makes up about half of the background, followed by \( b\bar{b}bj \) and \( b\bar{b}b \). The largest backgrounds with mistagged \( c \) jets are \( b\bar{b}cj \) and \( b\bar{b}c\), but they are relatively small.

Let us now consider different windows in the \((M_h, M_a)\)-plane, where we choose the masses of \( h \) and \( a \) to be \( M_h = 110, 130, 150 \) GeV and \( M_a = 20, 40, 60 \) GeV. The jets are paired such that their invariant masses are as close as possible. The windows have a size of 30 GeV for the invariant \( b\bar{b} \) and \( b\bar{b}b \) masses, again guided by Ref. [1]. The results are shown in Table III, the background is between 10 and 15 pb for all masses considered.

**Signal**.—The signal events have to pass the same cuts as the background processes (see Table I). Table III shows the product of the acceptance and tagging efficiency for the different choices of \( M_h \) and \( M_a \).

For a discovery of \( h \), the ratio \( S/\sqrt{B} \), where \( S \) and \( B \) are the signal and background, must be at least five. We use 2 \( fb^{-1} \) of integrated luminosity to derive the minimum signal cross section for a discovery of \( h \). We assume that all signal events pass the mass reconstruction constraints, which is a good approximation. We use an ideal branching ratio for \( h \to aa \to b\bar{b}b \) of 100%; the minimum signal cross section is increased by a factor of \( 1/BR \) for other branching ratios. The results are given in Table IV.

If one tags all four jets, the tagging efficiency for the signal drops by a factor of 5, due in part to combinatorics. Looking at Table I, one finds that the only significant background with all four jets tagged is \( b\bar{b}b \), and this also drops by the same factor of 5. Since this background \( \sqrt{7/5} \approx 1.2 \).

**Discussion**.—The minimum cross section required for discovery is an order of magnitude greater than the SM Higgs production cross section, confirming the belief that the backgrounds overwhelm the signal in this case.
TABLE V: Discovery cross section for the signal (pb) with 2 fb$^{-1}$ of data if all signal events pass the mass reconstruction constraints, assuming a branching ratio for $h \rightarrow aa \rightarrow b\bar{b}b\bar{b}$ of 100%.

| $M_h$ (GeV) | $M_a = 20$ GeV | $M_a = 40$ GeV | $M_a = 60$ GeV |
|-------------|----------------|----------------|----------------|
| $M_a = 110$ GeV | 12             | 11             | —              |
| $M_a = 130$ GeV | 7              | 9              | 3              |
| $M_a = 150$ GeV | 4              | 5              | 3              |

Increasing the integrated luminosity to 8 fb$^{-1}$ decreases the minimum cross section by a factor of two, still not enough to discover a SM-like Higgs in this decay mode. However, if there exist models in which the Higgs production cross section is enhanced by an order of magnitude, while still maintaining a significant branching ratio for $h \rightarrow aa \rightarrow b\bar{b}b\bar{b}$, then it appears possible to discover such a Higgs at the Tevatron. This is an open question in extensions of the MSSM.

Acknowledgments.—We are grateful for conversations with P. Bechtle, P. Fox, T. Junk, T. Liss and K. Pitts. S. W. thanks the Aspen Center for Physics for hospitality. This work was supported in part by the U. S. Department of Energy under contract No. DE-FG02-91ER40677.

[1] ALEPH, DELPHI, L3, OPAL and SLD Collaborations, LEP Electroweak Working Group, SLD Electroweak and Heavy Flavour Groups, Phys. Rept. 427, 257 (2006).
[2] R. Barate et al. [LEP Working Group for Higgs boson searches], Phys. Lett. B 565, 61 (2003).
[3] For a recent review, see E. Accomando et al., arXiv:hep-ph/0608079.
[4] J. F. Gunion, H. E. Haber and T. Moroi, arXiv:hep-ph/9603373; B. A. Dobrescu, G. Landsberg and K. T. Matchev, Phys. Rev. D 63, 075003 (2001); B. A. Dobrescu and K. T. Matchev, JHEP 0009, 031 (2000); U. Ellwanger, J. F. Gunion and C. Hugonie, arXiv:hep-ph/0111179; JHEP 0507, 041 (2005); U. Ellwanger, J. F. Gunion, C. Hugonie and S. Moretti, arXiv:hep-ph/0305109; arXiv:hep-ph/0401228; R. Dermisek and J. F. Gunion, Phys. Rev. Lett. 95, 041801 (2005); Phys. Rev. D 73, 111701 (2006); arXiv:hep-ph/0611142; S. Chang, P. J. Fox and N. Weiner, JHEP 0608, 068 (2006); arXiv:hep-ph/0608310; P. W. Graham, A. Pierce and J. G. Wacker, arXiv:hep-ph/0605142.
[5] S. Schael et al. [ALEPH, DELPHI, L3 and OPAL Collaborations and LEP Working Group for Higgs Boson Searches], Eur. Phys. J. C 47, 547 (2006).
[6] Scenarios where other decay channels become dominant have been studied in Refs. [4] as well.
[7] T. Stelzer and W. F. Long, Comput. Phys. Commun. 81, 357 (1994); F. Maltoni and T. Stelzer, JHEP 0302, 027 (2003).
[8] V. Barger, P. Langacker, H. S. Lee and G. Shaughnessy, Phys. Rev. D 73, 115010 (2006).
[9] For examples, see T. Hahn, S. Heinemeyer, F. Maltoni, G. Weiglein and S. Willenbrock, arXiv:hep-ph/0607308.
[10] A. A. Affolder et al. [CDF Collaboration], Phys. Rev. Lett. 86, 4472 (2001). V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 95, 151801 (2005);