Higgs Bosons with Large Bottom Quark Yukawa Coupling at the Fermilab Tevatron and CERN Large Hadron Collider

J. Lorenzo Diaz-Cruz,[1] Hong-Jian He,[2] Tim Tait,[2,3] and C.-P. Yuan[2]
[1]Instituto de Fisica, BUAP, 72570 Puebla, Pue, Mexico
[2]Michigan State University, East Lansing, Michigan 48824
[3]Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439
(Received 11 February 1998)

We study the discovery reach of the Fermilab Tevatron and the CERN large hadron collider (LHC) for detecting a Higgs boson (h), predicted in composite models of the electroweak symmetry breaking or in supersymmetric theories, with an enhanced b-quark Yukawa coupling via $p\bar{p}/pp \to b\bar{b}h(\to b\bar{b}) + X$. Our analysis shows that studying this process at the Tevatron Run II or the LHC can provide strong constraints on these models. [S0031-9007(98)06169-9]

PACS numbers: 14.80.Cp, 12.60.Jv, 13.85.Ni

The yet unverified Higgs sector in the standard model (SM) generates gauge boson masses via spontaneous electroweak symmetry breaking (EWSB) and fermion masses via Yukawa interactions. The large top quark mass, at the order of the EWSB scale, suggests that the top may play a special role in the generation of mass. This occurs in models with dynamical top-condensate/top-color scenarios [1] as well as in supersymmetric (SUSY) theories [2]. Since the bottom quark is the isospin partner of the top quark, its Yukawa coupling with a Higgs boson can be closely related to that of the top quark. Because of the small b mass ($m_b \sim 4.5$ GeV) relative to the top ($m_t \sim 175$ GeV), studying the b Yukawa couplings can effectively probe new physics beyond the SM.

In this Letter, we study the detection of a Higgs boson (h) at hadron colliders predicted by models where the bottom has an enhanced Yukawa coupling (y_b). We begin with a model-independent analysis for Higgs production associated with $b\bar{b}$ jets, $p\bar{p}/pp \to b\bar{b}h \to b\bar{b}b\bar{b} + X$, and determine the discovery reach of Tevatron Run II (a $p\bar{p}$ collider with $\sqrt{S} = 2$ TeV) and CERN large hadron collider (LHC) (a pp collider with $\sqrt{S} = 14$ TeV) for using this production mode to probe models of dynamical EWSB and SUSY theories.

To perform a model-independent analysis, we analyze the signal rate in terms of K, the factor of enhancement over the SM prediction for the $hb\bar{b} \to b\bar{b}b\bar{b}$ rate. By definition, $K = |y_b/(y_b)_{\rm SM}|^2 B(h \to b\bar{b})/B(h \to b\bar{b})_{\rm SM}$, where $y_b/(y_b)_{\rm SM}$ is the factor enhancing the h-b-$\bar{b}$ coupling relative to the SM coupling, and $B(h \to b\bar{b})$ is the branching ratio.

The relevant backgrounds to this signal at a hadron collider are QCD production of $b\bar{b}b\bar{b}$ and $b\bar{b}jj$, where j denotes a light quark or gluon, and production of $Zb\bar{b} \to b\bar{b}b\bar{b}$. We study the parton level $hb\bar{b}$ and $Zb\bar{b}$ rates at the leading order with the Monte Carlo program PAPAGENO [3]. The $b\bar{b}b\bar{b}$ and $b\bar{b}jj$ processes are also studied at the parton level, with matrix elements obtained from MADGRAPH [4]. In all cases, we include the full matrix elements for the gg as well as the $q\bar{q}$ (and in the case of the $b\bar{b}jj$ background, qg and $\bar{q}g$) initiated subprocesses, using the CTEQ4L parton distribution functions. We estimate next-to-leading order effects by including a k factor of 2 [5] for the signal and all of the background rates. We simulate the detector acceptance by requiring all four of the final state b (including $\bar{b}$) quarks to have $p_T \geq 20$ GeV, rapidity $|\eta| \leq 2$, and to be separated by a cone of $\Delta R \geq 0.4$.

In order to improve the signal to background ratio, we exploit the typical topology of the b quarks in the signal events. The h is radiated from one of the primary b quarks (by primary b quarks, we refer to those which do not result from the h decay), and thus there is typically one very energetic b quark with momentum on the order of the mass of h, m_h, balanced by the h and the other primary b, which is generally much softer. The h decays into a $b\bar{b}$ pair with typical transverse momentum on the order of $m_h/2$. Thus, in order to enhance the signal, we order the transverse momenta of the b quarks, $p_T^{(1)} \geq p_T^{(2)} \geq p_T^{(3)} \geq p_T^{(4)}$, and require $p_T^{(1)} \geq 75$ GeV, and $p_T^{(2,3)} \geq 40$ GeV. These cuts moderately reduce the signal rate by about 23%, while providing a large 90% reduction of the QCD $b\bar{b}b\bar{b}$ background. (Unless specified, our numerical results shown in this section are for detecting a scalar of mass 100 GeV at the Tevatron.)

To further improve the signal to background ratio, we find the pair of b momenta with invariant mass that best reconstructs m_h, and reject the event if the resulting invariant mass is more than Δm_h from m_h, where Δm_h is the maximum of either our estimation of the experimental mass resolution (which is assumed to be $0.10 m_h \sqrt{80\ {\rm GeV}/m_h}$ [6] or 10 GeV, whichever is higher) or the natural width (which is a calculable model-dependent quantity) of the scalar under study. We further require that the p_T of the h (taken to be the p_T of the sum of the four-momenta of the two b quarks which best reconstruct m_h) to be $\geq$50 GeV, and that the b quark with the largest p_T is not one of the two b quarks we have associated with the h decay. Because the signal generally produces an h whose p_T must balance $p_T^{(1)}$, this does not affect the signal rate, but further reduces the QCD $b\bar{b}b\bar{b}$ background by about 90%.

Finally, because the signal events typically produce a primary b and $\bar{b}$ on opposite sides of the detector, we require that the two b's which were not associated with the h decay have invariant mass $M_{bb} \geq 50$ GeV. This further reduces the QCD $b\bar{b}b\bar{b}$ background by about 60%. It is interesting to note that despite the fact that the $gg \to hb\bar{b}$ subprocess composes more than 95% of the signal rate at the Tevatron, if one applies only the basic acceptance cuts, the situation is entirely different for our optimized search strategy, for which the $q\bar{q} \to hb\bar{b}$ process makes up 93% of the signal.

In order to reduce the huge $b\bar{b}jj$ background, we require all four b quarks to be tagged, and estimate a 60% probability for tagging a b quark satisfying the cuts described above. We allow a 0.5% probability for a light quark or gluon to be mistaken for a b quark. After applying this requirement, we find that the $b\bar{b}jj$ background is very small. One can slightly improve the bounds obtained by requiring only three of the four jets to be b tagged, thus saving more of the signal rate.

In Table I we present the resulting number of events at the Tevatron (assuming 2 fb^{-1} of integrated luminosity) for the $hb\bar{b}$ signal [assuming $m_h = 100$ GeV, $\delta m_h = 10$ GeV, and $K = (m_t/m_b)^2 \simeq (39)^2$] as well as the background processes. In the second column we present the number of events after imposing the minimal acceptance cuts described above. In the third column, we show the number of events remaining after employing our optimized search strategy. In columns four and five we present the results after requiring three or four b tags, respectively. As can be seen from the table, our optimized result combined with three (four) b tags shows a significance (calculated as the number of signal events divided by the square root of the number of background events) of 43.0 (38.3). Thus it is possible to use Tevatron data to exclude this choice of parameters at better than 99%. We obtain similar results for $m_h = 100$ (200, 300, 400) GeV, finding a total number of background events (assuming four b tags and a Higgs with width less than the experimental mass resolution) of 59 (4, 2, 0) for a 10 fb^{-1} Tevatron and 2.5×10^5 (4.7×10^4, 1.7×10^4, 900) for a 100 fb^{-1} LHC.

From the results of our study we can determine the minimal value of K, $K_{\min}$, required to give a 95% C.L. deviation from the background for a given m_h, using Gaussian statistics when the number of background events is more than 10, and Poisson statistics if it is less than 10. From this we determine the curve of $K_{\min}$ versus m_h for the Tevatron Run II with 2, 10, and 30 fb^{-1}, and for the LHC with 100 fb^{-1}. We conservatively require four b tags to interpret these results in the context of the models with dynamical EWSB and the minimal supersymmetric SM (MSSM).

TABLE I. The signal and background events for 2 fb^{-1} of Tevatron data, assuming $m_h = 100$ GeV, $\Delta m_h = 10$ GeV, and $K = 39^2$.

Process	Acceptance	Optimized	3 b tagged	4 b tagged
$hb\bar{b}$	1690	979	465	127
$Zb\bar{b}$	300	54	26	7
$b\bar{b}b\bar{b}$	5071	33	16	4
$b\bar{b}jj$	5×10^7	2×10^4	73	0

Examples of the strongly interacting EWSB sector with composite Higgs boson(s) are top-condensate and topcolor models [1], in which new strong dynamics associated with the top quark play a crucial role for top and W, Z mass generation. A generic feature of these models is the naturally large Yukawa coupling of the bottom (y_b), of the same order as that of the top ($y_t \sim 1$), due to the infrared quasi-fixed-point structure [7] and their particular boundary conditions for (y_b, y_t) at the compositeness scale.

The effective theory of the top-condensate model is the SM without its elementary Higgs boson, but instead, with four-Fermi interaction terms induced from (unspecified) strong dynamics at a high scale Λ. The minimal Bardeen-Hill-Lindner (BHL) top-condensate model with three families [8] contains only one type of four-Fermi vertex for $\langle\bar{t}t\rangle$ condensation which generates the masses for the top, W, and Z, but the predicted m_t is too large to reconcile with experiment. Thus, we consider the two Higgs doublet extension (2HDE) [9] as an example (which, with some improvements [1,10], is expected to produce an acceptable m_t), and examine its prediction for the $hb\bar{b}$ rate. The four-Fermi interactions of the 2HDE model produce condensates in both $t\bar{t}$ and $b\bar{b}$ channels, which generate the EWSB and induce two composite Higgs doublets Φ_t and Φ_b so that the Yukawa interactions take the form of $y_t\ (\bar{\Psi}_L \Phi_t t_R + \text{H.c.})$ and $y_b\ (\bar{\Psi}_L \Phi_b b_R + \text{H.c.})$. Here, $\bar{\Psi}_L$ is the left-handed quark doublet and t_R is the right-handed top, etc. This model predicts $y_t(\Lambda) = y_b(\Lambda) \gg 1$ at the scale $\mu = \Lambda$ [1,9]. Therefore, $y_t(\mu) \approx y_b(\mu)$ for any $\mu < \Lambda$, because the renormalization group equations governing the running of y_t and y_b are similar except for the small difference in the t and b hypercharges [1,7]. Because of the dynamical $\langle\bar{t}t\rangle$ and $\langle\bar{b}b\rangle$ condensation, the two composite Higgs doublets develop vacuum expectation values (VEVs) $\langle\Phi_t\rangle = (v_t, 0)^T/\sqrt{2}$ and $\langle\Phi_b\rangle = (0, v_b)^T/\sqrt{2}$. Since $m_b(= y_b v_b/\sqrt{2})$ is fixed by the experimental value at $\mu = m_b$ and y_b is about equal to $y_t(\sim 1)$, this model predicts a large $\tan\beta \equiv v_t/v_b \approx m_t/m_b = O(39) \gg 1$.

The 2HDE has three neutral scalars, the lightest (with enhanced b coupling) being the pseudoscalar $P(= \sqrt{2}[\sin\beta \text{Im}\Phi_b^0 + \cos\beta \text{Im}\Phi_t^0])$, whose mass ($M_P$) is less than about 233 GeV for $\Lambda = 10^{15}$ GeV [9]. Given y_b and M_P, one can calculate the production rate of $Pb\bar{b}(\to b\bar{b}b\bar{b})$ at hadron colliders, and thus for a given M_P one can determine the minimal y_b value needed for the Tevatron and LHC to observe the signal. As shown in Fig. 1(a), the Tevatron data with 2 fb^{-1} will exclude such a model at 95% C.L.

The top-color assisted technicolor models (TCATC) [11] postulate the gauge structure $\mathcal{G} = \mathrm{SU}(3)_1 \otimes \mathrm{SU}(3)_2 \otimes \mathrm{U}(1)_1 \otimes \mathrm{U}(1)_2 \otimes \mathrm{SU}(2)_L$ at the scale above Λ to explain the dynamic origin of the four-Fermi coupling(s) in the top-condensate models. At $\Lambda \sim O(1)$ TeV, $\mathcal{G}$ spontaneously breaks down to $\mathrm{SU}(3)_c \otimes \mathrm{U}(1)_Y \otimes \mathrm{SU}(2)_L$, and additional massive gauge bosons are produced in color octet (B^a) and singlet (Z') states. Below the scale $\Lambda = \min(M_B, M_{Z'})$, the effective four-Fermi interactions are generated in the form of

$$\mathcal{L}_{4F} = \frac{4\pi}{\Lambda^2}\left[\left(\kappa + \frac{2\kappa_1}{9N_c}\right)\bar{\Psi}_L t_R \bar{t}_R \Psi_L + \left(\kappa - \frac{\kappa_1}{9N_c}\right)\bar{\Psi}_L b_R \bar{b}_R \Psi_L\right].$$

In the low energy effective theory at the EWSB scale, two composite Higgs doublets are induced with the Yukawa couplings $y_t = \sqrt{4\pi(\kappa + 2\kappa_1/9N_c)}$ and $y_b = \sqrt{4\pi(\kappa - \kappa_1/9N_c)}$, where κ and κ_1 originate from the strong $\mathrm{SU}(3)_1$ and $\mathrm{U}(1)_1$ dynamics, respectively. It is clear that, unless κ_1 is unnaturally larger than κ, y_b is expected to be only slightly below y_t. The $\mathrm{U}(1)_1$ force is attractive in the $\langle \bar{t}t \rangle$ channel but repulsive in the $\langle \bar{b}b \rangle$ channel, thus t, but not b, acquires a dynamical mass, provided $y_b(\Lambda) < y_{\mathrm{crit}} = \sqrt{8\pi^2/3} < y_t(\Lambda)$. (In this model, b acquires a mass mainly from the top-color instanton effect [11].) Furthermore, the composite Higgs doublet Φ_t, but not Φ_b, develops a VEV, i.e., $v_t \neq 0$ and $v_b = 0$.

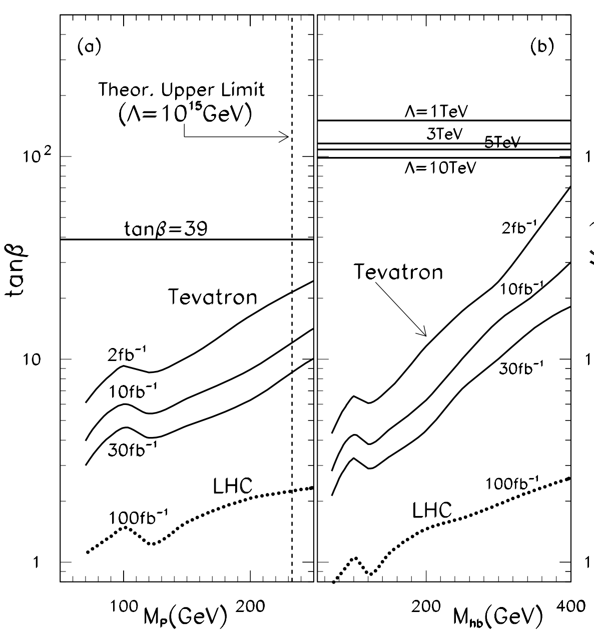

FIG. 1. Discovery reach of Tevatron and LHC for the models of 2HDE (a) and TCATC (b). Regions above the curves can be discovered at 95% C.L. In (b), the straight lines indicate $y_t(\mu = m_t)$ values for typical values of the top-color breaking scale Λ, and y_b is predicted to be very close to y_t.

In TCATC, the top-color interaction generates m_t but is not responsible for the entire EWSB. Thus, Λ can be as low as $O(1-10)$ TeV (which avoids the severe fine-tuning needed in the minimal models [8,9]), and correspondingly, $v_t = 64-88$ GeV for $\Lambda = 1-5$ TeV by the Pagels-Stokar formula. The smaller v_t value (as compared to $v = 246$ GeV) predicted in the TCATC model makes the top coupling to Φ_t stronger, i.e., $y_t = 2.8-3.9$ at $\mu = m_t$, than in the SM ($y_t \sim 1$). As explained above, this requires y_b to be also large. Thus, the neutral scalars h_b and A_b in the doublet Φ_b, which are about degenerate in mass, have an enhanced coupling to the b quark.

In Fig. 1(b), we show the minimal value of $y_b/(y_b)_{\mathrm{SM}}$ needed to observe the TCATC model signal as a function of M_{h_b}. As shown, if M_{h_b} is less than about 400 GeV, the Tevatron Run II data can effectively probe the scale of the top-color breaking dynamics, assuming the TCATC model signal is observed. If the signal is not found, the LHC can further explore this model up to large M_{h_b}. For example, for $M_{h_b} = 800$ GeV, the required minimal value of $y_b/(y_b)_{\mathrm{SM}}$ is about 4.9 at 95% C.L. Similar conclusions can be drawn for a recent left-right symmetric extension [12] of the top-condensate scenario, which also predicts a large b-quark Yukawa coupling.

The EWSB of the MSSM model includes two Higgs doublets with a mass spectrum including two neutral CP-even scalars h^0 and H^0, one CP-odd pseudoscalar A^0 and a charged pair $H^{\pm}$. The Higgs sector is completely determined at tree level by fixing two parameters, conventionally chosen to be $\tan\beta$ and the pseudoscalar mass m_A [13]. In this study we employ the full one loop results [14,15] to generate the Higgs mass spectrum assuming all sfermion masses, μ, scalar trilinear parameters, and $\mathrm{SU}(2)_L$ gaugino masses at the electroweak scale are equal to 500 GeV. We find that our results are fairly insensitive to this choice of parameters.

$\tan\beta$ is a free parameter of the MSSM. The current low energy bound gives $m_h, m_A > 75$ GeV for $\tan\beta > 1$ [16]. Since the couplings of h^0-b-$\bar{b}$, H^0-b-$\bar{b}$ and A^0-b-$\bar{b}$ are proportional to $\sin\alpha/\cos\beta$, $\cos\alpha/\cos\beta$, and $\tan\beta$, respectively, they can receive a large enhancing factor when $\tan\beta$ is large. This can lead to detectable $b\bar{b}b\bar{b}$ signal events at the Tevatron, as previously studied in Ref. [17]. Here, we improve the calculations in the signal and the background rates and the prediction of the MSSM by including large loop corrections. We calculate the enhancement factor K predicted by the MSSM for given values of $\tan\beta$ and m_A. In Fig. 2 we present the discovery reach of the Tevatron and the LHC, assuming a stop mass of 500 GeV and that all of the superparticles are so heavy that Higgs bosons will not decay into them at tree level. The branching ratio for $h \to b\bar{b}$ is close to one for most of the parameter space above the discovery curves. Moreover, for $\tan\beta \gg 1$, the h^0 is nearly mass degenerate with the A^0 (if m_A is less than $\sim$120 GeV) and otherwise with H^0. We thus include both scalars in the signal rate provided their masses differ by less than Δm_h.

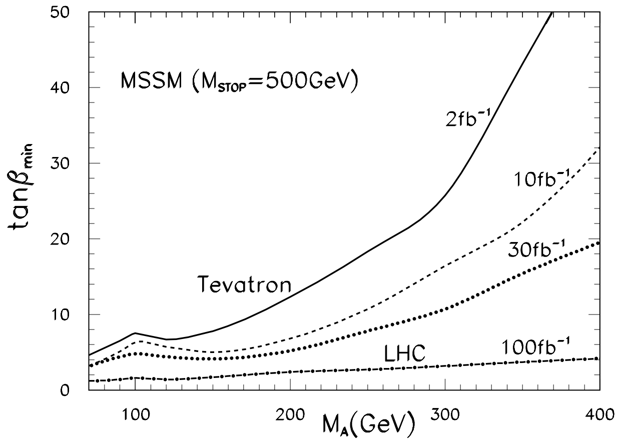

FIG. 2. The regions above the curves in the $\tan\beta$-m_A plane can be probed at Tevatron and LHC with a 95% C.L.

The MSSM can also produce additional $b\bar{b}b\bar{b}$ events through production of $h^0Z \to b\bar{b}b\bar{b}$ and $h^0A^0 \to b\bar{b}b\bar{b}$; however, these rates are expected to be relatively small when the Higgs-bottom coupling is enhanced, and the resulting kinematics are different from the $hb\bar{b}$ signal. Thus we conservatively do not include these processes in our signal rate.

From Fig. 2 we deduce that if a signal is not found, the MSSM with $\tan\beta > 23$ (16, 12) can be excluded for m_A up to 200 GeV at the 95% C.L. by Tevatron data with a luminosity of 2 (10, 30) fb^{-1}, while the LHC can exclude a much larger m_A (for $m_A = 800$ GeV, the minimal value of $\tan\beta$ is about 7.4). These Tevatron bounds thus improve a recent result obtained by studying the $b\bar{b}\tau\tau$ channel [18]. We note that studying the $hb\bar{b}$ mode can probe an important region of the $\tan\beta$-m_A plane which is not easily covered by other production modes at hadron colliders, such as $pp \to t\bar{t} + h(\to \gamma\gamma) + X$ and $pp \to h(\to ZZ^*) + X$ [19]. Also, in this region of parameter space the SUSY Higgs boson h^0 is clearly distinguishable from a SM one.

The above results provide a general test for many SUSY models, for which the MSSM is the low energy effective theory. In the MSSM, the effect of SUSY breaking is parametrized by a large set of soft-breaking (SB) terms [$\sim O(100)$], which, in principle, should be derived from an underlying model. We discuss, as examples, the supergravity and gauge-mediated (GM) models with large $\tan\beta$. In the supergravity-inspired model [20] the SUSY breaking occurs in a hidden sector at a very large scale, of $O(10^{10-11})$ GeV, and is communicated to the MSSM through gravitational interactions. In the simplest model of this kind, all of the SB parameters are expressed in terms of five universal inputs. The case of large $\tan\beta$, of $O(10)$, has been examined within this context [21], and it was found that in such a case $m_A \sim 100$ GeV. Hence, these models can be cleanly confirmed or excluded by measuring the $b\bar{b}b\bar{b}$ mode at the Tevatron and LHC.

The GM models assume that the SUSY-breaking scale is much lower, of $O(10^{4-5})$ GeV, and the SUSY breaking is communicated to the MSSM superpartners by ordinary gauge interaction [22]. This scenario can predict large $\tan\beta(\sim 30-40)$. However, in some models, it favors $m_A \gtrsim 400$ GeV [23], which would be difficult to test at the Tevatron, although quite easy at the LHC. Nevertheless, in some other models, a lighter pseudoscalar is possible (for instance, $\tan\beta = 45$ and $m_A = 100$) [24], and the $b\bar{b}b\bar{b}$ mode at hadron colliders can easily explore such a SUSY model.

In conclusion, the large QCD production rate at a hadron collider warrants the detection of a light scalar with large h-b-$\bar{b}$ coupling. At LEP-II and future e^+e^- linear colliders, because of the large phase space suppression factor, the $b\bar{b}A$ and $b\bar{b}h$ rates predicted by the MSSM are dominated by the production of Ah and hZ pairs via electroweak interaction. Hence, the e^+e^- collider is less able to directly probe the h-b-$\bar{b}$ coupling.

We thank E. L. Berger, B. A. Dobrescu, S. Mrenna, C. Schmidt, R. Vilar, and H. Weerts for useful discussions. J. L. D. C. is supported by the CONACYT-NSF international agreement, and H. J. H. and C. P. Y. by the U.S. NSF. T. T. was supported by ANL HEP division under U.S. DOE Contract No. W-31-109-Eng-38.

[1] For a review, see G. Cvetic, hep-ph/9702381.
[2] For a review, see, e.g., M. Dine, hep-ph/9612389.
[3] I. Hinchliffe, Proceedings of the Argonne Accelerator Physics Conference, 1993, p. 679 (unpublished).
[4] W. F. Long and T. Stelzer, Comput. Phys. Commun. **81**, 357 (1994).
[5] M. Mangano *et al.*, Nucl. Phys. **B373**, 295 (1992).
[6] D. Amidei and R. Brock, TeV2000 Report, 1995 (unpublished).
[7] C. T. Hill *et al.*, Nucl. Phys. **B262**, 517 (1985).
[8] W. Bardeen, C. Hill, and M. Linder, Phys. Rev. D **41**, 1647 (1990).
[9] M. A. Luty, Phys. Rev. D **41**, 2893 (1990).
[10] B. A. Dobrescu and C. T. Hill, hep-ph/9712319.
[11] C. T. Hill, Phys. Lett. B **345**, 483 (1995).
[12] M. Lindner and E. Schnapka, hep-ph/9712489.
[13] J. Gunion and H. Haber, Nucl. Phys. **B272**, 1 (1986).
[14] H. Haber, hep-ph/9707213, and references therein.
[15] M. Carena *et al.*, hep-ph/9508343; A. Djouadi *et al.*, hep-ph/970448.
[16] A. Sopczak, hep-ph/9712283.
[17] J. Dai, J. Gunion, and R. Vega, Phys. Lett. B **387**, 801 (1996).
[18] M. Drees *et al.*, hep-ph/9801229.
[19] J. Gunion and L. Orr, Phys. Rev. D **46** 2052 (1992); J. L. Diaz-Cruz and O. Sampayo, J. Mod. Phys. A **8** 4339 (1993).
[20] R. Arnowitt and P. Nath, hep-ph/9708254.
[21] M. Drees and M. Nojiri, Nucl. Phys. **B369**, 54 (1992).
[22] M. Dine *et al.*, Phys. Rev. D **53**, 2658 (1996).
[23] R. Rattazzi and U. Sarid, hep-ph/9612464.
[24] J. Bagger *et al.*, Phys. Rev. D **55**, 3188 (1997); H. Baer *et al.*, Phys. Rev. D **55**, 4463 (1997).