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(Received 11 July 2012; published 6 November 2012)

The combination of searches performed by the CDF and D0 collaborations at the Fermilab Tevatron Collider for neutral Higgs bosons produced in association with b quarks is reported. The data, corresponding to 2.6 fb^{-1} of integrated luminosity at CDF and 5.2 fb^{-1} at D0, have been collected in final states containing three or more b jets. Upper limits are set on the cross section multiplied by the branching ratio varying between 44 pb and 0.7 pb in the Higgs boson mass range 90 to 300 GeV, assuming production of a narrow scalar boson. Significant enhancements to the production of Higgs bosons can be found in theories beyond the standard model, for example, in supersymmetry. The results are interpreted as upper limits in the parameter space of the minimal supersymmetric standard model in a benchmark scenario favoring this decay mode.

DOI: [10.1103/PhysRevD.86.091101](https://doi.org/10.1103/PhysRevD.86.091101)

PACS numbers: 14.80.Da, 12.38.Qk, 12.60.Fr, 13.85.Rm

In the standard model (SM), electroweak symmetry breaking is achieved through the introduction of a single scalar doublet field, and the existence of a single neutral scalar boson [1–6] is predicted. However, extensions of the SM exist with richer structure. Introducing a second Higgs doublet, such as in type II 2-Higgs doublet models (2HDM) [7], leads to multiple scalar bosons and can give scenarios with enhanced couplings to down-type fermions. Supersymmetry is a plausible extension to the SM that introduces an additional symmetry between fermions and bosons. The two Higgs boson doublets in the minimal supersymmetric standard model (MSSM) [8,9] lead to five physical Higgs bosons: three neutral (collectively denoted as ϕ): h , H , and A ; and two charged: H^+ and

H^- . At leading order the MSSM is a type II 2HDM model, and two parameters are sufficient to describe the Higgs sector. These are conventionally chosen as the ratio of the two Higgs doublet vacuum expectation values, $\tan\beta$, and, M_A , the mass of the pseudoscalar boson, A . The couplings to the down-type fermions are enhanced by a factor of $\tan\beta$ relative to those in the SM. Thus, the main decay mode is $\phi \rightarrow b\bar{b}$, with branching fractions near 90% at leading order (the remainder being mostly $\phi \rightarrow \tau^+\tau^-$). While searches for τ -lepton-pair final states at hadron colliders are relatively insensitive to higher-order radiative corrections, due to cancellations between the production and decay processes, this is not the case for decays to $b\bar{b}$. Thus, information from decays to $b\bar{b}$ together with

stringent limits from decays to $\tau^+ \tau^-$ can constrain higher-order effects and yield additional information about electroweak symmetry breaking, supersymmetry, or other new physics beyond the SM with similar final states such as pair production of color octet scalars [10–12].

Since an inclusive search for $\phi \rightarrow b\bar{b}$ is difficult due to large multijet backgrounds, these searches rely on the case where the ϕ boson is produced in association with one or more b quarks. This final state with at least three b quarks represents a powerful search channel, with the third b jet providing additional suppression of the large multijet background at a hadron collider.

MSSM Higgs boson production has been studied at the CERN LEP $e^+ e^-$ collider excluding $M_{h,A} < 93$ GeV for all $\tan\beta$ values [13]. The CDF [14–16] and D0 [17–26] collaborations extended such searches to higher masses and for large $\tan\beta$. The most stringent upper limits on $\tan\beta$ in searches for neutral Higgs production for masses above the LEP bounds come from searches in final states with τ leptons pair produced at the Large Hadron Collider [27–29].

The results reported in this paper make use of $p\bar{p}$ collisions at a center of mass energy of 1.96 TeV. The data, corresponding to integrated luminosities of 2.6 fb^{-1} and 5.2 fb^{-1} , were collected during Run II at the Fermilab Tevatron Collider by the CDF and D0 collaborations, respectively. The combination of searches for neutral Higgs bosons in final states with three or more b jets [16,23] is presented.

The CDF and D0 detectors are described in Refs. [30–33]. A brief outline of the reconstruction of the final states and event selection used in these searches follows. A cone algorithm [34] with a radius of $\mathcal{R} = \sqrt{(\Delta y)^2 + (\Delta\varphi)^2} = 0.7$ (CDF) and 0.5 (D0), where y is the rapidity and φ the azimuthal angle, is used to reconstruct jets from energy deposition in the calorimeters. Identification of jets arising from b -quark fragmentation (b tagging) uses an algorithm based on reconstructing secondary vertices of charged particles displaced from the $p\bar{p}$ interaction vertex at CDF [35] and a neural network combining lifetime information from secondary vertices and the minimum distance of approach of charged particle trajectories to the primary interaction at D0 [36]. The performance of the b -tagging algorithms and the associated probabilities for jets to pass the tagging requirements are assessed from control samples in data.

Events are selected at CDF with dedicated online event selections (triggers) requiring at least two jets and using b -tagging information, while at least three jets are required at D0. For most of the data collected at D0, b -tagging information is also used in the trigger decision. Events are selected offline with at least three jets within the fiducial region. This is defined by requirements on the momentum transverse to the proton beam direction, p_T , and detector pseudorapidity, $\eta_{\text{det}} = -\ln(\tan(\theta/2))$, of jets, where θ is the polar angle with respect to the proton beam direction and an origin at the center of the detector: three

jets with $p_T > 20$ GeV and $|\eta_{\text{det}}| < 2.0$ at CDF and three jets with $p_T > 20$ GeV and at least two jets with $p_T > 25$ GeV, $|\eta_{\text{det}}| < 2.5$ at D0. Events with more jets are accepted at CDF but only the four jets with the highest p_T are used in the analysis. Exclusive channels with exactly three or exactly four jets are used at D0. The signal sample is defined by both experiments requiring at least three b -tagged jets, without distinguishing between those jets arising from b quark and anti- b quark fragmentation. In the CDF inclusive and the D0 four-jet channel the first two jets, ordered by decreasing p_T , and at least one of the third and fourth jets are required to be b tagged. In addition, a large sample requiring only two b -tagged jets is used by both experiments to build models of the multijet backgrounds.

At CDF, the background is modeled using a sum of templates of the invariant mass distribution of the two jets with the highest p_T , representing contributions from different background modes categorized according to kinematics and flavor content. The templates are constructed from events in the double-tagged data sample where at least one of the two highest p_T jets is b tagged. The events are then weighted according to the probability for at least one of the jets with no b tag to pass the tagging requirements under three different assumptions as to whether it arises from a b quark, a c quark, or a light quark (or gluon). This results in six different mass templates. The separation between the different components is enhanced by using an additional jet-flavor-sensitive discriminant, x_{tags} , that makes use of kinematic properties of the charged particles from secondary vertices associated with each b -tagged jet.

In the D0 analysis the background model is formed by correcting the shape of the dijet invariant mass distribution of a data sample with two b -tagged jets using the ratio of simulated multijet samples with three b tags and two b tags. The simulated samples are generated using ALPGEN [37] with showering and hadronization carried out using PYTHIA [38] and detailed simulation of the detector using GEANT [39]. Their flavor composition, in terms of the relative numbers of b , c , and light jets per event, is determined from a simultaneous fit to the data across samples with differing numbers of tagged jets, different b -tag operating points, and in small intervals of the scalar sum of the transverse momenta of the jets. The shape correction is applied as a function of the dijet invariant mass and the value of a likelihood-ratio discriminant, \mathcal{L} , designed to select signal-like events in preference to backgroundlike events. Only the two jet pairings from the highest p_T jet plus either the second or third highest p_T jet are considered when forming Higgs candidates, and the choice that gives the highest value of $\mathcal{L} > 0.65$ is selected. If neither pairing in the event is above this threshold then the event is discarded. Systematic uncertainties are assessed to take into account the imperfect modeling of the background simulation. However, the definition of the correction as a

ratio of distributions significantly reduces the sensitivity of the final model to these imperfections. Small contributions to the background from top-quark-pair production are simulated using ALPGEN and PYTHIA. Backgrounds from other sources, such as $Z \rightarrow b\bar{b}$ and single-top-quark production are negligible.

The efficiency for selecting signal is estimated for both analyses using events generated with PYTHIA. Associated production of a ϕ boson and a b quark, $gb \rightarrow \phi b$, with subsequent decay $\phi \rightarrow b\bar{b}$, is used to model the signal. The signal cross section, experimental acceptance, and the kinematics are corrected to next-to-leading order using MCFM [40,41], weighting events as a function of the kinematics of the highest p_T b -quark jet not associated with the Higgs decay.

Approximately 11 500 events are selected by CDF with at least three b tags and an estimated product of signal efficiency and acceptance varying as a function of M_ϕ between 0.18% at $M_\phi = 90$ GeV and 0.8% at $M_\phi = 200$ GeV. Approximately 15 000 and 11 000 events with at least

three b -tagged jets are accepted in the D0 three-jet and four-jet channels, respectively. The corresponding signal efficiencies for a Higgs of mass $M_\phi = 200$ GeV are 1.2% and 0.6%.

The channels are combined and exclusion limits set, using the modified frequentist technique [42,43], with a log likelihood ratio (LLR) as the test statistic:

$$\text{LLR} = -2 \ln \frac{p(X|H_1)}{p(X|H_0)}, \quad (1)$$

where p represents the probabilities that the data, X , are drawn from the background-only (H_0), and signal-plus-background (H_1) hypotheses, respectively. The likelihoods are constructed from the binned two-dimensional distribution of the dijet invariant mass versus the x_{tags} discriminant for CDF and the binned one-dimensional dijet invariant mass distribution for D0. Theoretical predictions of the absolute rates for the multijet backgrounds have large uncertainties. Therefore, additional scale factors are

TABLE I. Observed and expected upper limits at the 95% C.L., and the best-fit value, $\hat{\mu}$, on the product of cross section and branching ratio $\sigma(p\bar{p} \rightarrow \phi bX) \times BR(\phi \rightarrow bb)$, within the acceptance for the highest p_T b quark not arising from the Higgs decay [41]. Expected limits are given for the median and for ± 1 and ± 2 standard deviation (s.d.) variations of the background expectation. Values for the best-fit signal are extracted without a constraint that they remain positive.

M_ϕ (GeV)	Obs. (pb)	-2 s.d.	Expected upper limit (pb)			$\hat{\mu}$ (pb)	
			-1 s.d.	median	+1 s.d.		+2 s.d.
90	38	30	41	57	81	110	-42^{+28}_{-28}
100	43	22	30	42	62	86	1.6^{+20}_{-18}
110	43	15	20	27	39	53	21^{+14}_{-13}
120	44	12	15	20	29	39	27^{+9}_{-9}
130	25	8.1	9.6	14	19	25	15^{+7}_{-7}
140	26	5.1	7.3	10	14	20	16^{+6}_{-5}
150	18	4.1	5.5	7.4	11	15	11^{+5}_{-4}
160	12	3.3	4.5	6.0	8.5	12	$6.5^{+3.5}_{-3.1}$
170	9.4	2.5	3.6	5.0	7.0	9.5	$5.1^{+3.1}_{-2.6}$
180	7.1	2.4	3.2	4.2	6.0	8.2	$3.3^{+2.2}_{-2.0}$
190	5.7	2.2	2.5	4.0	5.0	7.0	$2.4^{+1.8}_{-1.6}$
200	5.0	2.0	2.4	3.0	4.4	6.0	$2.2^{+1.5}_{-1.4}$
210	3.8	1.6	2.2	2.6	3.7	5.0	$1.3^{+1.2}_{-1.1}$
220	3.3	1.2	1.7	2.2	3.2	4.7	$1.1^{+1.1}_{-1.0}$
230	2.5	1.0	1.5	2.0	3.0	4.1	$0.55^{+0.95}_{-0.87}$
240	2.0	0.9	1.2	1.8	2.5	3.5	$0.27^{+0.79}_{-0.76}$
250	2.0	0.9	1.1	1.6	2.3	3.2	$0.23^{+0.67}_{-0.64}$
260	1.7	0.7	1.0	1.4	2.2	2.8	$0.27^{+0.59}_{-0.56}$
270	1.3	0.7	0.9	1.2	2.0	2.4	$0.09^{+0.51}_{-0.49}$
280	1.1	0.6	0.8	1.1	1.7	2.4	$0.00^{+0.45}_{-0.43}$
290	0.82	0.6	0.8	1.1	1.9	2.4	$-0.43^{+0.42}_{-0.42}$
300	0.71	0.5	0.7	1.0	1.6	2.3	$-0.50^{+0.38}_{-0.38}$

applied to the background yield in the D0 analysis and the individual templates in the CDF analysis and introduced into the likelihood as parameters with no external constraints. Systematic uncertainties are introduced as either shape or normalization variations to the model probability density functions. These systematics are governed by nuisance parameters together with Gaussian constraint terms where appropriate [44]. Sources of uncertainty related to a common component of the luminosity determination and the theoretical modeling of the signal production are considered fully correlated. All other sources of uncertainty are assumed to be uncorrelated. The modeling of the b -jet-tagging efficiency and the contamination from light-quark and gluon jets are the dominant sources of uncertainty on the background model. These are implemented as uncertainties that affect the shape of the distributions entering the likelihood. Additional subdominant uncertainties are considered in the D0 analysis arising in the modeling of the trigger, jet efficiency, jet energy scale, and jet resolution. While most of those effects have a negligible impact on the background model, effects that are dependent on the differences between b , light, and gluon jets can be significant. Dominant experimental systematic uncertainties on the signal model can be attributed to luminosity (6%), b -tagging efficiency (11%–18%), and jet energy scale (2%–10% depending on the ϕ boson mass hypothesis).

Limits on the product of the cross section and the branching ratio using the LLR test statistic are extracted. The limits are model independent, apart from assuming a single narrow Higgs boson mass peak, dominated by experimental resolution effects. Together with the best-fit value of the product of the signal cross section times branching ratio, these are summarized in Table I, and presented in Fig. 1. The combination gives a sensitivity that is better than the D0 expected limit alone by $\approx 25\%$ at $M_\phi = 100$ GeV, steadily

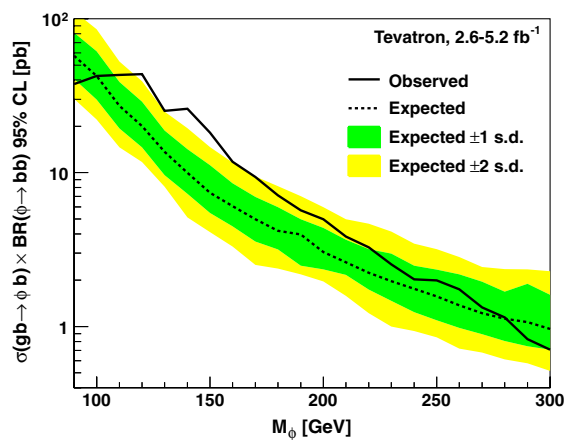


FIG. 1 (color online). Model-independent 95% C.L. upper limits on the product of cross section and branching ratio for the combined analyses, assuming a Higgs boson width significantly smaller than the experimental resolution. The dark and light shaded regions correspond to the one and two standard deviation bands around the median expected limit.

falling to $<1\%$ by $M_\phi = 300$ GeV. Excesses of events above the SM background expectation are observed for $M_\phi = 120$ and 140 GeV with significances of 2.5 standard deviations and 2.6 standard deviations, respectively. These are driven by the excesses observed in the individual contributing analyses of 2.8 standard deviations at $M_\phi = 150$ GeV at CDF and 2.5 standard deviations at $M_\phi = 120$ GeV at D0. A standard convention [45] is used to account for the effect that it is more likely to find a deviation (under the background-only) hypothesis when several mass regions are probed compared with only a single hypothesis. The significance of the excesses in the combined analysis is reduced to ≈ 2 standard deviations.

Though these limits are the key results of this search, it is interesting to interpret them in terms of constraints on benchmark models within the MSSM. As a consequence of the enhanced couplings to b quarks at large $\tan\beta$, the total width of the Higgs boson increases with $\tan\beta$. When this width becomes comparable to the experimental resolution of 15%–20% there is an impact on the sensitivity of the search. When interpreting the exclusion within the MSSM, the width of the Higgs boson and the enhancement of the product of cross section and branching ratio above that of the SM are calculated using FEYNHIGGS [46–51]. The width is included in the simulation of the signal as a function of mass and $\tan\beta$ by convoluting a relativistic Breit-Wigner function with the next-to-leading order cross section [40]. Additional uncertainties for these model-specific limits are considered that otherwise cancel in the model-independent limit. For comparison these are derived as in previous results [16,20,23]: uncertainties on the SM signal cross section are derived from varying the

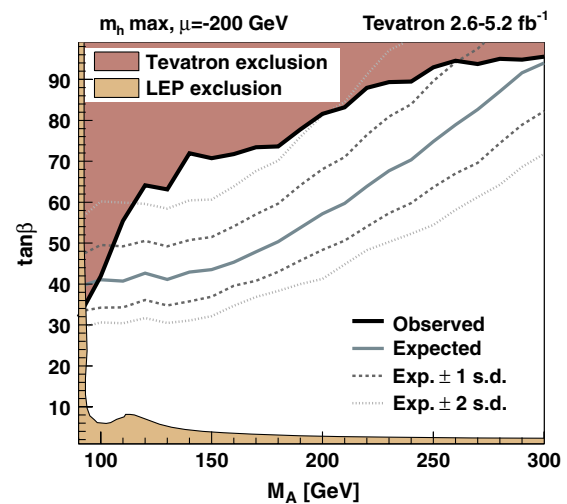


FIG. 2 (color online). 95% C.L. lower limit in the $(M_A, \tan\beta)$ plane for the m_h^{\max} , $\mu = -200$ GeV, including Higgs boson width effects and using the fact that for the $\tan\beta$ range considered, either h and A , or H and A (depending on M_A) are effectively mass degenerate. The exclusion limit obtained from the LEP experiments is also shown.

factorization and renormalization scales by a factor of 2 and from uncertainties on the parton distribution functions. The uncertainties assessed from scale variation are taken to be 10% and the parton distribution functions contribute an additional 3.5%–13%, depending on the mass hypothesis.

The masses and couplings of the Higgs bosons in the MSSM depend, in addition to $\tan\beta$ and M_A , on other parameters through radiative corrections. Limits on $\tan\beta$ as a function of M_A are derived for the m_h^{\max} scenario [52] that favors the $b\bar{b}$ final state, assuming a CP-conserving Higgs sector [53] and a negative value of the Higgs sector bilinear coupling μ . Figure 2 shows exclusion limits in the $(\tan\beta, M_A)$ plane for this scenario. Adding a further potential theoretical uncertainty on the signal cross section of 20%, independent of M_ϕ , would lead to an increase of 5% in the $\tan\beta$ limit.

In summary, the combination of results on neutral Higgs boson searches in multi- b -jet events from CDF and D0 has been presented. Upper limits are set on the product of the cross section and branching ratio and constraints are placed in the $(\tan\beta, M_A)$ plane for a particular MSSM scenario.

This combination, with more than half the integrated luminosity from the Tevatron still to be analyzed, provides the most stringent limits on neutral Higgs boson production and decay in the multi- b -jet mode.

We thank the Fermilab staff and technical staffs of the participating institutions for their vital contributions and acknowledge support from the DOE and NSF (USA), ARC (Australia), CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil), NSERC (Canada), NSC, CAS and CNSF (China), Colciencias (Colombia), MSMT and GACR (Czech Republic), the Academy of Finland, CEA and CNRS/IN2P3 (France), BMBF and DFG (Germany), DAE and DST (India), SFI (Ireland), INFN (Italy), MEXT (Japan), the Korean World Class University Program and NRF (Korea), CONACyT (Mexico), FOM (Netherlands), MON, NRC KI and RFBR (Russia), the Slovak R&D Agency, the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010 (Spain), The Swedish Research Council (Sweden), SNSF (Switzerland), STFC and the Royal Society (United Kingdom), and the A.P Sloan Foundation (USA).

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