

Search for Neutral Supersymmetric Higgs Bosons in Multijet Events at $\sqrt{s} = 1.96$ TeV

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We have performed a search for neutral Higgs bosons produced in association with bottom quarks in $p\bar{p}$ collisions, using 260 pb^{-1} of data collected with the D0 detector in Run II of the Fermilab Tevatron Collider. The cross sections for these processes are enhanced in many extensions of the standard model (SM), such as in its minimal supersymmetric extension at large $\tan\beta$. The results of our analysis agree with expectations from the SM, and we use our measurements to set upper limits on the production of neutral Higgs bosons in the mass range of 90 to 150 GeV.

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In two-Higgs-doublet models of electroweak symmetry breaking, such as the minimal supersymmetric extension of

the standard model (MSSM) [1], there are five physical Higgs bosons: two neutral CP -even scalars, h and H , with

H being the heavier state; a neutral CP -odd state, A ; and two charged states, H^\pm . The ratio of the vacuum expectation values of the two Higgs fields is defined as $\tan\beta = v_u/v_d$, where v_u and v_d refer to the fields that couple to the up-type and down-type fermions, respectively. At tree level, the coupling of the A boson to down-type quarks, such as the b quark, is enhanced by a factor of $\tan\beta$ relative to the standard model (SM), and the production cross section is therefore enhanced by $\tan^2\beta$ [2]. At large $\tan\beta$, this is also true either for the h or H bosons depending on their mass.

For several representative scenarios of the MSSM, LEP experiments have excluded at the 95% C.L. a light Higgs boson with mass $m_h < 92.9$ GeV [3]. At hadron colliders, neutral Higgs bosons can be produced in association with b quarks, leading to final states containing three or four b jets. The CDF experiment at the Tevatron Collider performed a search for these events in data from Run I [4]. Although their analysis was excluding some large values of $\tan\beta$ for m_A up to 250 GeV, the parton distribution functions (PDFs) used to simulate the signal have been superseded. The resulting limits with the most recent PDFs would be much less stringent, hence we do not compare our current results to those from Run I.

Higgs boson production in association with b quarks in $p\bar{p}$ collisions can be calculated in two ways: in the five-flavor scheme [5], only one b quark has to be present, while in the four-flavor scheme [6], two b quarks are explicitly required in the final state. Both calculations are now available at next-to-leading order (NLO), and agree within their respective theoretical uncertainties [7,8]. Figure 1 illustrates these processes for h production at leading order (LO), and analogous diagrams can be drawn for the H and A bosons.

In this Letter, we assume CP conservation in the Higgs sector. The masses, widths, and branching fractions for the neutral Higgs bosons into $b\bar{b}$ pairs are calculated using the CPSUPERH program [9,10]. The current analysis is sensitive

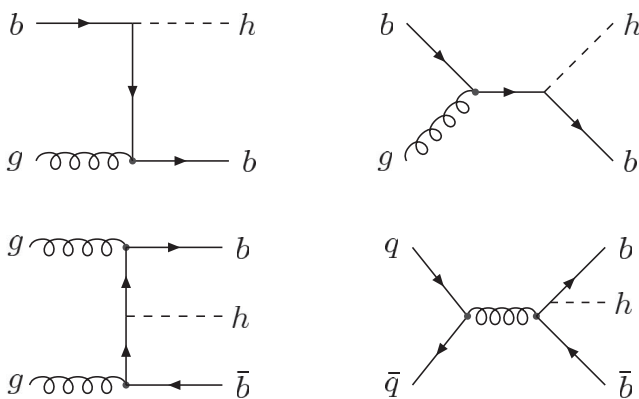


FIG. 1. Leading-order Feynman diagrams for neutral Higgs boson production in the five-flavor scheme (top) and four-flavor scheme (bottom).

to $\tan\beta$ in the range 50–100, and depends on the Higgs boson mass. In this region of $\tan\beta$, the A boson is nearly degenerate in mass with either the h or the H boson, and their widths are small compared to the di-jet mass resolution. Consequently, we cannot distinguish between the h/H and the A , and the total cross section for signal is assumed to be twice that of the A boson. In the region of m_A from 100 to 130 GeV, all three neutral Higgs bosons can be degenerate in mass and produced simultaneously [11]. Nevertheless, the total cross section still remains twice that of the A boson. Using data collected by the D0 detector from November 2002 to June 2004, corresponding to an integrated luminosity of about 260 pb^{-1} , we search for an excess in the invariant mass distribution of the two leading transverse momentum (p_T) jets in events containing three or more b quark candidates.

The D0 detector has a magnetic central tracking system surrounded by a uranium/liquid-argon calorimeter, contained within a muon spectrometer. The tracking system consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T solenoidal magnet [12]. The SMT and CFT have designs optimized for tracking and vertexing at pseudorapidities $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle with respect to the proton beam direction (z). The calorimeter has a central section (CC) covering up to $|\eta| \approx 1.1$, and two end calorimeters (EC) extending coverage to $|\eta| \approx 4.2$, all housed in separate cryostats [13]. The calorimeter is divided into an electromagnetic part followed by fine and coarse hadronic sections. Scintillators between the CC and EC cryostats provide additional sampling of developing showers for $1.1 < |\eta| < 1.4$. The muon system consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroidal magnets, followed by two similar layers behind the toroids, which provide muon tracking for $|\eta| < 2$. The luminosity is measured using scintillator arrays located in front of the EC cryostats, covering $2.7 < |\eta| < 4.4$. The trigger system comprises three levels ($L1$, $L2$, and $L3$), each performing an increasingly detailed event reconstruction in order to select the events of interest.

The large cross section for multijet production necessitates a specialized trigger to maximize signal acceptance while providing reasonable rates. This trigger at $L1$ requires signals in at least three calorimeter towers of size $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ (where ϕ is the azimuthal angle), each with transverse energy $E_T > 5$ GeV; three clusters and $H_T^{L2} > 50$ GeV at $L2$ ($H_T^{L2} \equiv$ scalar sum of the $L2$ clusters E_T with $E_T > 5$ GeV), and three jets with $p_T > 15$ GeV at $L3$. A total of 87×10^6 events were selected offline with one jet of $p_T > 20$ GeV and at least two more jets with $p_T > 15$ GeV. Jets are reconstructed using a Run II cone algorithm [14] with radius $\Delta\mathcal{R} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.5$, and are then required to pass a set of quality criteria. To be accepted for further analysis,

jets with $p_T > 15$ GeV must have $|\eta| < 2.5$. The jet energies are corrected to the particle level using η -dependent scale factors. Events with up to five jets are selected if they have a primary vertex position $|z| < 35$ cm and at least three jets with corrected $p_T > 35, 20,$ and 15 GeV. The final selections are chosen to optimize the expected signal significance, defined as S/\sqrt{B} , where $S(B)$ refers to the number of signal (background) events. The window size used for optimization is Higgs boson mass dependent, taken to be ± 1.5 s.d. of the signal peak, and varies from 24 to 36 GeV, for masses from 90 to 150 GeV. Jets containing b quarks are identified using a secondary vertex (SV) tagging algorithm. A jet is tagged as a b jet if it has at least one SV within $\Delta\mathcal{R} < 0.5$ of the jet axis and a transverse displacement from the primary vertex that exceeds 5 times the displacement uncertainty. Jets are b tagged up to $|\eta| < 2.5$, although the b tagging is about twice as efficient in the central region ($|\eta| < 1.1$) because of the CFT coverage. The b tagging efficiency is $\approx 55\%$ for central b jets of $p_T > 35$ GeV, with a light-quark (or gluon) tag rate of about 1%.

Signal events were simulated using the PYTHIA [15] event generator followed by the full D0 detector simulation and reconstruction chain. PYTHIA minimum-bias events were added to all generated events, using a Poisson probability with a mean of 0.4 events to match the instantaneous luminosities at which the data were taken $[(1-6) \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}]$. The bh events, with $g \rightarrow b\bar{b}$, were generated for Higgs boson masses from 90 to 150 GeV. Reconstructed jets in simulated events were corrected to match the jet reconstruction and identification efficiencies in data. The energy of simulated jets was smeared to match the measured jet energy resolution. The p_T and rapidity spectra of the Higgs bosons from PYTHIA were compared to those from the NLO calculation [5]. The shapes were similar, indicating that the PYTHIA kinematics are approximately correct. The simulated events were weighted to match the p_T spectrum of the Higgs boson given by NLO, resulting in a 10% reduction of the overall signal efficiency.

Of all SM processes, multijet production is the major source of background. This background is determined from data by normalizing distributions outside of the signal region. As a cross-check, we also compare data with simulations. ALPGEN [16] is used to generate three samples of events for $b\bar{b}j$ and $b\bar{b}jj$ with j corresponding to up, down, strange or charm quarks, or gluons, and $b\bar{b}b\bar{b}$ final states with generator-level requirements: $p_T^b > 25$ GeV, $p_T^j > 15$ GeV, $|\eta| < 3.0$, and $\Delta\mathcal{R} > 0.4$ between any two final-state partons. These selections do not introduce significant bias because the final sample contains much harder jets, after the application of trigger and b -tagging requirements. Samples of $b\bar{b}j$ and $b\bar{b}jj$ are added together, but the $b\bar{b}jj$ sample is weighted by 0.85 to match the jet multiplicity observed in doubly b -tagged data. The cross

sections obtained from ALPGEN are 8.9 nb, 3.9 nb, and 60 pb, for the respective three states. All other backgrounds are expected to be small and are simulated with PYTHIA: $p\bar{p} \rightarrow Z(\rightarrow b\bar{b}) + \text{jets}$, $p\bar{p} \rightarrow Zb$, and $p\bar{p} \rightarrow t\bar{t}$. Cross sections of 1.2 nb, 40 pb [17], and 7 pb are assumed, respectively.

There are two main categories of multijet background. One contains genuine heavy-flavor (HF) jets, while the other has only light-quark or gluon jets that are mistakenly tagged as b -quark jets, or correspond to gluons that branch into nearly collinear $b\bar{b}$ pairs. Using the selected data sample, before the application of b -tagging requirements, the probability to b tag a jet is measured as a function of its p_T in three $|\eta|$ regions. These functions are called “mistag” functions. They are corrected for the contamination from true HF events by subtracting the estimated fraction of $b\bar{b}j(j)$ events in the multijet data sample (1.2%), obtained from an initial fit to the doubly b -tagged data. These corrected mistag functions are then used to estimate the mistagged background by applying them to every jet reconstructed in the full data sample.

In order to test the modeling of the mistag background, the high statistics doubly b -tagged data are compared to simulations first, before extrapolating to the triply b -tagged background. The expected signal contribution to the doubly b -tagged data is negligible. The comparison in invariant mass spectrum of the two jets of highest p_T (not necessarily the two b -tagged jets) in the doubly b -tagged data with the expected background is shown in Fig. 2. The b tagging in this analysis does not distinguish between contributions from bottom and charm events. However, the efficiency for tagging a c jet is known from simulations to be about 1/4 of that for tagging a b jet. Therefore, when two b tags are required, the fraction of $c\bar{c}j(j)$ events relative to $b\bar{b}j(j)$ events will be a factor of ≈ 16 lower

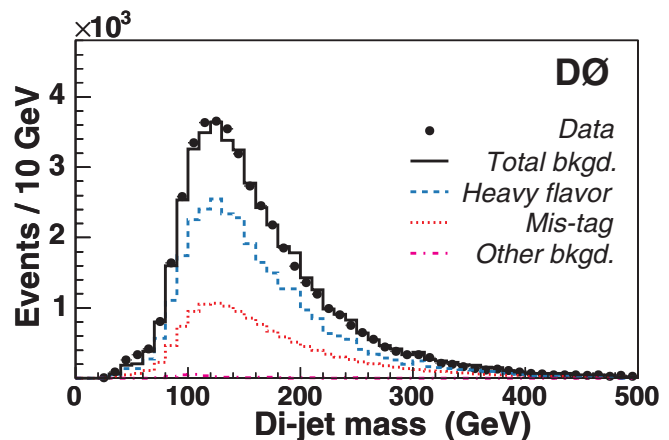


FIG. 2 (color online). Fit of the invariant mass spectrum of the two leading p_T jets in the doubly b -tagged data to a sum of backgrounds: mistags derived from data (dotted line), $b\bar{b}j(j)$ (dashed line), and other backgrounds ($Z(\rightarrow b\bar{b}) + \text{jets}$, Zb , $t\bar{t}$, and $b\bar{b}b\bar{b}$) (dash-dotted line).

TABLE I. Signal acceptances for each set of criteria (in %).

m_A (GeV)	Trigger	Kinematic	b Tag	Total
90	44	18	3.5	0.3
100	45	24	3.5	0.4
110	56	24	3.9	0.5
120	60	27	4.2	0.7
130	65	29	4.3	0.8
150	76	31	4.4	1.0

after tagging. We have estimated the fractions of $c\bar{c}jj$ to $b\bar{b}jj$ prior to b tagging using the MADGRAPH Monte Carlo generator [18]. The $c\bar{c}jj$ cross section is 22% higher than $b\bar{b}jj$ for the same generator-level selections. Therefore, the contribution of $c\bar{c}j(j)$ in the doubly b -tagged data sample is expected to represent about 8% of the events. Thus, when we refer to the $b\bar{b}j(j)$ normalization, it should be understood that approximately 8% of the events are from the $c\bar{c}j(j)$ process. After these corrections for $c\bar{c}j(j)$ events, the HF multijet processes are only a factor of 1.08 higher in data than predicted by ALPGEN. The shape of the estimated background agrees well with the data over the entire invariant mass region.

To estimate the background for triply b -tagged events, the mistag function is applied to the non- b -tagged jets in the doubly b -tagged events. This provides the shape of the multijet background distribution with at least three b -tagged jets. This neglects any contributions from processes with more than two true b jets, such as from $b\bar{b}b\bar{b}$ and $Z(\rightarrow b\bar{b})b\bar{b}$ production. However, the shapes of these backgrounds from simulations are similar to those of the doubly b -tagged spectra, and their rates are small. The overall background normalization is therefore determined by fitting the leading two jets invariant mass spectrum in triply b -tagged events outside of the hypothesized signal region to the estimated shape for triply b -tagged background. The systematic effect on the normalization of the background from any signal contributing outside the search window was studied and found to be small relative to other uncertainties, as described below.

The selections in this analysis can be grouped into trigger level, kinematic (p_T , η , η_j), where n_j is the number of untagged jets, and b tagging. Table I shows the acceptances for each set of criteria made in the analysis, for six values of Higgs boson mass. The systematic uncertainty on signal acceptance is nearly independent of assumed m_A , and is dominated by the uncertainty on b -tagging efficiency ($\pm 15\%$), followed by uncertainties on jet energy scale, resolution, and identification efficiency ($\pm 9\%$ in sum). These uncertainties are calculated by repeating the analysis with each value changed by ± 1 standard deviation (s.d.). The systematic uncertainties corresponding to uncertainties in p_T distributions for simulated signal at NLO, the integrated luminosity, and the trigger efficiency

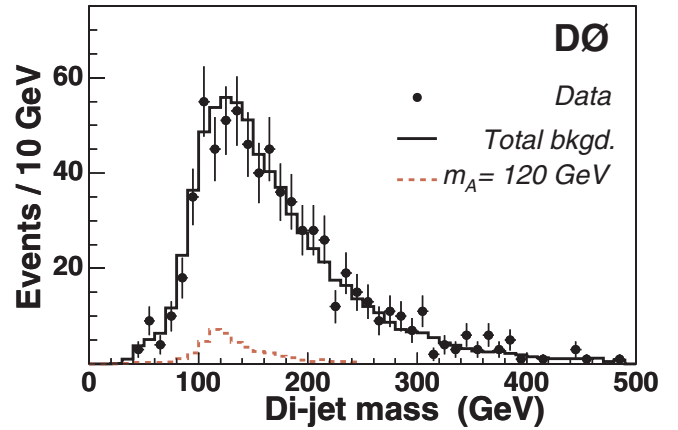


FIG. 3 (color online). Invariant mass spectrum of two leading jets in events with at least three b -tagged jets, estimated background, and the signal for a 120 GeV Higgs boson that can be excluded at the 95% C.L.

are found to be $\pm 5\%$, $\pm 6.5\%$, and $\pm 9\%$, respectively. These uncertainties, added in quadrature, result in a total systematic uncertainty of $\pm 21\%$.

The accuracy in modeling the shape of the background distribution can be estimated from the χ^2/dof between the estimated background and the data. The statistical error associated with the uncertainty in the normalization of the background (from the fit outside the signal region) is multiplied by $\sqrt{\chi^2/\text{dof}}$. The background uncertainty is estimated to be $\leq 3\%$. The systematic uncertainty arising from the width chosen for the search window is evaluated by varying it from ± 1 to ± 2 s.d., centered on the peak value. The resulting change in background normalization is

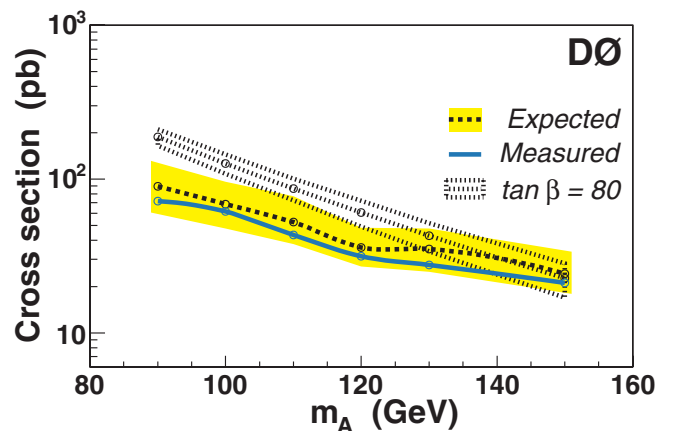


FIG. 4 (color online). The expected and measured 95% C.L. upper limits on the signal cross section as a function of m_A . The band indicates the ± 1 s.d. range on the expected limit. Also shown is the cross section for the signal at $\tan \beta = 80$ in the “no mixing” scenario of the MSSM, with the theoretical uncertainty indicated by the overlaid band.

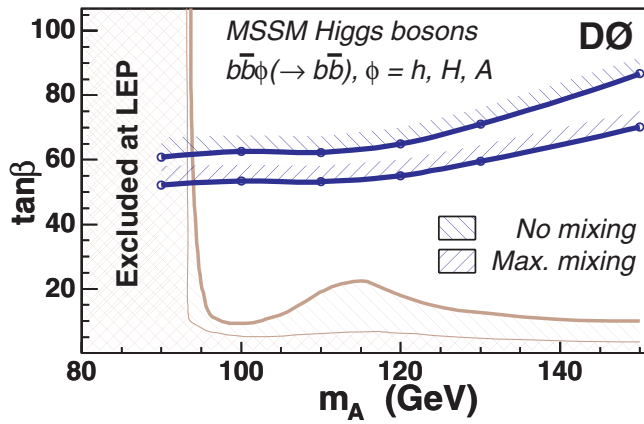


FIG. 5 (color online). The 95% C.L. upper limit on $\tan\beta$ as a function of m_A for two scenarios of the MSSM, “no mixing” and “maximal mixing.” Also shown are the limits obtained by the LEP experiments for the same two scenarios of the MSSM [3].

much smaller than from other sources of background uncertainties.

A modified frequentist method is used to set limits on the production of signal [19]. The di-jet invariant mass distributions in triply b -tagged events of data, simulated signal, and the normalized background were used as inputs. The value of $\tan\beta$ was varied until the confidence level for signal (C.L._s) was $<5\%$. Figure 3 shows the data, background, and simulated signal at the exclusion limit, for $m_A = 120$ GeV. This is converted to a cross section limit for signal production in Fig. 4, which also shows the expected MSSM Higgs boson production cross section as a function of m_A for $\tan\beta = 80$, and the median expected limit with the background-only hypothesis along with its ± 1 s.d. range. The NLO cross sections and their uncertainties from PDFs and scale dependence are taken from Refs. [5,8]. The MSSM cross section shown in Fig. 4 corresponds to no mixing in the scalar top quark sector [20], or $X_t = 0$, where $X_t = A_t - \mu \cot\beta$, A_t is the trilinear coupling, and the Higgsino mass parameter $\mu = -0.2$ TeV. We also interpret our results in the “maximal mixing” scenario with $X_t = \sqrt{6}M_{\text{SUSY}}$, where M_{SUSY} is the mass scale of supersymmetric particles, taken to be 1 TeV.

Results for both scenarios of the MSSM are shown in Fig. 5 as limits in the $\tan\beta$ versus m_A plane. The present D0 analysis, based on 260 pb^{-1} of data, excludes a significant portion of the parameter space, down to $\tan\beta = 50$, depending on m_A and the MSSM scenario assumed.

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