



## Search for the Higgs Boson in Events with Missing Transverse Energy and $b$ Quark Jets Produced in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We search for the standard model Higgs boson produced in association with an electroweak vector boson in events with no identified charged leptons, large imbalance in transverse momentum, and two jets where at least one contains a secondary vertex consistent with the decay of  $b$  hadrons. We use  $\sim 1 \text{ fb}^{-1}$  integrated luminosity of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$  recorded by the Collider Detector at Fermilab II experiment at the Tevatron. We find 268 (16) single (double)  $b$ -tagged candidate events, where  $248 \pm 43$  ( $14.4 \pm 2.7$ ) are expected from standard model background processes. We observe no significant excess over the expected background and thus set 95% confidence level upper limits on the Higgs boson production cross section for several Higgs boson masses ranging from 110 to 140  $\text{GeV}/c^2$ . For a mass of 115  $\text{GeV}/c^2$ , the observed (expected) limit is 20.4 (14.2) times the standard model prediction.

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The Higgs boson is an essential element of the standard model (SM) of particles and their interactions explaining the mass of elementary particles and playing a key role in

the mechanism of electroweak symmetry breaking. Precision measurements of the  $W$  boson and top quark masses suggest that the mass of the SM Higgs boson

should be less than  $182 \text{ GeV}/c^2$  (95% C.L.) [1] and therefore kinematically within reach at the Tevatron. Previous searches for the SM Higgs boson set limits on its mass [1] and production cross section [2]. The Collider Detector at Fermilab (CDF) Collaboration is now performing searches for the low mass Higgs boson produced in association with an electroweak vector boson  $V$  ( $Z$  or  $W$ ) followed by the decay  $H \rightarrow b\bar{b}$  in several final states which are not yet sensitive to the SM cross section. Each search is optimized separately and then combined. In this Letter, we describe the first search for the SM Higgs boson with a trigger based on an imbalance in energy in the plane transverse to the beam sensitive to both  $ZH$  and  $WH$  associated productions. In order to avoid overlap with the search for  $WH$  in a final state containing a high-energy electron or muon candidate, large missing transverse energy, and one or two  $b$  jets, we veto events with high-energy isolated leptons. Therefore, we search for  $VH$  events where  $H \rightarrow b\bar{b}$  and either  $Z \rightarrow \nu\bar{\nu}$  or  $W \rightarrow \ell\nu$ , where  $\ell$  indicates that the lepton was not identified in the detector. The signatures of these decay modes are final states with two  $b$  jets from the hadronization of the  $b$  quarks, missing transverse energy, and no isolated leptons. In this search, we use an integrated luminosity of  $0.97 \pm 0.06 \text{ fb}^{-1}$  collected in run II of the Tevatron. After describing the experiment, we introduce our event selection, major backgrounds, and systematic uncertainties and present the results.

CDF II is a multipurpose detector described in detail elsewhere [3]. Here we briefly describe the detector components used in this analysis. We use a cylindrical coordinate system around the proton beam axis in which  $\theta$  and  $\phi$  are the polar and azimuthal angles, respectively, and the pseudorapidity  $\eta$  is defined as  $\eta = -\ln[\tan(\frac{\theta}{2})]$ . The transverse momentum and energy of a particle are defined as  $p_T = p \sin\theta$  and  $E_T = E \sin\theta$ , respectively. The tracking system consists of a cylindrical open-cell drift chamber and silicon microstrip detectors in a 1.4 T magnetic field parallel to the beam axis. The silicon detectors [4] provide tracking information for  $|\eta| < 2$  and are used to detect collision and decay points. The drift chamber [5] surrounds the silicon detectors and covers the central rapidity region  $|\eta| < 1$ .

The energies of electrons and jets are measured in calorimeters, which cover the region  $|\eta| < 3.6$  and are segmented into towers pointing toward the center of the detector. Jets are reconstructed from energy depositions in the calorimeter towers by using a jet-clustering cone algorithm [6] with a cone size of radius  $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ . Corrections are applied to account for effects that can cause mismeasurements in the jet energy such as nonlinear calorimeter response, multiple beam interactions, or displacement of the event vertex from the nominal  $z = 0$  position [6].  $\cancel{E}_T$  is defined as the magnitude of  $\vec{\cancel{E}}_T = -\sum_i E^i \hat{n}_i$ , where  $\hat{n}_i$  is a unit vector parallel to the transverse component of the vector pointing

at the  $i$ th calorimeter tower and  $E^i$  is the energy therein. Both the magnitude and the direction of  $\vec{\cancel{E}}_T$  are recomputed after the jet energies are corrected.

We use loose electron and muon identification criteria in order to veto events with at least one high  $p_T$  isolated lepton [7]. Candidate muons are identified with  $p_T > 10 \text{ GeV}/c$  isolated tracks, which leave energy in the calorimeters that is consistent with a minimum ionizing particle. A track is called isolated if the total calorimeter energy in a 0.4 radius cone around the track is less than 10% of the track  $p_T$ . Candidate electrons are clustered energy deposits in the electromagnetic calorimeter with  $E_T > 10 \text{ GeV}$  which have an electromagnetic to hadronic energy ratio and a shower shape compatible with electrons and are associated with an isolated track.

The events used in this search are selected by a three-level trigger system. The level 1 trigger requires  $\cancel{E}_T \geq 25 \text{ GeV}$ , where  $\cancel{E}_T$  is determined by using calorimeter trigger towers with  $E_T > 1 \text{ GeV}$ . The level 2 trigger selects events with two jet clusters of  $E_T > 10 \text{ GeV}$ , where one of the clusters is required to be in the region  $|\eta| < 1.1$ . The level 3 requirement is  $\cancel{E}_T > 35 \text{ GeV}$ . After selections to remove the accelerator-produced and detector-related background, as well as cosmic ray events,  $4.3 \times 10^6$  events remain. This is about 60% of the initial sample. Further selection criteria are defined by using corrected observables in order to search in a region where the trigger is fully efficient, but the sensitivity of the search is not compromised. We require the events to have  $\cancel{E}_T > 50 \text{ GeV}$  and to contain exactly two jets with  $E_T > 20 \text{ GeV}$  and  $|\eta| < 2.4$  where the azimuthal separation of the two jets is  $\Delta\phi(\vec{E}_{1,T}, \vec{E}_{2,T}) > 1.0 \text{ rad}$ . Moreover, one of the two jets must be central with  $|\eta| < 0.9$ , and the jet of highest (second-highest) energy in the event must have  $E_{T,1} > 35 \text{ GeV}$  ( $E_{T,2} > 25 \text{ GeV}$ ). The trigger efficiency for such events is  $0.97 \pm 0.03$  [7].

We require at least one jet to be identified as a  $b$  jet by the  $b$ -tagging algorithm SECVTX [8]. This algorithm looks for tracks within jets that form a secondary vertex significantly displaced from the primary interaction point. The tagging efficiency for  $b$  jets of 50 GeV is  $\sim 42\%$ , the misidentification rate for 50 GeV light quark ( $u, d, s$ ) and gluon jets is  $\sim 1\%$  [8].

In order to avoid potential bias in the search, we test our understanding of the background in control regions that are defined *a priori*. The observed events are divided into three nonoverlapping parts: two control and one signal regions, which have different event topology and isolated high- $p_T$  lepton multiplicity. The backgrounds in the three regions have contributions from multijet,  $t\bar{t}$ ,  $W$  plus jets,  $Z$  plus jets, and electroweak ( $WW$ ,  $WZ$ , and  $ZZ$ ) processes. Control region 1 (CR1) is defined such that it is dominated by the multijet background. The events in this region do not contain any identified leptons, and the separation between the  $\vec{\cancel{E}}_T$  and the secondary jet  $[\Delta\phi(\vec{E}_{2,T}, \vec{\cancel{E}}_T)]$  is

required to be less than 0.4. Control region 2 (CR2) is selected by requiring at least one lepton and  $\Delta\phi(\vec{E}_{2,T}, \vec{\cancel{E}}_T) \geq 0.4$ . This region is sensitive to electroweak and top quark decays. The signal region contains events with no identified high- $p_T$  leptons,  $\Delta\phi(\vec{E}_{1,T}, \vec{\cancel{E}}_T) \geq 0.4$ , and  $\Delta\phi(\vec{E}_{2,T}, \vec{\cancel{E}}_T) \geq 0.4$ .

The agreement between the number of events expected and observed due to different processes is presented in Table I for single and double  $b$ -tagged events in CR1 and CR2. The signal and the physics backgrounds have been evaluated by using PYTHIA [9] Monte Carlo (MC) generation followed by the simulation of the CDF II detector. Light quark multijet production has a cross section about 9 orders of magnitude greater than the theoretical expectation for the signal before the  $b$ -tag requirement. Although this process generally does not have intrinsic  $\cancel{E}_T$ , mismeasured jets can cause an imbalance in the total  $E_T$  and fake the signal if one of the jets is misidentified as a  $b$  jet (mistag). Furthermore,  $b$  quark pair production yields  $b$  jets and  $\cancel{E}_T$  if one  $b$  quark undergoes a semileptonic decay. In both cases,  $\vec{\cancel{E}}_T$  tends to be aligned parallel or antiparallel to the first or second most energetic jet. We use MC simulation only to evaluate multijet processes which yield events with a  $b$  or  $c$  quark [heavy quark (h.q.)] pair. This background is denoted as QCD h.q. in Table I. The MC cross section for heavy quark jet production is scaled to the difference between the observed data and the predicted contribution of the other backgrounds. We determine the normalization factors  $k_{\text{QCD}}$  before the data are divided into control and signal regions to be  $1.30 \pm 0.04$  and  $1.47 \pm 0.07$  for events with one and two  $b$ -tagged jets, respectively [7]. The background due to light quarks being misidentified as  $b$  jets is denoted as mistags in Table I and is determined by using a  $b$ -jet misidentification rate that is measured from inclusive jet samples [8]. The  $t\bar{t}$  cross section of  $7.3 \pm 0.8$  pb is obtained from the combined CDF measurements [10]. A small contribution by single

top quark production is included, normalized with theoretical next-to-leading-order (NLO) production cross sections [11,12]. The electroweak backgrounds were generated at leading order with PYTHIA and increased by a factor of 1.4 to account for higher order effects [13,14].

Simulated distributions of kinematic variables such as the jet  $E_T$ , the dijet invariant mass, and  $\cancel{E}_T$  have been found to be in agreement with observations in the control regions [7]. In Figs. 1(a) and 1(b), we show the dijet invariant mass distributions when both jets are  $b$ -tagged in control region CR1 and CR2, respectively.

We optimize the sensitivity to Higgs boson production by maximizing the ratio  $N_{\text{Higgs}}/\sqrt{N_{\text{bck}}}$ , where  $N_{\text{Higgs}}$  and  $N_{\text{bck}}$  are the number of predicted Higgs boson and background events in the signal region, respectively. The final selection requires  $\Delta\phi(\vec{E}_{1,T}, \vec{\cancel{E}}_T) > 0.8$ ,  $\cancel{H}_T/H_T > 0.45$ ,  $E_{T,1} > 60$  GeV, and  $\cancel{E}_T > 70$  GeV. The variable  $H_T$  ( $\cancel{H}_T$ ) is the scalar (the magnitude of the vectorial) sum of the two jet energies in the transverse plane. The number of background events after the selections is shown in Table I. For a Higgs boson of mass 115 GeV/ $c^2$ , we expect a total of 1.2 (0.4) events with one (two)  $b$ -tagged jet(s) which corresponds to 2.1% (0.7%) signal efficiency [15].

The total systematic uncertainties on the background predictions are 17% and 19% in the single and double tag events, respectively [7]. One of the dominant correlated uncertainties for the background and signal predictions is due to the jet energy scale (JES) [6]. The JES uncertainty affects selection efficiencies nonuniformly over kinematic distributions leading to uncertainties in the distributions' shapes. The resulting systematic uncertainties are typically between 10% and 20% for multijet events depending on the kinematic selections, 15% for dibosons, 26% for  $W$  plus h.q., 17% for  $Z$  plus h.q., 1% for top quark, and 8% for signal events. The systematic uncertainty on the  $b$ -tagging efficiency is 4.3% for single and 8.6% for double  $b$ -tagged events. There is a 3% uncertainty on the trigger efficiency, 2% uncertainty on the signal and background acceptances

TABLE I. Comparison of the total number of expected and observed single and double  $b$ -tagged events in the control regions and in the optimized signal region.

Lepton	Control region 1		Control region 2		Signal region	
	Vetoed $\Delta\phi(\vec{E}_{2,T}, \vec{\cancel{E}}_T) < 0.4$		Identified $\Delta\phi(\vec{E}_{2,T}, \vec{\cancel{E}}_T) \geq 0.4$		Vetoed See text	
	Single	Double	Single	Double	Single	Double
QCD h.q.	$14868 \pm 1820$	$1175 \pm 179$	$61 \pm 25$	$3.2 \pm 1.7$	$93 \pm 23$	$3.74 \pm 1.27$
Top	$4.0 \pm 0.6$	$0.8 \pm 0.2$	$98 \pm 14$	$24.0 \pm 3.8$	$27.3 \pm 3.8$	$4.88 \pm 0.80$
Di-boson	$0.7 \pm 0.1$	$0.04 \pm 0.02$	$11.5 \pm 2.1$	$1.0 \pm 0.2$	$7.0 \pm 1.4$	$0.79 \pm 0.19$
$W$ + h.q.	$14.0 \pm 6.7$	$0.3 \pm 0.2$	$63 \pm 28$	$3.9 \pm 1.8$	$33.4 \pm 16.2$	$1.65 \pm 0.86$
$Z$ + h.q.	$5.3 \pm 2.2$	$0.3 \pm 0.2$	$12.9 \pm 5.9$	$0.5 \pm 0.4$	$18.3 \pm 8.1$	$1.67 \pm 0.77$
Mistags	$3450 \pm 433$	$73 \pm 14$	$85 \pm 11$	$2.2 \pm 0.6$	$69 \pm 9$	$1.64 \pm 0.48$
Expected	$18342 \pm 2031$	$1249 \pm 203$	$331 \pm 51$	$34.8 \pm 5.9$	$248 \pm 43$	$14.4 \pm 2.7$
Observed	18588	1251	373	28	268	16

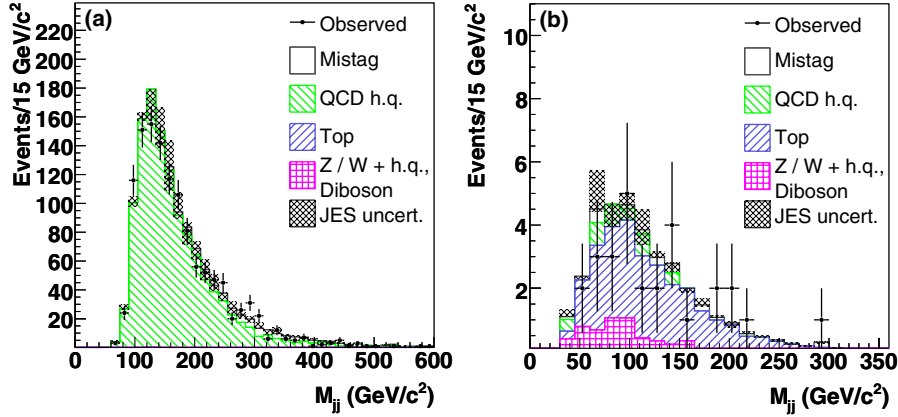


FIG. 1 (color online). Dijet invariant mass distribution for double-tagged events in (a) CR1 and (b) CR2.

due to uncertainties in the parton distribution functions, and 6% on luminosity. The dominant uncorrelated systematic uncertainties are due to the cross sections and the statistics of the simulated samples. We assign uncertainties of 11% to the top, 11.5% to the diboson, and 40% to the  $W$  plus h.q. and  $Z$  plus h.q. cross sections. Statistical uncertainties due to Monte Carlo sample sizes are 20%–32% on the multijet, 20% on the  $W$  plus h.q., and 11% on the  $Z$  plus h.q. predictions. Correlated and uncorrelated uncertainties are evaluated separately and combined in quadrature.

The signal region is analyzed after all of the background predictions and selection requirements were determined. The results are summarized in Table I. By requiring one (two)  $b$ -tagged jets, we observe 268 (16) events, where  $248 \pm 43$  ( $14.4 \pm 2.7$ ) are expected. The dijet invariant mass distributions in the signal region when one and two jets are  $b$ -tagged are shown in Fig. 2.

Since no significant excess is observed, we compute 95% C.L. upper limits for the Higgs boson production cross section times the branching fraction when the Higgs boson is produced in association with a  $Z$  or  $W$  boson and decays to two  $b$  quarks, while  $Z$  and  $W$  yield

large  $\cancel{E}_T$  and no identified leptons. The limits are computed by using the Bayesian likelihood method [16] with a flat prior probability for the signal cross section and Gaussian priors for the uncertainties on acceptance and backgrounds. The likelihood quantifies the agreement between the dijet mass spectrum in the observed data and the sum of the modeled background processes and  $VH$  signal as a function of the Higgs boson mass. We combine the channels, such as single  $b$ -tag, double  $b$ -tag,  $ZH$ , and  $WH$ , by taking the product of their likelihoods and simultaneously varying the correlated uncertainties. Table II summarizes the combined single and double  $b$ -tag upper limits separately for  $ZH$  and  $WH$  and the combined  $VH$  upper limits. The result is also expressed as the ratio of the upper limit to the SM cross sections at NLO as a function of the Higgs boson mass. The observed limits agree with the expected ones at the  $1\sigma$  level.

In summary, we have performed a direct search for the SM Higgs boson decaying into  $b$  jet pairs by using data with integrated luminosity of  $0.97 \pm 0.06 \text{ fb}^{-1}$  accumulated in run II of the CDF II detector. We observe no significant excess over the background predicted by the

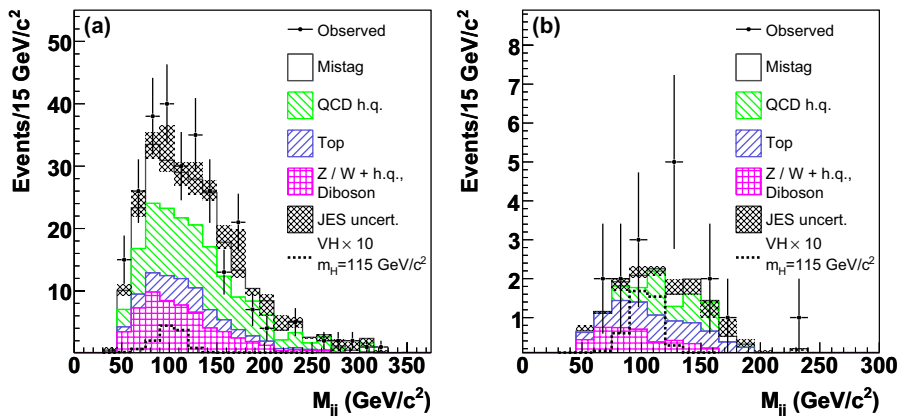


FIG. 2 (color online). Dijet invariant mass in the signal region for (a) single-tagged and (b) double-tagged events. The dotted line overlaid on the background shows 10 times the expected yield of  $115 \text{ GeV}/c^2$  Higgs bosons.

TABLE II. The expected cross-section limits of the  $ZH$  and  $WH$  processes and the expected and observed combined ( $VH$ ) cross-section limits when  $H \rightarrow b\bar{b}$ . The last column gives the ratio of the observed limit with respect to the SM cross section.

Higgs mass (GeV/ $c^2$ )	$\sigma(ZH) \times \text{Br}(H \rightarrow b\bar{b})$ Expected (pb)	$\sigma(WH) \times \text{Br}(H \rightarrow b\bar{b})$ Expected (pb)	$\sigma(VH) \times \text{Br}(H \rightarrow b\bar{b})$ Expected (pb)	Observed (pb)	Ratio Observed
110	2.1 + 0.9 – 0.7	4.8 + 2.7 – 1.2	3.1 + 1.8 – 0.9	4.7	17.9
115	2.1 + 0.8 – 0.7	4.6 + 2.2 – 1.4	3.0 + 1.4 – 0.9	4.4	20.4
120	1.8 + 0.8 – 0.6	4.4 + 1.9 – 1.4	2.9 + 1.3 – 0.9	4.3	24.8
125	1.7 + 0.7 – 0.6	3.9 + 2.0 – 1.0	2.5 + 1.0 – 0.6	4.0	30.2
130	1.6 + 0.9 – 0.5	3.4 + 1.2 – 1.0	2.4 + 1.1 – 0.8	3.8	38.3
135	1.5 + 0.7 – 0.5	3.2 + 1.9 – 0.8	2.3 + 1.0 – 0.6	3.5	48.5
140	1.4 + 0.6 – 0.4	3.2 + 1.8 – 1.0	2.3 + 1.2 – 0.7	3.3	65.8

SM and thus set 95% C.L. upper limits for the cross section of the Higgs boson production. The observed (expected) combined limit of the weak boson associated Higgs boson production cross sections set by this analysis for a Higgs boson mass of 115 GeV/ $c^2$  is 20.4 (14.2) times the SM prediction. These results significantly improve the combined limits on the allowed production rate for the SM Higgs boson at the Tevatron.

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