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 $\sim 1$ fb$^{-1}$ integrated luminosity of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the CDF 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 place 95% confidence level upper limits on the Higgs boson production cross section for several Higgs boson masses ranging from 110 GeV/$c^2$ to 140 GeV/$c^2$. For a mass of 115 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 GeV/c² (95\% C.L.) \(^1\) and therefore kinematically within reach at the Tevatron. Previous searches for the SM Higgs boson set limits on its production cross section at $\sqrt{s} = 1.8$ TeV and $\sqrt{s} = 1.96$ TeV \(^2\). The CDF Collaboration is now performing searches for associated productions. In order to avoid overlap with the trigger based on an imbalance in energy in the plane composed of two specific components used in this analysis. We use a cylindrical pseudorapidity $\eta$ defined as $\eta = -\ln(\tan(\theta/2))$. 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 \(^3\) 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 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 non-linear calorimeter response, multiple beam interactions, or displacement of the event vertex from the nominal $z = 0$ position \(^6\). The $\vec{E}_T$ is defined as the magnitude of $\vec{E}_T = -\sum_i E_i \hat{n}_i$, 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 magnitude and direction of the $\vec{E}_T$ are recomputed after the jet energies are corrected.

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 $\eta$ and $\phi$ are the polar and azimuthal angles, respectively, the pseudorapidity $\eta$ is defined as $\eta = -\ln(\tan(\theta/2))$. The
and the jet of highest (second highest) energy in the event must have $E_{T,1} > 35$ GeV ($E_{T,2} > 25$ 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 [5]. 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 non-overlapping 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 multi-jet, $t\bar{t}$, $W$ 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 multi-jet background. The events in this region do not contain any identified leptons, and the separation between the $\vec{E}_T$ and the secondary jet ($\Delta \phi (\vec{E}_{2, T}, \vec{E}_T)$) is required to be less than 0.4. Control region 2 (CR2) is selected by requiring at least one lepton and $\Delta \phi (\vec{E}_{2, T}, \vec{E}_T) \geq 0.4$. This region is sensitive to electroweak and top quark decays. The signal region contains events with no identified high-$p_T$ leptons, $\Delta \phi (\vec{E}_{1, T}, \vec{E}_T) \geq 0.4$, and $\Delta \phi (\vec{E}_{2, T}, \vec{E}_T) \geq 0.4$.

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 using pythia [9] Monte Carlo generation (MC) followed by the simulation of the CDF II detector. QCD light jet production has a cross section over nine orders of magnitude greater than the theoretical expectation for the signal before the tag requirement. Although this process generally does not have intrinsic $\vec{E}_T$, 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 $\vec{E}_T$ if one $b$ quark undergoes a semi-leptonic decay. In both cases, the $\vec{E}_T$ tends to be aligned parallel or anti-parallel to the first or second most energetic jet. We use MC simulation only to evaluate QCD 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, $k_{QCD}$, 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 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 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 the $\vec{E}_T$ have been found to be in agreement with observations in the control regions [7]. In Fig. I(a) and I(b) we show the dijet invariant mass distributions when both jets are $b$-tagged in control regions CR1 and CR2, respectively.

We optimize the sensitivity to Higgs boson production by maximizing the ratio of $N_{Higgs}/\sqrt{N_{bck}}$ where $N_{Higgs}$ and $N_{bck}$ are the number of predicted Higgs boson and background events in the signal region. The final selection requires $\Delta \phi (\vec{E}_{1, T}, \vec{E}_T) > 0.8$, $\vec{E}_T/H_T > 0.45$, $E_{T,1} > 60$ GeV, and $E_{T,T} > 70$ GeV. The variable $H_T$ ($\vec{H}_T$) 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 final selection is shown in Table II. 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 jets [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 non-uniformly over kinematic distributions leading to uncertainties in the distributions’ shapes. The resulting systematic uncertainties are typically between 10% and 20% for multi-jet 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 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 multi-jet, 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 the background
predictions and selection requirements were determined. The results are summarized in Table I. Requiring one (two) $b$-tagged jets we observe 268 (16) events, where 248 $\pm$ 6 (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 the $Z$ and $W$ yield large $E_T$ and no identified leptons. The limits are computed using the Bayesian likelihood method [11] with 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 I 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 using data with integrated luminosity of 0.97 $\pm$ 0.06 fb$^{-1}$ accumulated in Run II of the CDF II detector. We observe no significant excess over the background predicted by the 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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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) | $\sigma(ZH) \times Br(H \rightarrow b\bar{b})$ Expected (pb) | $\sigma(WH) \times Br(H \rightarrow b\bar{b})$ Expected (pb) | $\sigma(VH) \times Br(H \rightarrow b\bar{b})$ Expected (pb) | $\sigma(VH) \times Br(H \rightarrow b\bar{b})$ Observed (pb) | Ratio Observed |
|---------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|---------------|
| 110                 | 2.1$^{+0.9}_{-0.7}$                              | 4.8$^{+1.2}_{-1.4}$                              | 3.1$^{+1.8}_{-0.9}$                              | 4.7                                              | 17.9          |
| 115                 | 2.1$^{+0.8}_{-0.7}$                              | 4.6$^{+1.2}_{-1.4}$                              | 3.0$^{+1.4}_{-0.9}$                              | 4.4                                              | 20.4          |
| 120                 | 1.8$^{+0.7}_{-0.6}$                              | 4.4$^{+1.2}_{-1.4}$                              | 2.9$^{+1.3}_{-0.9}$                              | 4.3                                              | 24.8          |
| 125                 | 1.7$^{+0.7}_{-0.6}$                              | 3.9$^{+1.2}_{-1.4}$                              | 2.5$^{+1.0}_{-0.6}$                              | 4.0                                              | 30.2          |
| 130                 | 1.6$^{+0.7}_{-0.6}$                              | 3.4$^{+1.2}_{-1.4}$                              | 2.4$^{+1.1}_{-0.8}$                              | 3.8                                              | 38.3          |
| 135                 | 1.5$^{+0.7}_{-0.6}$                              | 3.2$^{+1.2}_{-1.4}$                              | 2.3$^{+1.0}_{-0.8}$                              | 3.5                                              | 48.5          |
| 140                 | 1.4$^{+0.6}_{-0.4}$                              | 3.2$^{+1.2}_{-1.4}$                              | 2.3$^{+1.0}_{-0.8}$                              | 3.3                                              | 65.8          |

FIG. 2: 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 GeV/c^2 Higgs bosons.
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