Search for Higgs Bosons Decaying to $b\bar{b}$ and Produced in Association with W Bosons in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$

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We present a search for Higgs bosons decaying into $b\bar{b}$ and produced in association with W bosons in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$. This search uses $320\,\mathrm{pb}^{-1}$ of the dataset accumulated by the upgraded Collider Detector at Fermilab. Events are selected that have a high-transverse momentum electron or muon, missing transverse energy, and two jets, at least one of which is consistent with the hadronization of a b quark. Both the number of events and the dijet mass distribution are consistent with standard model background expectations, and we set 95% confidence level upper limits on the production cross section times branching ratio for the Higgs boson or any new particle with similar decay kinematics. These upper limits range from 10 pb for $m_H = 110\,\mathrm{GeV}/c^2$ to 3 pb for $m_H = 150\,\mathrm{GeV}/c^2$.

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A central problem in elementary particle physics is the mechanism of electroweak symmetry breaking, by which weak vector bosons and massive fermions acquire nonzero masses. Physical manifestations of electroweak symmetry breaking may include the standard model (SM) Higgs boson [1]. The most recent global fit to the electroweak precision data yields an estimate of the SM Higgs boson mass $m_H = 91^{+45}_{-32}\,\mathrm{GeV}/c^2$ or $m_H \leq 186\,\mathrm{GeV}/c^2$ at 95% confidence level (C.L.) [2]. This estimate is consistent with results from direct searches at LEP that place a limit on the SM Higgs mass $m_H \geq 114\,\mathrm{GeV}/c^2$ at 95% C.L. [3]. Higgs boson searches at the Tevatron are expected to be sensitive to Higgs production at masses near the LEP limit [4]. The CDF collaboration has performed searches for new particles that decay into $b\bar{b}$ using $p\bar{p}$ collision data with $\sqrt{s} = 1.8\,\mathrm{TeV}$ [5]. Similar searches have been pursued by the DØ collaboration using $p\bar{p}$ collision data at 1.96 TeV [6].

In this Letter we present an updated search for Higgs bosons and other particles decaying into $b\bar{b}$ and produced in association with a W boson using data from Run II of the Tevatron collected with the Collider Detector at Fermilab (CDF II). The data sample corresponds to an integrated luminosity of $320\,\mathrm{pb}^{-1}$, nearly three times that collected during Run I. In addition, we expect a 20% increase of the WH production cross section due to the increase of the center-of-mass energy from 1.8 TeV (Run I) to 1.96 TeV (Run II). The standard model production cross section for $m_H = 115\,\mathrm{GeV}/c^2$ is predicted to be 0.2 pb at the higher energy [7]. The branching fraction $H \to b\bar{b}$ for that mass is 0.73 [8].

The upgrades to the CDF detector increase the signal yield with improved lepton acceptance and b quark identification. The search signature considered here is WH with $W \to e\nu$ or $\mu\nu$ and with $H \to b\bar{b}$, giving final states with one high-p_T lepton, large missing E_T ($\not\!\!E_T$), and two b-quark jets [9]. Requiring an associated W boson reduces the contribution from other physics processes. We focus our attention on the $W + 2$ jets signature with at least one identifed b jet since that signature contains most of the signal, while b-tagged $W+ \geq 3$ jets events are dominated by $t\bar{t}$ production.

The CDF II detector [10] is an azimuthally and forward-backward symmetric apparatus designed to study $p\bar{p}$ collisions at the Tevatron. The detector has a charged particle tracking system immersed in a 1.4 T magnetic field aligned coaxially with the colliding beams. A silicon microstrip detector provides tracking over the radial range from 1.5 to 28 cm. A 3.1 m long open-cell drift chamber, the Central Outer Tracker (COT), covers the radial range from 40 to 137 cm. The fiducial region of the silicon detector extends to absolute pseudorapidity $|\eta| \approx 2$, while the COT provides coverage for $|\eta| \leq 1$.

Segmented electromagnetic and hadronic sampling calorimeters surround the tracking system and measure particle energies in the pseudo-rapidity range $|\eta| < 3.6$. A set of drift chambers located outside the central hadron calorimeters and another set behind a 60 cm iron shield detect tracks from muon candidates with $|\eta| \leq 0.6$. Additional drift chambers and scintillation counters detect muons in the region $0.6 \leq |\eta| \leq 1.0$. The beam luminosity is determined using gas Cherenkov counters located in the $3.7 < |\eta| < 4.7$ region; the counters measure the average number of inelastic $p\bar{p}$ collisions per bunch crossing. The data used in this analysis are collected with high-E_T electron triggers or high-p_T muon triggers.

The signature of 2 jets plus a leptonically-decaying W boson allows us to make stringent event selection requirements. The event selection begins with the requirement of a primary lepton, either an isolated electron with $E_T > 20\,\mathrm{GeV}$ or an isolated muon with $p_T > 20\,\mathrm{GeV}/c$, in the central region ($|\eta| < 1.0$). The lepton isolation (I_{cal}) is defined by the additional energy deposited in a calorimeter cone of radius $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ around the lepton. We require I_{cal} be less than 10% of the lepton momentum. A W boson sample is selected by additionally requiring $\not\!\!E_T > 20\,\mathrm{GeV}$. Events that contain a second same-flavor opposite-charge lepton with $E_T(p_T) > 10$ GeV (10 GeV/c) are removed as possible Z boson candidates if the reconstructed dilepton invariant mass is between 76 and 106 GeV/c^2; these events are considered by a parallel search at CDF in the ZH production channel. We also reject cosmic ray muon events and dilepton events identified as top pair production using the selection in Ref. [11]. To further reduce this top dilepton background, we reject events with an additional high-p_T isolated track ($p_T > 20$ GeV/c) whose charge is opposite that of the primary lepton. The track isolation requirement is that the total p_T of all tracks within a cone of radius $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ around, but excluding, the candidate track, be less than 2.0 GeV/c. The remaining events are classified according to jet multiplicity. A jet is defined as a cluster of energy deposited in the calorimeter within a fixed radius $\Delta R = 0.4$. Candidate events are required to have two jets each with $E_T > 15\,\mathrm{GeV}$ and $|\eta| < 2.0$ after corrections for calorimeter response and multiple interactions. To remove other contributions from $t\bar{t}$ production, we veto events that have additional jets with $E_T > 8\,\mathrm{GeV}$ and $2.0 < |\eta| < 3.6$ as well as events that have jets with $8 < E_T < 15\,\mathrm{GeV}$ and $|\eta| < 2.0$.

The sample of events with $W + 2$ jets is expected to contain most of the signal, while the sample of events with only 1 jet is used to constrain the W + heavy flavor ($b\bar{b}$ and $c\bar{c}$) background, and the sample of events with 3 or more jets is used to estimate the $t\bar{t}$ contribution. In order to enhance the signal purity of the $W + 2$ jets sample, we require at least one jet be tagged by a secondary vertex algorithm (SECVTX) [12] as containing a B hadron. The SECVTX b tagging algorithm searches for secondary vertices formed by two or more tracks displaced with respect to the primary event vertex. A jet is declared tagged if it contains a secondary vertex with a significant transverse displacement from the primary vertex, positive if the displacement is along the jet direction and negative if opposite the jet direction.

Background events come predominantly from the direct production of W bosons in association with heavy quarks ($Wb\bar{b}$, $Wc\bar{c}$, Wc), W production in association with light flavor jets that are falsely tagged as b-quark jets, multi-jet events without W bosons, and $t\bar{t}$ and single top production. Other relatively small backgrounds include diboson (W^+W^-, ZZ, or WZ) and $Z \to \tau^+\tau^-$ production.

The fraction of W + jets events that contain heavy quarks is estimated using the ALPGEN [13] Monte Carlo program and is further calibrated using the inclusive jet data [12]. We find that this fraction must be scaled by an additional factor of 1.2 ± 0.2 to match the observed number of b tagged $W+1$ jet events. The estimated number of background events is then obtained by multiplying the heavy flavor fraction, the event b tagging efficiency, and the number of W + jets events in the data before b tagging. The largest uncertainty on this estimate comes from varying the parton shower cutoff scale and the initial and final state radiation effects.

To determine the number of false b tags of light-flavor jets, we first parameterize the negative tag rate in an inclusive jet sample [12] as a function of jet E_T, track multiplicity, η, ϕ, and the summed E_T of all the jets in the event. Negative tags are a good approximation of false positive tags, since false tags are mostly due to symmetric resolution effects. Long-lived particles and secondary interactions with the detector material contribute asymmetrically to the positive tag rate and cannot be predicted from the negative tags. By analyzing inclusive jet data, we find the rate of negative tags must be increased by a factor of 1.3 ± 0.1 to account for these asymmetries. We apply the same correction to the W + jets sample to estimate the expected number of false positive tagged events.

The remaining backgrounds are estimated from a combination of Monte Carlo simulation and data. The diboson and $Z \to \tau^+\tau^-$ contributions are estimated from PYTHIA Monte Carlo events. A substantial background contribution comes from events without W bosons. In these events a jet is misidentified as a high-p_T lepton, and mismeasured energies produce apparent missing E_T. We measure this "non-W" background by extrapolating the number of tagged events with an isolated lepton and low $\not\!\!E_T$ into the signal region [12]. The top quark production contributions are estimated using HERWIG [14] and MADEVENT+PYTHIA [15, 16] Monte Carlo calculations for $t\bar{t}$ and single top, respectively; $t\bar{t}$ production is normalized to the cross section measured in this dataset ($\sigma_{t\bar{t}} = 8.6 \pm 1.3\,\text{pb}$) [17], while the single top estimate uses cross section calculations [18] for a top quark mass of $175\,\text{GeV}/c^2$.

The number of observed b tagged events and the corresponding background estimates are listed in Table I. We find good agreement between data and background expectations.

TABLE I: The number of observed W + 2 jet events with ≥ 1 and ≥ 2 tagged jets and the background summary for an integrated luminosity of 320 pb^{-1}.

Number of tags:	$\geq$ 1 tags	$\geq$ 2 tags
False tags	39.3 ± 3.1	1.0 ± 0.1
$Wb\bar{b}$	54.0 ± 18.4	8.0 ± 3.0
$Wc\bar{c}$	19.5 ± 6.6	0.4 ± 0.2
Wc	16.8 ± 4.3	$0.0^{+0.1}_{-0.1}$
Diboson/$Z \to \tau^+\tau^-$	5.0 ± 1.1	0.3 ± 0.1
non-W	16.5 ± 3.2	0.4 ± 0.1
Single top	9.6 ± 2.0	1.3 ± 0.3
$t\bar{t}$	14.6 ± 2.5	3.1 ± 0.5
Total background	175 ± 26	15 ± 3
Observed positive tagged events	187	14
Events before b tagging	2072	

The acceptance for identifying $WH \to \ell\nu b\bar{b}$ events using the cuts described above is calculated as a function of the Higgs boson mass from PYTHIA Monte Carlo samples of $WH \to Wb\bar{b}$ events after full simulation of the CDF II detector response. The total acceptance is calculated as a product of the W leptonic branching fraction, the kinematic and geometric acceptance, the lepton identification efficiencies, the trigger efficiencies, and the b tagging efficiencies. An 11% systematic uncertainty comes from uncertainties in the modeling of initial (3%) and final (7%) state radiation, parton distribution function (1%), jet energy scale (3%), b tagging efficiency (5%), jet energy resolution (3%), electron and muon trigger efficiencies (< 1%), electron and muon ID efficiencies (5%), and integrated luminosity (6%). Acceptance for WH increases linearly from 1.5% to 1.7% as m_H increases from 110 to 150 GeV/c^2. For a Higgs boson mass of $115\,\text{GeV}/c^2$, we expect 0.65 WH events with an average efficiency of $50 \pm 3\%$ to tag at least one b jet.

We perform a direct search for a resonant mass peak in the reconstructed dijet invariant mass distribution, after having corrected for the calorimeter response to B-hadron jets. The reconstructed $b\bar{b}$ invariant mass resolution for WH events is estimated to be 17%. Figure 1 shows the dijet mass distribution in the $\geq$ 1-tag data. The expected mass distribution is also shown for the standard model Higgs boson but with a cross section 10 times the expected value [7]. The data match well the total predicted background, and we set an upper limit on the production cross section times branching ratio of $\sigma(p\bar{p} \to WH) \times \mathcal{B}(H \to b\bar{b})$ as a function of m_H using the number of events in the $W + 2$ jets sample.

We assume the data consist of three components: TOP ($t\bar{t}$ and single top), WH, and other SM processes labelled OTH (false tags, $Wb\bar{b}$, $Wc\bar{c}$, Wc, non-W, and diboson). A binned maximum likelihood technique is used to estimate upper limits on WH production by constraining the number of OTH and TOP events to the background expectations within their separate uncertainties. The expected number of events μ in each mass bin is

$$\mu = f_{\mathrm{OTH}} \cdot N_{\mathrm{OTH}} + f_{\mathrm{TOP}} \cdot N_{\mathrm{TOP}} + f_{WH} \cdot (\varepsilon \cdot \mathcal{L} \cdot \sigma_{WH} \cdot \mathcal{B}(H \to b\bar{b})),$$

where f_{OTH}, f_{TOP} and f_{WH} are the expected fraction of events in a given mass bin predicted by Monte Carlo simulation and N_{TOP}, N_{OTH}, ε, $\mathcal{L}$ and σ_{WH} are the expected number of top and non-top events, the detection efficiency, the integrated luminosity and the WH cross section to be estimated, respectively. The corresponding likelihood is

$$L = \prod_{i=\mathrm{bin}} \frac{\mu_i^{N_i} \cdot e^{-\mu_i}}{N_i!} \times G(N_{\mathrm{OTH}}, \sigma_{\mathrm{OTH}}) \times G(N_{\mathrm{TOP}}, \sigma_{\mathrm{TOP}}),$$

where N_i is the observed events from $W + 2$ jets sample and G is a Gaussian constraint, with width equal to the respective uncertainties, on the estimate of top and other background events from the counting experiment.

The resulting 95% confidence level upper limits range from 10 to 3 pb as a function of the Higgs mass and are shown in Figure 2 in comparison with the production cross section times branching fraction for the standard model Higgs boson. We generate background-only pseudo-experiments to calculate the expected performance of the analysis in the absence of signal events; the median results are also shown in Figure 2. These data are consistent with our expectations for a data sample of this size.

We have studied additional systematic effects related to the dijet mass distribution, including uncertainties in the b-jet energy measurement and the $Wb\bar{b}$ and $t\bar{t}$ two-jet invariant mass spectra; these have a negligible effect on the calculated upper limits, as do the correlations between the uncertainties for different backgrounds.

A closer look at the sample of double b-tagged events, with both jets tagged by SECVTX, still shows good agreement between the expected backgrounds and the observed number of data events (Table I). The corresponding dijet invariant mass distributions are shown in Figure 3. The total acceptance is reduced significantly with respect to the single-tagged sample, ranging from $0.32 \pm 0.05\%$ to $0.40 \pm 0.07\%$ for m_H between 110 and 150 GeV/c^2, where the errors include both statistical and systematic uncertainties described above. This reduced acceptance hampers the sensitivity of the double-tagged analysis with the current dataset; the sensitivity figure of merit $S/\sqrt{B}$ drops from 0.07 for the single-tagged sample to 0.05 for the double-tagged sample, assuming a Higgs mass of 115 GeV/c^2. We do not treat the double-tagged events as a separate search dataset because the event selection has not been optimized for that purpose.

In summary, this search with the CDF II detector is sensitive to new particles decaying into $b\bar{b}$ and produced in association with a W boson. The dijet mass spectrum shows no significant excess of events in the b-tagged

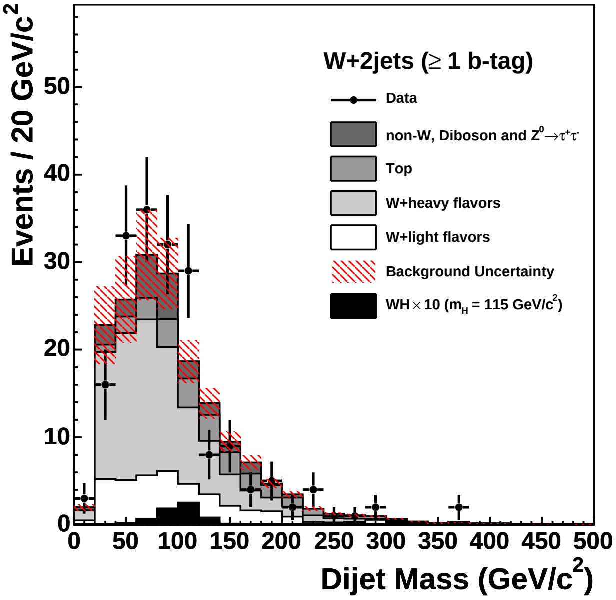

FIG. 1: The dijet mass distribution in the data along with the background expectations and the Higgs boson signal distribution (for mass 115 GeV/c^2) scaled up by a factor of 10.

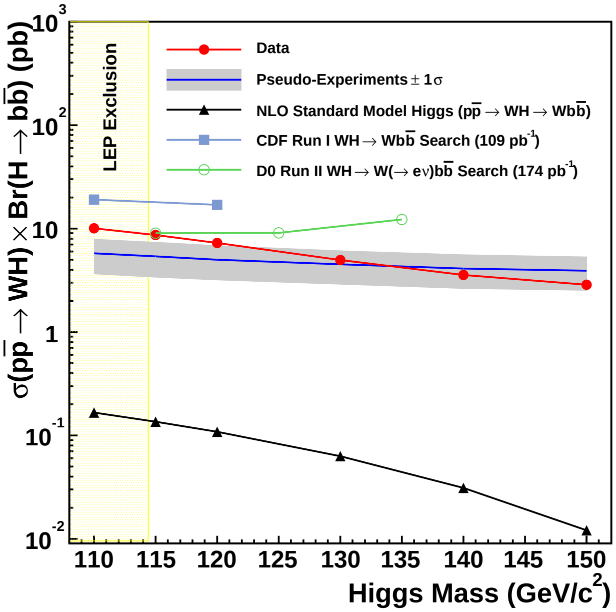

FIG. 2: The 95% C.L. upper limits (filled circles) on the WH cross section as a function of the Higgs boson mass for events with at least one b tag. Also shown is the theoretical cross section (triangles) for the production of a standard model Higgs boson in association with a W boson, and the expected results from background-only experiments (shaded band). The CDF Run I limits and the DØ Run II limits are also shown for comparison.

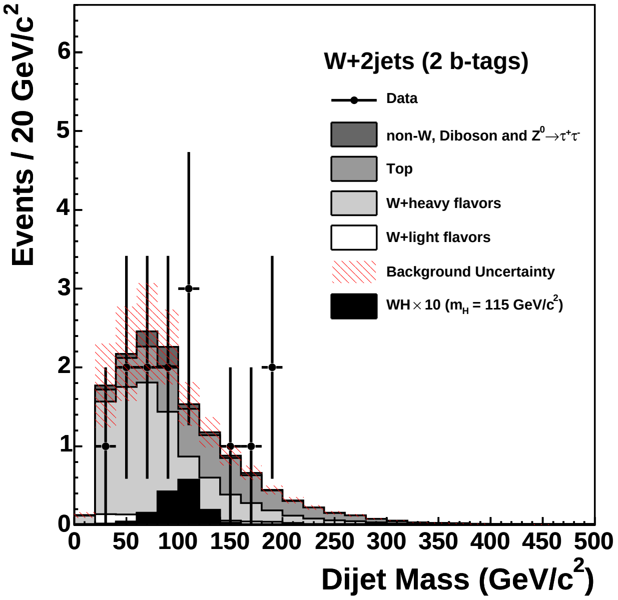

FIG. 3: The dijet mass distribution in the double b-tagged data along with the background expectations and the Higgs boson mass signal distribution (for mass 115 GeV/c^2) scaled up by a factor of 10.

$W + 2$ jets events. With a $320\,\mathrm{pb}^{-1}$ dataset, we set 95% C.L. upper limits on the production cross section times branching ratio ranging from 10 pb at $m_H = 110\,\mathrm{GeV}/c^2$ to 3 pb at $m_H = 150\,\mathrm{GeV}/c^2$. Although we have significantly improved the upper limits over Run I [5], the sensitivity of the present search is limited by statistics to a cross section approximately a factor of 50 higher than the predicted cross section for standard model Higgs boson production. Improvements in the b-tagging efficiency, lepton identification, and dijet mass resolution promise increased sensitivity for future searches with increased integrated luminosity.

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