A search for associated $W$ and Higgs Boson production in $pp$ collisions at
$\sqrt{s} = 1.96$ TeV


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We present results of a search for WH → tℓb̅b̅ production in pp collisions based on the analysis of 1.05 fb⁻¹ of data collected by the D0 experiment at the Fermilab Tevatron, using a neural network for separating the signal from backgrounds. No signal-like excess is observed, and we set 95% C.L. upper limits on the WH production cross section multiplied by the branching ratio for H → b̅b̅ for Higgs boson masses between 100 and 150 GeV. For a mass of 115 GeV, we obtain an observed (expected) limit of 1.5 (1.4) pb, a factor of 11.4 (10.7) times larger than standard model prediction.

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The Higgs boson is the last unobserved particle of the standard model (SM). As a remnant of spontaneous electroweak symmetry breaking, it is fundamentally different from the other elementary particles, and its observation would support the hypothesis that the Higgs mechanism generates the masses of the weak gauge bosons and the charged fermions. The Higgs boson mass ($m_H$) is not theoretically predicted, but the combination of results from direct searches at the CERN LEP collider [1] with the indirect constraints from precision electroweak measurements results in a preferred range of $114.4 < m_H < 190$ GeV at 95% C.L [2]. Such mass range can be probed at the Fermilab Tevatron collider. In this Letter, we concentrate on the most sensitive production channel at the Tevatron for Higgs bosons of mass below 125 GeV, i.e. the associated production of a Higgs boson with a $W$ boson. Several searches for $WH$ production have been published at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. Two [3, 4] used subsamples (0.17 fb$^{-1}$ and 0.44 fb$^{-1}$) of the data reported in this Letter, while two others, from the CDF collaboration, are based on 0.32 fb$^{-1}$ and 0.95 fb$^{-1}$ of integrated luminosity [5, 6].

This analysis uses 1.05 fb$^{-1}$ of D0 [7, 8] data, collected between April 2002 and February 2006. As in our previous $WH$ analyses [3, 4], we require one high transverse momentum ($p_T$) lepton (e or $\mu$) and missing transverse energy $E_T$ to account for the neutrino from the $W$ boson decay, and two jets from the decay of the Higgs boson, with at least one of them being identified as originating from a bottom (b) quark jet. We extend this data selection by including also events with three jets and events with “forward” electrons detected at pseudorapidities [9] $|\eta| > 1.5$. We also now accept the small contribution originating from misreconstructed $ZH$, in which only one lepton from the $Z$ is identified. In addition we use a more inclusive trigger selection in the muon channel, increasing the detection efficiency from approximately 70% to 100% [10], we improve the b-jet identification using a neural network algorithm [11], and we enhance the signal to background discrimination using a neural network for the $W + 2$ jet events. Overall, the improvements in analysis techniques have led to an increase of about 40% in the sensitivity (for an equivalent luminosity) to a Higgs boson with mass 115 GeV, with respect to our previous analysis [4].

For the e channel, the $W + \text{jets}$ candidate events are collected, with $\approx 90\%$ efficiency, by triggers that require at least one electromagnetic (EM) object in the calorimeter. In the $\mu$ channel, $\approx 90\%$ of the candidates are collected by triggers requiring a single muon or a muon plus a jet, while the remaining $10\%$ of events are collected by other triggers, for a total trigger efficiency of $\approx 100\%$, as estimated in data [10].

The event selection requires one lepton candidate with $p_T > 15$ GeV, $E_T > 20$ GeV ($p_T > 25$ GeV for events with a forward electron), and exactly two jets with $p_T > 25$ and 20 GeV, and $|\eta| < 2.5$, or exactly three jets with $p_T > 25, 20$ and 20 GeV, and $|\eta| < 2.5$. We also require the scalar sum of the $p_T$ of the jets to be $> 60$ GeV, the $W$ transverse mass $M_{W}^{\text{TM}}$ reconstructed from the $E_T$ and the lepton $p_T$ to be greater than 40 GeV$-0.5\times E_T$ to reject multijet background, and the primary interaction vertex to take place within the longitudinal acceptance of the vertex detector. Jets are reconstructed using a midpoint cone algorithm [12] with a radius of 0.5. The $E_T$ is calculated from energies in calorimeter cells and corrected for the $p_T$ of identified muons. All energy corrections applied to electrons or jets are also propagated to the $E_T$.

A central (forward) electron is required to have $|\eta| < 1.1$ (1.5 < $|\eta| < 2.5$). To reject fake electrons originating mostly from instrumental effects (track-photon overlap), the electron candidates must satisfy two sets of identification (“loose” and “tight”) criteria [4]. The efficiencies of these requirements are determined from a pure sample of $Z \rightarrow e^+e^-$ events. The differential multijet background for every relevant distribution is then estimated from the loose and tight lepton samples [4, 13]. The same statistical method is used for muons, but with different loose/tight definitions. Muons are reconstructed using information from the outer muon detector and the central tracker, and must have $|\eta| < 2.0$. To reject muons originating from semi-leptonic decays of heavy-flavor hadrons, we exploit the fact that they have lower $p_T$ than those originating from $W$ decay, and are generally not isolated because of accompanying jet fragments. The loose isolation criterion is thus defined by specifying a spatial separation between a muon and the closest jet in the $\eta - \phi$ plane of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} > 0.5$, where $\phi$ is the azimuthal angle. Tighter isolation is defined by requiring little tracking and calorimetric activity around the muon track.

The dominant backgrounds to $WH$ production are from $W+\text{heavy flavor}$ jets production, top quark pair production (t$t$), and single top quark production. Signal ($WH$ and $ZH$) and diboson processes ($WW$, $WZ$, $ZZ$) are simulated using the PYTHIA [14] event generator, and CTEQ6L [15] leading-order parton distribution functions. “$W+\text{jets}$” events refer to $W$ bosons produced in association with light-flavor jets (originating from $u$, $d$, $s$ quarks or gluons) or charm jets (originating from $c$ quarks), and constitute the dominant background before b-jet identification. $Wc\bar{c}$ and $Wbb$ are simulated individually and associated as “$Wb\bar{b}$” for purposes of accounting. These $W$ boson processes are generated with ALPGEN [16] interfaced to PYTHIA for showering and fragmentation, since ALPGEN provides a more complete simulation of processes with high jet multiplicities than PYTHIA. The $t\bar{t}$ and $Z+\text{jets}$, events are also generated using ALPGEN/PYTHIA. The production of single top quarks is simulated with COMPTOP [17]. The simulated backgrounds are normalized to their re-
spective NLO theoretical cross sections, with the exception of the $W^+ \text{ jets}$ and $W^+ \text{ heavy-flavor}$ samples, which are normalized to data after subtraction of all the other backgrounds, before b-jet identification. All generated events are processed through the D0 detector simulation based on GEANT [18]. Data collected with a random bunch crossing trigger are overlaid on the simulated events to model the occupancy of the detector which is dependent on the instantaneous luminosity. The resulting events are then passed through the reconstruction software. Finally, corrections are applied to account for the trigger efficiency and for residual discrepancies between the data and the simulation.

We use a neural network b-tagging (NNb) algorithm [11] to identify heavy-flavor jets. Its requirements are optimized for the best sensitivity to the Higgs boson signal. For each jet multiplicity, we form two statistically independent samples, one (2 b-tag) with two b-tagged jets using a loose NNb criterion resulting in a b-jet efficiency of 50% and a light-jet tagging (mistag) probability of 1.7%, and a second (1 b-tag) with exactly one b-tagged jet using a tighter NNb criterion (48% efficiency and 0.5% mistag probability). All efficiencies are determined for jets satisfying minimum requirements in terms of track quality and multiplicity (“taggable jets”), which constitute ≈80% of all jets. In the simulations, the b-tagged jets are weighted to reproduce the tagging rate measured in data samples.

Using these selection criteria, we observe 885 (385) in the 1 b-tag $W + 2 \text{ jet}$ ($W + 3 \text{ jet}$) samples and 136 (122) events in the corresponding 2 b-tag sample. Distributions of the dijet invariant mass, using the two jets of highest $p_T$, in $W + 2 \text{ jet}$ and $W + 3 \text{ jet}$ events are shown for the 1 b-tag and 2 b-tag samples in Fig. 1(a–d). The data are well described by the sum of the simulated SM processes and multijet background. The expected contributions from a Higgs boson with $m_H = 115 \text{ GeV}$ are also shown. The expected event yields for the backgrounds and a Higgs boson with $m_H = 115 \text{ GeV}$ are compared to the observed number of events in Table 1.

Although the dijet invariant mass is a powerful variable for separating a Higgs boson signal from background [4], the sensitivity of the analysis is enhanced through the use of multivariate techniques: in $W + 2 \text{ jet}$ events, a neural network is trained on simulated signal and $W\tau\tau$ events, using seven kinematic variables: $p_T$ of the highest and second-highest $p_T$ jet, $\Delta R(jet_1,jet_2)$, $\Delta\phi(jet_1,jet_2)$, $p_T$(dijet system), dijet invariant mass, and $p_T$(W boson candidate). The training is performed for every simulated Higgs signal (different test masses), and separately for $e$, $\mu$, 1 b-tag and 2 b-tag events. The resulting neural networks are then applied to $W + 2 \text{ jet}$ data and to the background and simulated signal samples. In the final limit-setting procedure, the distributions of the neural network discriminant corresponding to a specific Higgs boson test mass are used for analyzing the $W + 2 \text{ jet}$ events. The improvement in sensitivity over just using the dijet invariant mass is about 15% at $m_H = 115 \text{ GeV}$. The resulting neural network discriminants are shown in Fig. 1(e,f). For the $W + 3 \text{ jet}$ samples, whose dominant background is $t\bar{t}$, the limits are determined directly from the dijet mass distributions.

Systematic uncertainties on efficiencies and from the propagation of other systematics (e.g. energy calibration and detector response) are: (3–5)% for trigger efficiency; (4–5)% for lepton identification efficiency; 6% for jet identification efficiency and jet resolution; 5% from the modeling of the jet multiplicity spectrum; 3% due to the uncertainty in the jet energy calibration; 2–10% due to the uncertainty in modeling $W + \text{ jets}$, determined by comparing data and expectation before b-tagging and before reweighting the $W + \text{ jet}$ samples to match the data...
TABLE I: Summary of event yields for the $\ell$ ($e$ and $\mu$) + b-tagged jets + $E_T$ final state. Events in data are compared with the expected number of 1 b-tag and 2 b-tag events in the $W+2$ and $W+3$ jet samples, in simulated samples of diboson (labelled “$WZ$” in the table), $W/Z+bb$ or cc (“$Wbb$”), $W/Z+$ light quark jets (“$W+jets$”), top quark (“$tt$” and “single $t$”) production, and multijet background (“m-jet”) determined from data (see text). The $WH$ expectation is given for $m_H = 115$ GeV, and not included in the “Total” SM expectation.

<table>
<thead>
<tr>
<th></th>
<th>1 b-tag</th>
<th>2 b-tag</th>
<th>1 b-tag</th>
<th>2 b-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WH$</td>
<td>2.8 ± 0.3</td>
<td>1.5 ± 0.2</td>
<td>0.7 ± 0.1</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>$WZ$</td>
<td>34.5 ± 3.7</td>
<td>5.3 ± 0.6</td>
<td>9.1 ± 1.0</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>$Wbb$</td>
<td>268 ± 67</td>
<td>54 ± 14</td>
<td>87 ± 22</td>
<td>22.7 ± 5.7</td>
</tr>
<tr>
<td>$W+jets$</td>
<td>347 ± 87</td>
<td>14.0 ± 4.4</td>
<td>96 ± 24</td>
<td>8.5 ± 2.7</td>
</tr>
<tr>
<td>$tt$</td>
<td>95 ± 17</td>
<td>37.4 ± 7.0</td>
<td>156 ± 29</td>
<td>81 ± 15</td>
</tr>
<tr>
<td>single $t$</td>
<td>49.4 ± 9.0</td>
<td>12.4 ± 2.3</td>
<td>157 ± 2.9</td>
<td>6.7 ± 1.2</td>
</tr>
<tr>
<td>m-jet</td>
<td>104 ± 29</td>
<td>8.9 ± 2.1</td>
<td>54 ± 15</td>
<td>8.7 ± 2.1</td>
</tr>
<tr>
<td>Total</td>
<td>896 ± 177</td>
<td>132 ± 27</td>
<td>418 ± 76</td>
<td>129 ± 24</td>
</tr>
<tr>
<td>Data</td>
<td>885</td>
<td>136</td>
<td>385</td>
<td>122</td>
</tr>
</tbody>
</table>

(profiting in sensitivity is significant, and our expected limits scale approximately inversely with luminosity compared to our previous result. These limits are the most stringent to date in this process at a hadron collider.

In summary, we have presented 95% C.L. upper limits on the product of $W/H \rightarrow c\bar{t}b\bar{b}$ production cross section and branching fraction for $H \rightarrow b\bar{b}$. These range between 2.1 and 1.0 pb for $100 < m_H < 150$ GeV, while the corresponding SM predictions range from 0.23 to 0.01 pb. The sensitivity should increase significantly in the near future with the continuing accumulation of luminosity from the Tevatron and improvement in analysis techniques. A significant sensitivity gain has already been achieved by combining these data, with other Higgs boson searches done by the CDF and D0 collaborations [22].

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![FIG. 2: 95% C.L. cross section upper limit (and corresponding expected limit) on $\sigma(pp \rightarrow WH) \times B(H \rightarrow b\bar{b})$ vs. Higgs boson mass, compared to the SM expectation and the to the expected limit from our previous analysis [4]. Recent CDF results [6] are also shown. Solid (dashed) lines represent observed (expected) limits. The contribution of ZH reconstructed in the same final state is taken into account in the WH signal when deriving the limits, assuming the SM ratio of $ZH/WH$ cross sections.](image-url)
FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC (United Kingdom); MSMT and GACR (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); the Swedish Research Council (Sweden); CAS and CNSF (China); the Alexander von Humboldt Foundation (Germany).

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[f] Visitor from Universität Bern, Bern, Switzerland.
[g] Visitor from Universität Zürich, Zürich, Switzerland.
[h] Deceased.

[9] The pseudorapidity is given in terms of the polar angle \( \theta \) as \( \eta = -\ln(\tan \frac{\theta}{2}) \), where \( \theta \) is defined relative to the center of the detector.