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## Search for $Wb\bar{b}$ and $WH$ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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## Search for $Wb\bar{b}$ and $WH$ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present a search for  $Wb\bar{b}$  production in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV in events containing one electron, an imbalance in transverse momentum, and two  $b$ -tagged jets. Using  $174 \text{ pb}^{-1}$  of integrated luminosity accumulated by the D0 experiment at the Fermilab Tevatron collider, and the standard-model description of such events, we set a 95% C.L. upper limit on  $Wb\bar{b}$  production of  $6.6 \text{ pb}$  for  $b$  quarks with transverse momenta  $p_T^b > 20 \text{ GeV}$  and  $b\bar{b}$  separation in pseudorapidity-azimuth space  $\Delta\mathcal{R}_{bb} > 0.75$ . Restricting the search to optimized  $b\bar{b}$  mass intervals provides upper limits on  $WH$  production of  $9.0\text{--}12.2 \text{ pb}$  for Higgs-boson masses of  $105\text{--}135 \text{ GeV}$ .

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The Higgs boson is the only scalar elementary particle expected in the standard model (SM). Its discovery would be a major success for the SM and would provide further insights into the electroweak symmetry breaking mechanism. The constraints from precision measurements [1]

favor a Higgs boson sufficiently light to be accessible at the Fermilab Tevatron collider. Although the expected luminosity necessary for its discovery is higher than obtained thus far, the special role of the Higgs boson in the SM justifies extensive searches for a Higgs-like particle

independent of expected sensitivity. Such studies also provide an opportunity to investigate the main backgrounds, and, in particular, the interesting and thus far unobserved  $Wb\bar{b}$  production process.

In this Letter, we present a search for a Higgs ( $H$ ) boson with mass  $m_H$  between 105 and 135 GeV, in the production channel  $p\bar{p} \rightarrow WH \rightarrow evb\bar{b}$ , at  $\sqrt{s} = 1.96$  TeV. The expected  $WH$  cross section is of the order of 0.2 pb for this mass range [2]. Our search is based on an integrated luminosity of  $174 \pm 11$  pb $^{-1}$  accumulated by the D0 experiment during 2002 and 2003.

The experimental signature of  $WH \rightarrow evb\bar{b}$  relies on a final state with one high  $p_T$  electron, two  $b$  jets, and a large imbalance in transverse momentum ( $\cancel{E}_T$ ) resulting from the undetected neutrino. The dominant backgrounds to  $WH$  production are from  $Wb\bar{b}$ ,  $t\bar{t}$ , and single-top-quark production. The signal to background ratio is improved by requiring exactly two jets in the final state, because the fraction of  $t\bar{t}$  events that contain at most two reconstructed jets is small. We use the high statistics  $W + \geq 2$  jets data to check the validity of our simulation but restrict the selection to  $W + 2 b$  jets for the final results.

The D0 detector includes a magnetic tracking system surrounded by a uranium/liquid-argon calorimeter, which is enclosed in 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 superconducting solenoidal magnet [3]. The SMT and CFT have designs optimized for tracking and vertexing capabilities for pseudorapidities  $|\eta| < 3$  and  $|\eta| < 2.5$ , respectively [4]. The calorimeter has a central section (CC) covering  $\eta$  up to  $|\eta| \approx 1.1$ , and two end calorimeters (EC) extending coverage to  $|\eta| \approx 4.2$ , each housed in a separate cryostat [5]. For particle identification, the calorimeter is divided into an electromagnetic (EM) section, 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 magnetized iron toroids, 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  $2.7 < |\eta| < 4.4$ .

Event selection starts with the requirement of an isolated candidate electron, with  $p_T > 20$  GeV, in the central region of  $|\eta| < 1.1$ , but away ( $|\delta\varphi| > 0.02$ ) from the 32 boundaries of calorimeter modules at periodic azimuthal angle ( $\varphi$ ) values [6]. Such electrons are required to trigger the event. The average trigger efficiency is  $(94 \pm 3)\%$  for  $W + 2$  jet events. These initial electron candidates are selected by applying standard D0 criteria based on the characteristics of the energy deposited in a cone of radius  $\Delta\mathcal{R} = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2} = 0.2$  and requiring that there is a track pointing to the EM cluster [6]. Electron selection is

further refined using an electron likelihood discriminant based on the above estimators, as well as on additional tracking information. The combined reconstruction and identification efficiency for electrons passing all these requirements are determined from a  $Z \rightarrow e^+e^-$  sample to be  $(74 \pm 4)\%$  per electron.

To select  $W$  bosons, we require  $\cancel{E}_T > 25$  GeV. Events with a second isolated lepton ( $e$  or  $\mu$  [7]) with  $p_T > 15$  GeV and  $|\eta| < 2.4$  are rejected to suppress  $Z +$  jets and  $t\bar{t}$  backgrounds. Only events with a primary vertex at  $|z| < 60$  cm relative to the center of the detector are retained. At least two jets with  $p_T > 20$  GeV and  $|\eta| < 2.5$  are then required. A jet is defined as a cluster of calorimeter towers within a radius  $\Delta\mathcal{R} = 0.5$  [8], having a distance  $\Delta\mathcal{R}$  to any initial electron candidate greater than 0.5. The average jet reconstruction and identification efficiency is  $(95 \pm 5)\%$ , as determined from  $\gamma +$  jet events. For selecting  $b$  jets, we use an impact-parameter based algorithm [9], which has been cross-checked with a secondary-vertex reconstruction algorithm.

To improve calorimeter performance, before reconstructing the calorimeter objects, we use an algorithm that suppresses cells with negative energy (originating from fluctuations in noise) and cells with energies 4 standard deviations below the average electronics noise ( $\sigma_n$ ), when they do not neighbor a cell of higher energy,  $E > 4\sigma_n$ . The EM scale is calibrated using the peak in the  $Z \rightarrow e^+e^-$  reconstructed mass, and jet energies are then corrected to the EM scale using  $\gamma +$  jet events. These energy corrections, and the transverse momenta of any muons in the event, are propagated into the calculation of the  $\cancel{E}_T$ , which is estimated initially using all (unsuppressed) calorimeter cells.

The D0 detector simulation based on GEANT [10] and the reconstruction and analysis chain used for data are also used for obtaining expectations from the standard model, which are normalized to cross sections measured in data, or to calculations when no such measurements are available. Small additional energy smearing in  $\cancel{E}_T$  and in the energy of the simulated electrons is used to obtain a better agreement between data and simulation.

Before applying  $b$  tagging, we expect to have two main components in the data:  $W +$  jet events and multijet events in which a jet has been misidentified as an electron (called QCD background in the following).  $W +$  jet events are simulated using the leading-order matrix-element program ALPGEN [11] for the  $Wjj$  process (i.e., production of  $W + 2$  partons, which are in our case gluons or  $u, d, s, c$  quarks, since the  $Wb\bar{b}$  is simulated separately), followed by PYTHIA [12] for parton showering and hadronization. The QCD background is estimated from data using measured probabilities for jets to be misidentified and accepted as electrons.

We have compared the distribution of the dijet invariant mass in  $W + 2$  jet events to the simulation, in which the

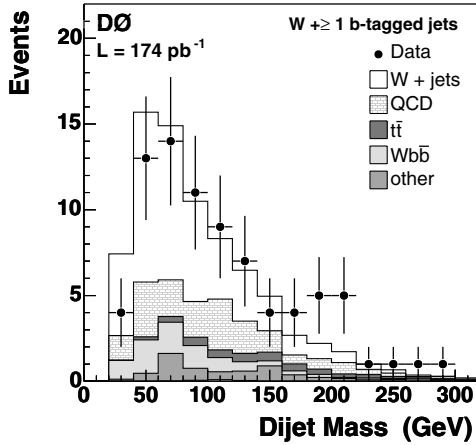


FIG. 1. Distribution of the dijet invariant mass for  $W + 2$  jet events, when at least one jet is  $b$  tagged, compared to expectation (cumulative). The other SM backgrounds include single-top events. The simulated contributions are normalized to the integrated luminosity of the data.

dominant  $Wjj$  expectation is normalized using the measured luminosity and the next-to-leading-order (NLO) MCFM calculation [13]. This, together with the QCD background estimated from the data, provides an expected rate for  $W + 2$  jet events in agreement with the measured rate. Taking into account uncertainties originating from the jet energy scale, we have checked that the shape of the distribution is also well described.

The systematic uncertainty associated with the selection of exactly two jets in the final state has been studied in data and in simulations. The rates for  $W + 3$  jet and  $W + 4$  jet events, after normalizing to the  $W + 2$  jet sample, are described by the ALPGEN-PYTHIA simulation to within 15% and 6%, respectively. The resulting systematic uncertainty on the expectation is  $\pm 5\%$ . This also includes a 4% uncertainty originating from the ALPGEN-PYTHIA combined simulation.

To search for  $Wb\bar{b}$  final states and to suppress the background, we apply the  $b$ -tagging algorithm to jets having at least two tracks, with  $p_T^{\text{track}1(2)} > 1.0(0.5)$  GeV. These requirements have a typical efficiency per jet of 80% for multijet events, which is reproduced to within 5% by the simulation. The  $b$ -tagging algorithm uses a lifetime probability that is estimated from the tracks associated with a given jet. A small probability corresponds to jets having tracks with large impact parameters that characterize  $b$ -hadron decays. Requiring a probability smaller than 0.7% yields a mistag (tagging of  $u$ ,  $d$ ,  $s$  or gluon jets as  $b$  jets) rate of  $(0.50 \pm 0.05)\%$ . The tagging efficiency for a central  $b$  jet with  $p_T$  between 35 and 55 GeV is measured to be  $(48 \pm 3)\%$ .

The tagging efficiency in the simulation is adjusted to the one measured in the data. A study of the  $p_T$  and  $\eta$  dependence in data and in simulation indicates a systematic uncertainty on tagging efficiencies of  $\pm 6\%$ . When tagging light quarks, there is a larger systematic uncertainty on the efficiency ( $\pm 25\%$ ) that originates from the direct application of the algorithm to simulated events, but this has only a small effect on the final results. For the tagging efficiency of  $c$  quarks, we use the same data/simulation efficiency ratio as for  $b$  quarks.

To reduce the presence of  $b$  jets from gluon splitting and to help assure an unambiguous determination of jet flavors in simulation, we require the separation between the two reconstructed jets ( $\Delta\mathcal{R}$ ) to be greater than 0.75. In Fig. 1 we show the distribution of the dijet mass for  $W + 2$  jet events in which at least one jet is  $b$  tagged. The data are well described by the sum of the multijet background and simulated SM processes (cf. Table I). The  $t\bar{t}$  contribution is simulated with PYTHIA ( $\sigma_{t\bar{t}} = 6.77 \pm 0.42$  pb [14]). Single-top production ( $\sigma_{W^* \rightarrow tb} = 1.98 \pm 0.32$  pb,  $\sigma_{gW \rightarrow tb} = 0.88 \pm 0.13$  pb [15]) is generated with COMPHEP [16], assuming a top-quark mass of 175 GeV, and is shown in Fig. 1, in combination with other pro-

TABLE I. Summary for the  $e + \cancel{E}_T + \text{jets}$  final state: the numbers of expected  $W + \geq 2$  jets and  $W + 2$  jet events, before and after  $b$  tagging, originating from  $WH$  (for  $m_H = 115$  GeV),  $WZ$ ,  $Wb\bar{b}$ , top production ( $t\bar{t}$  and single-top), QCD multijet background, and  $W$  or  $Z + \text{jets}$  (excluding  $Wb\bar{b}$  which is counted separately) are compared to the numbers of observed events. The last column shows the same comparison for the control sample of  $W + \geq 3$  jet events that contain two  $b$ -tagged jets.

	$W + \geq 2$ jets	$W + 2$ jets	$W + \text{two jets}$ (1 $b$ -tagged jet)	$W + 2$ jets (2 $b$ -tagged jets)	$W + \geq 3$ jets (2 $b$ -tagged jets)
$WH$	$0.6 \pm 0.1$	$0.4 \pm 0.1$	$0.14 \pm 0.03$	$0.054 \pm 0.012$	$0.014 \pm 0.004$
$WZ$	$1.4 \pm 0.3$	$1.2 \pm 0.3$	$0.38 \pm 0.09$	$0.13 \pm 0.03$	$0.02 \pm 0.01$
$Wb\bar{b}$	$24.7 \pm 6.2$	$21.4 \pm 5.3$	$6.6 \pm 1.5$	$1.72 \pm 0.41$	$0.37 \pm 0.09$
$t\bar{t}$	$41.4 \pm 8.7$	$8.6 \pm 1.8$	$2.7 \pm 0.6$	$0.78 \pm 0.19$	$4.63 \pm 1.11$
Single top	$11.6 \pm 2.4$	$8.3 \pm 1.7$	$2.7 \pm 0.6$	$0.47 \pm 0.11$	$0.30 \pm 0.07$
QCD multijet	$492 \pm 108$	$393 \pm 86$	$17.1 \pm 4.3$	$0.50 \pm 0.20$	$0.92 \pm 0.37$
$W$ or $Z + \text{jets}$	$2008 \pm 502$	$1672 \pm 418$	$43.0 \pm 12.9$	$0.78 \pm 0.22$	$0.86 \pm 0.24$
Total expectation	$2580 \pm 626$	$2106 \pm 513$	$72.6 \pm 20.0$	$4.44 \pm 1.17$	$7.12 \pm 1.89$
Observed events	2540	2116	76	6	7

cesses:  $Z \rightarrow ee$ ,  $W \rightarrow \tau\nu$  and  $WZ(\rightarrow b\bar{b})$ , which are simulated using PYTHIA with cross sections of 255 pb [17], 2775 pb [17], and 0.6 pb [13], respectively. As for the  $Wjj$  process, the  $Wb\bar{b}$  contribution is simulated using ALPGEN and PYTHIA, requiring  $p_T^b > 8$  GeV and  $\Delta\mathcal{R}_{bb} > 0.4$  at the parton level, with  $\sigma_{Wb\bar{b}} = 3.35$  pb computed at NLO using the MCFM program.  $WH$  production is simulated with PYTHIA using the computed cross section at NLO, which depends on  $m_H$  [2].

To further improve signal or background, we select events in which a second jet is  $b$  tagged. The final results for the number of observed and expected events are given in Table I. Data from the last column are not used in the analysis but provide a check of the accuracy of our expectations for events with two  $b$ -tagged jets in the control sample of  $W + \geq 3$  jet events, which is dominated by  $t\bar{t}$  production.

The distribution of the dijet mass for events with two  $b$ -tagged jets is shown in Fig. 2. The expected number of events is  $4.4 \pm 1.2$ , of which 1.7 events come from  $Wb\bar{b}$  production. The dominant systematic uncertainties on the expectation come from uncertainties on the  $b$ -tagging efficiency (11%) and jet energy corrections. The uncertainty on the latter propagates to uncertainties of 7% on  $Wb\bar{b}$  production, 4% on single-top and  $WH$  production, and 3% on  $t\bar{t}$  production. The total systematic uncertainty on the expectation is 26%, including the uncertainties on cross sections and luminosity (18% and 6.5%).

Assuming that the six observed events are consistent with the SM, without contributions from  $Wb\bar{b}$  and  $WH$ , and using the  $Wb\bar{b}$  signal efficiency of  $(0.90 \pm 0.14)\%$ , we set a 95% C.L. upper limit of 6.6 pb on the  $Wb\bar{b}$  cross section, for  $p_T^b > 20$  GeV and  $\Delta\mathcal{R}_{bb} > 0.75$  [18]. The limits on the cross sections are obtained using a Bayesian

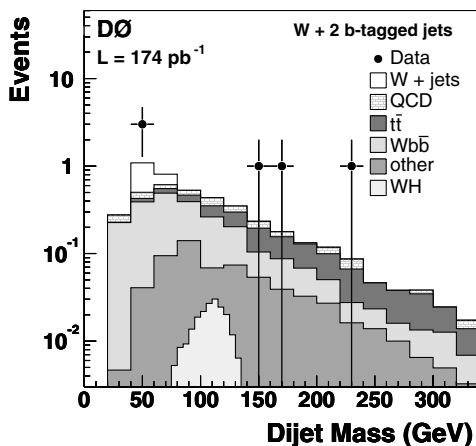


FIG. 2. Distribution of the dijet invariant mass for  $W + 2$   $b$ -tagged events, compared to expectation (cumulative). The simulated contributions are normalized to the integrated luminosity of the data. The expectation for a 115 GeV Higgs boson from  $WH$  production is also shown.

approach [19] that takes account of both statistical and systematic uncertainties.

The expected contribution from the  $b\bar{b}$  decay of a SM Higgs boson, with  $m_H = 115$  GeV produced with a  $W$ , is also shown in Fig. 2, and amounts to 0.05 events. The mean and width of a Gaussian fit to this expected contribution in the mass window 85–135 GeV are 110 and 16 GeV, respectively, a relative resolution of  $(14 \pm 1)\%$ . Similar resolutions are obtained for Higgs-boson masses in the 105–135 GeV region.

No events are observed in the dijet mass window of 85–135 GeV. The expected SM background (including  $Wb\bar{b}$ ) is  $1.07 \pm 0.26$  events, and the expected  $WH$  signal is  $0.049 \pm 0.012$  events, with a signal efficiency of  $(0.21 \pm 0.03)\%$ . In the absence of a signal, we set a limit on the cross section for  $\sigma(p\bar{p} \rightarrow WH) \times BR(H \rightarrow b\bar{b})$  of 9.0 pb at the 95% C.L., for a 115 GeV Higgs boson.

The same study was performed for  $m_H = 105, 125,$  and 135 GeV, for which 0, 0, and 1 event were observed in the corresponding mass windows. The resulting limits (11.0, 9.1, and 12.2 pb, respectively) are compared to the SM expectation in Fig. 3, and to the results published by the Collider Detector at Fermilab (CDF) Collaboration, using a smaller integrated luminosity of  $109 \text{ pb}^{-1}$  at  $\sqrt{s} = 1.8$  TeV, but for combined  $e$  and  $\mu$  channels [20].

In conclusion, we have performed a search for the  $Wb\bar{b}$  final state and have set an upper limit of 6.6 pb on this largest expected background to  $WH$  associated production. We have studied the dijet mass spectrum of two  $b$ -tagged jets in the region where we have the best sensitivity to a SM Higgs boson, and for Higgs-boson masses between 105 and 135 GeV we set 95% C.L. upper limits between 9.0 and 12.2 pb on the cross section for  $WH$  production multiplied by the branching ratio for  $H \rightarrow b\bar{b}$ .

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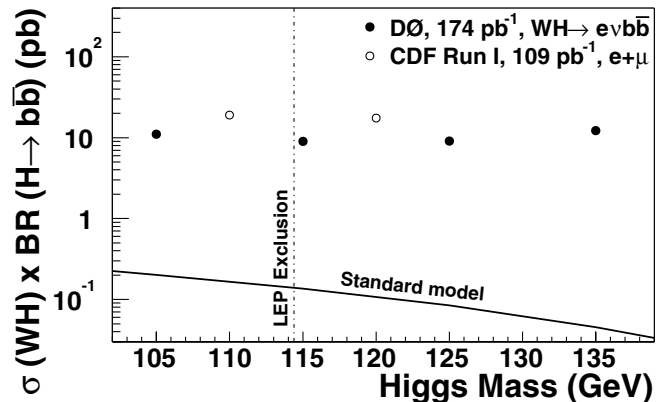


FIG. 3. 95% C.L. upper limit on  $\sigma(p\bar{p} \rightarrow WH) \times BR(H \rightarrow b\bar{b})$  compared to the SM expectation at  $\sqrt{s} = 1.96$  TeV, and to CDF results [20], which were obtained at  $\sqrt{s} = 1.8$  TeV. The predicted  $WH$  cross section at 1.96 TeV is approximately 15% larger than that at 1.8 TeV.

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