Search for a Standard Model Higgs Boson in $WH \rightarrow \ell\nu b\bar{b}$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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(Received 2 July 2009; published 1 September 2009)

We present a search for a standard model Higgs boson produced in association with a W boson using 2.7 fb^{-1} of integrated luminosity of $p\bar{p}$ collision data taken at $\sqrt{s} = 1.96$ TeV. Limits on the Higgs boson production rate are obtained for masses between 100 and 150 GeV/c^2. Through the use of multivariate techniques, the analysis achieves an observed (expected) 95% confidence level upper limit of 5.6 (4.8) times the theoretically expected production cross section for a standard model Higgs boson with a mass of 115 GeV/c^2.

DOI: 10.1103/PhysRevLett.103.101802 PACS numbers: 14.80.Bn, 13.85.Rm, 14.70.Fm

The standard model (SM) of particle physics has proven to be an extremely successful theory through its accurate predictions of many experimental results over the last few decades. In the SM, spontaneous electroweak symmetry breaking gives rise to the masses of the W and Z bosons. Although the Higgs mechanism [1–3] was proposed in the 1960s as the source of this symmetry breaking, the fundamental particle it predicts to exist, the Higgs boson, has yet to be discovered. The mass of the Higgs boson is a free parameter of the SM. However, direct limits from the LEP experiments exclude Higgs boson masses below 114.4 GeV/c^2 [4] at 95% confidence level (C.L.). Taking into account additional electroweak precision measurements places a 95% C.L. upper limit on the mass of a SM Higgs boson of 185 GeV/c^2 [5]. Recently, combined results from the CDF Collaboration and D0 Collaboration experiments have excluded at the 95% C.L. Higgs boson masses between 160 and 170 GeV/c^2 [6].

For Higgs boson masses below 135 GeV/c^2, $b\bar{b}$ is the main decay mode [7]. In this decay, each b quark fragments into a jet of hadrons and the Higgs boson signal may be reconstructed as a peak in the invariant mass distribution of these two jets. At the Tevatron associated production with a W boson (WH), where the W boson decays into a lepton (ℓ) and a neutrino (ν), provides one of the most sensitive search channels in this mass range, since the requirements of a charged lepton candidate and of large missing transverse energy dramatically reduce the backgrounds from multijet processes [8]. Both Tevatron experiments, CDF and D0, have published search results for $WH \to \ell\nu b\bar{b}$ [9–11]. Here we describe a new search for the Higgs boson in the $WH \to \ell\nu b\bar{b}$ channel with increased signal acceptance that employs improved analysis technique and 2.7 fb^{-1} of $p\bar{p}$ collision luminosity collected by the CDF experiment. Although we focus on the SM here, many plausible extensions, such as Ref. [12], predict a low-mass SM-like Higgs boson.

The CDF II apparatus [13,14] is a general-purpose detector located at the Tevatron collider at Fermilab. The detector consists of a solenoidal charged-particle spectrometer which includes a silicon microstrip detector array surrounded by a cylindrical drift chamber in a 1.4 T axial magnetic field. Outside the tracking chambers, the energies of electrons and jets are measured with segmented sampling calorimeters. Surrounding the calorimeters are layers of steel instrumented with planar drift chambers and scintillators used for muon identification.

Events are collected with energetic lepton triggers that require one of the following signatures [15]: a high-p_T electron candidate, a high-p_T muon candidate, or missing transverse energy ($\not{E}_T$ from the neutrino escaping detection) with an energetic forward ($|\eta| > 1.2$) electromagnetic cluster (designed to accept forward electrons from the W boson decay). An additional trigger is included that does not explicitly require an identified lepton, but instead requires large $\not{E}_T$ plus two well-separated jets in $\eta - \phi$ space [16]. For these events, the charged lepton from the W boson decay is reconstructed only as a high-p_T isolated track. The addition of this nontriggered lepton category increases $WH \to \ell\nu b\bar{b}$ signal acceptance by approximately 25% [17].

Candidate events are selected by requiring a lepton candidate (triggered lepton or isolated track) with $p_T^\ell > 20$ GeV/c, $\not{E}_T > 20$ GeV, and two jets with $|\eta| < 2.0$ and $E_T > 20$ GeV after correcting for instrumental effects [18]. At least one of the jets must have a displaced vertex (b tag) defined by the SECVTX algorithm [19] signaling that the jet likely originated from a b quark. An additional b-tagging algorithm that relies on high-impact-parameter tracks within jets, JETPROB [15], is used to increase the acceptance for double-tagged events. Vetoes are applied to remove events with more than one lepton and events without leptonic W boson decays [11].

The Higgs boson events are modeled with the PYTHIA [20] MC generator combined with a parametrized response of the CDF II detector [21,22] and tuned to the Tevatron underlying event data [23]. After basic event selection, the total expected signal event yield in the current data set is 5.1 ± 0.5 (3.5 ± 0.4) single (double)-tag events for a Higgs boson with a mass of 115 GeV/c^2 (see Table I for other masses).

Models for background processes are derived from a mixture of MC simulation and data-driven techniques [11]. Important backgrounds to $WH \to \ell\nu b\bar{b}$ include events with a W or Z boson produced in association with jets. These processes may include true b jets as in $W + b\bar{b}$, or other jets that have been misidentified as b jets like $W + c\bar{c}$ and $W + jj$, where j refers to jets not originating from heavy-flavor quarks. Events with a top quark ($t\bar{t}$ and single top quark production), diboson events, and multijet events without W bosons also contribute to the sample composition.

After applying the event selection defined above, the background expectation (1896 ± 301 for single-tag and 316 ± 60 for double-tag events) is significantly larger than the expected number of Higgs boson signal events. We have indicated that the dijet invariant mass is a useful variable for separating the Higgs boson signal from the dominant backgrounds, however its usefulness is limited by jet energy resolution and large background rate. These

TABLE I. The number of signal events expected to be accepted by our selection, the SM prediction for $\sigma \times \mathcal{B}(H \to b\bar{b})$, and the expected and observed limits at 95% C.L. on the Higgs boson production cross section relative to the SM value as shown in Fig. 2. The expected limits are also included for the NN and MEBDT analyses individually.

Mass (GeV/c^2)	100	105	110	115	120	125	130	135	140	145	150
Expt. signal (events)	12.8	11.7	10.3	8.6	6.9	5.6	4.3	3.1	2.1	1.4	0.9
SM $\sigma \times \mathcal{B}(H \to b\bar{b})$ (fb)	232	201	169	136	104	83	63	45	30	20	12
Expt. NN (95% C.L./SM)	4.3	4.6	5.0	5.8	6.9	8.2	10.0	13.8	19.4	28.9	43.2
Expt. MEBDT (95% C.L./SM)	3.8	4.0	4.5	5.2	6.3	8.0	10.0	13.4	19.2	27.0	48.7
Expt. combination (95% C.L./SM)	3.5	3.8	4.1	4.8	5.9	7.2	8.7	12.2	17.5	25.6	40.5
Observed (95% C.L./SM)	3.3	3.6	4.9	5.6	5.9	8.0	8.9	13.2	26.5	42.1	75.5

challenges require that we extract as much discrimination as possible from the full information available in each event. Multivariate techniques allow us to collect the discriminating power of many variables into a single output variable. We take advantage of the benefits from different techniques [24] by combining the discriminating power of two separate analyses that use the same event selection but follow different multivariate strategies. We validate the predictions of the background model for each input variable in data control regions. We optimize the discriminants separately for each Higgs boson mass hypothesis, and construct the discriminants so that they are not sensitive to statistical fluctuations in the background and signal samples. We first summarize the two analyses, and then discuss their combined result.

The first analysis uses an artificial neural network (NN, [25]) trained to discriminate $WH \to \ell\nu b\bar{b}$ signal from the background using the information contained in the following kinematic variables: the invariant mass of the two jets plus an additional "loose" jet [26] if it lies close to one of the primary jets [angular separation $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ less than 0.9]; the vector sum of the transverse energies ($\sum_{\rm jets}\vec{E}_T + \vec{p}_T{}^{\ell} + \vec{\not{E}}_T$); the scalar sum of the lepton and jet transverse momenta minus the $\not{E}_T$ ($\sum_{\rm jets}E_T + p_T{}^{\ell} - \not{E}_T$); the scalar sum of the loose jet transverse energy ($\sum_{\rm jets}E_T^{\rm loose}$) [26]; the minimum invariant mass of the lepton, $\vec{\not{E}}_T$, and one of the two jets [$\min(M_{\ell,\not{E}_T,j_1}, M_{\ell,\not{E}_T,j_2})$]; and ΔR between the lepton and the momentum of the neutrino [27]. The strongest discriminating variable of the NN is the dijet mass variable shown in Fig. 1(a).

The second analysis uses a boosted decision tree technique (MEBDT, [28,29]). The notation MEBDT underscores the use of inputs derived from the matrix-element approach developed in Refs. [30,31]. In the matrix-element method, probability densities are calculated for each event using the measured kinematic quantities. Some of the best discriminating inputs to the decision tree include ratios of the signal event probabilities to various combinations of

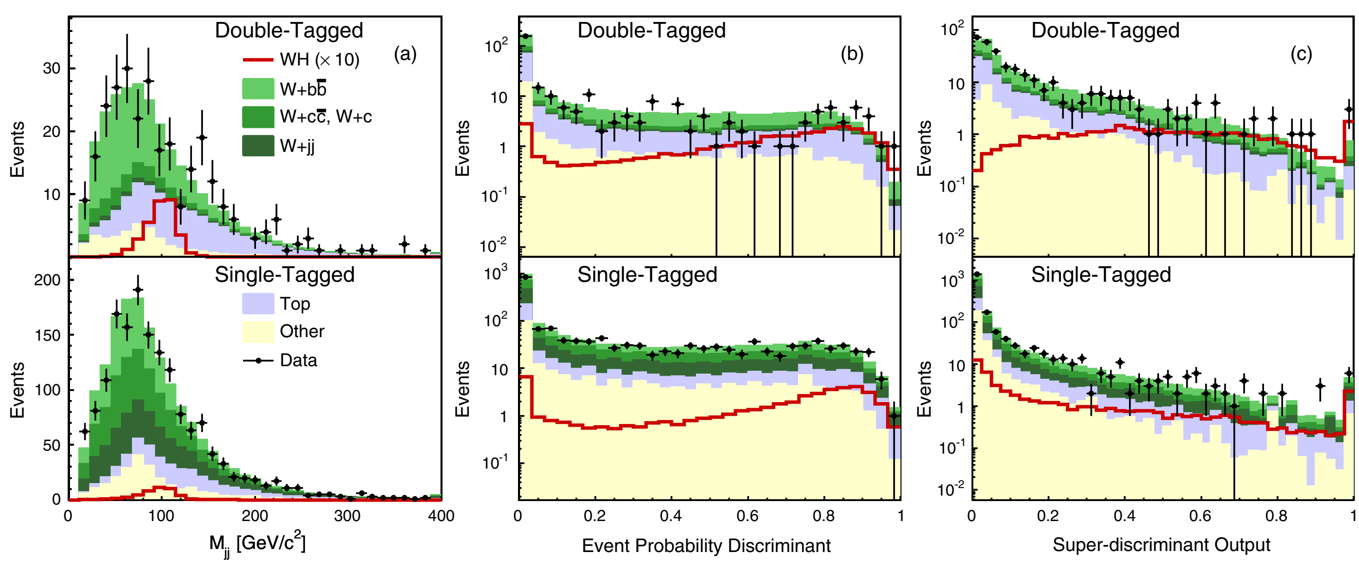

FIG. 1 (color online). The distribution for the dijet mass variable used in the NN analysis (a), the event probability discriminant used in the MEBDT analysis (b), and the SD output distribution (c), for double b-tag events (top) and single b-tag events (bottom). The background is normalized to its prediction and the signal expectation of a Higgs boson mass of 115 GeV/c^2 is scaled to 10 times the SM prediction. Statistical errors are shown for the data points.

the background probabilities, and an event probability discriminant (EPD) defined as the ratio of the signal event probability to the sum of the signal and all background event probabilities as in Ref. [30]. The EPD distributions for signal and backgrounds are shown in Fig. 1(b).

The MEBDT analysis also uses the output of a neural network that has been trained to separate jet flavors [32]. This network is based on secondary vertex tracking information and provides a continuous variable which helps to identify the portion of the background that does not contain real b-quark jets. The MEBDT analysis also includes the following inputs: the dijet mass, the E_T of both jets and $\not{E}_T$ of the event, the difference in azimuthal angles ($\Delta\phi$) between the leading jet and the $\vec{\not{E}}_T$, the $\Delta\phi$ between the lepton and the $\vec{\not{E}}_T$, the p_T and the η of the lepton, the scalar sum of the transverse energies $H_T = \sum_{\rm jets} E_T + {p_T}^{\ell} + \not{E}_T$, the cosine of the angle between the lepton and leading jet, and the transverse mass of the W boson $M_T(W) = \sqrt{2({p_T}^{\ell}\not{E}_T - {\vec{p}_T}^{\,\ell}\cdot\vec{\not{E}}_T)}$.

We performed the NN and the MEBDT analyses independently (see Table I), the results of which are partially correlated. The correlations between the discriminant outputs range between 50% and 75% for the major background and signal samples. These correlations, while high, do suggest that a sensitivity gain can be obtained by combining the two approaches. We combine the NN and MEBDT discriminants using a superdiscriminant (SD) technique first developed in the CDF single top quark search [30]. Here, a neural network using the discriminant outputs of the NN and MEBDT as inputs is optimized using genetic algorithms [33–35]. Three separate neural networks (one for each b-tag category: single SECVTX, SECVTX + JETPROB, and double SECVTX) are trained to separate the $WH \rightarrow \ell\nu b\bar{b}$ signal from the backgrounds for each Higgs boson mass using events from the signal and background samples described above. The distributions of the SD outputs of the neural network trained for a Higgs boson mass of 115 GeV/c^2 are shown in Fig. 1(c) for the combined double-tag categories and the single-tag category. The SD analysis improves the sensitivity compared to the best individual analysis by 5%–13% for the Higgs boson masses studied.

Finding no evidence for a Higgs boson signal, we calculate a Bayesian C.L. limit for each mass hypothesis based on the combined binned likelihood of the SD output distributions. The two lepton categories (triggered leptons and isolated tracks) and three tag categories yield six independent channels that are included in the likelihood. Systematic uncertainties on the rate of signal and background production from jet energy scale, b-tagging efficiencies, lepton identification and trigger efficiencies, the amount of initial and final state radiation, and the parton distribution functions are included in the limit calculation (for details on systematic studies, see [11,17]). Uncertainties on the discriminant output shapes were studied but found to have a negligible impact on sensitivity. A posterior density is obtained by multiplying this likelihood by Gaussian prior densities for the background normalizations and systematic uncertainties leaving $\sigma \times \mathcal{B}(H \rightarrow b\bar{b})$ with a uniform prior density. A 95% C.L. limit is then determined such that 95% of the posterior density for $\sigma \times \mathcal{B}(H \rightarrow b\bar{b})$ falls below the limit [36]. Removing systematic uncertainties completely from the limit calculation improves the expected limit by about 15%.

Table I shows the expected and observed limits calculated for different Higgs boson masses. The limits are displayed graphically in Fig. 2. We find an observed (expected) 95% C.L. limit of 5.6 (4.8) times the SM prediction of the production cross section for a Higgs boson mass of 115 GeV/c^2 (next-to-leading order theory predicts $\sigma \times \mathcal{B}(H \rightarrow b\bar{b}) = 136$ fb [37]). At this mass, the expected limit has improved by a factor of 1.7 over the 1.9 fb^{-1} result from CDF [11], which corresponds to a 40% improvement in sensitivity over what is expected from the increased data set [38]. The additional gain comes from our increased lepton acceptance through the inclusion of a nontriggered lepton category, a continuous jet flavor separator variable which improves discrimination of light-quark jets mistakenly tagged as b jets, and the use of new multivariate techniques. The excess in the observed limit at higher masses is due primarily to the slight excess observed at 150 GeV/c^2 in the dijet mass variable [see Fig. 1(a)] and is an indication of the large weight this variable carries in the full multivariate analysis. The successful previous application of many of the techniques to the CDF single top analysis [30,39], and the consistency of results obtained with NN and MEBDT algorithms provide further confidence in the robustness of the multivariate techniques. The increasing Tevatron data set together with future analysis improvements, a combination of re-

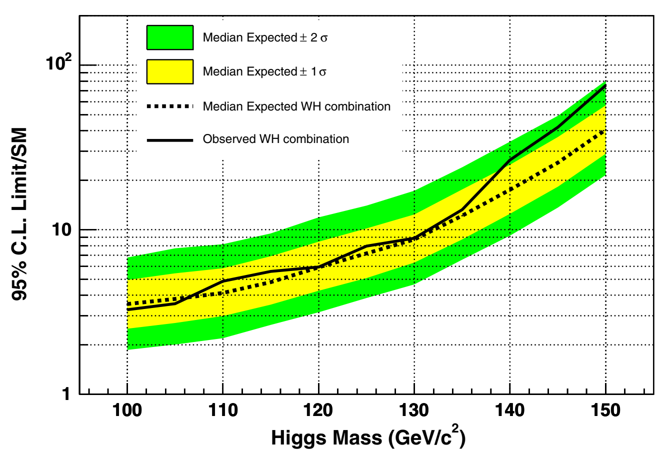

FIG. 2 (color online). The expected and observed 95% C.L. upper limits on the Higgs boson production cross section relative to the SM expectation as obtained from the SD combination as a function of the Higgs boson mass.

sults from all Higgs boson production and decay modes, as well as the combination with the results from the D0 experiment [6], will continue to provide improved levels of sensitivity to the SM Higgs boson searches at the Tevatron.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, U.K.; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

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