

## Search for the Standard Model Higgs Boson Decaying to a $b\bar{b}$ Pair in Events with One Charged Lepton and Large Missing Transverse Energy Using the Full CDF Data Set

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(Received 8 July 2012; published 10 September 2012)

We present a search for the standard model Higgs boson produced in association with a  $W$  boson in  $\sqrt{s} = 1.96$  TeV  $p\bar{p}$  collision data collected with the CDF II detector at the Tevatron corresponding to an integrated luminosity of  $9.45 \text{ fb}^{-1}$ . In events consistent with the decay of the Higgs boson to a bottom-quark pair and the  $W$  boson to an electron or muon and a neutrino, we set 95% credibility level upper limits on the  $WH$  production cross section times the  $H \rightarrow b\bar{b}$  branching ratio as a function of Higgs boson mass. At a Higgs boson mass of  $125 \text{ GeV}/c^2$ , we observe (expect) a limit of 4.9 (2.8) times the standard model value.

DOI: [10.1103/PhysRevLett.109.111804](https://doi.org/10.1103/PhysRevLett.109.111804)

PACS numbers: 14.80.Bn, 13.85.Rm, 14.40.Nd

The mechanism of electroweak symmetry breaking [1] in the standard model (SM) [2] predicts the existence of a fundamental scalar boson, the Higgs boson. The SM does not predict the mass of the Higgs boson, ( $m_H$ ), but through the combination of precision electroweak measurements [3], including recent top quark and  $W$  boson mass measurements from the Tevatron [4,5],  $m_H$  is constrained to be less than  $152 \text{ GeV}/c^2$  at the 95% confidence level. Direct searches at LEP2 [6], the Tevatron [7], and the LHC [8,9] exclude possible masses of the SM Higgs boson at the 95% confidence level or the 95% credibility level (C.L.), except within the ranges  $116.6\text{--}119.4 \text{ GeV}/c^2$  and  $122.1\text{--}127 \text{ GeV}/c^2$ . At the LHC experiments, sensitivity to the Higgs boson primarily comes from channels where the Higgs boson decays into two  $W$  bosons, two photons, or two  $Z$  bosons. At the Tevatron, searches for a  $116\text{--}127 \text{ GeV}/c^2$  Higgs boson are most sensitive to the  $b\bar{b}$  final state, which offer the complementary information

of the quark Yukawa couplings to the Higgs boson. These searches may then be able to establish the mechanism of electroweak symmetry breaking as the source of fermionic mass in the quark sector.

In the  $b\bar{b}$  final state, each  $b$  quark fragments into a jet of hadrons and the Higgs boson signal can be reconstructed as an enhancement in the invariant mass distribution of these jets. For a pair of jets, the dijet mass resolution at CDF is expected to be 10–15% of the pair's mean reconstructed mass [10], which is approximately 10 times larger than the reconstructed mass resolution in the leptonic or photonic search channels at the LHC. Searches for the Higgs boson produced in association with a  $W$  boson ( $WH$ ), where the  $W$  boson decays into a charged lepton ( $\ell$ ) and a neutrino ( $\nu$ ), provide the most sensitive search channel at the Tevatron in the mass range  $116\text{--}127 \text{ GeV}/c^2$ , because the requirements of a charged lepton candidate and of large missing transverse energy ( $\cancel{E}_T$ ) [11], consistent with a

neutrino escaping detection, significantly reduce the backgrounds from multijet processes. Searches for the SM Higgs boson including this final state have been reported by the CDF, D0, ATLAS, and CMS Collaborations [12–16].

In this Letter we describe a search for the Higgs boson in the  $WH \rightarrow \ell\nu b\bar{b}$  channel using the full data set collected during run II of the Collider Detector experiment at the Fermilab Tevatron (CDF). The CDF experiment is a general purpose detector described in Ref. [17]. These data correspond to a luminosity of  $9.45 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions. Many aspects of the analysis remain unchanged from a recent search based on  $7.5 \text{ fb}^{-1}$  and are described in more detail in Ref. [18]. Events are collected with on-line selection criteria (triggers) that require one of the following signatures: an electron candidate with transverse energy exceeding  $18 \text{ GeV}/c$  [19]; a muon candidate with transverse momentum ( $p_T$ ) exceeding  $18 \text{ GeV}/c$ ; or  $\cancel{E}_T(\text{cal}) > 15 \text{ GeV}$  with a forward ( $|\eta| > 1.2$ ) electromagnetic energy cluster satisfying  $E_T > 20 \text{ GeV}$  (designed to accept forward electrons from the  $W$  boson decay). An additional set of triggers is included that does not explicitly require an identified lepton, but instead requires  $\cancel{E}_T(\text{cal}) > 45 \text{ GeV}$  or  $\cancel{E}_T(\text{cal}) > 35 \text{ GeV}$  and a pair of jets [20].

The identification of leptons and jets closely follows that for the CDF single-top-quark discovery described in Ref. [21]. Candidate events are selected by requiring the presence of exactly one lepton candidate with  $p_T > 20 \text{ GeV}/c$ . The required  $\cancel{E}_T$  is specific to each class of reconstructed lepton candidate to satisfy trigger requirements and suppress instrumental backgrounds; events with an electron satisfying  $|\eta| \leq 1.1$ , electron satisfying  $|\eta| > 1.1$ , nonisolated electron [22], muon, or isolated track are required to have  $\cancel{E}_T > 20, 25, 25, 10,$  or  $20 \text{ GeV}$ , respectively. Events are required to have exactly two or three jets satisfying  $|\eta| < 2.0$  and  $E_T > 20 \text{ GeV}$  after corrections for instrumental effects [23]. Events are rejected if they are kinematically inconsistent with leptonic  $W$  boson decays as determined by a support vector model specific to each lepton category [24]. Each support vector model is a binary classifier resulting from supervised training using information about the energies and angles of the lepton, jets, and missing energy.

At least one of the jets must be identified (tagged) as consistent with the fragmentation of a  $b$  quark according to a neural network tagging algorithm [25]. For each jet containing at least one charged particle track, the algorithm produces a scalar value in the range  $-1$  to  $1$ . By comparing this value to two predetermined thresholds, the jet is classified as not tagged, *loose tagged* (L), or *tight tagged* (T), with all tight-tagged jets also satisfying the loose-tag definition. The thresholds are chosen to optimize the combined expected exclusion sensitivity in simulated events and the performance of the T and L  $b$  tag selection is described in Ref. [25]. The search sample is composed of seven orthogonal categories according to the exact number and

type of  $b$  tags in the event: TT, TL, T, LL, L for two-jet events, and TT, TL for three-jet events. If an event satisfies two categories, the category of highest signal purity is chosen. The inclusion of additional  $b$ -tag categories for events with three jets offers negligible improvement to the expected sensitivity and the additional  $b$ -tag categories are therefore not included. The tagging algorithm and strategy employed here is identical to that described in the Tevatron combined observation of diboson production with decays to heavy-flavor quarks [26].

The Higgs boson events are modeled with the PYTHIA [27] Monte Carlo event generator combined with a detailed simulation of the CDF II detector [28,29] and tuned to the Tevatron underlying-event data [30]. Small corrections to the simulated response of the detector are made based on data-simulation comparisons from orthogonal data sets [14,31]. Models for background processes are derived from a mixture of simulation and data-driven techniques [32]. Background processes to  $WH \rightarrow \ell\nu b\bar{b}$  include  $W$  or  $Z$  bosons produced in association with jets. These processes may include true  $b$  jets as in  $W + b\bar{b}$ , or non- $b$  jets that have been misidentified as  $b$  jets like  $W + c\bar{c}$ ,  $W + c j$ , and  $W + j j$ , 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.

The distributions of the reconstructed dijet invariant mass [33,34] of background and simulated Higgs boson events in the categories that contribute most to the sensitivity are shown in Fig. 1, with categories of comparable signal purity summed together. The two-jet single-loose-tagged sample,  $L$ , contains twice as many events and has 10 times smaller signal purity than the other two-jet categories combined. This category contributes less than 1% to the total expected exclusion sensitivity and is not presented in Fig. 1. Event yields are stated as sums of categories corresponding to those presented in the figure. The total expected signal yield in the current data set, assuming  $m_H = 125 \text{ GeV}/c^2$  and based on next-to-next-to-leading-order (NNLO) theory predictions for the production rate [35], is  $12.9 \pm 1.1$  ( $12.4 \pm 0.9$ ) for the TT + TL (T + LL) categories. Events with exactly three jets account for  $\sim 10\%$  of the total expected signal yield. The background expectation of  $1500 \pm 400$  ( $6600 \pm 1900$ ) for TT + TL (T + LL) events is significantly larger than the expected number of signal events. The invariant mass of jets is the most discriminating signal variable between signal and background, but greater signal significance is achieved by using additional kinematic information available in each event.

We employ a Bayesian artificial neural network (BNN) [36] trained to discriminate a  $WH \rightarrow \ell\nu b\bar{b}$  signal from the background using the information contained in the following kinematic variables: the invariant mass of the candidate

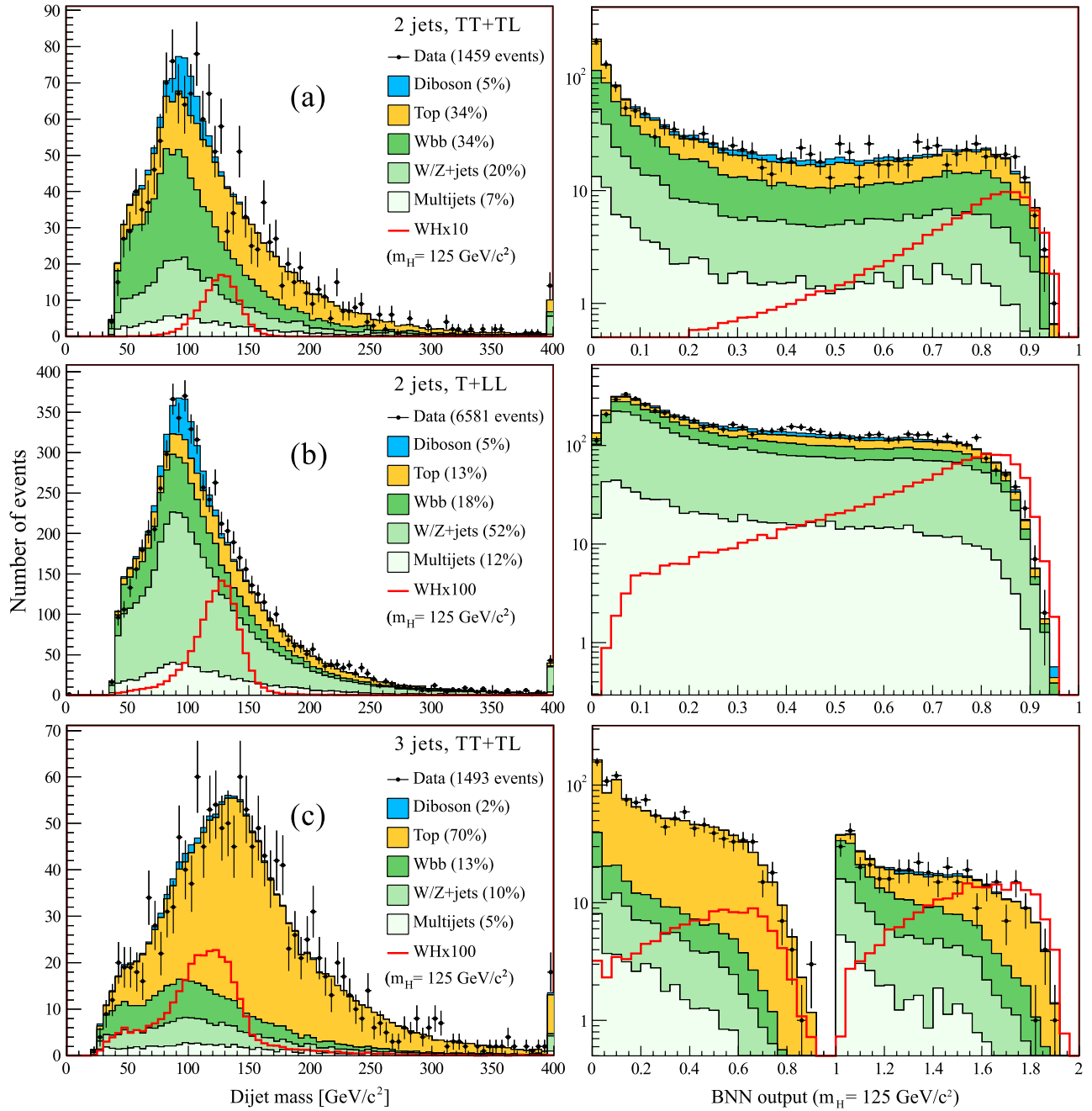


FIG. 1 (color online). The distribution for the dijet mass used as an input to the BNN (left), and the BNN output distribution (right). Event  $b$ -tag categories of comparable signal purity are combined and presented as three orthogonal subsamples: two-jet TT + TL (a), two-jet T + LL (b), and three-jet TT + TL (c). The background is normalized to its prediction and the signal expectation of a Higgs boson mass of  $125 \text{ GeV}/c^2$  is scaled to 10, 100, and 100 times the SM prediction in (a), (b), and (c), respectively. The right-hand panel of (c) shows the BNN distribution for events with exactly three jets, split into two regions based on an independent discriminant designed to separate top-quark-like events (assigned values between 0 and 1) from  $W$  + jets-like events (assigned values between one and two). Statistical uncertainties are shown for the data points.

Higgs-boson-decay jets [33]; the maximum invariant mass of the lepton,  $\vec{\not{E}}_T$ , and one of the two jets [ $\max(M_{\ell, \not{E}_{T,j_1}}, M_{\ell, \not{E}_{T,j_2}})$ ]; the lepton electric charge times its pseudorapidity; the scalar sum of the lepton and jet transverse momenta minus the  $\not{E}_T$ , ( $\sum_{\text{jets}} E_T + p_T^\ell - \not{E}_T$ );

the scalar sum of the transverse energy of calorimeter jets that fail the jet energy selection criteria ( $\sum_{\text{low-}E_T \text{ jets}} E_T$ ); the absolute value of the transverse momentum of the reconstructed  $W$  boson, reconstructed as  $p_T^\ell + \vec{\not{E}}_T$ ; and the scalar sum of the jet, lepton, and neutrino

transverse energies ( $\sum_{\text{jets}} E_T + p_T^\ell + \cancel{E}_T$ ). The BNN combines the discriminating power of these variables into a single output variable which, when used in searches for a 125 GeV/ $c^2$  Higgs boson, is capable of excluding cross sections times branching ratios 27% lower in the background-only hypothesis as compared to searches using the jet invariant mass alone. Improvements for other mass hypotheses are comparable. We validate the predictions of the background model for each input variable in data control regions and we optimize the discriminants separately for each Higgs boson mass hypothesis. The distributions of the BNN outputs of the neural network trained for a Higgs boson mass of 125 GeV/ $c^2$  are shown in the right-hand panels of Fig. 1. Additional sensitivity from the three-jet categories is gained by training and employing a BNN to separate top-quark-like from  $W$  + jets-like events, independently from the BNN trained to separate  $WH$  events from background. In the right-hand panel of Fig. 1(c), top-quark-like events occupy the range of 0–1 of the discriminant, while  $W$  + jets-like events occupy the range 1–2.

We calculate a Bayesian C.L. limit for each mass hypothesis using the combined binned likelihood of the BNN output distributions. Each of the seven jet-tagging categories is subdivided into four orthogonal lepton categories, depending on their distinct instrumental backgrounds. After exclusion of two low-signal combinations [37], the analysis comprises 26 independent channels that are included in the likelihood. The benefit of this subdivision of the search sample is both higher signal significance, and the isolation of individual background components for systematic constraint. 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, with priors truncated to prevent negative predictions. A 95% C.L. limit is determined such that 95% of the posterior density for  $\sigma \times \mathcal{B}(H \rightarrow b\bar{b})$  accumulates below the limit [38].

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 (ISR and FSR), and the parton distribution functions are included in the limit calculation [39]. In addition, the limit calculation includes shape uncertainties on the discriminant output [40], arising from uncertainties on the jet energy scale, ISR and FSR for all simulated samples, and arising from

uncertainties on the renormalization and factorization scale for  $W$  + jets samples. The expected exclusion limits are  $\sim 20\%$  tighter if the calculation is performed without including systematic uncertainties. The impact of kinematic differences between simulated and data events  $W$  + jets is investigated as a potential source of systematic uncertainty. The jet energies, angular separations, and invariant mass distributions of events selected prior to  $b$  tagging are used to derive shape corrections which are applied to simulated  $W$  + jets events in the search samples. These adjustments show negligible impact on the discriminant shape of the background prediction, and therefore are not considered in the final results.

Table I and Fig. 2 show the expected and observed limits calculated for different Higgs boson masses. We find an observed (expected) 95% C.L. limit of 4.9 (2.8) times the SM prediction of the production cross section times branching fraction for a Higgs boson mass of 125 GeV/ $c^2$  [NNLO theory predicts  $\sigma \times \mathcal{B}(H \rightarrow b\bar{b}) = 75$  fb] [35]. The resulting expected exclusion limit is approximately a factor of 2.6 lower than our previous Letter [12]. This improvement in expected sensitivity consists of a factor of approximately 1.9 due to the increased data set [41] and a factor of approximately 1.4 due to analysis technique improvements. Increased signal acceptance and background rejection gained from the improved  $b$ -tagging algorithm provide approximately 11% improvement in exclusion sensitivity. The inclusion of three-jet events, increased trigger acceptance, improved rejection of multi-jet events, and additional lepton acceptance via new reconstruction categories dominate the remaining improvement. The two-jet TT and TL categories offer the highest signal purity, driving the sensitivity of the analysis. Performing the analysis using these two categories alone produces expected and observed limits comparable to the full analysis combination, with an observed (expected) limit of 4.8 (3.2) times the SM  $\sigma \times \mathcal{B}(H \rightarrow b\bar{b})$  for  $m_H = 125$  GeV/ $c^2$ . The consistency of the observed limits with the signal hypothesis is tested by statistical sampling of the signal-plus-background model. These studies indicate that the median upper C.L. in the SM Higgs scenario is  $\sim 1$  unit of SM cross section higher than that for the background-only hypothesis over most of the 90–150 GeV/ $c^2$  search range, which is consistent with the observed limits to within 1 standard deviation.

In conclusion, we have presented a search for the SM Higgs boson produced in association with a  $W$  boson using

TABLE I. The SM prediction for  $\sigma \times \mathcal{B}(H \rightarrow b\bar{b})$ , as well as the expected and observed limits at 95% C.L. on the Higgs boson production cross section divided by the SM prediction as shown in Fig. 2.

Mass (GeV/ $c^2$ )	90	95	100	105	110	115	120	125	130	135	140	145	150
SM $\sigma \times \mathcal{B}(H \rightarrow b\bar{b})$ (fb)	321	268	223	185	152	123	98	75	55	39	27	17	10
Exp. (95% C.L./SM)	1.36	1.53	1.44	1.58	1.76	1.97	2.30	2.79	3.59	4.85	6.59	9.91	15.9
Observed (95% C.L./SM)	1.38	2.07	1.92	2.36	3.03	3.13	4.33	4.93	6.47	8.51	10.9	14.4	21.7

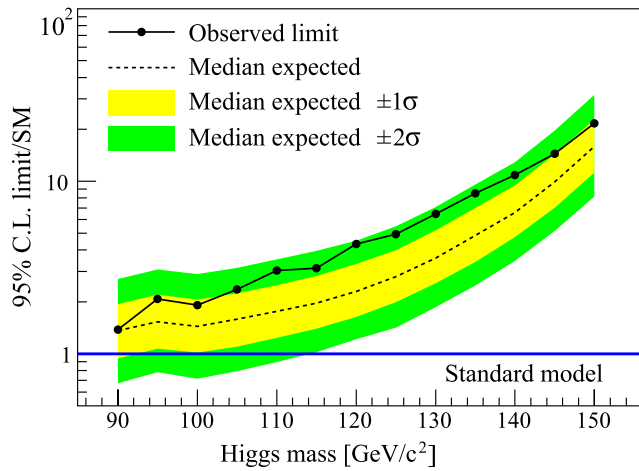


FIG. 2 (color online). The observed 95% C.L. upper limits on Higgs boson production relative to the SM expectation as a function of the Higgs boson mass. The median expected limits in the absence of a Higgs signal are indicated by the dashed line and the light and dark bands indicate the  $1\sigma$  and  $2\sigma$  ranges for individual experiments in this background-only scenario.

the complete CDF run II data set. This analysis employs methods used in CDF analyses of well-established SM processes, providing confidence in the robustness of the background model and search techniques. The observed exclusion limits exceed those expected in the background-only scenario over much of the 90–150  $\text{GeV}/c^2$  search range, with deviations from the background-only-hypothesis corresponding to local significances for tested Higgs boson masses between 120 and 135  $\text{GeV}/c^2$  of roughly  $2\sigma$ . While the LHC experiments have surpassed the Tevatron experiments in overall sensitivity to a SM Higgs boson, the  $WH \rightarrow \ell\nu b\bar{b}$  search reported here is currently the most sensitive single-channel search for a low-mass SM Higgs boson in its favored decay mode.

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 World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; the Academy of Finland; and the Australian Research Council (ARC).

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