Search for the standard model Higgs boson decaying to a $\bar{b}b$ pair in events with two oppositely-charged leptons using the full CDF data set

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We present a search for the standard model Higgs boson produced in association with a $Z$ boson in data collected with the CDF II detector at the Tevatron, corresponding to an integrated luminosity of 9.45 fb$^{-1}$. In events consistent with the decay of the Higgs boson to a bottom-quark pair and the $Z$ boson to electron or muon pairs, we set 95% credibility level upper limits on the $H \rightarrow b \bar{b}$ branching ratio as a function of Higgs boson mass. At a Higgs boson mass of 125 GeV/c$^2$ we observe (expect) a limit of 7.1 (3.9) times the standard model value.

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In the standard model of particle physics (SM) [1], electroweak symmetry breaking [2] generates a fundamental scalar boson known as the Higgs boson. Although there is strong evidence of electroweak symmetry breaking, the Higgs boson has yet to be observed. The SM does not predict the mass of the Higgs boson, $m_H$, but the combination of precision electroweak measurements [2], including recent top quark and $W$ boson mass measurements from the Tevatron [4, 5], constrains $m_H < 152$ GeV/c$^2$ at the 95% confidence level. Direct searches at LEP2 [6], the Tevatron [7], and the LHC [8] exclude all possible masses of the SM Higgs boson at the 95% confidence level or 95% credibility level (C.L.), except within the ranges 116.6 – 119.4 GeV/c$^2$ and 122.1 – 127 GeV/c$^2$. A SM Higgs boson in these mass ranges would be produced in the $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions of the Tevatron and have a branching fraction to $b\bar{b}$ greater than 50% [9–11]. While the most sensitive searches for the SM Higgs boson at the LHC are those based on Higgs boson decays...
to pairs of gauge bosons, the results presented here are currently the most sensitive for a SM Higgs boson decaying to a pair of $b$ quarks. The searches at the LHC in the four-lepton and diphoton final state offer precise measurements of the mass of the Higgs boson, while the results presented here provide information about the Higgs boson’s couplings to fermions and are therefore complementary to the primary LHC search modes. In searches for the production of a Higgs boson in association with a vector boson ($WH$ or $ZH$), leptonic decays of the vector boson provide effective discrimination between the expected signal and the large, uncertain hadronic backgrounds. Searches for $p\bar{p} \rightarrow Z(\rightarrow \ell^+\ell^-)H(\rightarrow b\bar{b})$ ($\ell = \text{electron or muon} [12]$) are among the most sensitive of the Tevatron low-mass Higgs boson searches, benefiting from low background rates and the ability to fully reconstruct both $Z$ and Higgs boson resonances. Previous searches in this final state have been reported by the LEP2, D0, CDF, CMS, and ATLAS collaborations [6, 13–16].

In this Letter, we present an updated search for $ZH \rightarrow \ell^+\ell^-b\bar{b}$ events in which we expand upon the techniques of the previous CDF search and analyze data corresponding to more than twice the integrated luminosity used therein [14]. This search introduces new multivariate $b$-jet and lepton identification techniques and updated multi-stage artificial neural network (NN) background discrimination. This results in up to a 65% improvement in sensitivity to a Higgs boson signal compared to the methods used in our previous search [14]. Due to the larger data set, improved $b$-jet identification techniques that differ significantly from previously used methods, and expanded online event selection, 85% of $ZH \rightarrow \ell^+\ell^-b\bar{b}$ candidate events identified in this search were not present in the search sample used in the previous analysis [14].

The data were collected by the upgraded CDF II detector, correspond to 9.45 fb$^{-1}$ of Tevatron $p\bar{p}$ collisions at $\sqrt{s}=1.96$ TeV, and constitute the final CDF II data set. The CDF II detector is described in detail elsewhere [17]. Charged-particle trajectory (track) reconstruction and momentum determination capabilities are provided by silicon-based tracking systems surrounded by a drift chamber immersed in a 1.4 T magnetic field [18, 19]. The tracking systems are surrounded by calorimeters that provide coverage for $|\eta| < 3.6$ [20–22]. Jets are identified using a cone algorithm [23] that combines calorimeter energy deposits to form jets with a radius of 0.4 in $\eta$-$\phi$ space. External to the calorimeters, an additional system of drift chambers and scintillation counters provides muon detection for $|\eta| < 1.5$ [24].

CDF II records only those collision events that meet the criteria of an online event selection (trigger) system. To maximize signal acceptance we trigger inclusively on the properties of the candidate events, using data selected by three sets of trigger algorithms [25, 26]. The first set consists of algorithms that require the presence of one or two electron candidates. The electron candidates are required to have a minimum transverse energy ($E_T$) of 8 to 18 GeV, depending on the specific algorithm. The second set of trigger algorithms requires the presence of a muon candidate with a minimum transverse momentum ($p_T$) of 18 to 22 GeV/c, again depending on the specific algorithm. Because muons deposit only a small fraction of their momentum in the calorimeter, we gain additional online efficiency by using a third set of algorithms that accept events with significant missing calorimeter transverse energy [27], generally above 30 GeV. Several of the algorithms in this set impose additional requirements on the number (typically two) and transverse energy (generally greater than 10 GeV) of jets in the event. The combined triggers have a selection efficiency of approximately 90% (100%) for events within the acceptance of the CDF II detector containing two energetic muons (electrons) and two or more jets.

Additional offline requirements are imposed on the events selected by the trigger algorithms. Several requirements are applied to select events consistent with the decay of a $Z$ boson to either pairs of electron or pairs of muons. Electrons and muons are selected by new NN-based algorithms optimized for efficient lepton identification [25, 26]. The NN algorithms combine muon detector, tracking, and calorimeter information, allowing for a 20% increase in $Z \rightarrow \ell^+\ell^-$ acceptance compared to the selections in Ref. [14]. We reject lepton candidates with $p_T < 10$ GeV/c and require that the lepton candidate pairs have opposite electric charge when they are muons, or are electrons satisfying $|\eta| < 1.1$ for each electron [28]. Events in which the reconstructed $Z$ boson has a mass of less than 76 GeV/$c^2$ or greater than 106 GeV/$c^2$ are rejected. In addition to a $Z \rightarrow \ell^+\ell^-$ candidate, we require the presence of a candidate $H \rightarrow b\bar{b}$ decay, selecting events with exactly two or three jets with $|\eta| < 2.0$ and an $E_T > 25$ GeV. Jet energies include corrections for local variations in calorimeter response, the energy contribution from additional $p\bar{p}$ interactions, and corrections specific to this analysis that assume that net missing transverse energy ($E_T$) [24] arises predominantly from the mismeasurement of jets [11, 22]. Events in which the combined mass of the two most energetic jets is less than 25 GeV/$c^2$ are removed. The resulting fractional resolution of the invariant mass of pairs of jets is estimated to be 11% [14].

Further event selection requires that at least one jet in the event, referred to as a $b$-tagged jet, be identified as consistent with the fragmentation of a $b$ quark. The data sample that satisfies all event selection criteria apart from the requirement of $b$-tagged jets is referred to as the PreTag sample. We perform the analysis on a subset of the PreTag sample that consists of events with at least one $b$-tagged jet. We employ a new multivariate $b$-tagging algorithm specifically designed to increase the $b$-tag efficiency and reduce the contamination of incorrectly tagged $q$ jets
We form four categories of events with \( b \)-tagged jets. Events with two or more jets with tight \( b \) tags constitute the \emph{double-tight} (TT) category. Events with one jet with a tight \( b \) tag and one or more jets with a loose \( b \) tag form the \emph{tight-loose} (TL) category. Those with one jet with a tight \( b \) tag, and no other tight or loose \( b \)-tagged jet make up the \emph{single tight} (Tx) category. Events with two or more jets with loose \( b \) tags comprise the \emph{double-loose} (LL) category. If a data event satisfies more than one tag category, then the category of highest expected signal-to-background ratio is chosen, ranked TT, TL, Tx, and LL in decreasing order. The \( b \)-tagging algorithm employed in this search improves sensitivity to a \( ZH \) signal by approximately 15\% compared to the strategy used in our previous Letter \cite{11}.

The four \( b \)-tag categories are subject to different systematic uncertainties, background compositions, and predicted \( ZH \) content, and are therefore maintained as separate analysis channels. We further divide events by the \( Z \) boson decay (\( Z \rightarrow e^+e^- \) or \( Z \rightarrow \mu^+\mu^- \)), and again by the number of jets in the event (two or three). In total we form 16 exclusive channels that are simultaneously examined for \( ZH \) content and jointly used to set upper limits on \( \sigma_{ZH} \times B(H \rightarrow bb) \). In simulated signal events we find a total selection efficiency of approximately 24\%.

Background processes that produce two leptons and two or three jets in the final state may satisfy the above selection criteria. Among these, the dominant background is \( Z+jets \) production, nearly saturated by \( Z+q\bar{q} \) before \( b \)-tag requirements are imposed. After \( b \) tagging, \( Z+b\bar{b} \) and \( Z+c\bar{c} \) are the most significant backgrounds. \( Z+jets \) events are modeled using ALPGEN \cite{30} with PYTHIA \cite{31} for particle showering and hadronization. Simulated \( Z+jets \) samples are normalized to match experimental measurements \cite{32} of the \( Z+jets \) production rate. As reported in Refs. \cite{33, 34}, ALPGEN underestimates the fraction of \( Z+heavy\)-flavor (\( b \) and \( c \)) jet events in inclusive \( Z+jets \) production. To compensate, we increase the normalization of \( Z+b\bar{b} \) and \( Z+c\bar{c} \) samples by a factor of 1.4 relative to the normalization of \( Z+q\bar{q} \) samples.

Signal, \( tt \), and diboson (\( WW, WZ, ZZ \)) processes are modeled with PYTHIA. The production rate of \(ZH \) and the Higgs boson branching ratios are set to the values in Refs. \cite{9}. The \( tt \) simulation assumes a top-quark mass of 172.5 GeV/\( c^2 \) and is normalized to a production rate of 7.04 pb \cite{35}. Diboson contributions are normalized to next-to-leading-order cross sections \cite{36}. Each simulated sample includes a detailed GEANT-based detector simulation \cite{37} and uses the CTEQ5L \cite{38} parton distribution functions.

We account for the contributions from QCD multijet and \( W+jets \) processes using a data-derived model for misidentified \( Z \rightarrow \ell^+\ell^- \) candidates. An electron and a jet have a small (\( < 10^{-3} \)) likelihood of being misidentified as two electrons. We model such misidentified \( Z \rightarrow e^+e^- \) candidates using events containing a single electron and several jets. Each electron-jet pair in these events contributes to the model of misidentified \( Z \rightarrow e^+e^- \) weighted by a factor reflecting the probability of the jet to be misidentified as an electron. The determination of the weights is described in Ref. \cite{23}. The misidentified \( Z \rightarrow \mu^+\mu^- \) contribution is modeled using like-sign muon pairs identified in the PreTag data \cite{24}.

We apply several corrections that affect the normalization of simulated samples. We correct the instantaneous luminosity profile of the simulated samples to match that observed in data. We correct the energy of lepton candidates to ensure agreement between the energy distributions in measured and simulated events, with corrections being approximately 1\% of the uncorrected value. In addition, we apply corrections for differences in lepton and \( b \) jet reconstruction and selection efficiencies in data and simulated samples. To account for the selection efficiency of the CDF II trigger system, we employ multivariate trigger emulation \cite{25, 26}. For each of the three sets of triggers detailed above, a NN is trained on data events to describe the likelihood that the trigger system will select the event. The training data is selected via triggers independent to the set which each seeks to describe, using the same event kinematic information as the trigger system. The output of each NN is applied to each simulated event as a normalization factor, to reflect the per-event, kinematics-dependent probability of online selection as observed in data. Combining all background processes, we expect a total PreTag background of 19 000 \pm 4 000 events, events, in good agreement with the observed total of 19 302. Event totals for observed data and expectations in the \( b \)-tagged sample are also in good agreement, with the background composition and totals listed for each \( b \)-tag category separately in Table I.

To separate a possible Higgs boson signal from background, we employ a method that utilizes NN discriminants. The multi-stage discriminant method enhances the isolation of simulated signal from background by combining a series of expert NN’s with a master network. The master network is constructed to isolate the \( ZH \) signal from all backgrounds simultaneously, while each ex-
Each NN is trained using simulated events meeting PreTag selection requirements. A $t\bar{t}$ expert network separates $ZH$ from $t\bar{t}$, a second $Z+\text{jets}$ expert network separates signal from $Z+q\bar{q}$ and $Z+c\bar{c}$, and a third diboson expert separates $ZH$ from diboson processes. No network specifically optimized for discriminating misidentified $Z$ events is used, because they are observed to be well separated from $ZH$ events using only the $t\bar{t}$ expert, due to their characteristics large values of $E_T$.

The final analysis is performed using the distribution of the master network scores for observed events in a binned final discriminant (BFD). A master network is optimized for 13 $m_H$-hypotheses (90 to 150 GeV/$c^2$ in 5 GeV/$c^2$ unit increments), with separate networks for two- and three-jet events. Each master NN is constructed to return a score between 0 and 0.25 for each event, while each expert returns a value between 0 and 1, with 0 being most background-like in all cases. The BFD has four regions (I, II, III, IV) each with a varying signal expectation and background composition. Events are sorted into one of the regions based on the output of the three expert networks. If the $t\bar{t}$ expert returns a value of less than 0.5 ($t\bar{t}$-like), the event is assigned to region I. Otherwise, if the expert for $Z+q\bar{q}$ and $Z+c\bar{c}$ returns a score of less than 0.5 ($Z+q\bar{q}$/$Z+c\bar{c}$-like), the event is assigned to region II. Remaining events for which the diboson expert returns a value of less than 0.5 (diboson-like) are assigned to region III, with the remaining events being assigned to region IV.

The BFD is formed from the distribution of the master NN outputs plus an offset factor. Offset factors of 0, 0.25, 0.5, and 0.75 are set for events assigned to regions I, II, III, and, IV, respectively. The output of the BFD is shown in Fig. 1(a) for Tx events and for the sum of TT, TL, and LL in Fig. 1(b).

We extract upper limits on the value of $\sigma_{ZH} \times B(H \rightarrow b\bar{b})$ production rate using a Bayesian likelihood formed as a product of likelihoods over bins of the BFD distribution for all $b$-tagged candidates. We assume a uniform prior on the signal rate, and Gaussian priors for each systematic uncertainty, truncated so that no prediction is negative. We set Bayesian 95% C.L. upper limits on $\sigma_{ZH} \times B(H \rightarrow b\bar{b})$ for each $m_H$ hypothesis. Expected upper limits are derived by randomly generating a series of statistical trials, derived from the background prediction and systematic uncertainties, and computing the median of the distribution of resulting upper limits. The upper limits on $\sigma_{ZH} \times B(H \rightarrow b\bar{b})$ are displayed in Fig. 2 and Table I.

We observe a broad excess for $m_H > 110$ GeV/$c^2$ peaking at 135 GeV/$c^2$ with local significance of 2.4 standard deviations. Taking the limited $m_H$ resolution of our BFD we account for a look-elsewhere effect of

| Process | TT | TL | Tx | LL |
|---------|----|----|----|----|
| $t\bar{t}$ | $55 \pm 8.3$ | $60 \pm 8.5$ | $90 \pm 12$ | $17 \pm 2.5$ |
| Diboson | $10 \pm 1.5$ | $14 \pm 1.9$ | $40 \pm 4.0$ | $8.7 \pm 1.0$ |
| $Z + b\bar{b}$ | $59 \pm 25$ | $83 \pm 35$ | $239 \pm 101$ | $32 \pm 14$ |
| $Z + c\bar{c}$ | $3.9 \pm 1.7$ | $19 \pm 8.4$ | $109 \pm 47$ | $24 \pm 11$ |
| $Z + q\bar{q}$ | $1.0 \pm 0.4$ | $14 \pm 3.5$ | $192 \pm 44$ | $55 \pm 14$ |
| Misid. $Z$ | $2.1 \pm 1.0$ | $15 \pm 7.6$ | $31 \pm 15.4$ | $10 \pm 5.1$ |

| $ZH$ (predicted) | $1.9 \pm 0.3$ | $2.0 \pm 0.3$ | $2.8 \pm 0.4$ | $0.5 \pm 0.1$ |
| Total bkg. | $131 \pm 26$ | $205 \pm 38$ | $701 \pm 122$ | $147 \pm 23$ |
| Data | $117$ | $199$ | $730$ | $165$ |

TABLE I: Comparison of the expected event totals for background and $ZH$ signal with the observed number of data events. Event totals are displayed grouped by $b$-tag category (TT, TL, Tx, LL). The $ZH$ totals assume $m_H = 125$ GeV/$c^2$. The displayed uncertainties are systematic. Statistical uncertainties are negligible for all model components except misidentified $Z$, for which they are comparable to the systematic uncertainty.
observe (expect) a 95% C.L. upper limit of 7.150 GeV branching ratio for Higgs boson masses between 90 and CDF II data set has improved sensitivity to the standard model prediction. Utilization of the full resulting in the most sensitive search for signal divided by the SM prediction are shown as a function on the evidence for the process, we set 95% C.L. upper limits produced in association with a Z to date.

In conclusion, we have searched for the SM Higgs boson produced in association with a Z boson, followed by the decays $Z \rightarrow \ell^+ \ell^-$ and $H \rightarrow b\bar{b}$. Finding no significant evidence for the process, we set 95% C.L. upper limits on the $ZH$ production cross section times the $H \rightarrow b\bar{b}$ branching ratio for Higgs boson masses between 90 and 150 GeV/c$^2$. For a Higgs boson mass of 125 GeV/c$^2$ we observe (expect) a 95% C.L. upper limit of 7.1 (3.9) times the standard model prediction. Utilization of the full CDF II data set has improved sensitivity to a $ZH$ signal by 34% compared to the previously published analysis. Improved analysis methods have produced an additional approximately 30% enhancement in sensitivity, resulting in the most sensitive search for $ZH \rightarrow \ell^+ \ell^- b\bar{b}$ to date.

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TABLE II: Expected (Exp.) and observed (Obs.) 95% C.L. upper limits on the $ZH$ production cross section times the branching ratio for $H \to bb$ normalized to the SM value for Higgs boson masses ($m_H$) between 90 and 150 GeV/c$^2$.

| $m_H$ (GeV/c$^2$) | 90   | 95   | 100  | 105  | 110  | 115  | 120  | 125  | 130  | 135  | 140  | 145  | 150  |
|------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Exp.             | 2.1  | 2.2  | 2.2  | 2.3  | 2.5  | 2.7  | 3.2  | 3.9  | 5.0  | 6.7  | 9.4  | 13.9 | 23.0 |
| Obs.             | 1.0  | 1.2  | 1.8  | 2.3  | 3.1  | 4.7  | 5.8  | 7.1  | 10.7 | 15.2 | 19.4 | 21.8 | 37.5 |

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