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We present a search for the standard model Higgs boson produced with a Z boson in 4.1 fb^{-1} of data collected with the CDF II detector at the Tevatron. In events consistent with the decay of the Higgs boson to a bottom-quark pair and the Z boson to electrons or muons, we set 95% credibility level upper limits on the ZH production cross section times the $H \rightarrow b\bar{b}$ branching ratio. Improved analysis methods enhance signal sensitivity by 20% relative to previous searches beyond the gain due to the larger data sample. At a Higgs boson mass of $115 \text{ GeV}/c^2$ we set a limit of 5.9 times the standard model value.

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Establishing the mechanism of electroweak symmetry breaking (EWSB) is one of the outstanding issues of particle physics. In the standard model (SM), EWSB is

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mediated by a Higgs field that manifests a particle, the as-yet-unobserved Higgs boson. A SM Higgs boson with mass (M_H) below $114.4 \text{ GeV}/c^2$ or with M_H between 162 and $166 \text{ GeV}/c^2$ has been excluded at 95% confidence level in direct searches at LEP [1] and the Tevatron [2]. A recently reported [3] preliminary update of the Tevatron result has expanded this 95% exclusion range to values of M_H between 158 and $175 \text{ GeV}/c^2$.

At the Tevatron, production of the Higgs boson is dominated by the direct production process $gg \rightarrow H$, and for $M_H < 135 \text{ GeV}/c^2$ the Higgs boson decays primarily to a pair of b quarks, $H \rightarrow b\bar{b}$ [4]. The process $gg \rightarrow H \rightarrow b\bar{b}$ is overwhelmed by multi-jet background. Associated production of a Higgs boson with a leptonically decaying W or Z boson yields a distinct signature for efficient selection and in turn greater sensitivity despite a significantly smaller cross section than direct production [5]. This Letter presents an improved search for the SM Higgs boson produced in association with a Z boson, $ZH \rightarrow \ell^+\ell^-b\bar{b}$ (where ℓ is either an electron, e , or muon, μ) using $1.96 \text{ TeV } p\bar{p}$ collision data corresponding to 4.1 fb^{-1} of integrated luminosity collected with the CDF II detector [6]. This search channel is one of the most sensitive to a low-mass SM Higgs boson at the Tevatron [7, 8].

Previous CDF efforts in this mode used an artificial neural network classifier (NN) [9] or a likelihood based on matrix-element probabilities (MEP) [10] for signal isolation. Here we enhance these techniques with NN-based b jet discrimination [11, 12] and an improved multivariate jet-energy correction to improve background rejection. New $Z \rightarrow e^+e^-$ selections increase the acceptance of ZH signal, and new combinations of b jet identifiers yield better signal sensitivity, as reflected in the expected cross section limit. These additions improve the expected sensitivity by a factor of 1.2 over the gain expected just from additional integrated luminosity.

The selection requirements most relevant to this analysis are discussed below; a detailed presentation can be found in [13]. We select ZH candidates by first identifying a sample of events containing a $Z \rightarrow \ell^+\ell^-$ decay. Events are selected in real time (triggered) based on the presence of high- p_T electron and muon [14] candidates. The majority ($\sim 80\%$) of ZH candidates pass the trigger selection requiring events to contain at least one central ($|\eta| \leq 1.0$) track of $p_T \geq 9 \text{ GeV}/c$ matched to an electromagnetic energy (EM) cluster of $E_T \geq 18 \text{ GeV}$ (a trigger electron) or at least one central track of $p_T \geq 20 \text{ GeV}/c$ pointing to signals in the muon detectors (a trigger muon). The remaining fraction of ZH candidate events comes from newly included data selected by a trigger that requires two or more EM clusters of $E_T \geq 18 \text{ GeV}$ and $|\eta| \leq 3.6$ without requiring that the clusters are associated with tracks (trackless trigger). Events are further required to contain a lepton pair that forms a Z candidate with mass in the range $76 \leq M_{\ell\ell} \leq 106 \text{ GeV}/c^2$. Pairs of

central leptons forming Z candidates must have opposite charge; electrons in the forward ($|\eta| > 1.0$) acceptance of the detector may not have an associated track and no charge requirement is imposed.

We divide the Z candidates into two categories based on signal-to-background ratio (S/B). The search for the signal in these two categories is conducted separately to improve sensitivity to a ZH signal. The high- S/B category includes Z candidates formed from a trigger muon and a second muon candidate with $p_T \geq 10 \text{ GeV}/c$, or a trigger electron paired with a second electron candidate formed from either a central EM cluster of $E_T \geq 10 \text{ GeV}$ matched to a track of $p_T \geq 5 \text{ GeV}/c$ or a forward EM cluster of $E_T \geq 18 \text{ GeV}$. The low- S/B category contains Z candidates in events satisfying the trackless trigger only or formed from a trigger electron paired with an isolated central track with $p_T \geq 20 \text{ GeV}/c$ pointing to an uninstrumented region of the calorimeter. The low- S/B category is included for the first time in the search for ZH production at CDF.

Higgs boson candidates are assembled from pairs of jets. We form jets from energy deposits in the calorimeter using the JETCLU algorithm [15] with a cone radius of 0.4. We consider only jets well contained in the calorimeter, $|\eta| \leq 2.0$, and well separated from the Z -decay leptons, $\Delta R \geq 0.4$ [16]. Measured jet energies are corrected to account for η -dependent variations in detector response, calorimeter coverage, and the expected contribution from additional $p\bar{p}$ pair interactions in the same event [17]. Events are required to have one jet with $E_T \geq 25 \text{ GeV}$ and a second of $E_T \geq 15 \text{ GeV}$. We refer to the events containing a Z boson candidate and two such jets as the PreTag sample; b quark identification (described below) is applied to the PreTag sample to form our final analysis samples. There are 11,806 (3,061) events in the high (low) S/B PreTag data sample, wherein we expect 5.0 ± 0.7 (0.8 ± 0.1) ZH signal events for $M_H = 115 \text{ GeV}/c^2$. Inclusion of the low- S/B subsample increases the total signal yield in the PreTag sample by 16%.

The PreTag sample consists mainly of Z +light flavor (l.f.) jet (u, d, s, g) events, with smaller contributions from Z +heavy flavor (h.f.) jet (c, b), $t\bar{t}$, and diboson processes. To reduce the Z +l.f. background, we look for b jets in the event. We use two algorithms to identify (tag) b jets: one based on evidence for a decay displaced spatially from the $p\bar{p}$ interaction point (SV) [6] and one based on track impact parameters with respect to the $p\bar{p}$ interaction point (JP) [18]. For the SV algorithm, there are two operating points: tight and loose [19]. The tight operating point has better l.f.-jet rejection (smaller mistag probability) at the expense of reduced b -jet identification efficiency.

We select events in the PreTag sample using the b tagging algorithms on the jet pairs forming Higgs candidates. We require the jet pairs to satisfy one of the following classifications, in order of precedence from highest to lowest ratio of ZH signal to background: a pair

containing two SV-tight-tagged jets is classified as tight-double-tagged (TDT); a pair consisting of one SV-loose-tagged jet and a second JP-tagged jet is classified as loose-double-tagged (LDT); and a pair where only one jet has a SV-tight-tag is classified as single-tagged (ST). When there are multiple $H \rightarrow b\bar{b}$ candidates in an event, the jet pair with the highest b tag class is selected (TDT > LDT > ST). This is the first time the JP algorithm has been used in the $ZH \rightarrow \ell^+\ell^-b\bar{b}$ channel. While the b tag selection matches the signal selection efficiency (approximately 60%) and background rejection rate (96%) of previous efforts, the addition of the new LDT class increases sensitivity to a ZH signal by 6%. Due to differing background composition, the events are divided into independent subsamples based on b -tagging class. With two Z boson S/B categories and three b -tagging classes, we form a total of six subsamples that we analyze for ZH content.

We compare the b -tag data to a model of signal and backgrounds to estimate the signal content. Signal, $t\bar{t}$, and diboson events are modeled with the PYTHIA [20] event generator. Backgrounds from $Z+h.f.$ processes are simulated at the quark level using ALPGEN [21], then passed to PYTHIA for hadronization. The detector response is modeled with a detailed detector simulation [6]. We estimate the background from $Z+l.f.$ mistags using re-weighted PreTag data with weights reflecting the probability for a l.f. jet to be erroneously b tagged. A small fraction, much less than 1%, of jets can be erroneously identified as electrons, resulting in a background of misidentified (misID) $Z \rightarrow ee$ candidates. The likelihood of jet-electron misidentification is measured in generic jet data and applied to all electron-jet and jet-jet pairings in the electron triggered samples to generate a model of misID Z events. The misID $Z \rightarrow \mu\mu$ background contribution is estimated from the events passing all selection requirements but containing like-charge muon pairs. Predicted and observed event totals are listed in Table I for the b -tagged subsamples.

To improve the separation of ZH from background, we utilize several multivariate techniques that use kinematic quantities as inputs. The dijet mass M_{jj} is one of the most useful quantities, with its separating power limited mainly by the jet-energy resolution. In ZH signal events with $Z \rightarrow \ell^+\ell^-$, incorrect measurement of jet energies results in apparent missing transverse energy $\vec{E}_T$ [22]. We correct jet energies, based upon the $\vec{E}_T$, and thereby improve the resolution on the dijet invariant mass. Jet-energy correction factors are computed by a NN trained to match measured jet energies to parton-level energies in Z +jets and signal events. In this analysis, this neural network is improved compared to the previous analysis [9] by utilizing additional input variables describing the recoil of the Z boson. The corrected jet energies are used to recompute the Higgs candidate mass M_H , the p_T of the jets, the p_T of the Higgs candidate, the projection of

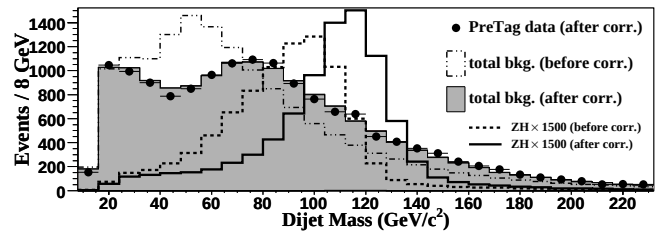


FIG. 1: The dijet invariant mass distribution of the two jets with the highest E_T in the PreTag sample. The distribution is shown for data after NN correction of jet energies. The dijet mass is shown for background before (dash-dotted line) and after (grey region) NN correction. The dotted (solid) curves show the dijet mass for signal ($M_H = 115 \text{ GeV}/c^2$ and scaled by a factor of 1500) before (after) correction.

$\vec{E}_T$ onto the lower- E_T Higgs jet, and the sphericity. The effect of the NN corrections on the reconstructed $H \rightarrow b\bar{b}$ mass is shown in Fig. 1. In signal the resolution [23] on M_H is improved from about 18% to 12%.

To exploit the combined signal-to-background discrimination power of event quantities and their correlations, we employ a neural network discriminant (NN_D) trained to simultaneously separate ZH , $t\bar{t}$, and Z +jets events. The NN_D is configured to return values of $(x, y) = (1, 0)$ for ZH events, $(0, 0)$ for Z +jets, and $(1, 1)$ for $t\bar{t}$. A separate NN_D is formed for each of the three b -tag classes. In addition to the quantities recomputed with corrected jet energies, the NN_D inputs include: $\vec{E}_T$; MEPs for ZH , $t\bar{t}$, and Z +jets processes; the number of jets in the event; and the output of a b jet identifying artificial neural network (NN_b) [11]. The ZH process MEP is computed [10] by convolving the theoretical matrix element for ZH production with detector resolution functions. The resulting MEP reflects the likelihood that an event is signal. We calculate two additional MEPs under the hypotheses that an event is Z +jets or $t\bar{t}$ to aid background rejection. The NN_b augments the performance of the SV algorithm by isolating incorrectly b -tagged l.f. jets. The addition of NN_b as an input enhances the ability of the NN_D to distinguish ZH from $Z+l.f.$, which constitutes 40% of the total background in the ST class. One-dimensional projections of NN_D output are shown in Fig. 2 for each b -tag class.

The effect of systematic uncertainties on the determination of signal content requires propagating uncertainties on NN_D input quantities to the output distributions. The dominant effect on the result comes from uncertainties on cross sections for background processes — a 40% uncertainty is assumed on the normalization of Z +h.f. samples [24], 11.5% for the diboson samples [25], 20% to account for the theoretical and experimental uncertainty on the $t\bar{t}$ cross section [26], and 5% for ZH signal [27]. Uncertainties of 4% (ST), 8% (TDT), and 11% (LDT) on the normalization of b -tagged samples are ap-

TABLE I: Comparison of the expected mean event totals for background and ZH signal with the observed number of data events. The totals are for full event selection, and systematic and statistical uncertainties are combined in quadrature. Systematic uncertainties dominate. The background composition is provided in the first five rows. Each of the six ZH subsamples is presented in a separate column.

Process	High S/B			Low S/B		
	TDT	LDT	ST	TDT	LDT	ST
$t\bar{t}$	7.0 ± 1.5	8 ± 2	17 ± 4	2.9 ± 0.6	3.2 ± 0.8	8.9 ± 1.9
Diboson	2.9 ± 0.4	4 ± 1	16 ± 2	0.5 ± 0.1	0.6 ± 0.1	3.3 ± 0.5
$Z + \text{h.f.}$	18 ± 7	30 ± 13	159 ± 67	3.5 ± 1.5	5.6 ± 2.4	32 ± 14
$Z + \text{l.f.}$	0.9 ± 0.3	9 ± 3	152 ± 23	0.4 ± 0.1	3.8 ± 1.3	50 ± 7.6
misID Z	0.7 ± 0.3	2 ± 1	22 ± 11	1.4 ± 0.7	1.1 ± 0.5	23 ± 12
Total Bkg.	29 ± 8	53 ± 14	366 ± 72	9 ± 2	14 ± 3	117 ± 20
$ZH(115 \text{ GeV}/c^2)$	0.7 ± 0.1	0.7 ± 0.1	1.7 ± 0.2	0.11 ± 0.01	0.11 ± 0.03	0.28 ± 0.05
Data	23	56	406	12	14	116

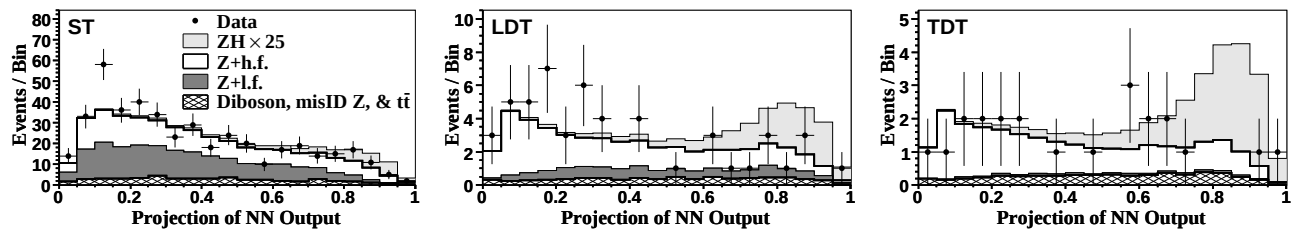


FIG. 2: Projections of the two-dimensional neural network (NN_D) output onto the x -axis (x and y are defined in the text) for events in the b -tag categories ST, LDT, and TDT. Events with a NN_D score of $y \geq 0.1$ are omitted to highlight the signal region. The ZH contribution is shown, multiplied by a factor of 25, for $M_H = 115 \text{ GeV}/c^2$.

plied to account for different b -tag efficiencies in data and simulation. Other uncertainties affecting sample normalizations include: 6% on the integrated luminosity, 1% on the trigger and lepton reconstruction efficiencies [28], 1.5% on the measurement of lepton energies, and a 50% uncertainty on the total lepton misID estimate. We include uncertainties on jet energies, the modeling of initial and final state radiation, and mistag event weighting as variations on the shape and normalization of the NN_D output.

We calculate a limit on the associated production of a SM Higgs boson and Z boson based on the comparison of the full NN_D output of the b -tagged data to expectations for signal and background. We consider eleven Higgs mass hypotheses between 100 and $150 \text{ GeV}/c^2$. We use a Bayesian algorithm [29] with a flat prior in the production cross section, integrating over the priors for the systematic uncertainties, incorporating correlated rate and shape uncertainties, and uncorrelated bin-by-bin statistical uncertainties [30]. Systematic uncertainties reduce the sensitivity of this search by 16%. The expected 95% credibility level (C.L.) limits are calculated assuming no signal, based on expected backgrounds only, as the median of 1000 simulated experiments. The $\pm 1\sigma$ and $\pm 2\sigma$ expected limits are derived from the distribution of the simulation limits at the 16th, 84th, 2nd, and 98th per-

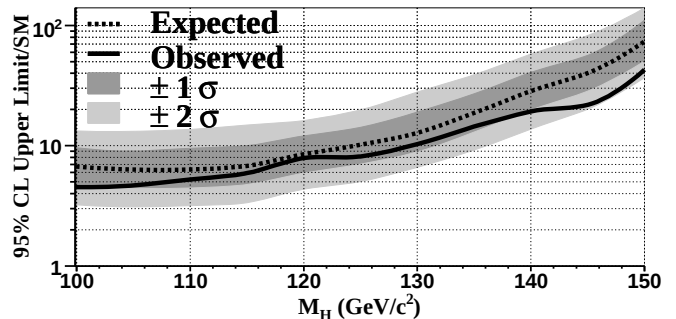


FIG. 3: The expected (dashed curve) and observed (solid curve) ZH cross section upper limits divided by the SM cross section are shown as a function of the Higgs boson mass. The dark (light) band represents the $\pm 1\sigma$ ($\pm 2\sigma$) expected limit range.

centiles of the distribution, respectively. The observed 95% C.L. on the ZH cross section are calculated from the b -tagged data, and displayed in Fig. 3 and summarized in Table II.

In conclusion, we have searched for the SM Higgs boson produced in association with a Z boson, where $Z \rightarrow \ell^+ \ell^-$ 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

TABLE II: Expected (Exp) and observed (Obs) 95% C.L. upper limits on the ZH production cross section times the branching ratio for $H \rightarrow b\bar{b}$ normalized to the SM value for Higgs masses between 100 and 150 GeV/ c^2 . The assumed ZH cross section and branching fraction for $H \rightarrow b\bar{b}$ are 0.11 pb [5] and 0.73 [4] for a 115 GeV/ c^2 Higgs boson.

M_H	100	105	110	115	120	125	130	135	140	145	150
Exp	6.7	6.4	6.3	6.8	8.5	10.	13	19	29	45	74
Obs	4.5	4.6	5.3	5.9	7.9	8.1	10.	14	19	24	43

Higgs boson masses between 100 and 150 GeV/ c^2 . For a Higgs boson mass of 115 GeV/ c^2 we set (expect) a 95% C.L. upper limit of 5.9 (6.8) times the standard model prediction. This result is an important step forward in the search for the Higgs boson and the source of EWSB, improving upon the previous observed (expected) limits in this channel by factors of 2.2 to 3.7 (1.9 to 2.4).

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[1] R. Barate *et al.* (LEP Working Group), Phys. Lett. B **565**, 61 (2003).
[2] T. Aaltonen *et al.* (CDF and D0 Collaborations), Phys. Rev. Lett. **104**, 061802 (2010).
[3] The TEVNPH Working Group (CDF and D0 Collaborations) (2010), arXiv:1007.4587.
[4] A. Djouadi, J. Kalinowski, and M. Spira, Comput. Phys. Commun. **108**, 56 (1998).
[5] K. A. Assamagan *et al.* (Higgs Working Group) (2004), arXiv:hep-ph/0406152v1.

[6] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 052003 (2005).
[7] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **103**, 101802 (2009).
[8] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **104**, 141801 (2010).
[9] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **101**, 251803 (2008).
[10] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **80**, 071101 (2009).
[11] S. Richter (2007), Ph.D. Thesis, Karlsruhe U., EKP, FERMILAB-THESIS-2007-35.
[12] T. Aaltonen *et al.* (CDF) (2010), submitted to Phys. Rev. D, arXiv:1004.1181.
[13] S. Z. Shalhout (2010), Ph.D. Thesis, Wayne State Univ., FERMILAB-THESIS-2010-33.
[14] We use a cylindrical coordinate system with z along the proton beam direction, r the perpendicular radius from the central axis of the detector, and ϕ the azimuthal angle. For θ the polar angle from the proton beam, we define $\eta = -\ln \tan(\theta/2)$, transverse momentum $p_T = p \sin \theta$ and transverse energy $E_T = E \sin \theta$.
[15] G. Blazey and B. Flaugher, Ann. Rev. Nucl. Part. Sci. **49**, 633 (1999).
[16] The ΔR between two objects is given by $\sqrt{\Delta\eta^2 + \Delta\phi^2}$.
[17] A. Bhatti *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **566**, 375 (2006).
[18] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. D **74**, 072006 (2006).
[19] C. Neu for the CDF Collaboration, presented at TOP 2006, Coimbra, Portugal, 12-15 Jan 2006.
[20] T. Sjöstrand *et al.*, Comput. Phys. Comm. **135**, 238 (2001). We use “PYTHIA Tune A”, R. Field and R. C. Group, arXiv:hep-ph/0510198v1.
[21] M. L. Mangano *et al.*, J. High Energy Phys. **07**, 001 (2003).
[22] The missing E_T ($\vec{E}_T$) is defined by the sum over calorimeter towers: $\vec{E}_T = -\sum_i E_T^i \hat{n}_i$, where i = calorimeter tower number with $|\eta| < 3.6$, $\hat{n}_i$ is a unit vector perpendicular to the beam axis and pointing at the i^{th} calorimeter tower. We also define $E_T = |\vec{E}_T|$.
[23] We define dijet mass resolution as the standard deviation of the dijet mass distribution divided by its mean.
[24] J. M. Campbell and R. K. Ellis, Phys. Rev. D **62**, 114012 (2000).
[25] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999).
[26] U. Langenfeld, S. Moch, and P. Uwer, Phys. Rev. D **80**, 054009 (2009).
[27] J. Baglio and A. Djouadi (2010), arXiv:1003.4266.
[28] D. Acosta *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **494**, 57 (2002).
[29] K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010).
[30] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **80**, 012002 (2009).