Improved Search for a Higgs Boson Produced in Association with $Z \to l^+ l^-$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We search for the standard model Higgs boson produced with a Z boson in 4.1 fb^{-1} of integrated luminosity 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 multiplied by the $H \to b\bar{b}$ branching ratio. Improved analysis methods enhance signal sensitivity by 20% relative to previous searches. At a Higgs boson mass of 115 GeV/c^2 we set a limit of 5.9 times the standard model cross section.

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In the standard model (SM), electroweak symmetry breaking is 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 GeV/c^2 or with M_H between 158 and 175 GeV/c^2 has been excluded at 95% confidence level in direct searches at LEP [1] and the Tevatron [2].

At the Tevatron, and for $M_H < 135$ GeV/c^2, the Higgs boson is primarily produced through direct production $gg \to H$, and decays to a b quark pair $H \to b\bar{b}$ [3]. While $gg \to H \to b\bar{b}$ is overwhelmed by multijet processes, associated production of a Higgs boson with a leptonically decaying W or Z boson yields a signature distinct from this background. This Letter presents an improved search for the SM Higgs boson produced in association with a Z boson, $ZH \to \ell^+\ell^- b\bar{b}$ ($\ell = e, \mu$) using 1.96 TeV $p\bar{p}$ collision data corresponding to 4.1 fb^{-1} of integrated luminosity collected with the CDF

II detector [4]. This channel is one of the most sensitive to a low-mass SM Higgs boson at the Tevatron [5,6].

A recent search in this channel performed by the D0 Collaboration is described in [7]. Previous CDF efforts used an artificial neural network classifier (NN) [8] or a likelihood based on matrix-element probabilities (MEP) [9] for signal isolation. Here we enhance these techniques with NN-based b jet discrimination [10] and an improved multivariate jet-energy correction. New $Z \to e^+e^-$ 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 signal sensitivity by a factor of 1.2 over the gain expected just from additional integrated luminosity.

The most relevant analysis details are discussed below; a full presentation can be found in Ref. [11]. We select ZH candidates by first identifying a sample of events containing a $Z \to \ell^+\ell^-$ decay. Events are selected in real time (triggered) based on the presence of high-p_T electron and muon [12] 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 $p_T \geq 9$ GeV$/c$ matched to an electromagnetic energy (EM) cluster of $E_T \geq 18$ GeV (a trigger electron) or at least one central track of $p_T \geq 20$ 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 $E_T \geq 18$ 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 $76 \leq M_{ll} \leq 106$ 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 might 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), where S (B) is the expected number of ZH (background) events. 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 $p_T \geq 10$ GeV$/c$, or a trigger electron paired with a second electron candidate formed from either a central EM cluster of $E_T \geq 10$ GeV matched to a track of $p_T \geq 5$ GeV$/c$ or a forward EM cluster of $E_T \geq 18$ 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 $p_T \geq 20$ 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 [13]. We consider only jets in the region $|\eta| \leq 2.0$ and well separated from the Z-decay leptons. Events are required to have one jet with $E_T \geq 25$ GeV and a second of $E_T \geq 15$ 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. 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. There are 11 806 (3061) 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 $M_H = 115$ GeV$/c^2$.

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) [4] and one based on track impact parameters with respect to the $p\bar{p}$ interaction point (JP) [14]. For the SV algorithm, there are two operating points: tight and loose [15]. 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 follow-

TABLE I. Comparison of the expected mean event totals for background and ZH signal with the observed number of data events for each of the six analyzed samples. Systematic and statistical uncertainties are combined in quadrature.

	High S/B			Low S/B		
Process	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 + h.f.	18 ± 7	30 ± 13	159 ± 67	3.5 ± 1.5	5.6 ± 2.4	32 ± 14
Z + l.f.	0.9 ± 0.3	9 ± 3	152 ± 23	0.4 ± 0.1	3.8 ± 1.3	50 ± 7.6
Misidentified Z	0.7 ± 0.3	2 ± 1	22 ± 11	1.4 ± 0.7	1.1 ± 0.5	23 ± 12
Total background	29 ± 8	53 ± 14	366 ± 72	9 ± 2	14 ± 3	117 ± 20
ZH(115 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

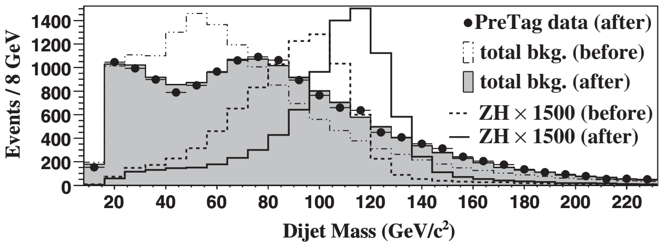

FIG. 1. The dijet invariant mass distribution of the two jets with the highest E_T in the PreTag sample. The distribution is shown for data after NN correction of jet energies. The dijet mass is shown for background and signal ($M_H = 115\ \mathrm{GeV}/c^2$, scaled by a factor of 1500) before and after correction.

ing classifications, in order of precedence from highest to lowest in S/B: a pair containing two SV-tight-tagged jets, or tight-double-tagged (TDT); a pair consisting of one SV-loose-tagged jet and a second JP-tagged jet, or loose-double-tagged (LDT); and a pair where only one jet has a SV-tight-tag, or single-tagged (ST). While this b tag selection has an $H \to b\bar{b}$ efficiency (60%) and a Z + l.f. rejection rate (96%) similar to those of previous efforts, the addition of the LDT class increases sensitivity to a ZH signal by 6%. With two Z boson S/B categories and three b-tagging classes, we form a total of six independent 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 [16] event generator. Backgrounds from Z + h.f. processes are simulated at the quark level using ALPGEN [17], then passed to PYTHIA for hadronization. The Z + h.f. samples are normalized using leading order ALPGEN cross sections, with a K factor of 1.4 [18]. We model Z + l.f. mistags using reweighted PreTag data with weights reflecting the probability for a l.f. jet to be erroneously b tagged. Less than 1% of jets can be erroneously identified as electrons, resulting in a background of misidentified $Z \to ee$ candidates. A model for these events is generated by measuring the misidentification rate in generic jet data and applying this rate to the data used in the analysis. The misidentified $Z \to \mu\mu$ background is modeled with like-charge muon pairs. Event totals are listed in Table I.

In $ZH \to \ell^+\ell^- b\bar{b}$ events, incorrect measurement of jet energies results in apparent missing transverse energy $\vec{E}_T$ [19]. We compute jet-energy corrections utilizing a NN trained to match measured jet energies to parton-level energies in Z + jets and ZH events. This NN is improved compared to that in the previous analysis [8] 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 $\vec{E}_T$ onto the lower-E_T Higgs jet, and the sphericity [20]. The effect of the NN corrections, which improve the resolution [21] of M_H from 18% to 12%, are shown in Fig. 1.

To exploit the combined signal-to-background discrimination power of event quantities and their correlations, we employ neural network discriminants (NN_D) trained to simultaneously separate ZH, $t\bar{t}$, and Z + jets events. The NN_D are configured to return values of $(x, y) = (1, 0)$ for ZH events, (0, 0) for Z + jets, and (1, 1) for $t\bar{t}$ and are trained separately for each b-tag class. In addition to the quantities recomputed with corrected jet energies, the NN_D inputs include E_T, MEPs for ZH, $t\bar{t}$, and Z + jets processes [9], the number of jets in the event, and the output of a b jet identifying artificial neural network (NN_b) [22]. 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. Projections of NN_D output are shown in Fig. 2.

We estimate the effect of systematic uncertainties by propagating uncertainties on NN_D input quantities to the output distributions. The dominant effects are the uncertainties on cross sections for background processes—a 40% uncertainty is assumed on the normalization of Z + h.f. samples [23,24], 11.5% for the diboson samples [25], 20% on $t\bar{t}$ [26], and 5% for ZH signal [27]. Uncertainty on the Z + l.f. normalization is set by the uncertainties on b-tag algorithm mistag probabilities and is 15% to 35% depending on b-tag class. Uncertainties of 4% (ST), 8% (TDT), and 11% (LDT) on the normalization of b-tagged samples are applied to account for different b-tag efficiencies in data and simulation. Other uncertainties affecting

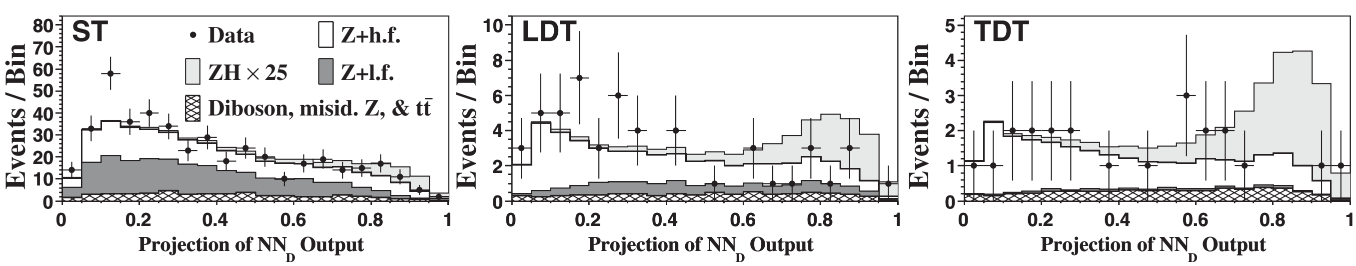

FIG. 2. Projections of the two-dimensional neural network (NN_D) output onto the x axis (x and y are defined in the text) for events in the b-tag categories ST, LDT, and TDT. Events with an NN_D score of $y \geq 0.1$ are omitted to highlight the signal region. The ZH contribution is shown, multiplied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

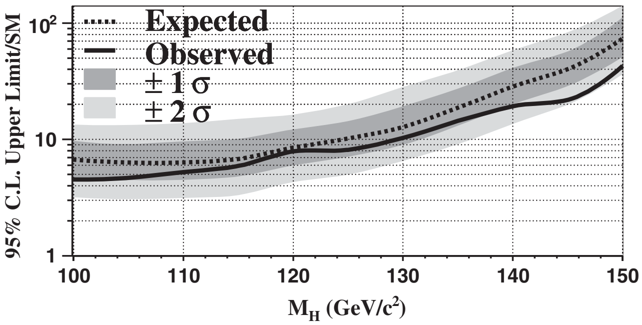

FIG. 3. The expected (dashed curve) and observed (solid curve) ZH cross section upper limits divided by the SM cross section are shown as a function of the Higgs boson mass.

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 misidentified Z estimate. We include additional uncertainties on jet energies [29] and the modeling of initial and final state radiation as variations on the shape and normalization of the NN_D output.

We calculate limits on ZH cross section based on comparisons of the full NN_D output of the b-tagged data to expectations for signal and background for eleven Higgs boson mass hypotheses between 100 and 150 GeV$/c^2$. We use a Bayesian algorithm [30] 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 [31]. Systematic uncertainties reduce the sensitivity of this search by 16%. The median of the 95% credibility level (C.L.) upper limits obtained from 1000 simulated experiments is taken as the expected 95% C.L. upper limit. The $\pm 1\sigma$ (where σ denotes the standard deviation) and $\pm 2\sigma$ expected limits are derived from the distribution of the simulation limits at the 16th, 84th, 2nd, and 98th percentiles of the distribution, respectively. The observed 95% C.L. on the ZH cross section are 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 multiplied by the $H \rightarrow b\bar{b}$ branching ratio. For $M_H = 115$ 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 electroweak symmetry breaking, improving upon the previous CDF [8] observed (expected) limits in this channel by factors of 2.2 to 3.7 (1.9 to 2.4).

TABLE II. The 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 expectation. The assumed ZH cross section and branching fraction for $H \rightarrow b\bar{b}$ are 0.11 pb [32,33] and 0.73 [3] for a 115 GeV$/c^2$ Higgs boson.

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

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