Search for $ZH \to l^+l^-b\bar{b}$ Production in 4.2 fb^{-1} of $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present a search for the standard model Higgs boson produced in association with a Z boson in 4.2 fb^{-1} of $p\bar{p}$ collisions, collected with the D0 detector at the Fermilab Tevatron at $\sqrt{s} = 1.96$ TeV. Selected events contain one reconstructed $Z \rightarrow e^+e^-$ or $Z \rightarrow \mu^+\mu^-$ candidate and at least two jets, including at least one b-tagged jet. In the absence of an excess over the background expected from other standard model processes, limits on the ZH cross section multiplied by the branching ratios are set. The limit at $M_H = 115$ GeV is a factor of 5.9 larger than the standard model prediction.

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In the standard model (SM), the spontaneous breakdown of the electroweak symmetry generates masses for the W and Z bosons and produces a scalar massive particle, the Higgs boson, which has so far eluded detection. The discovery of the Higgs boson would top a remarkable list of experimentally confirmed SM predictions. For Higgs boson masses M_H below 135 GeV, the primary Higgs boson decay in the SM is $H \rightarrow b\bar{b}$, which is challenging to discern amidst copious $b\bar{b}$ production at the Tevatron $p\bar{p}$ collider. Consequently, sensitivity to a low-mass Higgs boson is predominantly from its production in association with a W or Z boson that decays to leptons. In this Letter, we present a search for $ZH \rightarrow \ell^+\ell^- b\bar{b}$, where ℓ is either a muon or an electron. The searches for $ZH \rightarrow \nu\bar{\nu}b\bar{b}$ and $ZH \rightarrow \tau^+\tau^- b\bar{b}$ are treated elsewhere [1,2]. For the $\ell^+\ell^- b\bar{b}$ final states, the D0 Collaboration has previously used 0.45 fb^{-1} of integrated luminosity to report a cross section upper limit at the 95% C.L. that was 25 times larger than the SM prediction at $M_H = 115$ GeV [3], and the CDF Collaboration used 2.7 fb^{-1} to obtain a factor of 8 [4].

The data for this analysis were collected at the Fermilab Tevatron Collider with the D0 detector [5]. After imposing data quality requirements, the integrated luminosity is 4.2 fb^{-1}. Events passing selection requirements were predominantly acquired by triggers that provide real-time identification of electron and muon candidates, but events from all available triggers are considered. Selected events must have a primary $p\bar{p}$ interaction vertex (PV) that has at least three associated tracks and is located within 60 cm of the center of the detector along the direction of the beam. Selected events must also contain a Z boson candidate with a dilepton invariant mass $60 < m_{\ell\ell} < 150$ GeV.

The dimuon, $\mu\mu$, selection requires at least two muons matched to central tracks with transverse momenta

$p_T > 10$ GeV. Combined tracking and calorimeter isolation requirements are applied to the muon pair such that one muon does not need to be isolated if the other is sufficiently well isolated. For each muon track, the pseudorapidity $\eta_{\rm det}$, measured with respect to the center of the detector, must satisfy $|\eta_{\rm det}| < 2$ [6]. At least one muon must have $|\eta_{\rm det}| < 1.5$ and $p_T > 15$ GeV. The distance of closest approach of each track to the PV in the plane transverse to the beam direction $d_{\rm PV}$ must be less than 0.02 cm for tracks with at least one hit in the silicon microstrip tracker (SMT). A track without SMT hits must have $d_{\rm PV} < 0.2$ cm, and its p_T is corrected through a constraint to the position of the PV. An additional selection $\mu\mu_{\rm trk}$ requires one identified muon and one isolated track ($\mu_{\rm trk}$) in the central tracking detector with $p_T > 20$ GeV and $|\eta_{\rm det}| < 2$, at least one hit in the SMT, and $d_{\rm PV} <$ 0.02 cm [7]. The $\mu_{\rm trk}$ must be separated in pseudorapidity η and azimuth ϕ by $\Delta\mathcal{R} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.1$ from the other muon. The $\mu\mu_{\rm trk}$ selection adds 10% signal acceptance to the $\mu\mu$ selection, mainly from gaps in the muon detector. In both selections, the two muons must have opposite charge.

The dielectron, ee, selection requires at least two electrons of $p_T > 15$ GeV identified by electromagnetic showers in the calorimeter. Each shower must be isolated from other energy depositions and have a shape consistent with that of an electron. At least one electron must be identified in the central calorimeter (CC, $|\eta_{\rm det}| < 1.1$), and a second electron either in the CC or the end calorimeter (EC, $1.5 < |\eta_{\rm det}| < 2.5$). The CC electrons must match central tracks or produce a pattern of hits in the tracker consistent with that of an electron. An additional selection $ee_{\rm ICR}$ requires exactly one electron from the CC or EC, with a second electron identified as a narrow calorimeter cluster in the intercryostat region (ICR, $1.1 < |\eta_{\rm det}| <$ 1.5) that has a matching track in the central tracker [8]. A neural network ($\rm NN_{ICR}$) is used to differentiate ICR electrons from jets. The $ee_{\rm ICR}$ selection requires an explicit single-electron trigger, and adds 17% signal acceptance to the ee selection.

Jets are reconstructed in the calorimeter using the iterative midpoint cone algorithm [9] with a cone of radius 0.5. The energy scale of jets is corrected for detector response, the presence of noise and multiple $p\bar{p}$ interactions, and energy deposited outside of the reconstructed jet cone [10]. At least two jets with $|\eta_{\rm det}| < 2.5$ are required, with the leading jet of $p_T > 20$ GeV and additional jets of $p_T >$ 15 GeV. Both electrons in dielectron events are required to be isolated from any jet by $\Delta\mathcal{R} > 0.5$. Likewise, jets must be separated by $\Delta\mathcal{R} > 0.5$ from the $\mu_{\rm trk}$ candidate in the $\mu\mu_{\rm trk}$ channel, but no such requirement is applied to the muon candidates in either dimuon selection. To reduce the impact from multiple $p\bar{p}$ interactions at high instantaneous luminosities, jets must contain at least two tracks matched to the PV.

To distinguish the decay $H \to b\bar{b}$ from background processes involving light quarks and gluons, jets are identified as likely containing b quarks (b tagged) if they pass loose or tight requirements on the output of a neural network trained to separate b jets from light jets [11]. For $|\eta| < 0.7$ and $p_T > 45$ GeV, the b-tagging efficiency for b jets and the misidentification rate of light jets are, respectively, 74% and 8.5% for loose b tags, and 48% and 0.6% for tight b tags. Events with at least two loose b tags are classified as double-tagged (DT). Events not in the DT sample that contain a single tight b tag are classified as single-tagged (ST).

The background from multijet events with jets misidentified as leptons is estimated from the data. For the $\mu\mu$ channel, the multijet control sample contains events that fail the muon isolation requirement but otherwise pass the event selection. In the $\mu\mu_{\rm trk}$ multijet control sample, the μ and $\mu_{\rm trk}$ are required to have the same charge. For the ee channel, the electrons must fail isolation and shower shape requirements. The resulting trigger bias is corrected by reweighting distributions in lepton p_T and η. Misidentified ICR electrons in the $ee_{\rm ICR}$ channel are selected from a background region of the $\rm NN_{ICR}$ output.

The dominant background process is the production of a Z boson in association with jets, with the Z boson decaying to dileptons (Z + jets). The light-flavor component (Z + LF) includes jets from only light quarks (uds) or gluons. The heavy-flavor component (Z + HF) includes nonresonant $Z + b\bar{b}$ production, which has the same final state as the signal, and $Z + c\bar{c}$. The remaining backgrounds are from top quark pair ($t\bar{t}$) and diboson production. We simulate $ZH \to \ell^+\ell^- b\bar{b}$ and inclusive diboson production with PYTHIA [12] and Z + jets and $t\bar{t} \to \ell^+\nu b\ell^-\bar{\nu}\bar{b}$ processes with ALPGEN [13], using the CTEQ6L1 [14] leading-order parton distribution functions (PDFs). The events generated with ALPGEN are input to PYTHIA for parton showering and hadronization, which can produce additional jets. A matching procedure is used to avoid double counting partons produced by ALPGEN and those subsequently added by the showering in PYTHIA [13]. All samples are processed using a detector simulation program based on GEANT3 [15], and the same offline reconstruction algorithms used to process the data. Events from randomly chosen beam crossings are overlaid on the simulated events to reproduce the effect of multiple $p\bar{p}$ interactions and detector noise.

The cross section and branching ratio for the signal are taken from Refs. [16,17]. For the $t\bar{t}$ and diboson processes, the cross sections are taken from MCFM [18], calculated at next-to-leading order (NLO). The inclusive Z boson cross section is scaled to next-to-NLO [19], with additional NLO heavy-flavor corrections calculated from MCFM applied to $Z + b\bar{b}$ and $Z + c\bar{c}$.

Corrections are applied to the simulated events to improve the modeling. The simulated $ee_{\rm ICR}$, $\mu\mu$, and $\mu\mu_{\rm trk}$

TABLE I. Expected and observed event yields for all lepton channels combined with total statistical and systematic uncertainties where indicated. The ZH yields are for $M_H = 115$ GeV.

	Data	Total background	Multijet	Z + LF	Z + HF	Diboson & $t\bar{t}$	ZH
Inclusive	865 254	853 976	131 905	701 516	19 074	1481	9.14
Pretag	31 336	30 634	3449	23 234	3459	491	6.82
ST	728	707 ± 130	48.4	161	443	54.1	1.87 ± 0.25
DT	485	435 ± 68	29.5	106	237	61.8	2.34 ± 0.36

events are weighted by trigger efficiencies measured in data. For the ee channel, no correction is applied as the combination of lepton and jet triggers is nearly 100% efficient. Lepton identification efficiencies are corrected as a function of $\eta_{\rm det}$ and ϕ of the lepton. Jet energies are modified to reproduce the resolution observed in data. Scale factors are applied to correct for differences in jet reconstruction efficiency between data and simulation. The performance of the background model is evaluated in control samples with negligible signal contributions obtained by applying only the lepton selection requirements (inclusive) or all selection requirements except b tagging (pretag). The simulated Z boson events are reweighted such that the p_T distribution of the Z boson is consistent with the observed distribution [20]. To improve upon the ALPGEN modeling of Z + jets, motivated by a comparison with the SHERPA generator [21], the pseudorapidities of the two jets with the highest p_T, and the $\Delta\mathcal{R}$ between them are reweighted to match the distributions measured in the pretag data.

Normalization factors for the simulated and the multijet samples are determined from a fit to the $m_{\ell\ell}$ distributions in the inclusive and pretag data. This improves the accuracy of the background model and reduces the impact of systematic uncertainties that affect pretag event yields (e.g., uncertainties on luminosity). The region $40 < m_{\ell\ell} < 60$ GeV, where the multijet contribution is most prominent, is included in the fit to determine the size of this background more precisely. The inclusive control sample constrains the lepton trigger and identification efficiencies, while the pretag control sample, which includes jet requirements, constrains a common scale factor $k_{z+\rm jets}$ that corrects the Z + jets cross section. Systematic uncertainties due to this procedure are determined from the statistical uncertainties of the fit parameters, the correlated uncertainty from the inclusive Z cross section, and the observed change in $k_{z+\rm jets}$ when channels are fit independently of one another. The total event yields after applying all corrections and normalization factors are shown in Table I.

To exploit the kinematics of the $ZH \to \ell^+\ell^- b\bar{b}$ process, the energies of the candidate leptons and jets are adjusted within their experimental resolutions with a χ^2 fit that constrains $m_{\ell\ell}$ to the mass and width of the Z boson, and the p_T of the $\ell^+\ell^- b\bar{b}$ system to the expected distribution for ZH events before detector resolution effects [7]. A multivariate analysis based on a random forest (RF) [22] combines the most significant kinematic information into a single discriminant (RF output). The variables selected for the RF are the transverse momenta of the two b-jet candidates and the dijet invariant mass, before and after the jet energies are adjusted by the kinematic fit, angular differences within and between the dijet and dilepton systems, the angle between the proton beam and the Z boson candidate in the rest frame of the $\ell^+\ell^- b\bar{b}$ system [23], and composite kinematic variables such as the p_T of the dijet system and the scalar sum of the transverse momenta of the leptons and jets. The RF outputs with all lepton channels combined are shown separately for ST and DT events in Figs. 1(a) and 1(b).

Systematic uncertainties resulting from the background normalization are assessed for the multijet contribution (20%–60% depending on channel) and for effects of lepton efficiency (2%–10%), some of which are correlated among

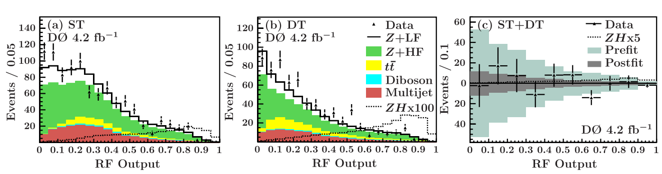

FIG. 1 (color online). Data and background RF outputs trained for $M_H = 115$ GeV with all lepton channels combined in (a) ST and (b) DT samples. The (c) background-subtracted ST and DT combination with the systematic uncertainty bands before and after the fit performed by the limit-setting program.

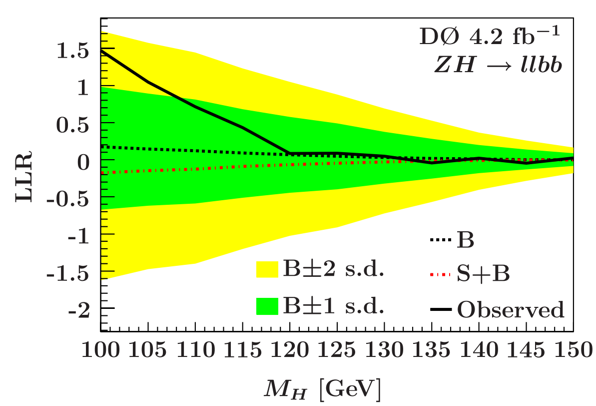

FIG. 2 (color online). Observed LLR as a function of M_H with the expected LLRs for the B and $S + B$ hypotheses and the one and 2 standard deviation (s.d.) bands of the B hypothesis.

TABLE II. The expected and observed 95% C.L. upper limits on the cross section for $ZH \rightarrow \ell^+\ell^- b\bar{b}$, expressed as a ratio to the SM cross section. The corresponding observed limits on the ZH production cross section multiplied by the branching ratio of $H \rightarrow b\bar{b}$ are also reported (in fb).

M_H(GeV)	100	105	110	115	120	125	130	135	140	145	150
Expected/SM:	5.1	5.6	6.2	7.1	8.4	10.0	12.7	16.8	23.6	34.0	53.6
Observed/SM:	3.0	3.8	4.6	5.9	7.9	9.2	12.1	17.3	22.3	39.4	49.3
Observed (fb):	41	44	44	47	50	45	45	46	41	47	36

all lepton channels (6%). The normalization of the Z + jets sample to the pretag data constrains the Z + jets cross section multiplied by any jet-dependent efficiency to within the statistical uncertainty of the pretag data (1%–2%). Additional systematic uncertainties (10%–20%) for possible jet-dependent efficiency effects absorbed into $k_{z+\text{jets}}$ are applied to the $t\bar{t}$, diboson and ZH samples. The normalization to the pretag data, which is dominated by Z + LF, does not strongly constrain the cross sections of other processes. A cross section uncertainty of 20% for Z + HF and 6%–10% for other backgrounds is determined from Ref. [18]. For the signal, the uncertainty is 6% [16]. The normalization to the dilepton mass distributions reduces the impact of many of the remaining systematic uncertainties on the background size (except those related to b tagging), but changes to the shape of the RF output distribution persist and are accounted for. Additional sources of systematic uncertainty include jet energy scale, jet energy resolution, jet identification efficiency, b-tagging and trigger efficiencies, PDFs, data-determined corrections to the model for Z + jets, and modeling of the underlying event. The uncertainties from the factorization and renormalization scales in the simulation of Z + jets are estimated by scaling these parameters by factors of 0.5 and 2.

No significant excess above the background expectation is observed. Therefore, we set limits on the ZH production cross section with a modified frequentist (C.L.s) method that uses a negative log likelihood ratio (LLR) of the signal-plus-background ($S + B$) hypothesis to the background-only (B) hypothesis [24]. The RF output distributions and corresponding systematic uncertainties of the ST and DT samples from each leptonic channel are analyzed by the limit-setting program. To minimize the impact of the systematic uncertainties, the likelihood of the B and $S + B$ hypotheses are each maximized by independent fits that vary nuisance parameters used to model the systematic effects [25]. The correlations among systematic uncertainties are maintained across channels, as well as backgrounds and signal. The background-subtracted RF distribution is shown in Fig. 1(c).

Figure 2 shows the observed LLR as a function of M_H with the expected (median) LLRs for the B and $S + B$ hypotheses. A signal-like excess would result in a negative value of observed LLR. The 95% C.L. upper limit on the cross section times branching ratio, expressed as a ratio to the SM prediction, for each M_H is presented in Table II. At $M_H = 115$ GeV, the observed (expected) limit on this ratio is 5.9 (7.1). In the combination of D0 searches this is one of the three most sensitive channels for this mass. Compared to the previous best expected limit in this channel [4], this represents a 40% improvement. A similar improvement was obtained by the CDF Collaboration [26] after the submission of this Letter.

Supplementary material is available in [27].

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