Evidence for a Particle Produced in Association with Weak Bosons and Decaying to a Bottom-Antibottom Quark Pair in Higgs Boson Searches at the Tevatron

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We combine searches by the CDF and D0 Collaborations for the associated production of a Higgs boson with a W or Z boson and subsequent decay of the Higgs boson to a bottom-antibottom quark pair. The data, originating from Fermilab Tevatron $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, correspond to integrated luminosities of up to 9.7 fb^{-1}. The searches are conducted for a Higgs boson with mass in the range 100–150 GeV/c^2. We observe an excess of events in the data compared with the background predictions, which is most significant in the mass range between 120 and 135 GeV/c^2. The largest local significance is 3.3 standard deviations, corresponding to a global significance of 3.1 standard deviations. We interpret this as evidence for the presence of a new particle consistent with the standard model Higgs boson, which is produced in association with a weak vector boson and decays to a bottom-antibottom quark pair.

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The standard model (SM) [1, 2] Higgs boson H is predicted to be produced in association with a W or Z boson at the Fermilab Tevatron $p\bar{p}$ Collider if it is within kinematic reach, and its dominant decay mode is predicted to be into a bottom-antibottom quark pair ($b\bar{b}$), if its mass m_H is less than 135 GeV/c^2 [3, 4]. An observation of this process would support the SM prediction that the mechanism for electroweak symmetry breaking, which gives mass to the weak vector bosons, is also the source of fermionic mass in the quark sector. The leptonic decays of the W and Z vector bosons and the decays of the H to $b\bar{b}$ provide distinctive signatures of Higgs boson production, which are used to discriminate signal events from the copious backgrounds [5]. In this Letter, we combine the searches from the CDF and D0 Collaborations for H bosons produced in association with a vector boson, with subsequent decays $H \to b\bar{b}$. Both collaborations consider the processes $WH \to \ell\nu b\bar{b}$, $ZH \to \ell^+\ell^- b\bar{b}$, and $WH, ZH \to \not\!\!E_T b\bar{b}$ [6–11] (where ℓ is either e or μ and $\not\!\!E_T$ denotes missing transverse energy [12]), and separately combine results within their collaborations [13, 14]. This is the first publication of a combination of CDF and D0's searches for $H \to b\bar{b}$, which is based on the preliminary findings reported in Ref. [15].

Much is known about the Higgs boson from other experiments. The direct searches at LEP2 in the $e^+e^- \to ZH(\to b\bar{b})$ mode, with a small contribution from vector boson fusion, are very similar to those combined here, and exclude SM Higgs boson masses below 114.4 GeV/c^2 at the 95% confidence level (C.L.) [16]. Direct searches for $VH \to Vb\bar{b}$ at the LHC, where $V = W$ or Z [17, 18], do not yet constrain the allowed SM Higgs boson mass range. Including other search modes, direct searches at the LHC for the SM Higgs boson limit its mass to be between 116.6 and 119.4 GeV/c^2 or between 122.1 and 127.0 GeV/c^2, at the 95% C.L. [19, 20]. Within these searches, both LHC experiments observe local excesses above the background expectations for a Higgs boson mass of approximately 125 GeV/c^2 [21]. Much of the power of the LHC searches comes from $gg \to H$ production and Higgs boson decays to $\gamma\gamma$, W^+W^-, and ZZ, which probe the couplings of the Higgs boson to other bosons. In the allowed mass range, the Tevatron experiments are particularly sensitive to VH production with $H \to b\bar{b}$, which probes the Higgs boson's coupling to b quarks. We search for Higgs bosons of masses $100 < m_H < 150$ GeV/c^2 and interpret our results independently of searches which are not sensitive to the specific Higgs boson production and decay modes studied here. We also report results assuming $m_H = 125$ GeV/c^2.

Higgs boson signal events are simulated using the leading order (LO) calculation from PYTHIA [22], with CTEQ5L (CDF) and CTEQ6L1 (D0) [23] parton distribution functions (PDFs). We normalize our Higgs boson signal-rate predictions to the highest-order calculations available. The WH and ZH cross section calculations are performed at next-to-next-to leading order (NNLO) precision in QCD and next-to-leading-order (NLO) precision in the electroweak corrections [3]. We use the branching fractions for Higgs boson decay from Ref. [4]. These rely on calculations using HDECAY [24] and PROPHECY4F [25]. Assuming the $m_H = 125$ GeV/c^2 hypothesis, we expect approximately 155 Higgs boson signal events to pass our selection requirements, along with 9.2×10^4 background events from all other SM sources.

We model SM and instrumental background processes using a mixture of Monte Carlo (MC) and data-driven methods. For CDF, backgrounds from SM processes with electroweak gauge bosons or top quarks are modeled using PYTHIA, ALPGEN [26], MC@NLO [27], and HERWIG [28]. For D0, these backgrounds are modeled using PYTHIA, ALPGEN, and COMPHEP [29]. An interface to PYTHIA provides parton showering and hadronization for generators without this functionality.

Diboson (WW, WZ, ZZ) MC samples are normalized using the NLO calculations from MCFM [30]. For $t\bar{t}$, we use a production cross section of 7.04±0.70 pb [31], which is based on a top-quark mass of 173 GeV/c^2 [32] and MSTW 2008 NNLO PDFs [33]. The single-top-quark production cross section is taken to be 3.15±0.31 pb [34].

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Data-driven methods are used to normalize the W/Z plus light-flavor and heavy-flavor jet backgrounds [35] using W/Z data events containing no b-tagged jets [36], which have negligible signal content [13, 14].

The CDF and D0 detectors are multipurpose solenoidal spectrometers surrounded by hermetic calorimeters and muon detectors and are designed to study the products of 1.96 TeV proton-antiproton collisions [37, 38]. All searches combined here use the complete Tevatron data sample, which after data quality requirements corresponds to 9.45 fb^{-1}–9.7 fb^{-1}; the size of the analyzed data set depends on the experiment and the search channel. The online event selections (triggers) rely on fast reconstruction of combinations of high-p_T lepton candidates, jets, and $\not\!\!E_T$. Event selections are similar in the CDF and D0 analyses, consisting typically of a preselection based on event topology and kinematics, and a subsequent selection using b-tagging. Both collaborations use multivariate analysis (MVA) techniques that combine several discriminating variables into a single final discriminant which is used to separate signal from background. Each channel is divided into exclusive sub-channels according to various lepton, jet multiplicity, and b-tagging characterization criteria aimed at grouping events with similar signal-to-background ratio and so optimize the overall sensitivity. Due to the importance of b-tagging, both collaborations have developed multivariate approaches to maximize the performance of the b-tagging algorithms. A boosted decision tree algorithm is used in the D0 analysis, which builds and improves upon the previous neural network b-tagger [39], giving an identification efficiency of $\approx$ 80% for b-jets with a mis-identification rate of $\approx$ 10%. The CDF b-tagging algorithm has been recently augmented with an MVA [40], providing a b-tagging efficiency of $\approx$ 70% and a mis-identification rate of $\approx$ 5%.

The reconstructed dijet mass provides discrimination between signal and background. The decay width of the Higgs boson is expected to be much narrower than the experimental dijet mass resolution, which is typically 15% of the mean reconstructed mass. A SM Higgs boson signal would appear as a broad enhancement in the reconstructed dijet mass distribution. The sensitivity is enhanced by combining the dijet mass with other kinematic information using multivariate discriminants. The MVA functions are optimized separately for each sub-channel and for each hypothesized value of m_H in the range 100–150 GeV/c^2, in 5 GeV/c^2 intervals. The results from each sub-channel are summarized in histograms of the MVA discriminants for the expected Higgs boson signals, the backgrounds itemized by source, and the observed data.

We interpret the results using both Bayesian and modified frequentist techniques, separately at each value of m_H. These methods are described in Refs. [15, 41, 42]. These techniques are built on a likelihood function which is a product of Poisson probabilities for observing the data in each bin of each sub-channel. Systematic uncertainties are parametrized with nuisance parameters, which affect the rates of the predicted signal and background yields in each bin. A nuisance parameter may affect the predictions of multiple sources of signal and background in multiple sub-channels, thus taking correlations into account. A nuisance parameter may also affect multiple bins' predictions by different amounts, thus parameterizing uncertainty in the shapes of distributions. Gaussian priors are assumed for the nuisance parameters, truncated to ensure that no prediction is negative. The signal predictions used correspond to SM Higgs boson production and decay, scaled by a factor R for all bins of all sub-channels. By scaling all signal contributions by the same factor, we assume that the relative contributions of the different processes are as predicted by the SM.

In the Bayesian technique, we assume a uniform prior in R and integrate the likelihood function multiplied by the priors of the nuisance parameters to obtain the posterior density for R. The observed 95% credibility level upper limit on R, R_{95}^{obs}, is such that 95% of the integral of the posterior of R is below R_{95}^{obs}. The expected distribution of R_{95} is computed in an ensemble of simulated experimental outcomes assuming no signal is present. In each simulated outcome, random values of the nuisance parameters are drawn from their priors. A combined measurement of the cross section for Higgs boson production times the branching fraction $\mathcal{B}(H \to b\bar{b})$, in units of the SM production rate, is given by R^{fit}, which is the value of R that maximizes the posterior density. The 68% credibility interval, which corresponds to one standard deviation (s.d.), is quoted as the smallest interval containing 68% of the integral of the posterior.

We also perform calculations using the modified frequentist technique [42], CL_s, using a log-likelihood ratio (LLR) as the test statistic:

$$LLR = -2 \ln \frac{p(\text{data}|H_1)}{p(\text{data}|H_0)}, \tag{1}$$

where H_1 denotes the test hypothesis, which admits the presence of SM backgrounds and a Higgs boson signal, H_0 denotes the null hypothesis, for only SM backgrounds, and 'data' are either simulated data constructed from the expected signal and backgrounds, or the actual observed data. The probabilities p are computed using the best-fit posterior values of the nuisance parameters for each simulated experimental outcome, separately for each of the two hypotheses, and include the Poisson probabilities of observing the data multiplied by Gaussian constraint terms for the values of the nuisance parameters. The CL_s technique involves computing two p-values,

$$\text{CL}_\text{b} = p(LLR \geq LLR_{\text{obs}}|H_0), \tag{2}$$

where LLR_{obs} is the value of the test statistic computed for the data, and

$$\mathrm{CL_{s+b}} = p(LLR \geq LLR_{\mathrm{obs}}|H_1). \qquad (3)$$

To compute limits, we use the ratio of p-values, $\mathrm{CL_s} = \mathrm{CL_{s+b}}/\mathrm{CL_b}$. If $\mathrm{CL_s} < 0.05$ for a particular choice of H_1, parametrized by the signal scale factor R, that hypothesis is excluded at the 95% C.L. The median expected limit is computed using the median LLR value expected in the background-only hypothesis.

The uncertainties on the signal production cross sections are estimated from the factorization and renormalization scale variations, which include the impact of uncalculated higher-order corrections, as well as uncertainties due to PDFs, and the dependence on the strong coupling constant, α_s. The resulting uncertainties on the inclusive WH and ZH production rates are 7% [3]. We assign uncertainties to the prediction of $\mathcal{B}(H \rightarrow b\bar{b})$ as calculated in Ref. [43]. These uncertainties arise from imperfect knowledge of the mass of the b and c quarks, α_s, and theoretical uncertainties in the $b\bar{b}$ and W^+W^- decay rates.

The largest sources of uncertainty on the dominant backgrounds are the rates of tagged V+heavy flavor jets, which are typically 20-30% of the predicted values. The posterior uncertainties on these rates are typically 8% or less. Uncertainties on lepton identification and trigger efficiencies range from 2% to 6% and are applied to both signal- and MC-based background predictions. These uncertainties are estimated from data-based methods separately by CDF and D0, and differ based on lepton flavor and identification category. The b-tag efficiencies and mistag rates are similarly constrained by auxiliary data samples, such as inclusive jet data or $t\bar{t}$ events. The uncertainty on the per-jet b-tag efficiency is approximately 4%, and the mistag uncertainties vary between 7% and 15%. The uncertainties on the measurements of the integrated luminosities, which are used to normalize the expected signal yields and the MC-based backgrounds, are 6% (CDF) [44] and 6.1% (D0) [45]. Of these values, 4% arises from the inelastic $p\bar{p}$ cross section, which is taken to be correlated between CDF and D0.

To validate our background modeling and search methods, we perform a search for SM diboson production in the same final states used for the SM $H \rightarrow b\bar{b}$ searches. The NLO SM cross section for VZ times the branching fraction of $Z \rightarrow b\bar{b}$ is 0.68 ± 0.05 pb, which is about six times larger than the 0.12 ± 0.01 pb cross section times branching fraction of $VH(H \rightarrow b\bar{b})$ for a 125 GeV/c^2 SM Higgs boson. The data sample, reconstruction, process modeling, uncertainties, and sub-channel divisions are identical to those of the SM Higgs boson search. However, discriminant functions are trained to distinguish the contributions of SM diboson production from those of other backgrounds, and potential contributions from Higgs boson production are not considered. The measured cross section for VZ is 3.9 ± 0.6 (stat) ± 0.7 (syst) pb, which is consistent with the SM prediction of 4.4 ± 0.3 pb.

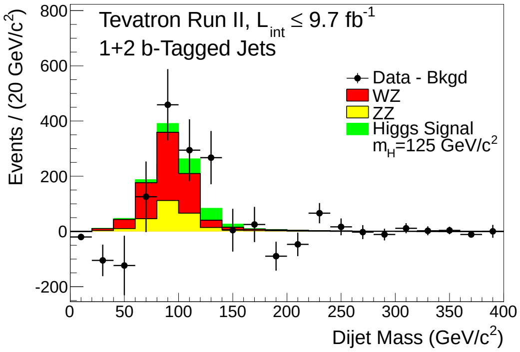

FIG. 1: Background-subtracted distribution of the reconstructed dijet mass m_{jj}, summed over all input channels. The VZ signal and the background contributions are fit to the data, and the fitted background is subtracted. The fitted VZ and expected SM Higgs ($m_H = 125$ GeV/c^2) contributions are shown with filled histograms.

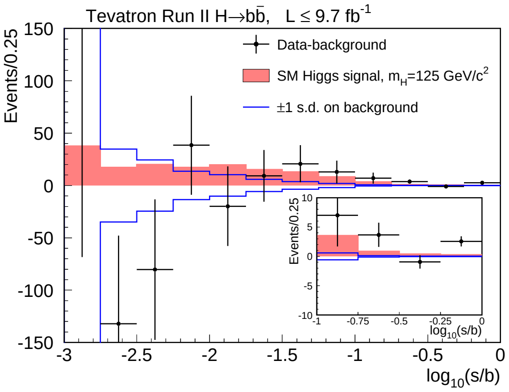

FIG. 2: Background-subtracted distribution for the discriminant histograms, summed for bins with similar signal-to-background ratio (s/b), for the $H \rightarrow b\bar{b}$ ($m_H = 125$ GeV/c^2) search. The solid histogram shows the uncertainty on the background after the fit to the data as discussed in the text. The signal model, scaled to the SM expectation, is shown with a filled histogram. Uncertainties on the data points correspond to the square root of the sum of the expected signal and background yields in each bin.

The combined background-subtracted reconstructed dijet mass (m_{jj}) distribution for the VZ analysis is shown in Fig. 1. The VZ signal and the background contributions are fit to the data, and the fitted background is subtracted. Also shown is the contribution expected from a SM Higgs boson with $m_H = 125$ GeV/c^2.

To visualize the results produced by the multivariate VH analyses, we combine the histograms of the final discriminants, adding the contents of bins with similar signal-to-background ratio (s/b). Figure 2 shows the signal expectation and the data with the background (including VZ) subtracted, as a function of the s/b of the collected bins, for the combined Higgs boson search, assuming $m_H = 125$ GeV/c^2. The background model is fit to the data, and the uncertainties on the background are those after the nuisance parameters have been constrained in the fit. An excess of events in the highest s/b bins relative to the background-only expectation is observed. We also show the LLR as a function of m_H in Fig. 3, along with its expected values under the hypotheses H_0 and H_1, and also the hypothesis that a SM Higgs boson is present with $m_H = 125$ GeV/c^2.

We extract limits on SM Higgs boson production as a function of m_H in the range 100–150 GeV/c^2 in terms of $R_{95}^{\rm obs}$, the observed limit relative to the SM rate. These limits are shown in Fig. 4, together with the median expected values and distributions in simulated experimental outcomes assuming a signal is absent. We also show the median expected limits assuming the SM Higgs boson, with $m_H = 125$ GeV/c^2, is present. We exclude $m_H < 106$ GeV/c^2 at the 95% credibility level, while our median expected limit on m_H is 116 GeV/c^2, if no signal were present. The exclusions obtained with the $\mathrm{CL_s}$ technique match those computed with the Bayesian technique.

The observed limits are weaker than expected due to an excess events in the data with respect to the background predictions in the most sensitive bins of the discriminant distributions, favoring the hypothesis that a signal is present. We characterize this excess by computing the best-fit rate parameter $R^{\rm fit}$, which, when multiplied by the SM prediction for the associated production cross section times the decay branching ratio $(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \to b\bar{b})$, yields the best fit value for this quantity. We show our fitted $(\sigma_{WH}+\sigma_{ZH})\times\mathcal{B}(H \to b\bar{b})$ as a function of m_H, along with the SM prediction, in Fig. 5. The figure also shows the expected cross section fits for each m_H assuming that the SM Higgs boson, with $m_H = 125$ GeV/c^2, is present. The expected fits are shown for both the expected SM rate and the best fitted rate from data, which corresponds to $(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \to b\bar{b}) = 0.23^{+0.09}_{-0.08}$ (stat + syst) pb. The corresponding SM prediction for $m_H = 125$ GeV/c^2 is 0.12 ± 0.01 pb.

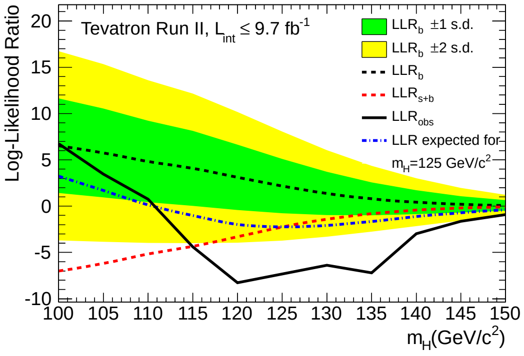

FIG. 3: The log-likelihood ratio LLR as a function of Higgs boson mass. The dark and light-shaded bands correspond to the regions encompassing 1 s.d. and 2 s.d. fluctuations of the background, respectively. The dot-dashed line shows the median expected LLR assuming the SM Higgs boson is present at $m_H = 125$ GeV/c^2.

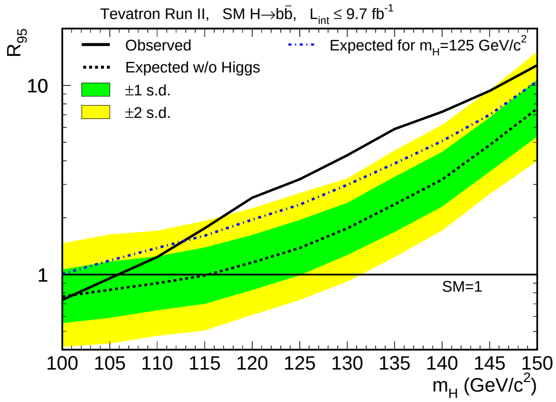

FIG. 4: The observed 95% credibility level upper limits on SM Higgs boson production (R_{95}) as a function of Higgs boson mass. The dashed line indicates the median expected value in the absence of a signal, and the shaded bands indicate the 1 s.d. and 2 s.d. ranges in which R_{95} is expected to fluctuate. The dot-dashed line shows the median expected limit if the SM Higgs boson is present at $m_H = 125$ GeV/c^2.

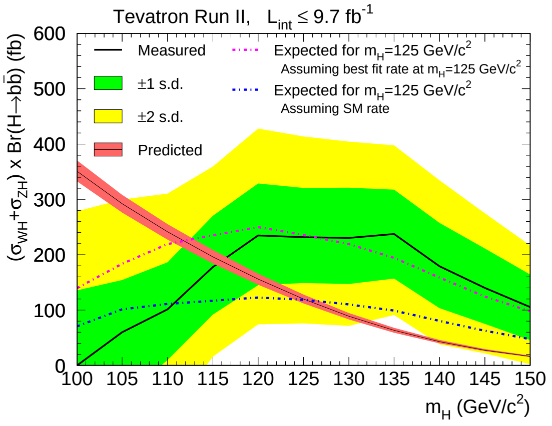

FIG. 5: The best-fit cross section times branching ratio $(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \to b\bar{b})$ as a function of m_H. The dark and light-shaded regions indicate the 1 s.d. and 2 s.d. measurement uncertainties, and the SM prediction is shown as the smooth, falling curve with a narrow band indicating the theoretical uncertainty. The expected cross section fit values assuming the SM Higgs boson is present at $m_H = 125$ GeV/c^2 are shown with dot-dashed lines for the cases of the expected SM rate (dark blue) and the best fitted rate from data (light magenta).

The significance of the excess in the data over the background prediction is computed at each hypothesized Higgs boson mass in the range 100–150 GeV/c^2 by cal-

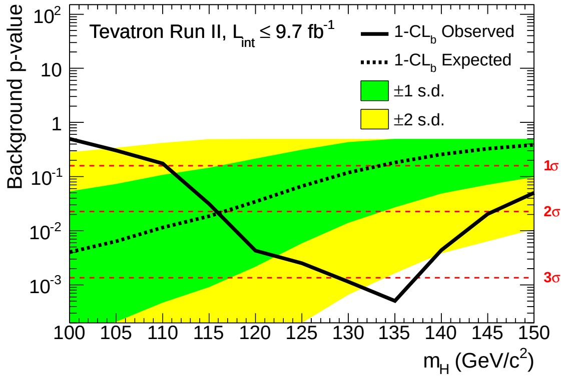

FIG. 6: The p-value as a function of m_H under the background-only hypothesis. Also shown are the median expected values assuming a SM signal is present, evaluated separately at each m_H. The associated dark and light-shaded bands indicate the 1 s.d. and 2 s.d. fluctuations of possible experimental outcomes.

culating the local p-value under the background-only hypothesis using R^{fit} as the test statistic. This p-value expresses the probability to obtain the value of R^{fit} observed in the data or larger, assuming a signal is truly absent. These p-values are shown in Fig. 6 along with the expected p-values assuming a SM signal is present, separately for each value of m_H. The observed p-value as a function of m_H exhibits a broad minimum and the maximum local significance corresponds to 3.3 standard deviations at $m_H = 135$ GeV/c^2.

The Look-Elsewhere Effect (LEE) [46, 47] accounts for the possibility of a background fluctuation affecting the local p-value anywhere in the tested m_H range. In the mass range from 115 GeV/c^2 (the prior bound from the LEP2 direct search [16]) to 150 GeV/c^2, the reconstructed mass resolution is typically 15%, and the resulting LEE factor is approximately 2. Correcting for the LEE yields a global significance of 3.1 standard deviations. Taking into account the exclusion limits for the SM Higgs boson mentioned earlier, there is no LEE and we derive a significance of 2.8 standard deviations for $m_H = 125$ GeV/c^2.

We interpret this result as evidence for the presence of a particle that is produced in association with a W or Z boson and decays to a bottom-antibottom quark pair. The excess seen in the data is most significant in the mass range between 120 and 135 GeV/c^2, and is consistent with production of the SM Higgs boson within this mass range. Assuming a Higgs boson exists in this mass range, these results provide a direct probe of its coupling to b quarks.

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