



Combined Search for the Standard Model Higgs Boson Decaying to $b\bar{b}$ Using the D0 Run II Data Set

V. M. Abazov,³² B. Abbott,⁶⁹ B. S. Acharya,²⁶ M. Adams,⁴⁶ T. Adams,⁴⁴ G. D. Alexeev,³² G. Alkhazov,³⁶ A. Alton,^{58,*} G. Alverson,⁵⁷ A. Askew,⁴⁴ S. Atkins,⁵⁵ K. Augsten,⁷ C. Avila,⁵ F. Badaud,¹⁰ L. Bagby,⁴⁵ B. Baldin,⁴⁵ D. V. Bandurin,⁴⁴ S. Banerjee,²⁶ E. Barberis,⁵⁷ P. Baringer,⁵³ J. F. Bartlett,⁴⁵ U. Bassler,¹⁵ V. Bazterra,⁴⁶ A. Bean,⁵³ M. Begalli,² L. Bellantoni,⁴⁵ S. B. Beri,²⁴ G. Bernardi,¹⁴ R. Bernhard,¹⁹ I. Bertram,³⁹ M. Besançon,¹⁵ R. Beuselinck,⁴⁰ P. C. Bhat,⁴⁵ S. Bhatia,⁶⁰ V. Bhatnagar,²⁴ G. Blazey,⁴⁷ S. Blessing,⁴⁴ K. Bloom,⁶¹ A. Boehnlein,⁴⁵ D. Boline,⁶⁶ E. E. Boos,³⁴ G. Borissov,³⁹ T. Bose,⁵⁶ A. Brandt,⁷² O. Brandt,²⁰ R. Brock,⁵⁹ A. Bross,⁴⁵ D. Brown,¹⁴ J. Brown,¹⁴ X. B. Bu,⁴⁵ M. Buehler,⁴⁵ V. Buescher,²¹ V. Bunichev,³⁴ S. Burdin,^{39,†} C. P. Buszello,³⁸ E. Camacho-Pérez,²⁹ B. C. K. Casey,⁴⁵ H. Castilla-Valdez,²⁹ S. Caughron,⁵⁹ S. Chakrabarti,⁶⁶ D. Chakraborty,⁴⁷ K. M. Chan,⁵¹ A. Chandra,⁷⁴ E. Chapon,¹⁵ G. Chen,⁵³ S. Chevalier-Théry,¹⁵ D. K. Cho,⁷¹ S. W. Cho,²⁸ S. Choi,²⁸ B. Choudhary,²⁵ S. Cihangir,⁴⁵ D. Claes,⁶¹ J. Clutter,⁵³ M. Cooke,⁴⁵ W. E. Cooper,⁴⁵ M. Corcoran,⁷⁴ F. Couderc,¹⁵ M.-C. Cousinou,¹² A. Croc,¹⁵ D. Cutts,⁷¹ A. Das,⁴² G. Davies,⁴⁰ S. J. de Jong,^{30,31} E. De La Cruz-Burelo,²⁹ F. Déliot,¹⁵ R. Demina,⁶⁵ D. Denisov,⁴⁵ S. P. Denisov,³⁵ S. Desai,⁴⁵ C. Deterre,¹⁵ K. DeVaughan,⁶¹ H. T. Diehl,⁴⁵ M. Diesburg,⁴⁵ P. F. Ding,⁴¹ A. Dominguez,⁶¹ A. Dubey,²⁵ L. V. Dudko,³⁴ D. Duggan,⁶² A. Duperrin,¹² S. Dutt,²⁴ A. Dyshkant,⁴⁷ M. Eads,⁶¹ D. Edmunds,⁵⁹ J. Ellison,⁴³ V. D. Elvira,⁴⁵ Y. Enari,¹⁴ H. Evans,⁴⁹ A. Evdokimov,⁶⁷ V. N. Evdokimov,³⁵ G. Facini,⁵⁷ L. Feng,⁴⁷ T. Ferbel,⁶⁵ F. Fiedler,²¹ F. Filthaut,^{30,31} W. Fisher,⁵⁹ H. E. Fisk,⁴⁵ M. Fortner,⁴⁷ H. Fox,³⁹ S. Fuess,⁴⁵ A. Garcia-Bellido,⁶⁵ J. A. García-González,²⁹ G. A. García-Guerra,^{29,‡} V. Gavrilov,³³ P. Gay,¹⁰ W. Geng,^{12,59} D. Gerbaudo,⁶³ C. E. Gerber,⁴⁶ Y. Gershtein,⁶² G. Ginther,^{45,65} G. Golovanov,³² A. Goussiou,⁷⁶ P. D. Grannis,⁶⁶ S. Greder,¹⁶ H. Greenlee,⁴⁵ G. Grenier,¹⁷ Ph. Gris,¹⁰ J.-F. Grivaz,¹³ A. Grohsjean,^{15,§} S. Grünendahl,⁴⁵ M. W. Grünewald,²⁷ T. Guillemin,¹³ G. Gutierrez,⁴⁵ P. Gutierrez,⁶⁹ S. Hagopian,⁴⁴ J. Haley,⁵⁷ L. Han,⁴ K. Harder,⁴¹ A. Harel,⁶⁵ J. M. Hauptman,⁵² J. Hays,⁴⁰ T. Head,⁴¹ T. Hebbeker,¹⁸ D. Hedin,⁴⁷ H. Hegab,⁷⁰ A. P. Heinson,⁴³ U. Heintz,⁷¹ C. Hensel,²⁰ I. Heredia De La Cruz,²⁹ K. Herner,⁵⁸ G. Hesketh,^{41,||} M. D. Hildreth,⁵¹ R. Hirosky,⁷⁵ T. Hoang,⁴⁴ J. D. Hobbs,⁶⁶ B. Hoeneisen,⁹ J. Hogan,⁷⁴ M. Hohlfeld,²¹ I. Howley,⁷² Z. Hubacek,^{7,15} V. Hynek,⁷ I. Iashvili,⁶⁴ Y. Ilchenko,⁷³ R. Illingworth,⁴⁵ A. S. Ito,⁴⁵ S. Jabeen,⁷¹ M. Jaffré,¹³ A. Jayasinghe,⁶⁹ M. S. Jeong,²⁸ R. Jesik,⁴⁰ P. Jiang,⁴ K. Johns,⁴² E. Johnson,⁵⁹ M. Johnson,⁴⁵ A. Jonckheere,⁴⁵ P. Jonsson,⁴⁰ J. Joshi,⁴³ A. W. Jung,⁴⁵ A. Juste,³⁷ K. Kaadze,⁵⁴ E. Kajfasz,¹² D. Karmanov,³⁴ P. A. Kasper,⁴⁵ I. Katsanos,⁶¹ R. Kehoe,⁷³ S. Kermiche,¹² N. Khalatyan,⁴⁵ A. Khanov,⁷⁰ A. Kharchilava,⁶⁴ Y. N. Kharzheev,³² I. Kiselevich,³³ J. M. Kohli,²⁴ A. V. Kozelov,³⁵ J. Kraus,⁶⁰ S. Kulikov,³⁵ A. Kumar,⁶⁴ A. Kupco,⁸ T. Kurča,¹⁷ V. A. Kuzmin,³⁴ S. Lammers,⁴⁹ G. Landsberg,⁷¹ P. Lebrun,¹⁷ H. S. Lee,²⁸ S. W. Lee,⁵² W. M. Lee,⁴⁵ X. Lei,⁴² J. Lellouch,¹⁴ D. Li,¹⁴ H. Li,¹¹ L. Li,⁴³ Q. Z. Li,⁴⁵ J. K. Lim,²⁸ D. Lincoln,⁴⁵ J. Linnemann,⁵⁹ V. V. Lipaev,³⁵ R. Lipton,⁴⁵ H. Liu,⁷³ Y. Liu,⁴ A. Lobodenko,³⁶ M. Lokajicek,⁸ R. Lopes de Sa,⁶⁶ H. J. Lubatti,⁷⁶ R. Luna-Garcia,^{29,**} A. L. Lyon,⁴⁵ A. K. A. Maciel,¹ R. Madar,¹⁵ R. Magaña-Villalba,²⁹ S. Malik,⁶¹ V. L. Malyshev,³² Y. Maravin,⁵⁴ J. Martínez-Ortega,²⁹ R. McCarthy,⁶⁶ C. L. McGivern,⁴¹ M. M. Meijer,^{30,31} A. Melnitchouk,⁶⁰ D. Menezes,⁴⁷ P. G. Mercadante,³ M. Merkin,³⁴ A. Meyer,¹⁸ J. Meyer,²⁰ F. Miconi,¹⁶ N. K. Mondal,²⁶ M. Mulhearn,⁷⁵ E. Nagy,¹² M. Naimuddin,²⁵ M. Narain,⁷¹ R. Nayyar,⁴² H. A. Neal,⁵⁸ J. P. Negret,⁵ P. Neustroev,³⁶ H. T. Nguyen,⁷⁵ T. Nunnemann,²² J. Orduna,⁷⁴ N. Osman,¹² J. Osta,⁵¹ M. Padilla,⁴³ A. Pal,⁷² N. Parashar,⁵⁰ V. Parihar,⁷¹ S. K. Park,²⁸ R. Partridge,^{71,||} N. Parua,⁴⁹ A. Patwa,⁶⁷ B. Penning,⁴⁵ M. Perfilov,³⁴ Y. Peters,⁴¹ K. Petridis,⁴¹ G. Petrillo,⁶⁵ P. Pétrouff,¹³ M.-A. Pleier,⁶⁷ P. L. M. Podesta-Lerma,^{29,††} V. M. Podstavkov,⁴⁵ A. V. Popov,³⁵ M. Prewitt,⁷⁴ D. Price,⁴⁹ N. Prokopenko,³⁵ J. Qian,⁵⁸ A. Quadt,²⁰ B. Quinn,⁶⁰ M. S. Rangel,¹ K. Ranjan,²⁵ P. N. Ratoff,³⁹ I. Razumov,³⁵ P. Renkel,⁷³ I. Ripp-Baudot,¹⁶ F. Rizatdinova,⁷⁰ M. Rominsky,⁴⁵ A. Ross,³⁹ C. Royon,¹⁵ P. Rubinov,⁴⁵ R. Ruchti,⁵¹ G. Sajot,¹¹ P. Salcido,⁴⁷ A. Sánchez-Hernández,²⁹ M. P. Sanders,²² A. S. Santos,^{1,‡‡} G. Savage,⁴⁵ L. Sawyer,⁵⁵ T. Scanlon,⁴⁰ R. D. Schamberger,⁶⁶ Y. Scheglov,³⁶ H. Schellman,⁴⁸ S. Schlobohm,⁷⁶ C. Schwanenberger,⁴¹ R. Schwienhorst,⁵⁹ J. Sekaric,⁵³ H. Severini,⁶⁹ E. Shabalina,²⁰ V. Shary,¹⁵ S. Shaw,⁵⁹ A. A. Shchukin,³⁵ R. K. Shivpuri,²⁵ V. Simak,⁷ P. Skubic,⁶⁹ P. Slattery,⁶⁵ D. Smirnov,⁵¹ K. J. Smith,⁶⁴ G. R. Snow,⁶¹ J. Snow,⁶⁸ S. Snyder,⁶⁷ S. Söldner-Rembold,⁴¹ L. Sonnenschein,¹⁸ K. Soustruznik,⁶ J. Stark,¹¹ D. A. Stoyanova,³⁵ M. Strauss,⁶⁹ L. Suter,⁴¹ P. Svoisky,⁶⁹ M. Takahashi,⁴¹ M. Titov,¹⁵ V. V. Tokmenin,³² Y.-T. Tsai,⁶⁵ K. Tschann-Grimm,⁶⁶ D. Tsybychev,⁶⁶ B. Tuchming,¹⁵ C. Tully,⁶³ L. Uvarov,³⁶ S. Uvarov,³⁶ S. Uzunyan,⁴⁷ R. Van Kooten,⁴⁹ W. M. van Leeuwen,³⁰ N. Varelas,⁴⁶ E. W. Varnes,⁴² I. A. Vasilyev,³⁵ P. Verdier,¹⁷ A. Y. Verkhnev,³² L. S. Vertogradov,³² M. Verzocchi,⁴⁵ M. Vesterinen,⁴¹ D. Vilanova,¹⁵ P. Vokac,⁷ H. D. Wahl,⁴⁴ M. H. L. S. Wang,⁴⁵ R.-J. Wang,⁵⁷ J. Warchol,⁵¹ G. Watts,⁷⁶ M. Wayne,⁵¹ J. Weichert,²¹ L. Welty-Rieger,⁴⁸ A. White,⁷² D. Wicke,²³

M. R. J. Williams,³⁹ G. W. Wilson,⁵³ M. Wobisch,⁵⁵ D. R. Wood,⁵⁷ T. R. Wyatt,⁴¹ Y. Xie,⁴⁵ R. Yamada,⁴⁵ S. Yang,⁴ W.-C. Yang,⁴¹ T. Yasuda,⁴⁵ Y. A. Yatsunenکو,³² W. Ye,⁶⁶ Z. Ye,⁴⁵ H. Yin,⁴⁵ K. Yip,⁶⁷ S. W. Youn,⁴⁵ J. M. Yu,⁵⁸ J. Zennamo,⁶⁴ T. Zhao,⁷⁶ T. G. Zhao,⁴¹ B. Zhou,⁵⁸ J. Zhu,⁵⁸ M. Zielinski,⁶⁵ D. Zieminska,⁴⁹ and L. Zivkovic⁷¹

(D0 Collaboration)

¹LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

²Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

³Universidade Federal do ABC, Santo André, Brazil

⁴University of Science and Technology of China, Hefei, People's Republic of China

⁵Universidad de los Andes, Bogotá, Colombia

⁶Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic

⁷Czech Technical University in Prague, Prague, Czech Republic

⁸Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

⁹Universidad San Francisco de Quito, Quito, Ecuador

¹⁰LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France

¹¹LPSC, Université Joseph Fourier Grenoble I, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France

¹²CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

¹³LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France

¹⁴LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France

¹⁵CEA, Ifu, SPP, Saclay, France

¹⁶IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France

¹⁷IPNL, Université Lyon I, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France

¹⁸III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany

¹⁹Physikalisches Institut, Universität Freiburg, Freiburg, Germany

²⁰II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany

²¹Institut für Physik, Universität Mainz, Mainz, Germany

²²Ludwig-Maximilians-Universität München, München, Germany

²³Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany

²⁴Panjab University, Chandigarh, India

²⁵Delhi University, Delhi, India

²⁶Tata Institute of Fundamental Research, Mumbai, India

²⁷University College Dublin, Dublin, Ireland

²⁸Korea Detector Laboratory, Korea University, Seoul, Korea

²⁹CINVESTAV, Mexico City, Mexico

³⁰Nikhef, Science Park, Amsterdam, Netherlands

³¹Radboud University Nijmegen, Nijmegen, Netherlands

³²Joint Institute for Nuclear Research, Dubna, Russia

³³Institute for Theoretical and Experimental Physics, Moscow, Russia

³⁴Moscow State University, Moscow, Russia

³⁵Institute for High Energy Physics, Protvino, Russia

³⁶Petersburg Nuclear Physics Institute, St. Petersburg, Russia

³⁷Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d'Altes Energies (IFAE), Barcelona, Spain

³⁸Uppsala University, Uppsala, Sweden

³⁹Lancaster University, Lancaster LA1 4YB, United Kingdom

⁴⁰Imperial College London, London SW7 2AZ, United Kingdom

⁴¹The University of Manchester, Manchester M13 9PL, United Kingdom

⁴²University of Arizona, Tucson, Arizona 85721, USA

⁴³University of California Riverside, Riverside, California 92521, USA

⁴⁴Florida State University, Tallahassee, Florida 32306, USA

⁴⁵Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

⁴⁶University of Illinois at Chicago, Chicago, Illinois 60607, USA

⁴⁷Northern Illinois University, DeKalb, Illinois 60115, USA

⁴⁸Northwestern University, Evanston, Illinois 60208, USA

⁴⁹Indiana University, Bloomington, Indiana 47405, USA

⁵⁰Purdue University Calumet, Hammond, Indiana 46323, USA

⁵¹University of Notre Dame, Notre Dame, Indiana 46556, USA

⁵²Iowa State University, Ames, Iowa 50011, USA

⁵³University of Kansas, Lawrence, Kansas 66045, USA

- ⁵⁴Kansas State University, Manhattan, Kansas 66506, USA
⁵⁵Louisiana Tech University, Ruston, Louisiana 71272, USA
⁵⁶Boston University, Boston, Massachusetts 02215, USA
⁵⁷Northeastern University, Boston, Massachusetts 02115, USA
⁵⁸University of Michigan, Ann Arbor, Michigan 48109, USA
⁵⁹Michigan State University, East Lansing, Michigan 48824, USA
⁶⁰University of Mississippi, University, Mississippi 38677, USA
⁶¹University of Nebraska, Lincoln, Nebraska 68588, USA
⁶²Rutgers University, Piscataway, New Jersey 08855, USA
⁶³Princeton University, Princeton, New Jersey 08544, USA
⁶⁴State University of New York, Buffalo, New York 14260, USA
⁶⁵University of Rochester, Rochester, New York 14627, USA
⁶⁶State University of New York, Stony Brook, New York 11794, USA
⁶⁷Brookhaven National Laboratory, Upton, New York 11973, USA
⁶⁸Langston University, Langston, Oklahoma 73050, USA
⁶⁹University of Oklahoma, Norman, Oklahoma 73019, USA
⁷⁰Oklahoma State University, Stillwater, Oklahoma 74078, USA
⁷¹Brown University, Providence, Rhode Island 02912, USA
⁷²University of Texas, Arlington, Texas 76019, USA
⁷³Southern Methodist University, Dallas, Texas 75275, USA
⁷⁴Rice University, Houston, Texas 77005, USA
⁷⁵University of Virginia, Charlottesville, Virginia 22904, USA
⁷⁶University of Washington, Seattle, Washington 98195, USA
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We present the results of the combination of searches for the standard model Higgs boson produced in association with a W or Z boson and decaying into $b\bar{b}$ using the data sample collected with the D0 detector in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron Collider. We derive 95% C.L. upper limits on the Higgs boson cross section relative to the standard model prediction in the mass range $100 \text{ GeV} \leq M_H \leq 150 \text{ GeV}$, and we exclude Higgs bosons with masses smaller than 102 GeV at the 95% C.L. In the mass range $120 \text{ GeV} \leq M_H \leq 145 \text{ GeV}$, the data exhibit an excess above the background prediction with a global significance of 1.5 standard deviations, consistent with the expectation in the presence of a standard model Higgs boson.

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Despite its success as a predictive tool, the standard model (SM) of particle physics [1] remains incomplete without a means to explain electroweak symmetry breaking. The simplest proposed mechanism [2] involves the introduction of a complex doublet of scalar fields that generates the masses of elementary particles via their mutual interactions. After accounting for longitudinal polarizations for the electroweak bosons, this mechanism also gives rise to a single scalar boson, the SM Higgs boson, with an unpredicted mass (M_H). Direct searches for $e^+e^- \rightarrow Z^* \rightarrow ZH$ at the CERN e^+e^- Collider (LEP) yielded a lower mass limit of $M_H > 114.4$ GeV [3] at 95% confidence level (C.L.). Precision electroweak measurements [4], including the latest W boson mass measurements [5,6] at the Fermilab Tevatron Collider, result in an upper 95% C.L. limit of $M_H < 152$ GeV. Direct searches at LEP [3], the Tevatron [7], and the CERN Large Hadron Collider (LHC) [8,9] exclude at the 95% C.L. most of the allowed mass range, except for $116.6 \text{ GeV} < M_H < 119.4 \text{ GeV}$ and $122.1 \text{ GeV} < M_H < 127.0 \text{ GeV}$. In addition, the ATLAS and CMS Collaborations have published [8,9] excesses above background expectations at a mass of

≈ 125 GeV and have recently published results [10] confirming these excesses at the level of 5 standard deviations (s.d.), driven by searches for $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$, where ℓ and ℓ' denote an electron or muon. These searches primarily exploit the gluon-gluon fusion production mechanism for the Higgs boson, $gg \rightarrow H$, mediated by a top-quark loop, while $H \rightarrow \gamma\gamma$ searches are also sensitive to vector ($V = W, Z$) boson fusion, $q\bar{q}' \rightarrow Hq\bar{q}'$. In the allowed mass range, the Tevatron experiments are particularly sensitive to the SM Higgs boson produced in association with a vector boson, VH , and the Higgs boson decaying into $b\bar{b}$, the primary decay mode for a Higgs boson with $M_H < 135$ GeV. Searches at both hadron colliders have a high degree of complementarity, with the main search channels at the LHC being particularly sensitive to the Higgs boson mass and couplings to vector bosons, while searches at the Tevatron provide information on the Higgs boson coupling to b quarks.

This Letter describes the combination of searches for $VH, H \rightarrow b\bar{b}$ production at the D0 experiment using the sample of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV collected during run II of the Fermilab Tevatron Collider. These

searches are focused on leptonic W and Z boson decays that allow us to efficiently suppress the large multijet background present at a hadron collider and are restricted to the mass range $100 \text{ GeV} \leq M_H \leq 150 \text{ GeV}$. Therefore, the signal processes being targeted are $WH \rightarrow \ell \nu b \bar{b}$ [11], $ZH \rightarrow \nu \bar{\nu} b \bar{b}$ [12], and $ZH \rightarrow \ell^+ \ell^- b \bar{b}$ [13]. A similar combination of searches in the $H \rightarrow b \bar{b}$ decay mode has recently been reported by the CDF Collaboration [14] and previously by the ATLAS [15], CMS [16], and LEP [3] Collaborations.

The D0 detector is described elsewhere [17]. Details on the reconstruction and identification criteria for the physics objects used in these searches [electrons, muons, jets, and missing transverse energy (\cancel{E}_T)] can be found elsewhere [11–13,18]. Jets are identified as consistent with the fragmentation of a b quark (b -tagged) by a multivariate algorithm [19] combining information from the impact parameter of displaced tracks and the topological properties of secondary vertices reconstructed in the jet.

The main backgrounds affecting these searches originate from W/Z + heavy-flavor jets (jets initiated by b and c quarks) and from top-quark pair ($t\bar{t}$) production. Smaller contributions arise from W/Z + light-flavor jets, single top-quark, diboson (WW , WZ , ZZ), and multijet production. Multijet events contribute to the selected samples via the misidentification of a jet or a photon as an electron, the presence of a nonprompt lepton from a semileptonic b - or c -hadron decay ($WH \rightarrow \ell \nu b \bar{b}$ and $ZH \rightarrow \ell^+ \ell^- b \bar{b}$ analyses), or jet energy mismeasurements resulting in apparent large \cancel{E}_T ($ZH \rightarrow \nu \bar{\nu} b \bar{b}$ analysis). In all instances, the normalization and kinematic distributions of multijet events are estimated via data-driven methods. The remaining backgrounds, as well as the signal, are estimated with Monte Carlo simulation. Samples of W/Z + jets and $t\bar{t}$ events are generated by using the ALPGEN [20] tree-level matrix element generator, while samples of single top-quark and diboson events are generated by using the SINGLETOP [21] and PYTHIA [22] leading-order (LO) generators, respectively. These samples are normalized to next-to-next-to-LO (NNLO) [23], approximate NNLO [24,25], and next-to-LO [26] theoretical cross sections. Samples of WH and ZH signal events are generated by using the PYTHIA generator for a range of masses, $100 \text{ GeV} \leq M_H \leq 150 \text{ GeV}$, in steps of 5 GeV and are normalized to the most recent theoretical predictions [27–29]. All Monte Carlo samples are generated by using the CTEQ6L1 parton distribution function set [30] and processed through PYTHIA to model parton showering and fragmentation. Signal and background samples are processed by a GEANT3-based [31] simulation of the D0 detector and reconstructed by using the same algorithms applied to the collider data. Simulated events are corrected so that the object identification efficiencies, energy scales, and energy resolutions match those determined in data control samples. More details on the simulation and

normalization of the signal and background samples can be found elsewhere [11–13].

In the case of the $ZH \rightarrow \nu \bar{\nu} b \bar{b}$ analysis, the data were collected by using triggers requiring jets plus \cancel{E}_T and correspond to an integrated luminosity of 9.5 fb^{-1} [32]. The $ZH \rightarrow \ell^+ \ell^- b \bar{b}$ and $WH \rightarrow \ell \nu b \bar{b}$ analyses use a logical OR of triggers dominated by single lepton, dilepton, lepton-plus-jets, and jet-plus- \cancel{E}_T triggers, resulting in an integrated luminosity of 9.7 fb^{-1} . The analyses select non-overlapping subsets of data via different requirements on lepton multiplicity: (i) exactly two opposite-charge leptons ($ZH \rightarrow \ell^+ \ell^- b \bar{b}$), (ii) exactly one charged lepton and large \cancel{E}_T ($WH \rightarrow \ell \nu b \bar{b}$), and (iii) exactly zero charged leptons and large \cancel{E}_T ($ZH \rightarrow \nu \bar{\nu} b \bar{b}$). A significant fraction of signal events selected by the $ZH \rightarrow \nu \bar{\nu} b \bar{b}$ analysis originate from WH production, where the charged lepton is not reconstructed. In addition, events are required to have two or three reconstructed jets, with the exception of the $ZH \rightarrow \nu \bar{\nu} b \bar{b}$ analysis, which is restricted to events with exactly two jets. The signal-to-background ratio is significantly enhanced by requiring one or two b -tagged jets in an event. The sensitivity of the searches is maximized by categorizing events into different analysis subchannels depending on the flavor and quality of the charged leptons, jet multiplicity, b -tagged jet multiplicity, and b -tagged jet quality. The primary discriminating variable between the VH signal and the backgrounds is the dijet invariant mass, for which the signal shows a distinct resonant structure; however, by combining this variable with several other kinematic variables via a multivariate approach, the sensitivity of the searches is improved by approximately 25%. Therefore, the final observable for each of the subchannels in the different searches is a one-dimensional multivariate discriminant optimized for each hypothesized M_H value.

We interpret the result of the searches via the CL_s method [33,34], which employs a log-likelihood ratio $\text{LLR} = -2 \ln(L_{s+b}/L_b)$ as a test statistic, where L_{s+b} (L_b) is a Poisson likelihood to observe the data under the signal-plus-background (background-only) hypothesis. Separate channels are combined by summing LLR values over all bins, thus maintaining the individual channel sensitivities. The per-bin signal and background predictions are parameterized in terms of nuisance parameters that describe the effect of systematic uncertainties. The impact of systematic uncertainties on the search sensitivity is reduced by maximizing both likelihood functions L_{s+b} and L_b , with respect to these nuisance parameters, subject to Gaussian constraints of their prior values. CL_s is defined as the ratio of the confidence levels for the signal-plus-background (CL_{s+b}) and background-only (CL_b) hypotheses, which are each evaluated by integrating the corresponding LLR distributions populated by simulating outcomes via Poisson statistics. Systematic uncertainties are incorporated via Gaussian fluctuations on the expected number of signal and background events per bin, taking

into account correlations across processes and channels [35]. Signal cross sections resulting in $CL_s < 0.05$ are excluded at the 95% C.L.

The systematic uncertainties differ between analyses, but we summarize here the largest contributions. We account for the impact of these uncertainties both on the integrated signal and background yields and on the shapes of the final discriminants where relevant. The $ZH \rightarrow \nu\bar{\nu}b\bar{b}$ and $WH \rightarrow \ell\nu b\bar{b}$ analyses carry a correlated uncertainty on the integrated luminosity of 6.1% [32]. The $ZH \rightarrow \ell^+\ell^-b\bar{b}$ analysis normalizes the predictions using the peak from $Z \rightarrow \ell^+\ell^-$ decays from data and the corresponding NNLO cross section [23]. The b -tagging efficiency has an uncertainty of $\approx 1\%$ –15%, depending on the sample and b -tagging criteria. The uncertainty due to acceptance and energy measurement of jets is typically around 7%. Uncertainties due to acceptance and energy measurement of leptons range from 1% to 9%, depending on the final state. A significant source of uncertainty comes from the $V + \text{jets}$ background cross sections, which have uncertainties of 4%–10% for light flavor jets and $\approx 22\%$ for heavy flavor jets. These account for both the uncertainty on the theoretical cross section calculations and the uncertainties on the higher-order correction factors. The uncertainty on the expected multijet background is dominated by the statistics of the data sample from which it is estimated and is considered separately from the other cross section uncertainties. All analyses take into account the uncertainties on the theoretical production cross sections for the different signal processes due to parton distribution function and scale choice. In addition, analyses incorporate differential uncertainties on the dominant backgrounds to allow for potential variations of the final discriminants due to generator and background modeling uncertainties. The total impact of systematic uncertainties on the combined sensitivity is $\approx 20\%$.

To confirm the ability of these analyses to measure a signal and to validate the background modeling, we perform a measurement of the VZ production cross section in the same final states. The only difference from the Higgs boson search is to use SM WZ and ZZ production as the signal instead of WH and ZH , while the rest of the SM processes, including WW production, are treated as backgrounds. Multivariate discriminants using the same input variables as in the Higgs boson searches are trained to separate the VZ signal from the backgrounds, and the resulting distributions are fit to determine the VZ cross section. The combination of all three analyses yields $\sigma(VZ) = 3.3 \pm 1.4$ pb, consistent with the SM prediction of 4.4 ± 0.3 pb [26]. The observed (expected) significance of the measured excess is 2.5 (3.4) s.d.

The statistical analysis makes use of simultaneous fits to the individual final discriminants, but it is useful for presentation purposes to collect all of the inputs into a single distribution. This is done by reordering the bins from the

input distributions according to their signal-to-background ratios (s/b), so that bins with similar $\log_{10}(s/b)$ are combined. Figure 1 shows this distribution for the VZ cross section measurement and for the Higgs boson search with $M_H = 125$ GeV after subtracting the expected background from the data. The subtracted background corresponds to the maximum-likelihood fit of the nuisance parameters to the data, and the posterior uncertainty from that fit is also shown in the plot.

We derive limits on SM Higgs boson production $\sigma(VH) \times \text{BR}(H \rightarrow b\bar{b})$, with BR the branching fraction, for Higgs boson masses in the range $100 \text{ GeV} \leq M_H \leq 150 \text{ GeV}$ in steps of 5 GeV. We assume the relative contributions of the different production and decay modes as given by the SM prediction. We present our results in terms of the ratio of 95% C.L. upper cross section limits to the SM predicted cross section. The SM prediction for Higgs boson

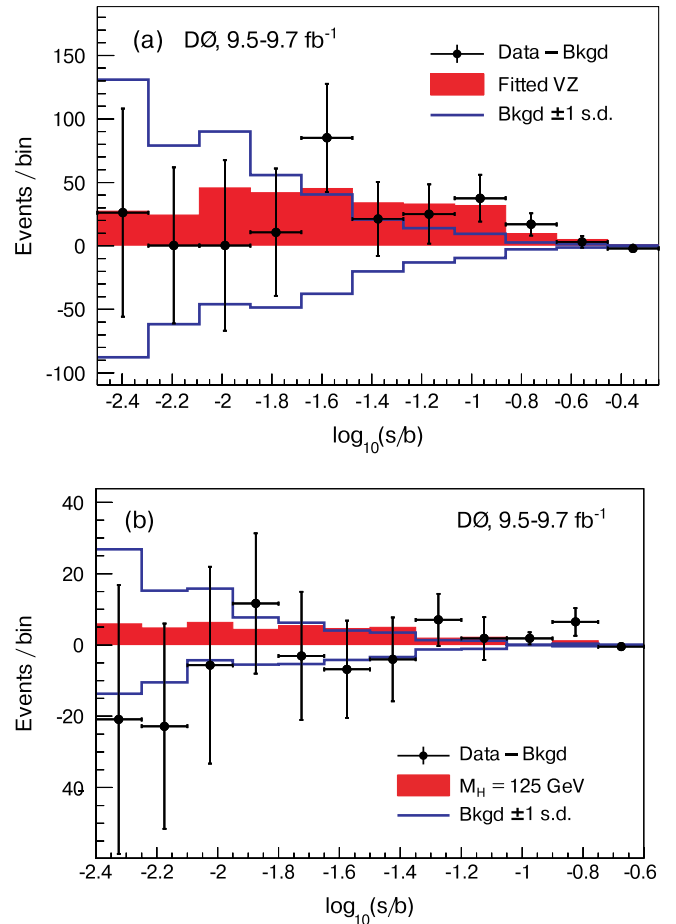


FIG. 1 (color online). Background-subtracted data distributions of $\log_{10}(s/b)$ in (a) the VZ analysis after a fit of the VZ and background contributions to the data and (b) the $VH, H \rightarrow b\bar{b}$ search for $M_H = 125$ GeV after a fit of the backgrounds to the data. The background-subtracted data are shown as points, and the signal is shown as the red histogram in each plot. The blue lines indicate the posterior uncertainty on the background prediction.

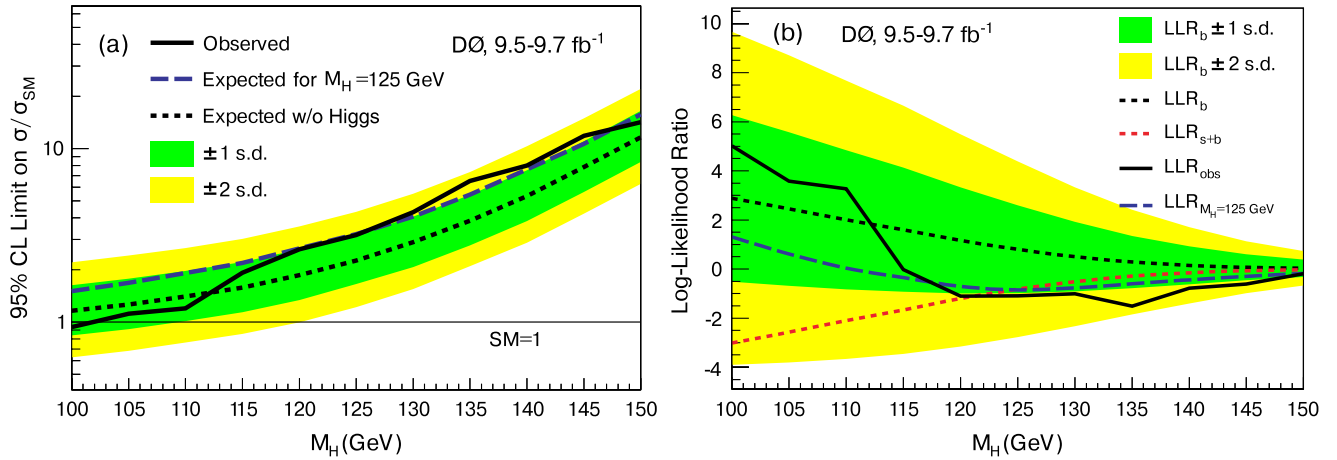


FIG. 2 (color online). (a) The 95% C.L. cross section upper limit ratios versus M_H , and (b) LLR distribution versus M_H , for the combined $VH, H \rightarrow b\bar{b}$ analyses. The solid lines represent the observed values in the data. The short-dashed black (red) lines represent the median expected values under the background-only (signal-plus-background) hypothesis at each mass. The long-dashed blue lines show the expected outcome from injecting a SM Higgs boson signal with $M_H = 125$ GeV. The green and yellow shaded bands correspond to the regions enclosing 1 and 2 s.d. variations about the median expected values under the background-only hypothesis, respectively.

production would therefore be considered excluded at 95% C.L. when this limit ratio falls below unity. Figure 2(a) shows the combined expected and observed 95% C.L. cross section limits as a ratio to the SM cross section as a function of M_H . These results are also summarized in Table I. The LLR distributions for the combination are shown in Fig. 2(b). Although consistent with the background-only hypothesis for $M_H < 115$ GeV, the observed LLR exhibits a signal-like excess at the level of 1–1.7 s.d. for the mass range $120 \text{ GeV} \leq M_H \leq 145 \text{ GeV}$.

To understand the compatibility of this excess with the hypothesis of a SM Higgs boson, we obtain the best-fit cross section for the Higgs boson signal relative to the SM prediction (R^{fit}) as a function of M_H . This value is obtained by performing a maximum-likelihood fit over all search channels simultaneously, allowing the fit to vary all nuisance parameters within their priors and with the Higgs boson cross section as a free parameter. Figure 3 shows the measured $\sigma(VH) \times \text{BR}(H \rightarrow b\bar{b})$ as a function of M_H , including its ± 1 s.d. uncertainty band, and compared with the SM prediction. At a mass of 125 GeV, the best-fit cross section is $\sigma(VH) \times \text{BR}(H \rightarrow b\bar{b}) = 140_{-130}^{+140}$ pb, which is $1.2_{-1.1}^{+1.2}$ times the SM prediction.

The significance of the data excess above the background prediction is estimated by computing the p value under the background-only hypothesis using R^{fit} as the test statistic for each value of M_H . This p value represents the

probability to have a value of R^{fit} as large or larger than that observed in the data due to a background fluctuation. The smallest p value is obtained at a mass of 135 GeV and corresponds to a significance of 1.7 s.d. above the background-only prediction. This significance does not take into account the look-elsewhere effect [36], which accounts for the possibility of a background fluctuation in the local p value anywhere in the tested mass range. By taking into account existing limits on M_H in the $b\bar{b}$ decay mode [3], the search region becomes $115 \text{ GeV} \leq M_H \leq 150 \text{ GeV}$. Given the expected mass resolution of these searches of $\approx 16\%$, this translates into a look-elsewhere-effect factor of ≈ 1.6 for a global significance of 1.5 s.d. Also taking into account the existing SM Higgs boson exclusions from the LHC [8,9] experiments, there is no look-elsewhere effect, and we find an excess at $M_H = 125$ GeV with a significance of 1.1 s.d.

In summary, we have presented a combination of searches for the SM Higgs boson produced in association with a vector boson and decaying into $b\bar{b}$, using the data sample collected with the D0 detector in run II of the Fermilab Tevatron Collider. We achieve a sensitivity that is competitive with other searches in this final state [14–16], deriving 95% C.L. upper limits on the Higgs boson cross section relative to the SM prediction in the mass range $100 \text{ GeV} \leq M_H \leq 150 \text{ GeV}$ and excluding Higgs bosons with masses smaller than 102 GeV at the

TABLE I. Expected (median) and observed 95% C.L. cross section upper limit ratios for the combined $VH, H \rightarrow b\bar{b}$ analyses over the $100 \text{ GeV} \leq M_H \leq 150 \text{ GeV}$ mass range.

M_H (GeV)	100	105	110	115	120	125	130	135	140	145	150
Expected	1.2	1.3	1.4	1.6	1.9	2.3	2.9	3.8	5.3	7.8	12
Observed	0.94	1.1	1.2	1.9	2.6	3.2	4.3	6.5	8.0	12	14

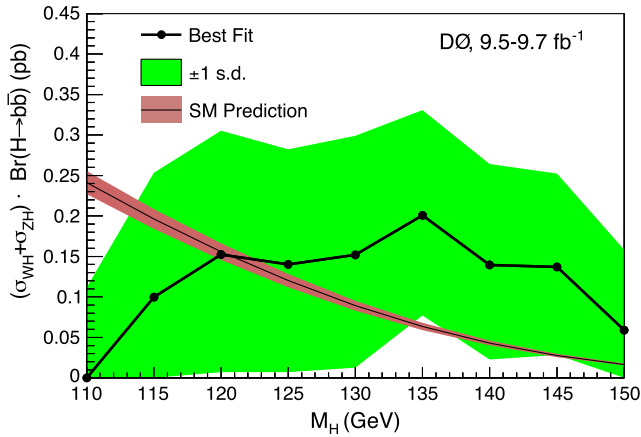


FIG. 3 (color online). The best-fit value for $\sigma(VH) \times \text{BR}(H \rightarrow b\bar{b})$ as a function of M_H . The green shaded band corresponds to the 1 s.d. uncertainty around the best-fit cross section. Also shown is the SM prediction including the theoretical uncertainties.

95% C.L. In the mass range $120 \text{ GeV} \leq M_H \leq 145 \text{ GeV}$, the data exhibit an excess above the background prediction with a global significance of 1.5 s.d. and a magnitude consistent with that expected for the SM Higgs boson.

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*Visitor from Augustana College, Sioux Falls, SD, USA.

†Visitor from The University of Liverpool, Liverpool, United Kingdom.

‡Visitor from UPIITA-IPN, Mexico City, Mexico.

§Visitor from DESY, Hamburg, Germany.

||Visitor from SLAC, Menlo Park, CA, USA.

¶Visitor from University College London, London, United Kingdom.

**Visitor from Centro de Investigacion en Computacion—IPN, Mexico City, Mexico.

††Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacán, Mexico.

‡‡Visitor from Universidade Estadual Paulista, São Paulo, Brazil.

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