Search for the Higgs boson in events with missing transverse energy and b quark jets produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen,[23] J. Adelman,[13] T. Akimoto,[54] M.G. Albrow,[17] B. Álvarez González,[11] S. Amerio,[42] D. Amidei,[34] A. Anastassov,[51] A. Annovi,[19] J. Antos,[14] M. Aoki,[24] G. Apollinari,[17] A. Apresyan,[47] T. Arisawa,[56] A. Artikov,[15] W. Ashmanskas,[17] A. Attal,[3] A. Aurisano,[52] F. Azfar,[41] P. Azzi-Bacchetta,[42] P. Azzurri,[45] N. Bacchetta,[42] W. Badgett,[17] A. Barbaro-Galtieri,[28] V.E. Barnes,[47] B.A. Barnett,[25] S. Baroiant,[7] V. Bartsch,[30] G. Bauer,[32] P.-H. Beauchemin,[33] F. Bedeschi,[45] P. Bednar,[14] S. Behari,[25] G. Bellettini,[45] J. Bellinger,[58] A. Belloni,[22] D. Benjamin,[16] A. Beretvas,[17] J. Beringer,[28] T. Berry,[29] A. Bhatti,[49] M. Binkley,[17] D. Bisello,[42] I. Bizjak,[30] R.E. Blair,[2] C. Blocker,[6] B. Blumenfeld,[25] A. Bocci,[16] A. Bodek,[48] V. Boisvert,[48] G. Bolla,[47] A. Bolshov,[32] D. Bortoletto,[47] J. Boudreau,[46] A. Boveia,[10] B. Brau,[10] A. Bridgeman,[24] L. Brigliadori,[5] C. Bromberg,[35] E. Brubaker,[13] J. Budagov,[15] H.S. Budd,[48] S. Budd,[24] K. Burkett,[17] G. Busetto,[42] P. Bussey,[21] A. Buzatu,[33] K. L. Byrum,[2] S. Cabrera[r],[16] M. Campanelli,[35] M. Campbell,[34] F. Canelli,[17] A. Canepa,[44] D. Carlsmith,[58] R. Carosi,[45] S. Carrillo[l],[18] S. Carron,[33] B. Casal,[11] M. Casarsa,[17] A. Castro,[5] P. Catastini,[45] D. Cauz,[53] M. Cavalli-Sforza,[3] A. Cerri,[28] L. Cerrito[p],[30] S.H. Chang,[27] Y.C. Chen,[1] M. Chertok,[7] G. Chiarelli,[45] G. Chlachidze,[17] F. Chlebana,[17] K. Cho,[27] D. Chokheli,[15] J.P. Chou,[22] G. Choudalakis,[32] S.H. Chuang,[51] K. Chung,[12] W.H. Chung,[58] Y.S. Chung,[48] C.I. Ciobanu,[24] M.A. Ciocci,[45] A. Clark,[20] D. Clark,[6] G. Compostella,[42] M.E. Convery,[17] J. Conway,[7] B. Cooper,[30] K. Copic,[34] M. Cordelli,[19] G. Cortiana,[42] F. Crescioli,[45] C. Cuenca Almenar[r],[7] J. Cuevas[o],[11] R. Culbertson,[17] J.C. Cully,[34] D. Dagenhart,[17] M. Datta,[17] T. Davies,[21] P. de Barbaro,[48] S. De Cecco,[50] A. Deisher,[28] G. De Lentdecker[d],[48] G. De Lorenzo,[3] M. Dell'Orso,[45] L. Demortier,[49] J. Deng,[16] M. Deninno,[5] D. De Pedis,[50] P.F. Derwent,[17] G.P. Di Giovanni,[43] C. Dionisi,[50] B. Di Ruzza,[53] J.R. Dittmann,[4] M. D'Onofrio,[3] S. Donati,[45] P. Dong,[8] J. Donini,[42] T. Dorigo,[42] S. Dube,[51] J. Efron,[38] R. Erbacher,[7] D. Errede,[24] S. Errede,[24] R. Eusebi,[17] H.C. Fang,[28] S. Farrington,[29] W.T. Fedorko,[13] R.G. Feild,[59] M. Feindt,[26] J.P. Fernandez,[31] C. Ferrazza,[45] R. Field,[18] G. Flanagan,[47] R. Forrest,[7] S. Forrester,[7] M. Franklin,[22] J.C. Freeman,[28] I. Furic,[18] M. Gallinaro,[49] J. Galyardt,[12] F. Garberson,[10] J.E. Garcia,[45] A.F. Garfinkel,[47] K. Genser,[17] H. Gerberich,[24] D. Gerdes,[34] S. Giagu,[50] V. Giakoumopolou[a],[45] P. Giannetti,[45] K. Gibson,[46] J.L. Gimmell,[48] C.M. Ginsburg,[17] N. Giokaris[a],[15] M. Giordani,[53] P. Giromini,[19] M. Giunta,[45] V. Glagolev,[15] D. Glenzinski,[17] M. Gold,[36] N. Goldschmidt,[18] A. Golossanov,[17] G. Gomez,[11] G. Gomez-Ceballos,[32] M. Goncharov,[52] O. González,[31] I. Gorelov,[36] A.T. Goshaw,[16] K. Goulianos,[49] A. Gresele,[42] S. Grinstein,[22] C. Grosso-Pilcher,[13] R.C. Group,[17] U. Grundler,[24] J. Guimaraes da Costa,[22] Z. Gunay-Unalan,[35] C. Haber,[28] K. Hahn,[32] S.R. Hahn,[17] E. Halkiadakis,[51] A. Hamilton,[20] B.-Y. Han,[48] J.Y. Han,[48] R. Handler,[58] F. Happacher,[19] K. Hara,[54] D. Hare,[51] M. Hare,[55] S. Harper,[41] R.F. Harr,[57] R.M. Harris,[17] M. Hartz,[46] K. Hatakeyama,[49] J. Hauser,[8] C. Hays,[41] M. Heck,[26] A. Heijboer,[44] B. Heinemann,[28] J. Heinrich,[44] C. Henderson,[32] M. Herndon,[58] J. Heuser,[26] S. Hewamanage,[4] D. Hidas,[16] C.S. Hill[c],[10] D. Hirschbuehl,[26] A. Hocker,[17] S. Hou,[1] M. Houlden,[29] S.-C. Hsu,[9] B.T. Huffman,[41] R.E. Hughes,[38] U. Husemann,[59] J. Huston,[35] J. Incandela,[10] G. Introzzi,[45] M. Iori,[50] A. Ivanov,[7] B. Iyutin,[32] E. James,[17] B. Jayatilaka,[16] D. Jeans,[50] E.J. Jeon,[27] S. Jindariani,[18] W. Johnson,[7] M. Jones,[47] K.K. Joo,[27] S.Y. Jun,[12] J.E. Jung,[27] T.R. Junk,[24] T. Kamon,[52] D. Kar,[18] P.E. Karchin,[57] Y. Kato,[40] R. Kephart,[17] U. Kerzel,[26] V. Khotilovich,[52] B. Kilminster,[38] D.H. Kim,[27] H.S. Kim,[27] J.E. Kim,[27] M.J. Kim,[17] S.B. Kim,[27] S.H. Kim,[54] Y.K. Kim,[13] N. Kimura,[54] L. Kirsch,[6] S. Klimenko,[18] M. Klute,[32] B. Knuteson,[32] B.R. Ko,[16] S.A. Koay,[10] K. Kondo,[56] D.J. Kong,[27] J. Konigsberg,[18] A. Korytov,[18] A.V. Kotwal,[16] J. Kraus,[24] M. Kreps,[26] J. Kroll,[44] N. Krumnack,[4] M. Kruse,[16] V. Krutelyov,[10] T. Kubo,[54] S. E. Kuhlmann,[2] T. Kuhr,[26] N.P. Kulkarni,[57] Y. Kusakabe,[56] S. Kwang,[13] A.T. Laasanen,[47] S. Lai,[33] S. Lami,[45] S. Lammel,[17] M. Lancaster,[30] R.L. Lander,[7] K. Lannon,[38] A. Lath,[51] G. Latino,[45] I. Lazzizzera,[42] T. LeCompte,[2] J. Lee,[48] J. Lee,[27] Y.J. Lee,[27] S.W. Lee[q],[52] R. Lefèvre,[20] N. Leonardo,[32] S. Leone,[45] S. Levy,[13] J.D. Lewis,[17] C. Lin,[59] C.S. Lin,[28] J. Linacre,[41] M. Lindgren,[17] E. Lipeles,[9] A. Lister,[7] D.O. Litvintsev,[17] T. Liu,[17] N.S. Lockyer,[44] A. Loginov,[59] M. Loreti,[42] L. Lovas,[14] R.-S. Lu,[1] D. Lucchesi,[42] J. Lueck,[26] C. Luci,[50] P. Lujan,[28] P. Lukens,[17] G. Lungu,[18] L. Lyons,[41] J. Lys,[28] R. Lysak,[14] E. Lytken,[47] P. Mack,[26] D. MacQueen,[33] R. Madrak,[17] K. Maeshima,[17] K. Makhoul,[32] T. Maki,[23] P. Maksimovic,[25] S. Malde,[41] S. Malik,[30] G. Manca,[29] A. Manousakis[a],[15] F. Margaroli,[47] C. Marino,[26] C.P. Marino,[24] A. Martin,[59] M. Martin,[25] V. Martin[j],[21] M. Martínez,[3] R. Martínez-Ballarín,[31] T. Maruyama,[54] P. Mastrandrea,[50] T. Masubuchi,[54] M.E. Mattson,[57] P. Mazzanti,[5] K.S. McFarland,[48] P. McIntyre,[52] R. McNulty[i],[29] A. Mehta,[29] P. Mehtala,[23] S. Menzemer[k],[11] A. Menzione,[45] P. Merkel,[47] C. Mesropian,[49] A. Messina,[35] T. Miao,[17]

N. Miladinovic,[6] J. Miles,[32] R. Miller,[35] C. Mills,[22] M. Milnik,[26] A. Mitra,[1] G. Mitselmakher,[18] H. Miyake,[54] S. Moed,[22] N. Moggi,[5] C.S. Moon,[27] R. Moore,[17] M. Morello,[45] P. Movilla Fernandez,[28] J. Mülmenstädt,[28] A. Mukherjee,[17] Th. Muller,[26] R. Mumford,[25] P. Murat,[17] M. Mussini,[5] J. Nachtman,[17] Y. Nagai,[54] A. Nagano,[54] J. Naganoma,[56] K. Nakamura,[54] I. Nakano,[39] A. Napier,[55] V. Necula,[16] C. Neu,[44] M.S. Neubauer,[24] J. Nielsen[f],[28] L. Nodulman,[2] M. Norman,[9] O. Norniella,[24] E. Nurse,[30] S.H. Oh,[16] Y.D. Oh,[27] I. Oksuzian,[18] T. Okusawa,[40] R. Oldeman,[29] R. Orava,[23] K. Osterberg,[23] S. Pagan Griso,[42] C. Pagliarone,[45] E. Palencia,[17] V. Papadimitriou,[17] A. Papaikonomou,[26] A.A. Paramonov,[13] B. Parks,[38] S. Pashapour,[33] J. Patrick,[17] G. Pauletta,[53] M. Paulini,[12] C. Paus,[32] D.E. Pellett,[7] A. Penzo,[53] T.J. Phillips,[16] G. Piacentino,[45] J. Piedra,[43] L. Pinera,[18] K. Pitts,[24] C. Plager,[8] L. Pondrom,[58] X. Portell,[3] O. Poukhov,[15] N. Pounder,[41] F. Prakoshyn,[15] A. Pronko,[17] J. Proudfoot,[2] F. Ptohos[h],[17] G. Punzi,[45] J. Pursley,[58] J. Rademacker[c],[41] A. Rahaman,[46] V. Ramakrishnan,[58] N. Ranjan,[47] I. Redondo,[31] B. Reisert,[17] V. Rekovic,[36] P. Renton,[41] M. Rescigno,[50] S. Richter,[26] F. Rimondi,[5] L. Ristori,[45] A. Robson,[21] T. Rodrigo,[11] E. Rogers,[24] S. Rolli,[55] R. Roser,[17] M. Rossi,[53] R. Rossin,[10] C. Rott,[47] P. Roy,[33] A. Ruiz,[11] J. Russ,[12] V. Rusu,[17] H. Saarikko,[23] A. Safonov,[52] W.K. Sakumoto,[48] G. Salamanna,[50] O. Saltó,[3] L. Santi,[53] S. Sarkar,[50] L. Sartori,[45] K. Sato,[17] A. Savoy-Navarro,[43] T. Scheidle,[26] P. Schlabach,[17] E.E. Schmidt,[17] M.A. Schmidt,[13] M.P. Schmidt,[59] M. Schmitt,[37] T. Schwarz,[7] L. Scodellaro,[11] A.L. Scott,[10] A. Scribano,[45] F. Scuri,[45] A. Sedov,[47] S. Seidel,[36] Y. Seiya,[40] A. Semenov,[15] L. Sexton-Kennedy,[17] A. Sfyrla,[20] S.Z. Shalhout,[57] M.D. Shapiro,[28] T. Shears,[29] P.F. Shepard,[46] D. Sherman,[22] M. Shimojima[n],[54] M. Shochet,[13] Y. Shon,[58] I. Shreyber,[20] A. Sidoti,[45] P. Sinervo,[33] A. Sisakyan,[15] A.J. Slaughter,[17] J. Slaunwhite,[38] K. Sliwa,[55] J.R. Smith,[7] F.D. Snider,[17] R. Snihur,[33] M. Soderberg,[34] A. Soha,[7] S. Somalwar,[51] V. Sorin,[35] J. Spalding,[17] F. Spinella,[45] T. Spreitzer,[33] P. Squillacioti,[45] M. Stanitzki,[59] R. St. Denis,[21] B. Stelzer,[8] O. Stelzer-Chilton,[41] D. Stentz,[37] J. Strologas,[36] D. Stuart,[10] J.S. Suh,[27] A. Sukhanov,[18] H. Sun,[55] I. Suslov,[15] T. Suzuki,[54] A. Taffard[e],[24] R. Takashima,[39] Y. Takeuchi,[54] R. Tanaka,[39] M. Tecchio,[34] P.K. Teng,[1] K. Terashi,[49] J. Thom[g],[17] A.S. Thompson,[21] G.A. Thompson,[24] E. Thomson,[44] P. Tipton,[59] V. Tiwari,[12] S. Tkaczyk,[17] D. Toback,[52] S. Tokar,[14] K. Tollefson,[35] T. Tomura,[54] D. Tonelli,[17] S. Torre,[19] D. Torretta,[17] S. Tourneur,[43] W. Trischuk,[33] Y. Tu,[44] N. Turini,[45] F. Ukegawa,[54] S. Uozumi,[54] S. Vallecorsa,[20] N. van Remortel,[23] A. Varganov,[34] E. Vataga,[36] F. Vázquez[l],[18] G. Velev,[17] C. Vellidis[a],[45] V. Veszpremi,[47] M. Vidal,[31] R. Vidal,[17] I. Vila,[11] R. Vilar,[11] T. Vine,[30] M. Vogel,[36] I. Volobouev[q],[28] G. Volpi,[45] F. Würthwein,[9] P. Wagner,[44] R.G. Wagner,[2] R.L. Wagner,[17] J. Wagner-Kuhr,[26] W. Wagner,[26] T. Wakisaka,[40] R. Wallny,[8] S.M. Wang,[1] A. Warburton,[33] D. Waters,[30] M. Weinberger,[52] W.C. Wester III,[17] B. Whitehouse,[55] D. Whiteson[e],[44] A.B. Wicklund,[2] E. Wicklund,[17] G. Williams,[33] H.H. Williams,[44] P. Wilson,[17] B.L. Winer,[38] P. Wittich[g],[17] S. Wolbers,[17] C. Wolfe,[13] T. Wright,[34] X. Wu,[20] S.M. Wynne,[29] A. Yagil,[9] K. Yamamoto,[40] J. Yamaoka,[51] T. Yamashita,[39] C. Yang,[59] U.K. Yang[m],[13] Y.C. Yang,[27] W.M. Yao,[28] G.P. Yeh,[17] J. Yoh,[17] K. Yorita,[13] T. Yoshida,[40] G.B. Yu,[48] I. Yu,[27] S.S. Yu,[17] J.C. Yun,[17] L. Zanello,[50] A. Zanetti,[53] I. Zaw,[22] X. Zhang,[24] Y. Zheng[b],[8] and S. Zucchelli[5]

(CDF Collaboration*)

[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2]*Argonne National Laboratory, Argonne, Illinois 60439*
[3]*Institut de Fisica d'Altes Energies, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*
[4]*Baylor University, Waco, Texas 76798*
[5]*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*
[6]*Brandeis University, Waltham, Massachusetts 02254*
[7]*University of California, Davis, Davis, California 95616*
[8]*University of California, Los Angeles, Los Angeles, California 90024*
[9]*University of California, San Diego, La Jolla, California 92093*
[10]*University of California, Santa Barbara, Santa Barbara, California 93106*
[11]*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[12]*Carnegie Mellon University, Pittsburgh, PA 15213*
[13]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[14]*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*
[15]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[16]*Duke University, Durham, North Carolina 27708*
[17]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[18]*University of Florida, Gainesville, Florida 32611*
[19]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[20]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[21]*Glasgow University, Glasgow G12 8QQ, United Kingdom*

[22]*Harvard University, Cambridge, Massachusetts 02138*
[23]*Division of High Energy Physics, Department of Physics,*
University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland
[24]*University of Illinois, Urbana, Illinois 61801*
[25]*The Johns Hopkins University, Baltimore, Maryland 21218*
[26]*Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
[27]*Center for High Energy Physics: Kyungpook National University,*
Daegu 702-701, Korea; Seoul National University, Seoul 151-742,
Korea; Sungkyunkwan University, Suwon 440-746,
Korea; Korea Institute of Science and Technology Information, Daejeon,
305-806, Korea; Chonnam National University, Gwangju, 500-757, Korea
[28]*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[29]*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[30]*University College London, London WC1E 6BT, United Kingdom*
[31]*Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain*
[32]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[33]*Institute of Particle Physics: McGill University, Montréal,*
Canada H3A 2T8; and University of Toronto, Toronto, Canada M5S 1A7
[34]*University of Michigan, Ann Arbor, Michigan 48109*
[35]*Michigan State University, East Lansing, Michigan 48824*
[36]*University of New Mexico, Albuquerque, New Mexico 87131*
[37]*Northwestern University, Evanston, Illinois 60208*
[38]*The Ohio State University, Columbus, Ohio 43210*
[39]*Okayama University, Okayama 700-8530, Japan*
[40]*Osaka City University, Osaka 588, Japan*
[41]*University of Oxford, Oxford OX1 3RH, United Kingdom*
[42]*University of Padova, Istituto Nazionale di Fisica Nucleare,*
Sezione di Padova-Trento, I-35131 Padova, Italy
[43]*LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France*
[44]*University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[45]*Istituto Nazionale di Fisica Nucleare Pisa, Universities of Pisa,*
Siena and Scuola Normale Superiore, I-56127 Pisa, Italy
[46]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[47]*Purdue University, West Lafayette, Indiana 47907*
[48]*University of Rochester, Rochester, New York 14627*
[49]*The Rockefeller University, New York, New York 10021*
[50]*Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1,*
University of Rome "La Sapienza," I-00185 Roma, Italy
[51]*Rutgers University, Piscataway, New Jersey 08855*
[52]*Texas A&M University, College Station, Texas 77843*
[53]*Istituto Nazionale di Fisica Nucleare, University of Trieste/ Udine, Italy*
[54]*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[55]*Tufts University, Medford, Massachusetts 02155*
[56]*Waseda University, Tokyo 169, Japan*
[57]*Wayne State University, Detroit, Michigan 48201*
[58]*University of Wisconsin, Madison, Wisconsin 53706*
[59]*Yale University, New Haven, Connecticut 06520*

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We search for the standard model Higgs boson produced in association with an electroweak vector boson in events with no identified charged leptons, large imbalance in transverse momentum, and two jets where at least one contains a secondary vertex consistent with the decay of b hadrons. We use $\sim$1 fb^{-1} integrated luminosity of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the CDF II experiment at the Tevatron. We find 268 (16) single (double) b-tagged candidate events, where 248 ± 43 (14.4 ± 2.7) are expected from standard model background processes. We place 95% confidence level upper limits on the Higgs boson production cross section for several Higgs boson masses ranging from 110 GeV/c^2 to 140 GeV/c^2. For a mass of 115 GeV/c^2 the observed (expected) limit is 20.4 (14.2) times the standard model prediction.

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*With visitors from [a]University of Athens, 15784 Athens, Greece, [b]Chinese Academy of Sciences, Beijing 100864, China, [c]University

The Higgs boson is an essential element of the standard model (SM) of particles and their interactions explaining the mass of elementary particles and playing a key role in the mechanism of electroweak symmetry breaking. Precision measurements of the W boson and top quark masses suggest that the mass of the SM Higgs boson should be less than 182 GeV/c^2 (95% C.L.) [1] and therefore kinematically within reach at the Tevatron. Previous searches for the SM Higgs boson set limits on its production cross section at $\sqrt{s} = 1.8$ TeV and $\sqrt{s} = 1.96$ TeV [2]. The CDF Collaboration is now performing searches for the low mass Higgs boson produced in association with an electroweak vector boson V (Z or W) followed by the decay $H \to b\bar{b}$ in several final states which are optimized separately and then combined. In this Letter, we describe the first search for the SM Higgs boson with a trigger based on an imbalance in energy in the plane transverse to the beam sensitive to both ZH and WH associated productions. In order to avoid overlap with the search for WH in a final state containing a high-energy electron or muon candidate, large missing transverse energy, and one or two b jets, we veto events with high energy isolated leptons. Therefore, we search for VH events where $H \to b\bar{b}$ and either $Z \to \nu\bar{\nu}$ or $W \to \not{\ell}\nu$, where $\not{\ell}$ indicates that the lepton was not identified in the detector. The signatures of these decay modes are final states with two b jets from the hadronization of the b quarks, missing transverse energy, and no isolated leptons. In this search we use an integrated luminosity of 0.97 ± 0.06 fb^{-1} collected in Run II of the Tevatron. After describing the experiment, we introduce our event selection, major backgrounds, and systematic uncertainties, and present the results.

CDF II is a multipurpose detector described in detail elsewhere [3]. Here, we briefly describe the detector components used in this analysis. We use a cylindrical coordinate system around the proton beam axis in which θ and ϕ are the polar and azimuthal angles, respectively, the pseudorapidity η is defined as $\eta = -\ln(\tan(\frac{\theta}{2}))$. The transverse momentum and energy of a particle are defined as $p_T = p \sin\theta$ and $E_T = E \sin\theta$, respectively. The tracking system consists of a cylindrical open-cell drift chamber and silicon microstrip detectors in a 1.4 T magnetic field parallel to the beam axis. The silicon detectors [4] provide tracking information for $|\eta| < 2$ and are used to detect collision and decay points. The drift chamber [5] surrounds the silicon detectors and covers the central rapidity region $|\eta| < 1$.

The energies of electrons and jets are measured in calorimeters which cover the region $|\eta| < 3.6$ and are segmented into towers pointing toward the center of the detector. Jets are reconstructed from energy depositions in the calorimeter towers using a jet clustering cone algorithm [6] with a cone size of radius $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$. Corrections are applied to account for effects that can cause mismeasurements in the jet energy such as non-linear calorimeter response, multiple beam interactions, or displacement of the event vertex from the nominal $z = 0$ position [6]. The $\not{E}_T$ is defined as the magnitude of $\vec{\not{E}}_T = -\sum_i E^i \hat{n}_i$, where $\hat{n}_i$ is a unit vector parallel to the transverse component of the vector pointing at the i^{th} calorimeter tower, and E^i is the energy therein. Both magnitude and direction of the $\vec{\not{E}}_T$ are recomputed after the jet energies are corrected.

We use loose electron and muon identification criteria in order to veto events with at least one high p_T isolated lepton. Candidate muons are identified with $p_T > 10$ GeV/c isolated tracks which leave energy in the calorimeters that is consistent with a minimum ionizing particle. A track is called isolated if the total calorimeter energy in a 0.4 radius cone around the track is less than 10% of the track p_T. Candidate electrons are clustered energy deposits in the electromagnetic calorimeter with $E_T > 10$ GeV which have electromagnetic to hadronic energy ratio and shower shape compatible with electrons and are associated with an isolated track.

The events used in this search are selected by a three-level trigger system. The Level 1 trigger requires $\not{E}_T \geq 25$ GeV , where the $\not{E}_T$ is determined using calorimeter trigger towers with $E_T > 1$ GeV. The Level 2 trigger selects events with two jet clusters of $E_T > 10$ GeV, where one of the clusters is required to be in the region $|\eta| < 1.1$. The Level 3 requirement is $\not{E}_T > 35$ GeV. After selections to remove accelerator-produced and detector-related background, as well as cosmic ray events, 4.3 million events remain. This is about 60% of the initial sample. Further selection criteria are defined using corrected observables in order to search in a region where the trigger is fully efficient, but the sensitivity of the search is not compromised. We require the events to have $\not{E}_T > 50$ GeV and to contain exactly two jets with $E_T > 20$ GeV and $|\eta| < 2.4$ where the azimuthal separation of the two jets is $\Delta\phi(\vec{E}_{1,T}, \vec{E}_{2,T}) > 1.0$ rad. Moreover one of the two jets must be central with $|\eta| < 0.9$,

of Bristol, Bristol BS8 1TL, United Kingdom, [d]University Libre de Bruxelles, B-1050 Brussels, Belgium, [e]University of California Irvine, Irvine, CA 92697, [f]University of California Santa Cruz, Santa Cruz, CA 95064, [g]Cornell University, Ithaca, NY 14853, [h]University of Cyprus, Nicosia CY-1678, Cyprus, [i]University College Dublin, Dublin 4, Ireland, [j]University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom, [k]University of Heidelberg, D-69120 Heidelberg, Germany, [l]Universidad Iberoamericana, Mexico D.F., Mexico, [m]University of Manchester, Manchester M13 9PL, England, [n]Nagasaki Institute of Applied Science, Nagasaki, Japan, [o]University de Oviedo, E-33007 Oviedo, Spain, [p]Queen Mary, University of London, London, E1 4NS, England, [q]Texas Tech University, Lubbock, TX 79409, [r]IFIC(CSIC-Universitat de Valencia), 46071 Valencia, Spain,

and the jet of highest (second highest) energy in the event must have $E_{T,1} > 35$ GeV ($E_{T,2} > 25$ GeV). The trigger efficiency for such events is 0.97 ± 0.03 [7].

We require at least one jet to be identified as a b jet by the b-tagging algorithm SECVTX [8]. This algorithm looks for tracks within jets that form a secondary vertex significantly displaced from the primary interaction point. The tagging efficiency for b jets of 50 GeV is ~42%, the misidentification rate for 50 GeV light quark (u, d, s) and gluon jets is ~1% [8].

In order to avoid potential bias in the search, we test our understanding of the background in control regions that are defined *a priori*. The observed events are divided into three non-overlapping parts, two control and one signal regions, which have different event topology and isolated high-p_T lepton multiplicity. The backgrounds in the three regions have contributions from multi-jet, $t\bar{t}$, W plus jets, Z plus jets, and electroweak (WW, WZ, and ZZ) processes. Control region 1 (CR1) is defined such that it is dominated by the multi-jet background. The events in this region do not contain any identified leptons, and the separation between the $\vec{\not\!\!E}_T$ and the secondary jet ($\Delta\phi(\vec{E}_{2,T},\vec{\not\!\!E}_T)$) is required to be less than 0.4. Control region 2 (CR2) is selected by requiring at least one lepton and $\Delta\phi(\vec{E}_{2,T},\vec{\not\!\!E}_T) \geq 0.4$. This region is sensitive to electroweak and top quark decays. The signal region contains events with no identified high-p_T leptons, $\Delta\phi(\vec{E}_{1,T},\vec{\not\!\!E}_T) \geq 0.4$, and $\Delta\phi(\vec{E}_{2,T},\vec{\not\!\!E}_T) \geq 0.4$.

Agreement between the number of events expected and observed due to different processes is presented in Table I for single and double b-tagged events in CR1 and CR2. The signal and the physics backgrounds have been evaluated using PYTHIA [9] Monte Carlo generation (MC) followed by the simulation of the CDF II detector. QCD light jet production has a cross section about nine orders of magnitude greater than the theoretical expectation for the signal before the b-tag requirement. Although this process generally does not have intrinsic $\not\!\!E_T$, mismeasured jets can cause an imbalance in the total E_T and fake the signal if one of the jets is misidentified as a b jet (mistag). Furthermore, b quark pair production yields b jets and $\not\!\!E_T$ if one b quark undergoes a semi-leptonic decay. In both cases, the $\vec{\not\!\!E}_T$ tends to be aligned parallel or anti-parallel to the first or second most energetic jet. We use MC simulation only to evaluate QCD processes which yield events with a b or c quark (heavy quark, h.q.) pair. This background is denoted as QCD h.q. in Table I. The MC cross section for heavy quark jet production is scaled to the difference between the observed data and the predicted contribution of the other backgrounds. We determine the normalization factors, $k_{\rm QCD}$, before the data are divided into control and signal regions to be 1.30 ± 0.04 and 1.47 ± 0.07 for events with one and two b-tagged jets, respectively [7]. The background due to light quarks being misidentified as b jets is denoted as mistags in Table I and is determined using a b-jet misidentification rate that is measured from inclusive jet samples [8]. The $t\bar{t}$ cross section of 7.3 ± 0.8 pb is obtained from the combined CDF measurements [10]. A small contribution by single top quark production is included, normalized with theoretical NLO production cross sections [11, 12]. The electroweak backgrounds were generated at leading order with PYTHIA and increased by a factor of 1.4 to account for higher order effects [13, 14].

Simulated distributions of kinematic variables such as the jet E_T, the dijet invariant mass, and the $\not\!\!E_T$ have been found to be in agreement with observations in the control regions [7]. In Fig. 1 (a) and 1 (b) we show the dijet invariant mass distributions when both jets are b-tagged in control regions CR1 and CR2, respectively.

We optimize the sensitivity to Higgs boson production by maximizing the ratio of $N_{\rm Higgs}/\sqrt{N_{\rm bck}}$ where $N_{\rm Higgs}$ and $N_{\rm bck}$ are the number of predicted Higgs boson and background events in the signal region. The final selection requires $\Delta\phi(\vec{E}_{1,T},\vec{\not\!\!E}_T) > 0.8$, $\not\!\!H_T/H_T > 0.45$, $E_{T,1} > 60$ GeV, and $\not\!\!E_T > 70$ GeV. The variable H_T ($\not\!\!H_T$) is the scalar (the magnitude of the vectorial) sum of the two jet energies in the transverse plane. The number of background events after the final selection is shown in Table I. For a Higgs boson of mass 115 GeV/c^2 we expect a total of 1.2 (0.4) events with one (two) b-tagged jets [15].

The total systematic uncertainties on the background predictions are 17% and 19% in the single and double tag events, respectively [7]. One of the dominant correlated uncertainties for the background and signal predictions is due to the jet energy scale (JES) [6]. The JES uncertainty affects selection efficiencies non-uniformly over kinematic distributions leading to uncertainties in the distributions' shapes. The resulting systematic uncertainties are typically between 10% and 20% for multi-jet events depending on the kinematic selections, 15% for dibosons, 26% for W plus h.q., 17% for Z plus h.q., 1% for top quark, and 8% for signal events. The systematic uncertainty on the b-tagging efficiency is 4.3% for single and 8.6% for double b-tagged events. There is a 3% uncertainty on the trigger efficiency, 2% uncertainty on the signal and background acceptances due to uncertainties in the parton distribution functions, and 6% on luminosity. The dominant uncorrelated systematic uncertainties are due to the cross sections and the statistics of the simulated samples. We assign uncertainties of 11% to the top, 11.5% to the diboson, and 40% to the W plus h.q. and Z plus h.q. cross sections. Statistical uncertainties due to Monte Carlo sample sizes are 20%-32% on the multi-jet, 20% on the W plus h.q., and 11% on the Z plus h.q. predictions. Correlated and uncorrelated uncertainties are evaluated separately and combined in quadrature.

The signal region is analyzed after all the background

TABLE I: Comparison of the total number of expected and observed single and double b-tagged events in the control regions and in the optimized signal region.

	Control Region 1		Control Region 2		Signal Region	
Lepton	Vetoed		Identified		Vetoed	
	$\Delta\phi(\vec{E}_{2,T}, \not\!\!\vec{E}_T) < 0.4$		$\Delta\phi(\vec{E}_{2,T}, \not\!\!\vec{E}_T) \geq 0.4$		See text	
B-tag	Single	Double	Single	Double	Single	Double
QCD h.q.	14868 ± 1820	1175 ± 179	61 ± 25	3.2 ± 1.7	93 ± 23	3.74 ± 1.27
Top	4.0 ± 0.6	0.8 ± 0.2	98 ± 14	24.0 ± 3.8	27.3 ± 3.8	4.88 ± 0.80
Di-boson	0.7 ± 0.1	0.04 ± 0.02	11.5 ± 2.1	1.0 ± 0.2	7.0 ± 1.4	0.79 ± 0.19
$W+$ h.q.	14.0 ± 6.7	0.3 ± 0.2	63 ± 28	3.9 ± 1.8	33.4 ± 16.2	1.65 ± 0.86
$Z+$ h.q.	5.3 ± 2.2	0.3 ± 0.2	12.9 ± 5.9	0.5 ± 0.4	18.3 ± 8.1	1.67 ± 0.77
Mistags	3450 ± 433	73 ± 14	85 ± 11	2.2 ± 0.6	69 ± 9	1.64 ± 0.48
Expected	18342 ± 2031	1249 ± 203	331 ± 51	34.8 ± 5.9	248 ± 43	14.4 ± 2.7
Observed	18588	1251	373	28	268	16

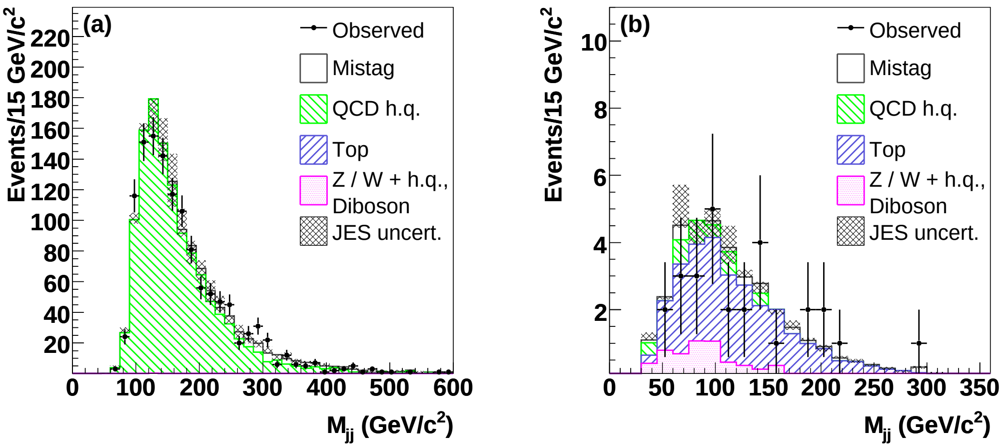

FIG. 1: Dijet invariant mass distribution for double-tagged events in (a) CR 1 and (b) CR 2

predictions and selection requirements were determined. The results are summarized in Table I. Requiring one (two) b-tagged jets we observe 268 (16) events, where 248 ± 43 (14.4 ± 2.7) are expected. The dijet invariant mass distributions in the signal region when one and two jets are b-tagged are shown in Fig. 2.

Since no significant excess is observed, we compute 95% C.L. upper limits for the Higgs boson production cross section times the branching fraction when the Higgs boson is produced in association with a Z or W boson and decays to two b quarks while the Z and W yield large $\not\!\!E_T$ and no identified leptons. The limits are computed using the Bayesian likelihood method [16] with flat prior probability for the signal cross section and Gaussian priors for the uncertainties on acceptance and backgrounds. The likelihood quantifies the agreement between the dijet mass spectrum in the observed data and the sum of the modeled background processes and VH signal as a function of the Higgs boson mass. We combine the channels, such as single b-tag, double b-tag, ZH, and WH by taking the product of their likelihoods and simultaneously varying the correlated uncertainties. Table II summarizes the combined single and double b-tag upper limits separately for ZH and WH, and the combined VH upper limits. The result is also expressed as the ratio of the upper limit to the SM cross sections at NLO as a function of the Higgs boson mass. The observed limits agree with the expected ones at the $1\,\sigma$ level.

In summary, we have performed a direct search for the SM Higgs boson decaying into b jet pairs using data with integrated luminosity of 0.97 ± 0.06 fb^{-1} accumulated in Run II of the CDF II detector. We observe no significant excess over the background predicted by the SM and thus set 95% C.L. upper limits for the cross section of the Higgs boson production. The observed (expected) combined limit of the weak boson associated Higgs boson production cross sections set by this analysis for a Higgs boson mass of 115 GeV/c^2 is 20.4 (14.2) times the SM prediction. These results significantly improve the combined limits on the allowed production rate for the SM Higgs boson at the Tevatron.

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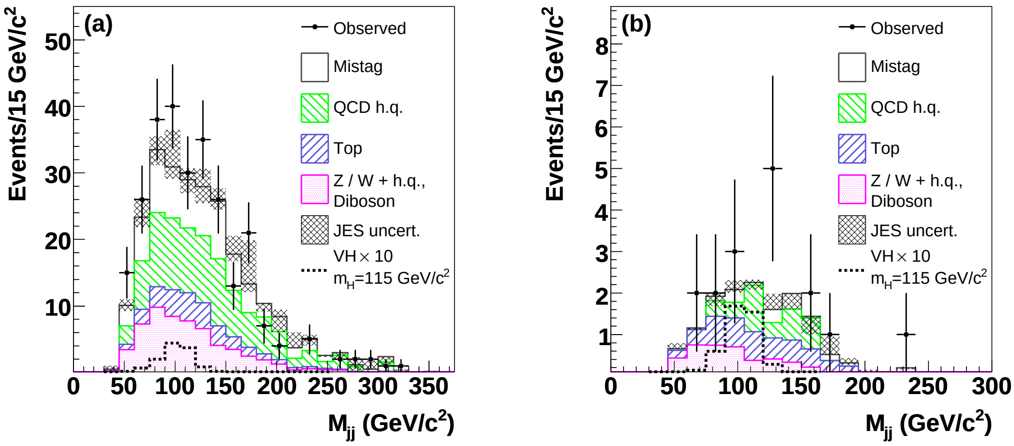

FIG. 2: Dijet invariant mass in the signal region for (a) single-tagged and (b) double-tagged events. The dotted line overlaid on the background shows 10 times the expected yield of 115 GeV/c^2 Higgs bosons.

TABLE II: The expected cross section limits of the ZH and WH processes, and the expected and observed combined (VH) cross section limits when $H \to b\bar{b}$. The last column gives the ratio of the observed limit with respect to the SM cross section.

Higgs mass	$\sigma(ZH) \times$ Br($H \to b\bar{b}$)	$\sigma(WH) \times$ Br($H \to b\bar{b}$)	$\sigma(VH) \times$ Br($H \to b\bar{b}$)		Ratio
	Expected	Expected	Expected	Observed	Observed
(GeV/c^2)	(pb)	(pb)	(pb)	(pb)	
110	$2.1^{+0.9}_{-0.7}$	$4.8^{+2.7}_{-1.2}$	$3.1^{+1.8}_{-0.9}$	4.7	17.9
115	$2.1^{+0.8}_{-0.7}$	$4.6^{+2.2}_{-1.4}$	$3.0^{+1.4}_{-0.9}$	4.4	20.4
120	$1.8^{+0.8}_{-0.6}$	$4.4^{+1.9}_{-1.4}$	$2.9^{+1.3}_{-0.9}$	4.3	24.8
125	$1.7^{+0.7}_{-0.6}$	$3.9^{+2.0}_{-1.0}$	$2.5^{+1.0}_{-0.6}$	4.0	30.2
130	$1.6^{+0.9}_{-0.5}$	$3.4^{+1.2}_{-1.0}$	$2.4^{+1.1}_{-0.8}$	3.8	38.3
135	$1.5^{+0.7}_{-0.5}$	$3.2^{+1.9}_{-0.8}$	$2.3^{+1.0}_{-0.6}$	3.5	48.5
140	$1.4^{+0.6}_{-0.4}$	$3.2^{+1.8}_{-1.0}$	$2.3^{+1.2}_{-0.7}$	3.3	65.8

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