Search for Heavy Bottomlike Quarks Decaying to an Electron or Muon and Jets in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen,[22] B. Álvarez González,[10,w] S. Amerio,[42a] D. Amidei,[33] A. Anastassov,[37] A. Annovi,[18] J. Antos,[13] G. Apollinari,[16] J. A. Appel,[16] A. Apresyan,[47] T. Arisawa,[57] A. Artikov,[14] J. Asaadi,[52] W. Ashmanskas,[16] B. Auerbach,[60] A. Aurisano,[52] F. Azfar,[41] W. Badgett,[16] A. Barbaro-Galtieri,[27] V. E. Barnes,[47] B. A. Barnett,[24] P. Barria,[45c,45a] P. Bartos,[13] M. Bauce,[42b,42a] G. Bauer,[31] F. Bedeschi,[45a] D. Beecher,[29] S. Behari,[24] G. Bellettini,[45b,45a] J. Bellinger,[59] D. Benjamin,[15] A. Beretvas,[16] A. Bhatti,[1] M. Binkley,[16,a] D. Bisello,[42b,42a] I. Bizjak,[29,aa] K. R. Bland,[5] B. Blumenfeld,[24] A. Bocci,[15] A. Bodek,[48] D. Bortoletto,[47] J. Boudreau,[46] A. Boveia,[12] B. Brau,[16,b] L. Brigliadori,[6b,6a] A. Brisuda,[13] C. Bromberg,[34] E. Brucken,[22] M. Bucciantonio,[45b,45a] J. Budagov,[14] H. S. Budd,[48] S. Budd,[23] K. Burkett,[16] G. Busetto,[42b,42a] P. Bussey,[20] A. Buzatu,[32] C. Calancha,[30] S. Camarda,[4] M. Campanelli,[34] M. Campbell,[33] F. Canelli,[12,16] A. Canepa,[44] B. Carls,[23] D. Carlsmith,[59] R. Carosi,[45a] S. Carrillo,[17,l] S. Carron,[16] B. Casal,[10] M. Casarsa,[16] A. Castro,[6b,6a] P. Catastini,[16] D. Cauz,[53a] V. Cavaliere,[45c,45a] M. Cavalli-Sforza,[4] A. Cerri,[27,g] L. Cerrito,[29,r] Y. C. Chen,[1] M. Chertok,[7] G. Chiarelli,[45a] G. Chlachidze,[16] F. Chlebana,[16] K. Cho,[26] D. Chokheli,[14] J. P. Chou,[21] W. H. Chung,[59] Y. S. Chung,[48] C. I. Ciobanu,[43] M. A. Ciocci,[45c,45a] A. Clark,[19] G. Compostella,[42b,42a] M. E. Convery,[16] J. Conway,[7] M. Corbo,[43] M. Cordelli,[18] C. A. Cox,[7] D. J. Cox,[7] F. Crescioli,[45b,45a] C. Cuenca Almenar,[60] J. Cuevas,[10,w] R. Culbertson,[16] D. Dagenhart,[16] N. d'Ascenzo,[43,u] M. Datta,[16] P. de Barbaro,[48] S. De Cecco,[50a] G. De Lorenzo,[4] M. Dell'Orso,[45b,45a] C. Deluca,[4] L. Demortier,[1] J. Deng,[15,d] M. Deninno,[6a] F. Devoto,[22] M. d'Errico,[42b,42a] A. Di Canto,[45b,45a] B. Di Ruzza,[45a] J. R. Dittmann,[5] M. D'Onofrio,[28] S. Donati,[45b,45a] P. Dong,[16] M. Dorigo,[53a] T. Dorigo,[42a] K. Ebina,[57] A. Elagin,[52] A. Eppig,[33] R. Erbacher,[7] D. Errede,[23] S. Errede,[23] N. Ershaidat,[43,z] R. Eusebi,[52] H. C. Fang,[27] S. Farrington,[41] M. Feindt,[25] J. P. Fernandez,[30] C. Ferrazza,[45d,45a] R. Field,[17] G. Flanagan,[47,s] R. Forrest,[7] M. J. Frank,[5] M. Franklin,[21] J. C. Freeman,[16] Y. Funakoshi,[57] I. Furic,[17] M. Gallinaro,[1] J. Galyardt,[11] J. E. Garcia,[19] A. F. Garfinkel,[47] P. Garosi,[45c,45a] H. Gerberich,[23] E. Gerchtein,[16] S. Giagu,[50b,50a] V. Giakoumopoulou,[3] P. Giannetti,[45a] K. Gibson,[46] C. M. Ginsburg,[16] N. Giokaris,[3] P. Giromini,[18] M. Giunta,[45a] G. Giurgiu,[24] V. Glagolev,[14] D. Glenzinski,[16] M. Gold,[36] D. Goldin,[52] N. Goldschmidt,[17] A. Golossanov,[16] G. Gomez,[10] G. Gomez-Ceballos,[31] M. Goncharov,[31] O. González,[30] I. Gorelov,[36] A. T. Goshaw,[15] K. Goulianos,[1] A. Gresele,[42a] S. Grinstein,[4] C. Grosso-Pilcher,[12] R. C. Group,[56] J. Guimaraes da Costa,[21] Z. Gunay-Unalan,[34] C. Haber,[27] S. R. Hahn,[16] E. Halkiadakis,[51] A. Hamaguchi,[40] J. Y. Han,[48] F. Happacher,[18] K. Hara,[54] D. Hare,[51] M. Hare,[55] R. F. Harr,[58] K. Hatakeyama,[5] C. Hays,[41] M. Heck,[25] J. Heinrich,[44] M. Herndon,[59] S. Hewamanage,[5] D. Hidas,[51] A. Hocker,[16] W. Hopkins,[16,h] D. Horn,[25] S. Hou,[1] R. E. Hughes,[38] M. Hurwitz,[12] U. Husemann,[60] N. Hussain,[32] M. Hussein,[34] J. Huston,[34] G. Introzzi,[45a] M. Iori,[50b,50a] A. Ivanov,[7,p] E. James,[16] D. Jang,[11] B. Jayatilaka,[15] E. J. Jeon,[26] M. K. Jha,[6a] S. Jindariani,[16] W. Johnson,[7] M. Jones,[47] K. K. Joo,[26] S. Y. Jun,[11] T. R. Junk,[16] T. Kamon,[52] P. E. Karchin,[58] Y. Kato,[40,o] W. Ketchum,[12] J. Keung,[44] V. Khotilovich,[52] B. Kilminster,[16] D. H. Kim,[26] H. S. Kim,[26] H. W. Kim,[26] J. E. Kim,[26] M. J. Kim,[18] S. B. Kim,[26] S. H. Kim,[54] Y. K. Kim,[12] N. Kimura,[57] M. Kirby,[16] S. Klimenko,[17] K. Kondo,[57] D. J. Kong,[26] J. Konigsberg,[17] A. V. Kotwal,[15] M. Kreps,[25] J. Kroll,[44] D. Krop,[12] N. Krumnack,[5,m] M. Kruse,[15] V. Krutelyov,[52,e] T. Kuhr,[25] M. Kurata,[54] S. Kwang,[12] A. T. Laasanen,[47] S. Lami,[45a] S. Lammel,[16] M. Lancaster,[29] R. L. Lander,[7] K. Lannon,[38,v] A. Lath,[51] G. Latino,[45c,45a] I. Lazzizzera,[42a] T. LeCompte,[2] E. Lee,[52] H. S. Lee,[12] J. S. Lee,[26] S. W. Lee,[52,x] S. Leo,[45b,45a] S. Leone,[45a] J. D. Lewis,[16] C.-J. Lin,[27] J. Linacre,[41] M. Lindgren,[16] E. Lipeles,[44] A. Lister,[19] D. O. Litvintsev,[16] C. Liu,[46] Q. Liu,[47] T. Liu,[16] S. Lockwitz,[60] N. S. Lockyer,[44] A. Loginov,[60] D. Lucchesi,[42b,42a] J. Lueck,[25] P. Lujan,[27] P. Lukens,[16] G. Lungu,[1] J. Lys,[27] R. Lysak,[13] R. Madrak,[16] K. Maeshima,[16] K. Makhoul,[31] P. Maksimovic,[24] S. Malik,[1] G. Manca,[28,c] A. Manousakis-Katsikakis,[3] F. Margaroli,[47] C. Marino,[25] M. Martínez,[4] R. Martínez-Ballarín,[30] P. Mastrandrea,[50a] M. Mathis,[24] M. E. Mattson,[58] P. Mazzanti,[6a] K. S. McFarland,[48] P. McIntyre,[52] R. McNulty,[28,j] A. Mehta,[28] P. Mehtala,[22] A. Menzione,[45a] C. Mesropian,[1] T. Miao,[16] D. Mietlicki,[33] A. Mitra,[1] H. Miyake,[54] S. Moed,[21] N. Moggi,[6a] M. N. Mondragon,[16,l] C. S. Moon,[26] R. Moore,[16] M. J. Morello,[16] J. Morlock,[25] P. Movilla Fernandez,[16] A. Mukherjee,[16] Th. Muller,[25] P. Murat,[16] M. Mussini,[6b,6a] J. Nachtman,[16,n] Y. Nagai,[54] J. Naganoma,[57] I. Nakano,[39] A. Napier,[55] J. Nett,[52] C. Neu,[56] M. S. Neubauer,[23] J. Nielsen,[27,f] L. Nodulman,[2] O. Norniella,[23] E. Nurse,[29] L. Oakes,[41] S. H. Oh,[15] Y. D. Oh,[26] I. Oksuzian,[56] T. Okusawa,[40] R. Orava,[22] L. Ortolan,[4] S. Pagan Griso,[42b,42a] C. Pagliarone,[53a] E. Palencia,[10,g] V. Papadimitriou,[16] A. A. Paramonov,[2] J. Patrick,[16] G. Pauletta,[53b,53a] M. Paulini,[11] C. Paus,[31] D. E. Pellett,[7] A. Penzo,[53a] T. J. Phillips,[15] G. Piacentino,[45a] E. Pianori,[44] J. Pilot,[38] K. Pitts,[23] C. Plager,[9] L. Pondrom,[59] K. Potamianos,[47] O. Poukhov,[14,a] F. Prokoshin,[14,y] A. Pronko,[16] F. Ptohos,[18,i] E. Pueschel,[11] G. Punzi,[45b,45a] J. Pursley,[59] A. Rahaman,[46] V. Ramakrishnan,[59] N. Ranjan,[47] I. Redondo,[30]

P. Renton,[41] M. Rescigno,[50a] F. Rimondi,[6b,6a] L. Ristori,[45a,16] A. Robson,[20] T. Rodrigo,[10] T. Rodriguez,[44] E. Rogers,[23] S. Rolli,[55] R. Roser,[16] M. Rossi,[53a] F. Rubbo,[16] F. Ruffini,[45c,45a] A. Ruiz,[10] J. Russ,[11] V. Rusu,[16] A. Safonov,[52] W. K. Sakumoto,[48] Y. Sakurai,[57] L. Santi,[53b,53a] L. Sartori,[45a] K. Sato,[54] V. Saveliev,[43,u] A. Savoy-Navarro,[43] P. Schlabach,[16] A. Schmidt,[25] E. E. Schmidt,[16] M. P. Schmidt,[60,a] M. Schmitt,[37] T. Schwarz,[7] L. Scodellaro,[10] A. Scribano,[45c,45a] F. Scuri,[45a] A. Sedov,[47] S. Seidel,[36] Y. Seiya,[40] A. Semenov,[14] F. Sforza,[45b,45a,aa] A. Sfyrla,[23] S. Z. Shalhout,[7] T. Shears,[28] P. F. Shepard,[46] M. Shimojima,[54,t] S. Shiraishi,[12] M. Shochet,[12] I. Shreyber,[35] A. Simonenko,[14] P. Sinervo,[32] A. Sissakian,[14,a] K. Sliwa,[55] J. R. Smith,[7] F. D. Snider,[16] A. Soha,[16] S. Somalwar,[51] V. Sorin,[4] P. Squillacioti,[16] M. Stancari,[16] M. Stanitzki,[60] R. St. Denis,[20] B. Stelzer,[32] O. Stelzer-Chilton,[32] D. Stentz,[37] J. Strologas,[36] G. L. Strycker,[33] Y. Sudo,[54] A. Sukhanov,[17] I. Suslov,[14] K. Takemasa,[54] Y. Takeuchi,[54] J. Tang,[12] M. Tecchio,[33] P. K. Teng,[1] J. Thom,[16,h] J. Thome,[11] G. A. Thompson,[23] E. Thomson,[44] P. Ttito-Guzmán,[30] S. Tkaczyk,[16] D. Toback,[52] S. Tokar,[13] K. Tollefson,[34] T. Tomura,[54] D. Tonelli,[16] S. Torre,[18] D. Torretta,[16] P. Totaro,[53b,53a] M. Trovato,[45d,45a] Y. Tu,[44] F. Ukegawa,[54] S. Uozumi,[26] A. Varganov,[33] F. Vázquez,[17,l] G. Velev,[16] C. Vellidis,[3] M. Vidal,[30] I. Vila,[10] R. Vilar,[10] J. Vizán,[10] M. Vogel,[36] G. Volpi,[45b,45a] P. Wagner,[44] R. L. Wagner,[16] T. Wakisaka,[40] R. Wallny,[9] S. M. Wang,[1] A. Warburton,[32] D. Waters,[29] M. Weinberger,[52] W. C. Wester III,[16] B. Whitehouse,[55] D. Whiteson,[8] A. B. Wicklund,[2] E. Wicklund,[16] S. Wilbur,[12] F. Wick,[25] H. H. Williams,[44] J. S. Wilson,[38] P. Wilson,[16] B. L. Winer,[38] P. Wittich,[16,h] S. Wolbers,[16] H. Wolfe,[38] T. Wright,[33] X. Wu,[19] Z. Wu,[5] K. Yamamoto,[40] J. Yamaoka,[15] T. Yang,[16] U. K. Yang,[12,q] Y. C. Yang,[26] W.-M. Yao,[27] G. P. Yeh,[16] K. Yi,[16,n] J. Yoh,[16] K. Yorita,[57] T. Yoshida,[40,k] G. B. Yu,[15] I. Yu,[26] S. S. Yu,[16] J. C. Yun,[16] A. Zanetti,[53a] Y. Zeng,[15] and S. Zucchelli[6b,6a]

(CDF Collaboration)

[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*University of Athens, 157 71 Athens, Greece*
[4]*Institut de Fisica d'Altes Energies, ICREA, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*
[5]*Baylor University, Waco, Texas 76798, USA*
[6a]*Istituto Nazionale di Fisica Nucleare Bologna, I-40127 Bologna, Italy*
[6b]*University of Bologna, I-40127 Bologna, Italy*
[7]*University of California, Davis, Davis, California 95616, USA*
[8]*University of California, Irvine, Irvine, California 92697, USA*
[9]*University of California, Los Angeles, Los Angeles, California 90024, USA*
[10]*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[11]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[12]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*
[13]*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*
[14]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[15]*Duke University, Durham, North Carolina 27708, USA*
[16]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[17]*University of Florida, Gainesville, Florida 32611, USA*
[18]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[19]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[20]*Glasgow University, Glasgow G12 8QQ, United Kingdom*
[21]*Harvard University, Cambridge, Massachusetts 02138, USA*
[22]*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*
[23]*University of Illinois, Urbana, Illinois 61801, USA*
[24]*The Johns Hopkins University, Baltimore, Maryland 21218, USA*
[25]*Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany*
[26]*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; Chonbuk National University, Jeonju 561-756, Korea*
[27]*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[28]*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[29]*University College London, London WC1E 6BT, United Kingdom*
[30]*Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain*
[31]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

[32]*Institute of Particle Physics: McGill University, Montréal, Québec, Canada H3A 2T8; Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6; University of Toronto, Toronto, Ontario, Canada M5S 1A7; and TRIUMF, Vancouver, British Columbia, Canada V6T 2A3*
[33]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[34]*Michigan State University, East Lansing, Michigan 48824, USA*
[35]*Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*
[36]*University of New Mexico, Albuquerque, New Mexico 87131, USA*
[37]*Northwestern University, Evanston, Illinois 60208, USA*
[38]*The Ohio State University, Columbus, Ohio 43210, USA*
[39]*Okayama University, Okayama 700-8530, Japan*
[40]*Osaka City University, Osaka 588, Japan*
[41]*University of Oxford, Oxford OX1 3RH, United Kingdom*
[42a]*Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy*
[42b]*University of Padova, 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, USA*
[45a]*Istituto Nazionale di Fisica Nucleare Pisa, I-56127 Pisa, Italy*
[45b]*University of Pisa, I-56127 Pisa, Italy*
[45c]*University of Siena, I-56127 Pisa, Italy*
[45d]*Scuola Normale Superiore, I-56127 Pisa, Italy*
[46]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
[47]*Purdue University, West Lafayette, Indiana 47907, USA*
[48]*University of Rochester, Rochester, New York 14627, USA*
[1]*The Rockefeller University, New York, New York 10065, USA*
[50a]*Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, I-00185 Roma, Italy*
[50b]*Sapienza Università di Roma, I-00185 Roma, Italy*
[51]*Rutgers University, Piscataway, New Jersey 08855, USA*
[52]*Texas A&M University, College Station, Texas 77843, USA*
[53a]*Istituto Nazionale di Fisica Nucleare Trieste/Udine, I-34100 Trieste, Italy*
[53b]*University of Trieste/Udine, I-33100 Udine, Italy*
[54]*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[55]*Tufts University, Medford, Massachusetts 02155, USA*
[56]*University of Virginia, Charlottesville, Virginia 22906, USA*
[57]*Waseda University, Tokyo 169, Japan*
[58]*Wayne State University, Detroit, Michigan 48201, USA*
[59]*University of Wisconsin, Madison, Wisconsin 53706, USA*
[60]*Yale University, New Haven, Connecticut 06520, USA*
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We report the most sensitive direct search for pair production of fourth-generation bottomlike chiral quarks (b') each decaying promptly to tW. We search for an excess of events with an electron or muon, at least five jets (one identified as due to a b or c quark), and an imbalance of transverse momentum by using data from $p\bar{p}$ collisions collected by the CDF II detector at Fermilab with an integrated luminosity of 4.8 fb^{-1}. We observe events consistent with background expectation, calculate upper limits on the b' pair-production cross section ($\sigma_{b\bar{b}'} \lesssim 30$ fb for $m_{b'} > 375$ GeV$/c^2$), and exclude $m_{b'} < 372$ GeV$/c^2$ at 95% confidence level assuming a 100% branching ratio of b' to tW.

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The standard model of particle physics accommodates three generations of fundamental fermions but is agnostic on the issue of a fourth generation. Precision measurements in the electroweak sector are not inconsistent with a fourth generation of fermions if there is a 50–100 GeV$/c^2$ splitting in the quark and lepton masses [1]. A four-generation model [2] could provide a source of particle-antiparticle asymmetry large enough to account for the baryon asymmetry of the Universe [3] and accommodate a heavier Higgs boson (the source of mass generation) than a three-generation model [4]. Direct searches for production of chiral fourth-generation quarks restrict their masses to be greater than 335 GeV$/c^2$ [5] for an up-type quark t' decaying via $t' \rightarrow Wq$ and 338 GeV$/c^2$ [6] for a down-type quark b' decaying via $b' \rightarrow tW$.

This Letter reports a search for pair production via strong interactions of a heavy chiral [7] bottomlike quark b' followed by prompt decay to a t quark and a W boson with branching ratio $\mathcal{B}(b' \to Wt) = 100\%$. The assumption that b' decays exclusively to tW is reasonable if the coupling to light quarks is small, as expected from precision meson-mixing measurements [8], and in the hypothesis that $m_{b'} > m_t + m_W$. In the case that the branching fraction deviates from 100%, the limits can be interpreted under different assumptions [9]. Previous searches considered the mode in which two same-charge W bosons decayed leptonically [6], which gives a low-background signature but a low selection efficiency due to the small $W \to \ell\nu$ branching ratio. We consider the mode $b'\bar{b}' \to W^+tW^-\bar{t} \to W^+W^-bW^+W^-\bar{b} \to \ell\nu qq'bqq'qq'b$ in which one W boson decays leptonically (including τ decays to e or μ) and the remaining three W bosons decay hadronically, giving a selection efficiency nearly 4 times the previous search. The larger standard model backgrounds can be separated from a potential signal by comparing the total reconstructed transverse momentum in the event.

Events were recorded by CDF II [10,11], a general purpose detector designed to study collisions at the Fermilab Tevatron $p\bar{p}$ collider at $\sqrt{s} = 1.96$ TeV. A charged-particle tracking system immersed in a 1.4 T magnetic field consists of a silicon microstrip tracker and a drift chamber. Electromagnetic and hadronic calorimeters surround the tracking system and measure particle energies. Drift chambers located outside the calorimeters detect muons. We use a data sample corresponding to an integrated luminosity of $4.8 \pm 0.3\ \text{fb}^{-1}$.

The data acquisition system is triggered by e or μ candidates [12] with transverse momentum p_T [11] greater than 18 GeV/c. Electrons and muons are reconstructed off-line and selected if they have absolute value of pseudorapidity η [11] less than 1.1, $p_T \geq 20$ GeV/c, and satisfy the standard CDF identification and isolation requirements [12]. Jets are reconstructed in the calorimeter by using the JETCLU [13] algorithm with a clustering radius of 0.4 in azimuth-pseudorapidity space and corrected by using the standard techniques [14]. Jets are selected if they have $p_T \geq 15$ GeV/c and $|\eta| < 2.4$. Each jet is considered for heavy-flavor tagging by using the default CDF b-jet identification algorithm (SECVTX [15]) that searches in the jet for a secondary vertex which results from the displaced decay of a B hadron inside the jet. Missing transverse momentum [16] is reconstructed by using fully corrected calorimeter and muon information [12].

Production and decay of b' pairs would appear as events with a charged lepton and missing transverse momentum from the leptonically decaying W and a large number of jets from the two b quarks and the hadronic decays of the other three W bosons. We select events with exactly one electron or muon, at least five jets, and at least 20 GeV/c of missing transverse momentum. At least one of the jets must be identified as due to b quark decay. We find 357 events satisfying these requirements.

We model the production and decay of b' pairs with MADGRAPH [17]. Additional radiation, hadronization, and showering are provided by PYTHIA [18]. The detector response for all simulated samples is modeled by CDFSIM [19]. The signal efficiency for the above requirements is approximately 9%, rising with b' mass. There are eight quarks produced in the decay, but the most likely number of reconstructed jets is six, as quarks that are close together are likely to be merged into a single jet, and some of the quarks produce jets which fall below the transverse momentum threshold. Complete mass reconstruction is therefore not possible in the majority of the events; instead, we examine the event S_T, the scalar sum of the transverse momentum of the lepton, jets, and missing transverse momentum. This is well correlated with the mass of the heavy quark and serves as an approximate mass reconstruction.

The dominant background (80%) is top-quark pair production with additional jets from initial or final state radiation. This background can be distinguished from the signal as it has smaller S_T. We model this background by using MADGRAPH $t\bar{t}$ production with $m_t = 172.5\ \text{GeV}/c^2$ in which radiation of up to three additional hard partons (including heavy flavor) are described explicitly by using matrix elements, and additional radiation is described by the parton shower; the MLM [20] scheme is used to match the matrix-element and parton-shower contributions. This gives a precise description of events with ≤ 7 jets, where a b' signal would be expected. Events with eight jets and above are described by the parton shower, which has significantly larger systematic uncertainties. We normalize the $t\bar{t}$ background to the next-to-leading-order (NLO) cross section [21] and confirm that it is well modeled by examining $t\bar{t}$-dominated regions in the data.

The second dominant background process ($\approx 10\%$) is the associated production of W boson and jets. Samples of simulated W + jets events with light- and heavy-flavor jets are generated by using the ALPGEN [22] program, interfaced with the parton-shower model from PYTHIA. The W + jets samples are normalized to the measured W cross section, with an additional multiplicative factor for the relative contribution of heavy- and light-flavor jets, the standard technique in measuring the top-quark pair-production cross section [15]. A multijet background ($\approx 5\%$), in which a jet is misreconstructed as a lepton, is modeled by using a jet-triggered sample normalized in a background-dominated region at low missing transverse momentum. The remaining backgrounds, single top and diboson production, are modeled by using PYTHIA and normalized to next-to-leading order cross sections [23]. The combined background expectation is 365 ± 194 events, including systematic and statistical uncertainties.

A b' signal would be readily separated from the background in both the number of jets and the S_T. To take advantage of both of these characteristics, we introduce a variable $S_T^{N_{\rm jet}}$ which equals S_T for events with exactly 5 jets, $S_T^{N_{\rm jet}} = S_T + 1000$ GeV for events with exactly 6 jets, and $S_T^{N_{\rm jet}} = S_T + 2000$ GeV for events with at least 7 jets. This is equivalent to a two-dimensional analysis in $N_{\rm jets}$ and S_T. Figure 1 shows the distributions of an example b' signal with $m_{b'} = 350$ GeV$/c^2$ and the backgrounds in jet multiplicity and $S_T^{N_{\rm jet}}$, as well as the expected backgrounds and observed data.

We consider several sources of systematic uncertainty on both the background rates and distributions, as well as on the expectations for the signal. The dominant systematic uncertainties are the jet energy scale [14], contributions from multiple interaction in the same bunch crossing, and descriptions of initial and final state radiation [24]. The

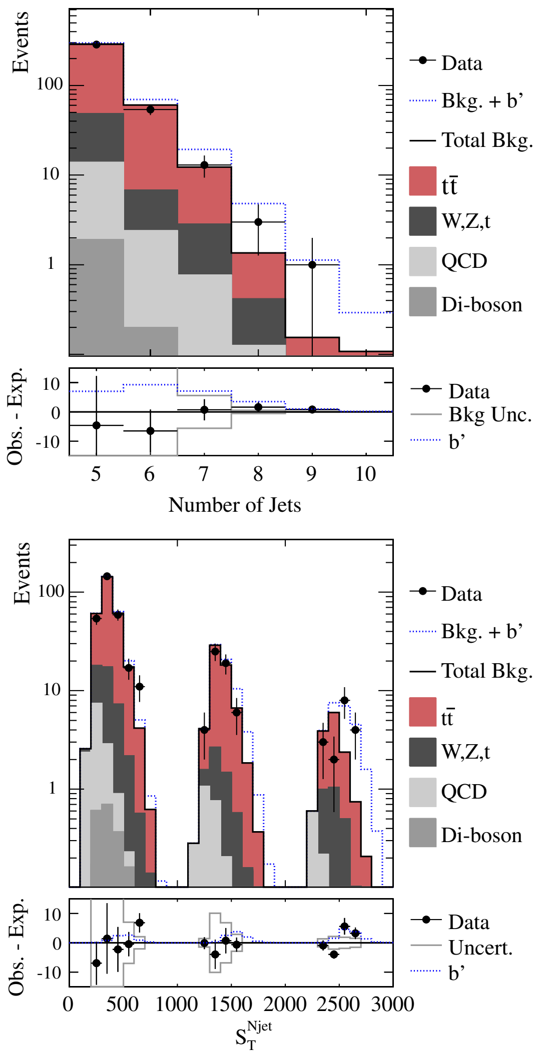

FIG. 1 (color online). Distributions in jet multiplicity and $S_T^{N_{\rm jet}}$ (defined in the text). The example b' signal has $m_{b'} = 350$ GeV$/c^2$ and would have 29 ± 4.5 events expected in this sample. The top panel is log scale; the bottom panel shows the difference between expected and observed events on a linear scale, as well as the total uncertainty on the expected events. The background uncertainty (Bkg Unc.) is shown as a solid gray line.

TABLE I. Expected and observed events in a background-dominated control region ($S_T < 400$, 450, and 500 for $N_{\rm jet} = 5$, 6, and ≥ 7, respectively) and in a signal-dominated region ($S_T > 400$, 450, and 500 for $N_{\rm jet} = 5$, 6, and ≥ 7, respectively) for our selection (see the text). Uncertainties are statistical and systematic, combined in quadrature.

	Control region		Signal region		Sum	
Jets	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
5	207 ± 125	199	84 ± 65	87	291 ± 190	286
6	43 ± 31	40	18 ± 12	14	61 ± 43	54
≥ 7	11 ± 3.9	5	3.4 ± 3.4	12	14 ± 7.1	17

impact on the cross-section upper limits of the uncertainty due to each source was estimated by varying it according to the amount of its uncertainty and observing the resulting effects on the $S_T^{N_{\rm jet}}$ spectrum. Each uncertainty weakens the expected 95% confidence level (C.L.) cross-section upper limit by $\approx 60\%$ individually. Additional uncertainty comes from parton distribution functions [25,26], the matching scale used between the matrix element and the parton shower, overall background normalization, and uncertainties in performance of the b-quark identification algorithm. The overall impact on the expected sensitivity is $\approx 100\%$ in the cross section and ≈ 20 GeV$/c^2$ on the expected mass limit.

To validate the description of the backgrounds, we verify that the low S_T region is well-described where there is little signal expected. See Table I. In events with ≥ 7 jets, the observed S_T is larger than predicted by our background model. The number of observed events with ≥ 7 jets and $S_T > 500$ GeV is 12 where we expect 3.4 ± 3.4. However, the total number of events observed in the low S_T and high S_T regions combined is consistent with expectation. Considering only the number of events in the high S_T regions and taking into account the systematic uncertainties in the background prediction, we see a more significant excess than that observed in the data in 12% of simulated experiments.

The full $S_T^{N_{\rm jet}}$ spectrum is used in the analysis. Since there is no evidence for the presence of b' events in the data, we calculate 95% C.L. upper limits on the b'

TABLE II. Theoretical cross sections ($\sigma_{\rm NLO}$ in fb [21,29]), selection efficiency ϵ, expected b' yield ($N_{\rm exp}$) after selection, median expected 95% C.L. limit ($\sigma_{\rm exp}$ in fb), and observed 95% C.L. limit ($\sigma_{\rm obs}$ in fb) for b' at varying masses. $\sigma_{\rm NLO}$ and $N_{\rm exp}$ have 10% uncertainties.

Mass [GeV$/c^2$]	260	300	325	350	375	400	425
$\sigma_{\rm NLO}$	630	227	125	65	34	19	9.5
$\epsilon(\%)$	7	8	9	9	9	9	9
$N_{\rm exp}$	203.2	91.5	53.0	28.1	14.9	7.6	4.0
$\sigma_{\rm exp}$	72	49	40	34	34	34	34
$\sigma_{\rm obs}$	72	72	66	53	36	33	34

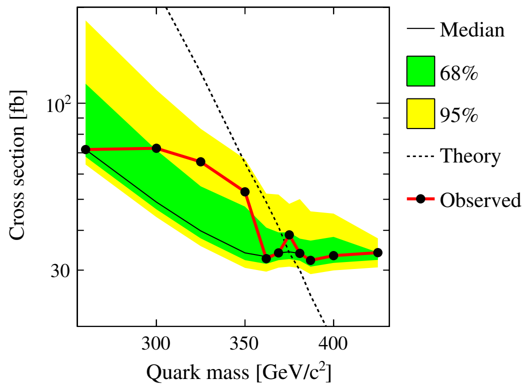

FIG. 2 (color online). Upper limits on b' production cross section at 95% C.L. assuming $\mathcal{B}(b' \rightarrow Wt) = 100\%$. The solid black line is the median expected upper limit in simulated experiments without a b' signal; green and yellow bands represent 68% and 95% of simulated experiments, respectively; the solid red line is the observed limit. The dashed black line is the NLO b' production cross section [21,29].

production cross section, by performing a binned maximum-likelihood fit in the $S_T^{N_{\rm jet}}$ variable and allowing for systematic and statistical fluctuations via template morphing [27]. We use the likelihood-ratio ordering prescription [28] to construct classical confidence intervals in the theoretical cross section by generating ensembles of simulated experiments that describe expected fluctuations of statistical and systematic uncertainties on both the signal and backgrounds. The observed limits are consistent with expectation in the background-only hypothesis and are given together with theoretical NLO cross sections [21,29] in Table II and shown in Fig. 2.

We convert upper limits on the pair-production cross sections to lower limits on the fermion masses. The relative cross-section uncertainty of $\approx 10\%$ due to scale and parton distribution function uncertainties translates into ≈ 3 GeV$/c^2$ for the mass lower limits.

In conclusion, we have searched for pair production of b' quarks with subsequent decay to tW. Though there are events with larger S_T than expected in the 7-jet event distribution in Fig. 1, we do not see evidence of a signal. We calculate upper limits on the b' pair-production cross section ($\lesssim 30$ fb for $m_{b'} > 375$ GeV$/c^2$) and set the most restrictive direct lower limit on the mass of a down-type fourth-generation quark, increasing the limit by 34 GeV$/c^2$ beyond previous limits and significantly reducing the allowed mass range to $m_{b'} \geq 372$ GeV$/c^2$.

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[a]Deceased.
[b]Visitor from University of Massachusetts Amherst, Amherst, MA 01003, USA.
[c]Visitor from Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy.
[d]Visitor from University of California Irvine, Irvine, CA 92697, USA.
[e]Visitor from University of California Santa Barbara, Santa Barbara, CA 93106, USA.
[f]Visitor from University of California Santa Cruz, Santa Cruz, CA 95064, USA.
[g]Visitor from CERN, CH-1211 Geneva, Switzerland.
[h]Visitor from Cornell University, Ithaca, NY 14853, USA.
[i]Visitor from University of Cyprus, Nicosia CY-1678, Cyprus.
[j]Visitor from University College Dublin, Dublin 4, Ireland.
[k]Visitor from University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017.
[l]Visitor from Universidad Iberoamericana, Mexico D.F., Mexico.
[m]Visitor from Iowa State University, Ames, IA 50011, USA.
[n]Visitor from University of Iowa, Iowa City, IA 52242, USA.
[o]Visitor from Kinki University, Higashi-Osaka City, Japan 577-8502.
[p]Visitor from Kansas State University, Manhattan, KS 66506, USA.
[q]Visitor from University of Manchester, Manchester M13 9PL, United Kingdom.
[r]Visitor from Queen Mary, University of London, London, E1 4NS, United Kingdom.
[s]Visitor from Muons, Inc., Batavia, IL 60510, USA.
[t]Visitor from Nagasaki Institute of Applied Science, Nagasaki, Japan.
[u]Visitor from National Research Nuclear University, Moscow, Russia.
[v]Visitor from University of Notre Dame, Notre Dame, IN 46556, USA.
[w]Visitor from Universidad de Oviedo, E-33007 Oviedo, Spain.
[x]Visitor from Texas Tech University, Lubbock, TX 79609, USA.

[y]Visitor from Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile.
[z]Visitor from Yarmouk University, Irbid 211-63, Jordan.
[aa]On leave from J. Stefan Institute, Ljubljana, Slovenia.

[1] O. Cobanoglu *et al.*, arXiv:1005.2784
[2] P. Frampton, P. Hung, and M. Sher, Phys. Rep. **330**, 263 (2000).
[3] W.-S. Hou, Chin. J. Phys. (Taipei) **47**, 134 (2009).
[4] G. Kribs, T. Plehn, M. Spannowsky, and T. Tait, Phys. Rev. D **76**, 075016 (2007).
[5] A. Lister, in Proceedings of ICHEP2010 (to be published).
[6] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **104**, 091801 (2010).
[7] We specify chiral quarks to distinguish from theories of a vectorlike fourth generation.
[8] O. Eberhardt, A. Lenz, and J. Rohrwild, Phys. Rev. D **82**, 095006 (2010).
[9] C. Flacco *et al.*, Phys. Rev. Lett. **105**, 111801 (2010).
[10] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).
[11] CDF uses a cylindrical coordinate system with the z axis along the proton beam axis. Pseudorapidity is $\eta \equiv -\ln[\tan(\theta/2)]$, where θ is the polar angle relative to the proton beam direction and ϕ is the azimuthal angle while $p_T = |p| \sin\theta$ and $E_T = E \sin\theta$.
[12] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **97**, 082004 (2006); D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **94**, 091803 (2005).
[13] F. Abe *et al.* (CDF Collaboration), Phys. Rev. D **45**, 1448 (1992).
[14] A. Bhatti *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **566**, 375 (2006).
[15] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. D **74**, 072006 (2006).
[16] Missing transverse momentum $\not\!\!E_T$ is defined as the magnitude of the vector $-\sum_i E_T^i \vec{n}_i$, where E_T^i are the magnitudes of transverse energy contained in each calorimeter tower i and $\vec{n}_i$ is the unit vector from the interaction vertex to the tower in the transverse (x, y) plane.
[17] J. Alwall *et al.* J. High Energy Phys. 28 (2007) 09, version 4.4.24.
[18] T. Sjostrand *et al.*, Comput. Phys. Commun. **238**, 135 (2001), version 6.422.
[19] E. Gerchtein *et al.*, arXiv:physics/0306031.
[20] M. Mangano, arXiv:hep-ph/0602031
[21] R. Bonciani, S. Catani, M. L. Mangano, and P. Nason, Nucl. Phys. **B529**, 424 (1998).
[22] M. Mangano *et al.*, J. High Energy Phys. 07 (2003) 001.
[23] J. Campbell and R. Ellis, Phys. Rev. D **60**, 113006 (1999).
[24] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. D **73**, 032003 (2006).
[25] J. Pumplin *et al.* (CTEQ Collaboration), J. High Energy Phys. 07 (2002) 012.
[26] A. D. Martin *et al.* (MRST Collaboration), Phys. Lett. B **356**, 89 (1995).
[27] A. Read, Nucl. Instrum. Methods Phys. Res., Sect. A **425**, 357 (1999).
[28] G. Feldman and R. Cousins, Phys. Rev. D **57**, 3873 (1998).
[29] M. Cacciari, S. Frixione, M. L. Mangano, P. Nason, and G. Ridolfi, J. High Energy Phys. 04 (2004) 068.