University of Nebraska - Lincoln
DigitalCommons@University of Nebraska - Lincoln

Kenneth Bloom Publications | Research Papers in Physics and Astronomy

1-31-2000

Search for a Fourth-Generation Quark More Massive than the Z^0 Boson in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.8 TeV

T. Affolder
Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California

Kenneth A. Bloom
University of Nebraska-Lincoln, kenbloom@unl.edu

Collider Detector at Fermilab Collaboration

Follow this and additional works at: https://digitalcommons.unl.edu/physicsbloom

Part of the Physics Commons

Affolder, T.; Bloom, Kenneth A.; and Fermilab Collaboration, Collider Detector at, "Search for a Fourth-Generation Quark More Massive than the Z^0 Boson in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.8 TeV" (2000). *Kenneth Bloom Publications*. 115.
https://digitalcommons.unl.edu/physicsbloom/115

This Article is brought to you for free and open access by the Research Papers in Physics and Astronomy at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Kenneth Bloom Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

Search for a Fourth-Generation Quark More Massive than the Z^0 Boson in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

T. Affolder,[21] H. Akimoto,[43] A. Akopian,[36] M. G. Albrow,[10] P. Amaral,[7] S. R. Amendolia,[32] D. Amidei,[24] J. Antos,[1] G. Apollinari,[36] T. Arisawa,[43] T. Asakawa,[41] W. Ashmanskas,[7] M. Atac,[10] F. Azfar,[29] P. Azzi-Bacchetta,[30] N. Bacchetta,[30] M. W. Bailey,[26] S. Bailey,[14] P. de Barbaro,[35] A. Barbaro-Galtieri,[21] V. E. Barnes,[34] B. A. Barnett,[17] M. Barone,[12] G. Bauer,[22] F. Bedeschi,[32] S. Belforte,[40] G. Bellettini,[32] J. Bellinger,[44] D. Benjamin,[9] J. Bensinger,[4] A. Beretvas,[10] J. P. Berge,[10] J. Berryhill,[7] S. Bertolucci,[12] B. Bevensee,[31] A. Bhatti,[36] C. Bigongiari,[32] M. Binkley,[10] D. Bisello,[30] R. E. Blair,[2] C. Blocker,[4] K. Bloom,[24] B. Blumenfeld,[17] B. S. Blusk,[35] A. Bocci,[32] A. Bodek,[35] W. Bokhari,[31] G. Bolla,[34] Y. Bonushkin,[5] D. Bortoletto,[34] J. Boudreau,[33] A. Brandl,[26] S. van den Brink,[17] C. Bromberg,[25] N. Bruner,[26] E. Buckley-Geer,[10] J. Budagov,[8] H. S. Budd,[35] K. Burkett,[14] G. Busetto,[30] A. Byon-Wagner,[10] K. L. Byrum,[2] M. Campbell,[24] A. Caner,[32] W. Carithers,[21] J. Carlson,[24] D. Carlsmith,[44] J. Cassada,[35] A. Castro,[30] D. Cauz,[40] A. Cerri,[32] P. S. Chang,[1] P. T. Chang,[1] J. Chapman,[24] C. Chen,[31] Y. C. Chen,[1] M.-T. Cheng,[1] M. Chertok,[38] G. Chiarelli,[32] I. Chirikov-Zorin,[8] G. Chlachidze,[8] F. Chlebana,[10] L. Christofek,[16] M. L. Chu,[1] S. Cihangir,[10] C. I. Ciobanu,[27] A. G. Clark,[13] M. Cobal,[32] E. Cocca,[32] A. Connolly,[21] J. Conway,[37] J. Cooper,[10] M. Cordelli,[12] D. Costanzo,[32] J. Cranshaw,[39] D. Cronin-Hennessy,[9] R. Cropp,[23] R. Culbertson,[7] D. Dagenhart,[42] F. DeJongh,[10] S. Dell'Agnello,[12] M. Dell'Orso,[32] R. Demina,[10] L. Demortier,[36] M. Deninno,[3] P. F. Derwent,[10] T. Devlin,[37] J. R. Dittmann,[10] S. Donati,[32] J. Done,[38] T. Dorigo,[14] N. Eddy,[16] K. Einsweiler,[21] J. E. Elias,[10] E. Engels, Jr.,[33] W. Erdmann,[10] D. Errede,[16] S. Errede,[16] Q. Fan,[35] R. G. Feild,[45] C. Ferretti,[32] I. Fiori,[3] B. Flaugher,[10] G. W. Foster,[10] M. Franklin,[14] J. Freeman,[10] J. Friedman,[22] Y. Fukui,[20] S. Gadomski,[23] S. Galeotti,[32] M. Gallinaro,[36] T. Gao,[31] M. Garcia-Sciveres,[21] A. F. Garfinkel,[34] P. Gatti,[30] C. Gay,[45] S. Geer,[10] D. W. Gerdes,[24] P. Giannetti,[32] P. Giromini,[12] V. Glagolev,[8] M. Gold,[26] J. Goldstein,[10] A. Gordon,[14] A. T. Goshaw,[9] Y. Gotra,[33] K. Goulianos,[36] H. Grassmann,[40] C. Green,[34] L. Groer,[37] C. Grosso-Pilcher,[7] M. Guenther,[34] G. Guillian,[24] J. Guimarães da Costa,[24] R. S. Guo,[1] C. Haber,[21] E. Hafen,[22] S. R. Hahn,[10] C. Hall,[14] T. Handa,[15] R. Handler,[44] W. Hao,[39] F. Happacher,[12] K. Hara,[41] A. D. Hardman,[34] R. M. Harris,[10] F. Hartmann,[18] K. Hatakeyama,[36] J. Hauser,[5] J. Heinrich,[31] A. Heiss,[18] B. Hinrichsen,[23] K. D. Hoffman,[34] C. Holck,[31] R. Hollebeek,[31] L. Holloway,[16] R. Hughes,[27] J. Huston,[25] J. Huth,[14] H. Ikeda,[41] M. Incagli,[32] J. Incandela,[10] G. Introzzi,[32] J. Iwai,[43] Y. Iwata,[15] E. James,[24] H. Jensen,[10] M. Jones,[31] U. Joshi,[10] H. Kambara,[13] T. Kamon,[38] T. Kaneko,[41] K. Karr,[42] H. Kasha,[45] Y. Kato,[28] T. A. Keaffaber,[34] K. Kelley,[22] M. Kelly,[24] R. D. Kennedy,[10] R. Kephart,[10] D. Khazins,[9] T. Kikuchi,[41] M. Kirk,[4] B. J. Kim,[19] H. S. Kim,[23] S. H. Kim,[41] Y. K. Kim,[21] L. Kirsch,[4] S. Klimenko,[11] D. Knoblauch,[18] P. Koehn,[27] A. Köngeter,[18] K. Kondo,[43] J. Konigsberg,[11] K. Kordas,[23] A. Korytov,[11] E. Kovacs,[2] J. Kroll,[31] M. Kruse,[35] S. E. Kuhlmann,[2] K. Kurino,[15] T. Kuwabara,[41] A. T. Laasanen,[34] N. Lai,[7] S. Lami,[36] S. Lammel,[10] J. I. Lamoureux,[4] M. Lancaster,[21] G. Latino,[32] T. LeCompte,[2] A. M. Lee IV,[9] S. Leone,[32] J. D. Lewis,[10] M. Lindgren,[5] T. M. Liss,[16] J. B. Liu,[35] Y. C. Liu,[1] N. Lockyer,[31] J. Loken,[29] M. Loreti,[30] D. Lucchesi,[30] P. Lukens,[10] S. Lusin,[44] L. Lyons,[29] J. Lys,[21] R. Madrak,[14] K. Maeshima,[10] P. Maksimovic,[14] L. Malferrari,[3] M. Mangano,[32] M. Mariotti,[30] G. Martignon,[30] A. Martin,[45] J. A. J. Matthews,[26] P. Mazzanti,[3] K. S. McFarland,[35] P. McIntyre,[38] E. McKigney,[31] M. Menguzzato,[30] A. Menzione,[32] E. Meschi,[32] C. Mesropian,[36] C. Miao,[24] T. Miao,[10] R. Miller,[25] J. S. Miller,[24] H. Minato,[41] S. Miscetti,[12] M. Mishina,[20] N. Moggi,[32] E. Moore,[26] R. Moore,[24] Y. Morita,[20] A. Mukherjee,[10] T. Muller,[18] A. Munar,[32] P. Murat,[32] S. Murgia,[25] M. Musy,[40] J. Nachtman,[5] S. Nahn,[45] H. Nakada,[41] T. Nakaya,[7] I. Nakano,[15] C. Nelson,[10] D. Neuberger,[18] C. Newman-Holmes,[10] C.-Y. P. Ngan,[22] P. Nicolaidi,[40] H. Niu,[4] L. Nodulman,[2] A. Nomerotski,[11] S. H. Oh,[9] T. Ohmoto,[15] T. Ohsugi,[15] R. Oishi,[41] T. Okusawa,[28] J. Olsen,[44] C. Pagliarone,[32] F. Palmonari,[32] R. Paoletti,[32] V. Papadimitriou,[39] S. P. Pappas,[45] A. Parri,[12] D. Partos,[4] J. Patrick,[10] G. Pauletta,[40] M. Paulini,[21] A. Perazzo,[32] L. Pescara,[30] T. J. Phillips,[9] G. Piacentino,[32] K. T. Pitts,[10] R. Plunkett,[10] A. Pompos,[34] L. Pondrom,[44] G. Pope,[33] F. Prokoshin,[8] J. Proudfoot,[2] F. Ptohos,[12] G. Punzi,[32] K. Ragan,[23] D. Reher,[21] A. Reichold,[29] W. Riegler,[14] A. Ribon,[30] F. Rimondi,[3] L. Ristori,[32] W. J. Robertson,[9] A. Robinson,[23] T. Rodrigo,[6] S. Rolli,[42] L. Rosenson,[22] R. Roser,[10] R. Rossin,[30] W. K. Sakumoto,[35] D. Saltzberg,[5] A. Sansoni,[12] L. Santi,[40] H. Sato,[41] P. Savard,[23] P. Schlabach,[10] E. E. Schmidt,[10] M. P. Schmidt,[45] M. Schmitt,[14] L. Scodellaro,[30] A. Scott,[5] A. Scribano,[32] S. Segler,[10] S. Seidel,[26] Y. Seiya,[41] A. Semenov,[8] F. Semeria,[3] T. Shah,[22] M. D. Shapiro,[21] P. F. Shepard,[33] T. Shibayama,[41] M. Shimojima,[41] M. Shochet,[7] J. Siegrist,[21] G. Signorelli,[32] A. Sill,[39] P. Sinervo,[23] P. Singh,[16] A. J. Slaughter,[45] K. Sliwa,[42] C. Smith,[17] F. D. Snider,[10] A. Solodsky,[36] J. Spalding,[10] T. Speer,[13] P. Sphicas,[22] F. Spinella,[32] M. Spiropulu,[14] L. Spiegel,[10] L. Stanco,[30] J. Steele,[44] A. Stefanini,[32] J. Strologas,[16] F. Strumia,[13]

D. Stuart,[10] K. Sumorok,[22] T. Suzuki,[41] R. Takashima,[15] K. Takikawa,[41] M. Tanaka,[41] T. Takano,[28] B. Tannenbaum,[5] W. Taylor,[23] M. Tecchio,[24] P.K. Teng,[1] K. Terashi,[41] S. Tether,[22] D. Theriot,[10] R. Thurman-Keup,[2] P. Tipton,[35] S. Tkaczyk,[10] K. Tollefson,[35] A. Tollestrup,[10] H. Toyoda,[28] W. Trischuk,[23] J.F. de Troconiz,[14] S. Truitt,[24] J. Tseng,[22] N. Turini,[32] F. Ukegawa,[41] J. Valls,[37] S. Vejcik III,[10] G. Velev,[32] R. Vidal,[10] R. Vilar,[6] I. Vologouev,[21] D. Vucinic,[22] R.G. Wagner,[2] R.L. Wagner,[10] J. Wahl,[7] N.B. Wallace,[37] A.M. Walsh,[37] C. Wang,[9] C.H. Wang,[1] M.J. Wang,[1] T. Watanabe,[41] D. Waters,[29] T. Watts,[37] R. Webb,[38] H. Wenzel,[18] W.C. Wester III,[10] A.B. Wicklund,[2] E. Wicklund,[10] H.H. Williams,[31] P. Wilson,[10] B.L. Winer,[27] D. Winn,[24] S. Wolbers,[10] D. Wolinski,[24] J. Wolinski,[25] S. Worm,[26] X. Wu,[13] J. Wyss,[32] A. Yagil,[10] W. Yao,[21] G.P. Yeh,[10] P. Yeh,[1] J. Yoh,[10] C. Yosef,[25] T. Yoshida,[28] I. Yu,[19] S. Yu,[31] A. Zanetti,[40] F. Zetti,[21] and S. Zucchelli[3]

(CDF Collaboration)

[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2]*Argonne National Laboratory, Argonne, Illinois 60439*
[3]*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*
[4]*Brandeis University, Waltham, Massachusetts 02254*
[5]*University of California at Los Angeles, Los Angeles, California 90024*
[6]*Instituto de Fisica de Cantabria, University of Cantabria, 39005 Santander, Spain*
[7]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[8]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[9]*Duke University, Durham, North Carolina 27708*
[10]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[11]*University of Florida, Gainesville, Florida 32611*
[12]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[13]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[14]*Harvard University, Cambridge, Massachusetts 02138*
[15]*Hiroshima University, Higashi-Hiroshima 724, Japan*
[16]*University of Illinois, Urbana, Illinois 61801*
[17]*The Johns Hopkins University, Baltimore, Maryland 21218*
[18]*Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
[19]*Korean Hadron Collider Laboratory, Kyungpook National University, Taegu 702-701, Korea*
and Seoul National University, Seoul 151-742, Korea
and SungKyunKwan University, Suwon 440-746, Korea
[20]*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan*
[21]*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[22]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[23]*Institute of Particle Physics, McGill University, Montreal, Canada H3A 2T8*
and University of Toronto, Toronto, Canada M5S 1A7
[24]*University of Michigan, Ann Arbor, Michigan 48109*
[25]*Michigan State University, East Lansing, Michigan 48824*
[26]*University of New Mexico, Albuquerque, New Mexico 87131*
[27]*The Ohio State University, Columbus, Ohio 43210*
[28]*Osaka City University, Osaka 588, Japan*
[29]*University of Oxford, Oxford OX1 3RH, United Kingdom*
[30]*Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*
[31]*University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[32]*Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*
[33]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[34]*Purdue University, West Lafayette, Indiana 47907*
[35]*University of Rochester, Rochester, New York 14627*
[36]*Rockefeller University, New York, New York 10021*
[37]*Rutgers University, Piscataway, New Jersey 08855*
[38]*Texas A&M University, College Station, Texas 77843*
[39]*Texas Tech University, Lubbock, Texas 79409*
[40]*Istituto Nazionale di Fisica Nucleare, University of Trieste, Udine, Italy*
[41]*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[42]*Tufts University, Medford, Massachusetts 02155*
[43]*Waseda University, Tokyo 169, Japan*
[44]*University of Wisconsin, Madison, Wisconsin 53706*
[45]*Yale University, New Haven, Connecticut 06520*
(Received 13 September 1999)

We present the results of a search for pair production of a fourth-generation charge $-\frac{1}{3}$ quark (b') in $\sqrt{s} = 1.8$ TeV $p\overline{p}$ collisions using 88 pb^{-1} of data obtained with the Collider Detector at Fermilab. We assume that both quarks decay via the flavor-changing neutral current process $b' \rightarrow bZ^0$ and that the b' mass is greater than $m_Z + m_b$. We studied the decay mode $b'\overline{b'} \rightarrow Z^0Z^0b\overline{b}$ where one Z^0 decays into e^+e^- or $\mu^+\mu^-$ and the other decays hadronically, giving a signature of two leptons plus jets. An upper limit on the $\sigma_{p\overline{p}\rightarrow b'\overline{b'}} \times [B(b' \rightarrow bZ^0)]^2$ is established as a function of the b' mass. We exclude at 95% confidence level a b' quark with mass between 100 and 199 GeV$/c^2$ for $B(b' \rightarrow bZ^0) = 100\%$.

PACS numbers: 13.85.Rm, 13.85.Qk, 14.65.–q

The standard model (SM) with three generations of quarks and leptons is in excellent agreement with all experimental data available today. There is no strong reason to believe that an extra fermion generation exists. However, the SM does not explain either the fermion family replication or the fermion mass hierarchy. Several models have been proposed to solve shortcomings in the SM specifically through the introduction of extra quarks and leptons. In addition, grand unification, supersymmetry, supergravity, and superstrings predict or can accommodate extra quarks [1]. An extensive discussion of such models can be found in a recent review [2].

In general, flavor-changing neutral current (FCNC) processes in the standard model are highly suppressed. However, if a fourth-generation charge $-\frac{1}{3}$ quark (b') exists and is lighter than both the t' [its partner in an SU(2) doublet] and the top quark (t), the charged-current (CC) decays $b' \rightarrow tW^-$ and $b' \rightarrow t'W^-$ are kinematically forbidden. The leading charged-current decay mode will then be $b' \rightarrow cW^-$, which is doubly Cabibbo-suppressed. In this situation loop-induced FCNC decays can dominate [2–4] provided $|V_{cb'}|/|V_{tb'}|$ is less than roughly 10^{-2} to 10^{-3}, depending on the b' and t' masses [4]. If $m_{b'} > m_Z + m_b$, the dominant FCNC decay mode is $b' \rightarrow bZ^0$ [4] as long as $b' \rightarrow bH$ is kinematically suppressed or forbidden [5]. For $m_t < m_{b'} < m_t + m_W$, the decay mode $b' \rightarrow tW^*$ becomes available but is suppressed by three-body phase space, and the $b' \rightarrow bZ^0$ channel can still dominate over the CC decay for b' masses up to about 230 GeV$/c^2$ [2,6].

Several experiments have searched explicitly for b' quarks decaying via FCNC [7]. The most stringent limit comes from the D0 Collaboration, which searched in the $b'\overline{b'} \rightarrow \gamma g b\overline{b}$ and $b'\overline{b'} \rightarrow \gamma\gamma b\overline{b}$ channels, excluding a b' quark mass up to $m_Z + m_b$ for a FCNC branching fraction larger than 50% [8]. CDF has excluded a long-lived b' quark with mass up to 148 GeV$/c^2$ and a lifetime of $\tau \approx 3.3 \times 10^{-11}$ sec, assuming $B(b' \rightarrow bZ^0) = 100\%$ [9]. If the CC decay $b' \rightarrow cW^-$ dominates, the lower mass bound of 128 GeV found in a D0 top quark search [10] also applies to the b' quark [11].

In this Letter, we report on a search for a b' quark using 88 ± 4 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected with the CDF detector from 1994 to 1995. Fourth-generation b' quarks can be pair-produced in $p\overline{p}$ collisions through gg fusion and $q\overline{q}$ annihilation with the same cross section, for a given mass, as the top quark. We search for pair-produced b' quarks decaying via FCNC into bZ^0, where one Z^0 decays into leptons and the other decays hadronically. The signature is two high transverse momentum (p_T) leptons from the Z^0 decay, two high-p_T jets from the second Z^0, and two b jets whose p_T scales with the b' mass.

A detailed description of the CDF detector can be found elsewhere [12]. We briefly describe the components most relevant for this analysis. Inside a 1.4 T solenoidal magnetic field, the silicon vertex detector (SVX), the vertex time projection chamber (VTX), and the central tracking chamber (CTC) provide tracking information. The SVX, positioned immediately outside the beampipe and inside the VTX, consists of four layers of silicon microstrip detectors and covers $|z| < 25$ cm [13]. It provides precise track reconstruction in the plane transverse to the beam and is used to identify secondary vertices from the decay of b hadrons. The VTX is used to measure the position of the primary interaction vertex along the z axis. The CTC is a cylindrical drift chamber that covers the pseudorapidity range $|\eta| < 1.1$ and consists of 84 layers that are grouped in nine alternating superlayers of axial and stereo wires. Outside the solenoid, electromagnetic and hadronic calorimeters, arranged in a projective tower geometry, surround the tracking volume and are used to identify electrons and jets over the range $|\eta| < 4.2$. The electron energy is measured in the central electromagnetic calorimeter (CEM) ($|\eta| < 1.1$) and the end-plug electromagnetic calorimeter (PEM) ($1.1 < |\eta| < 2.4$). Outside the calorimeters, three systems of drift chambers in the region $|\eta| < 1.0$ provide muon identification.

We select events satisfying a high-p_T lepton trigger, containing a well-identified muon or electron in the central region, whose primary vertex is within 60 cm of the nominal interaction position. A trigger that requires one jet with $E_T > 10$ GeV, in addition to the lepton, is also used for muon events. Inclusive $Z^0 \rightarrow e^+e^-$ and $Z^0 \rightarrow \mu^+\mu^-$ samples are selected by requiring one primary lepton that satisfies tight lepton identification cuts and a second lepton satisfying loose identification cuts [14]. Dielectron events are selected by requiring at least one tight electron with transverse energy $E_T > 20$ GeV in the CEM and a second loose electron with $E_T > 10$ GeV in either the CEM or PEM calorimeters. Dimuon events are required to have one tight muon with transverse momentum $p_T > 20$ GeV$/c$ in the central region and a second loose muon with $p_T > 10$ GeV$/c$. A calorimeter isolation cut is imposed on the second lepton. We accept events if the reconstructed ee or $\mu\mu$ invariant mass is between 75 and

105 GeV$/c^2$. After this selection there are 6287 (2940) Z^0 events remaining in the electron (muon) data sample.

In order to optimize our sensitivity to a b' quark signal we make a jet selection that depends on the b' mass being considered. Hadronic jets are selected using a clustering algorithm [15] with a cone size of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$. Each event is required to have at least three jets within $|\eta| < 2.0$, two of which with $E_T > 15$ GeV. For b' masses above 120 GeV$/c^2$, the third jet is required to have $E_T > 15$ GeV. For $m_{b'} \leq 120$ GeV$/c^2$, the E_T requirement on the third jet is relaxed to $E_T > 7$ GeV since the b jets for b' masses near the $m_Z + m_b$ threshold have low momentum. We define the variable $\sum E_T^{\text{jets}}$ as the summed transverse energy of jets with $E_T > 15$ GeV and $|\eta| < 2.0$ and require this quantity to be larger than $m_{b'}c^2 - 60$ GeV. Figure 1 shows the $\sum E_T^{\text{jets}}$ distribution for e^+e^- and $\mu^+\mu^-$ events passing the three-jet requirement for b' masses above 120 GeV$/c^2$. Also shown are the distributions expected from SM background and from a b' quark with a mass of 150 GeV$/c^2$ (see below).

We further require at least one jet to be tagged as a b quark by the SVX b-tagging algorithm developed for the top quark analysis [16]. The number of events passing each major selection criterion for each leptonic channel is shown in Table I. One $\mu\mu$ event passes all our selection criteria for $m_{b'} \leq 120$ GeV$/c^2$. This event has a third jet with $E_T = 8.3$ GeV which fails the third-jet E_T requirement for larger b' masses.

The signal acceptance and detection efficiencies are estimated from a combination of data and Monte Carlo simulation. We have generated $b'\overline{b'} \rightarrow bZ^0\overline{b}Z^0$ Monte Carlo samples for different b' masses between 100 and 210 GeV$/c^2$ using the HERWIG program [17] with MRSD0$'$ structure functions [18]. One Z^0 is required to decay into muons or electrons while the other is allowed to decay through any available decay channel. The CLEO QQ Monte Carlo program [19] is used to model the decays of b hadrons. These events are passed through a simulation of the CDF detector and are subjected to the same selection requirements as the data.

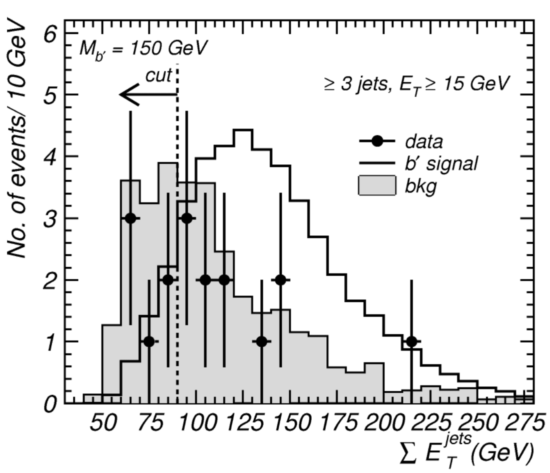

FIG. 1. $\sum E_T^{\text{jets}}$ distribution for events with at least 3 jets with $E_T > 15$ GeV and $|\eta| < 2$, before the b-tagging requirement. The expected SM background is shown shaded. The expected signal event distribution for a b' quark mass of 150 GeV$/c^2$ is shown as a solid line. The vertical dashed line represents the $\sum E_T^{\text{jets}}$ cut for this specific b' mass. Events to the right of this line are accepted.

The electron trigger efficiency is determined from data to be $(92 \pm 1)\%$, while the muon trigger efficiency per event $(82 \pm 4)\%$ is obtained from a combination of data and simulation. The efficiencies of the lepton identification cuts are determined using a $Z^0 \rightarrow e^+e^-$ $(\mu^+\mu^-)$ data sample with an unbiased selection on one of the leptons. The $Z^0 \rightarrow e^+e^-$ and $Z^0 \rightarrow \mu^+\mu^-$ geometric and kinematic acceptance was obtained from the HERWIG Monte Carlo program. The total Z^0 detection efficiency times acceptance, including the isolation efficiency, is $(41 \pm 3)\%$ for e^+e^- and $(30 \pm 3)\%$ for $\mu^+\mu^-$ and is nearly independent of the b' mass.

The event b-tag efficiency rises with $m_{b'}$ from 17% for $m_{b'} = 100$ GeV$/c^2$ to values between 50% and 57% for masses above 150 GeV$/c^2$. The total acceptance times efficiency, not including the $B(Z \rightarrow l^+l^-)$, increases from 1.7% (1.6%) to 14% (11%) for the electron (muon) channel as $m_{b'}$ increases from 100 to 210 GeV$/c^2$ (Table II). This increase is due to the fact that a more massive b' leads to a more central event with more energetic jets in which, in addition, the b-tag algorithm is more efficient.

The dominant systematic uncertainties on the acceptance times efficiency arise from the jet energy scale and gluon radiation [14]. By varying parameters in the Monte Carlo simulation we estimate that the systematic uncertainty due to the jet energy scale in the electron (muon) channel is 16% (14%) for $m_{b'} = 100$ GeV$/c^2$ and less than 13% for higher masses. The presence of gluon radiation increases the jet multiplicity and therefore increases the efficiency of the three-jet requirement. This effect is more pronounced at low b' mass because the b quarks from low-mass b' decay are produced near threshold and therefore are detected with low efficiency. We estimate the systematic uncertainty due to this effect to be 19% (18%) in the electron (muon) channel for $m_{b'} = 100$ GeV$/c^2$, and less than 9% for a heavier b'. Other important systematic uncertainties arise from the b-tag efficiency (10%), parton distribution function (5%), total integrated luminosity

TABLE I. Events observed in data after each main selection requirement in both the electron and the muon channels.

$m_{b'}$	$Z^0 \rightarrow e^+e^-$			$Z^0 \rightarrow \mu^+\mu^-$		
(GeV$/c^2$)	3 jets	$\sum E_T^{\text{jets}}$	b-tag	3 jets	$\sum E_T^{\text{jets}}$	b-tag
100	34	31	0	32	29	1
120	34	20	0	32	21	1
140	9	8	0	8	5	0
160	9	4	0	8	4	0
180	9	1	0	8	3	0
200	9	1	0	8	2	0

TABLE II. Total acceptance (A) times efficiency (ϵ) and relative systematic uncertainties ($\delta_{\rm total}$) in the electron and muon channels, 95% C.L. upper limit on the pair-production cross section times the branching ratio of $b' \to bZ^0$ squared, and theoretical pair-production cross section [20].

	$Z^0 \to e^+e^-$		$Z^0 \to \mu^+\mu^-$			
$m_{b'}$ (GeV/c^2)	$(A \times \epsilon)$ (%)	$\delta_{\rm total}$ (%)	$(A \times \epsilon)$ (%)	$\delta_{\rm total}$ (%)	$\sigma \times B^2_{95\%\,{\rm C.L.}}$ (pb)	$\sigma_{\rm theory}$ (pb)
100	1.7	29	1.6	27	37	102
110	4.6	21	4.2	21	11	61.6
120	7.6	20	6.4	19	6.5	38.9
130	8.2	19	6.8	19	3.8	25.4
140	9.9	19	8.3	19	3.1	16.9
150	11	19	9.2	19	2.8	11.7
160	12	19	9.8	19	2.6	8.16
170	12	19	10	19	2.5	5.83
180	13	19	10	19	2.4	4.21
190	13	19	11	19	2.4	3.06
200	13	19	11	19	2.4	2.26
210	14	19	11	19	2.3	1.68

(4.1%), lepton identification efficiency (4% for electrons, 5% for muons), isolation efficiency (4%), and trigger efficiency (1% for electrons, 5% for muons). The total uncertainty on the acceptance times efficiency is shown as a function of b' mass in Table II.

The only non-negligible background is from Z^0 events with associated QCD hadronic jets. This background is estimated using a combination of the VECBOS [21] and HERWIG Monte Carlo programs. VECBOS calculates the leading-order matrix elements for Z^0 + three partons events using the MRSD0$'$ structure functions [22]. A partial higher-order correction to the tree-level diagrams is obtained by including gluon radiation and hadronic fragmentation using HERWIG. These Z^0 events are then passed through a simulation of the CDF detector. We estimate the b-tag rate in Z^0 plus jet events directly from data using a technique developed for the top analysis [23]. We apply the b-tag rates measured in an inclusive jet sample to the Z^0 + jets events that pass all the other selection criteria. This method overestimates the background because the inclusive jet sample contains heavy-quark contributions that are not present in Z^0 + jets events. We expect approximately two background events for $m_{b'} \leq 120$ GeV/c^2 and less than one event for $m_{b'} > 120$ GeV/c^2, in agreement with the number of events observed in the data.

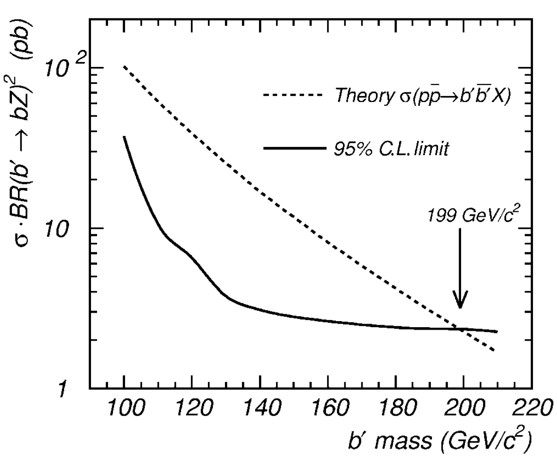

FIG. 2. The 95% confidence level upper limit on $p\overline{p} \to b'\overline{b'}X$ production cross section times the $b' \to bZ^0$ branching ratio squared (solid). The dashed curve shows the predicted $\sigma_{p\overline{p}\to b'\overline{b'}} \times [B(b' \to bZ^0)]^2$ with the NLO production cross section from Ref. [20] and $B(b' \to bZ^0) = 1$.

Under the assumption that the observed $\mu\mu$ event is from signal, that is, without subtracting background, we obtain a conservative 95% confidence level upper limit on the $\sigma_{p\overline{p}\to b'\overline{b'}} \times [B(b' \to bZ^0)]^2$. The limit is presented as a function of the b' mass in Table II. We have used a Bayesian method to calculate the limit and treat the number of expected signal events as a Poisson distribution convoluted with a Gaussian systematic uncertainty. Using the theoretical next-to-leading-order (NLO) b' pair production cross section [20] and assuming that $B(b' \to bZ^0)$ is 100%, we exclude at 95% confidence level b' masses from 100 to 199 GeV/c^2, as shown in Fig. 2. This search is also sensitive to other b' decay channels such as $b' \to bH$ or $b' \to cW^-$ as long as $B(b' \to bZ)$ is not negligible, since the hadronic decays of the H or W are kinematically similar to those of the Z. The acceptance for $b'\overline{b'} \to b\overline{b}ZH$ is 1.7 to 0.5 times the acceptance for $b'\overline{b'} \to b\overline{b}ZZ$, depending on the Higgs and b' masses and not including the $B(Z \to l^+l^-)$. However, if we conservatively assume no sensitivity to these decay modes, we exclude a b' mass from 104 to 152 GeV for $B(b' \to bZ) \geq 50\%$.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Science, Sports and Culture of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A. P. Sloan Foundation; and the Bundesministerium fuer Bildung und Forschung, Germany.

[1] W. J. Marciano, Phys. Rev. D **41**, 219 (1990); P. H. Frampton and D. Ng, *ibid.* **43**, 3034 (1991); P. Q. Hung, Phys. Rev. Lett. **80**, 3000 (1998); J. F. Gunion, D. W. McKay, and H. Pois, Phys. Rev. D **53**, 1616 (1996); V. Barger, M. S. Berger, and R. J. N. Phillips, *ibid.* **52**, 1663 (1995); M. Carena, H. E. Haber, and C. E. M. Wagner, Nucl. Phys. **B472**, 55 (1996); Z. Berezhiani and E. Nardi, Phys. Lett. B **355**, 199 (1995).
[2] P. Frampton, P. Q. Hung, and M. Sher, hep-ph/9903387, Phys. Rep. (to be published).
[3] V. Barger, R. J. N. Phillips, and A. Soni, Phys. Rev. Lett. **57**, 1518 (1986).
[4] W. S. Hou and R. G. Stuart, Nucl. Phys. **B320**, 277 (1989); Phys. Rev. Lett. **62**, 617 (1989).
[5] W. S. Hou and R. G. Stuart, Phys. Rev. D **43**, 3669 (1991).
[6] P. H. Frampton and P. Q. Hung, Phys. Rev. D **58**, 057704 (1998).
[7] K. Abe *et al.*, Phys. Rev. Lett. **63**, 1776 (1989); S. Eno *et al.*, *ibid.* **63**, 1910 (1989); G. S. Abrams *et al.*, *ibid.* **63**, 2447 (1989); I. Adachi *et al.*, Phys. Lett. B **234**, 197 (1990); D. Decamp *et al.*, *ibid.* **236**, 511 (1990); M. Z. Akrawy *et al.*, *ibid.* **246**, 285 (1990).
[8] S. Abachi *et al.*, Phys. Rev. Lett. **78**, 3818 (1997).
[9] F. Abe *et al.*, Phys. Rev. D **58**, 051102 (1998).
[10] S. Abachi *et al.*, Phys. Rev. D **52**, 4877 (1995).
[11] C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998).
[12] F. Abe *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **271**, 387 (1988); P. Azzi *et al.*, *ibid.* **360**, 137 (1995).
[13] The CDF coordinate system uses (θ, ϕ, z), where the proton beam is in the z direction and θ and ϕ are, respectively, the polar angle and the azimuthal angle. The transverse momentum of a particle is $p_T = p \sin\theta$.
[14] J. Guimarães da Costa, Ph.D. thesis, University of Michigan, 2000 (unpublished).
[15] F. Abe *et al.*, Phys. Rev. D **45**, 1448 (1992).
[16] F. Abe *et al.*, Phys. Rev. D **51**, 4623 (1995).
[17] G. Marchesini and B. R. Webber, Nucl. Phys. **B310**, 461 (1988); G. Marchesini *et al.*, Comput. Phys. Commun. **67**, 465 (1992).
[18] A. D. Martin, R. G. Roberts, and W. J. Stirling, Phys. Lett. B **306**, 145 (1993); **309**, 492(E) (1993).
[19] P. Avery, K. Read, and G. Trahern, Cornell Internal Note CSN-212, 1985 (unpublished).
[20] E. Laenen *et al.*, Phys. Lett. B **321**, 254 (1994); E. Laenen (private communication).
[21] F. A. Berends *et al.*, Nucl. Phys. **B357**, 32 (1991).
[22] The QCD renormalization and factorization scales are set by the $\langle p_T \rangle^2$ of the generated partons. The outgoing partons are generated with a minimum p_T of 6 GeV$/c$, $|\eta| < 2.5$, and $\Delta R > 0.4$ between partons.
[23] F. Abe *et al.*, Phys. Rev. D **50**, 2966 (1994); Phys. Rev. Lett. **73**, 225 (1994).