Search for a Fourth Generation Charge −1/3 Quark via Flavor Changing Neutral Current Decay

S. Abachi,[14] B. Abbott,[28] M. Abolins,[25] B. S. Acharya,[43] I. Adam,[12] D. L. Adams,[37] M. Adams,[17] S. Ahn,[14] H. Aihara,[22] G. A. Alves,[10] E. Amidi,[29] N. Amos,[24] E. W. Anderson,[19] R. Astur,[42] M. M. Baarmand,[42] A. Baden,[23] V. Balamurali,[32] J. Balderston,[16] B. Baldin,[14] S. Banerjee,[43] J. Bantly,[5] J. F. Bartlett,[14] K. Bazizi,[39] A. Belyaev,[26] S. B. Beri,[34] I. Bertram,[31] V. A. Bezzubov,[35] P. C. Bhat,[14] V. Bhatnagar,[34] M. Bhattacharjee,[13] N. Biswas,[32] G. Blazey,[30] S. Blessing,[15] P. Bloom,[7] A. Boehnlein,[14] N. I. Bojko,[35] F. Borcherding,[14] J. Borders,[39] C. Boswell,[9] A. Brandt,[14] R. Brock,[25] A. Bross,[14] D. Buchholz,[31] V. S. Burtovoi,[35] J. M. Butler,[3] W. Carvalho,[10] D. Casey,[39] H. Castilla-Valdez,[11] D. Chakraborty,[42] S.-M. Chang,[29] S. V. Chekulaev,[35] L.-P. Chen,[22] W. Chen,[42] S. Choi,[41] S. Chopra,[24] B. C. Choudhary,[9] J. H. Christenson,[14] M. Chung,[17] D. Claes,[27] A. R. Clark,[22] W. G. Cobau,[23] J. Cochran,[9] W. E. Cooper,[14] C. Cretsinger,[39] D. Cullen-Vidal,[5] M. A. C. Cummings,[16] D. Cutts,[5] O. I. Dahl,[22] K. De,[44] K. Del Signore,[24] M. Demarteau,[14] D. Denisov,[14] S. P. Denisov,[35] H. T. Diehl,[14] M. Diesburg,[14] G. Di Loreto,[25] P. Draper,[44] J. Drinkard,[8] Y. Ducros,[40] L. V. Dudko,[26] S. R. Dugad,[43] D. Edmunds,[25] J. Ellison,[9] V. D. Elvira,[42] R. Engelmann,[42] S. Eno,[23] G. Eppley,[37] P. Ermolov,[26] O. V. Eroshin,[35] V. N. Evdokimov,[35] T. Fahland,[8] M. Fatyga,[4] M. K. Fatyga,[39] J. Featherly,[4] S. Feher,[14] D. Fein,[2] T. Ferbel,[39] G. Finocchiaro,[42] H. E. Fisk,[14] Y. Fisyak,[7] E. Flattum,[25] G. E. Forden,[2] M. Fortner,[30] K. C. Frame,[25] S. Fuess,[14] E. Gallas,[44] A. N. Galyaev,[35] P. Gartung,[9] T. L. Geld,[25] R. J. Genik II,[25] K. Genser,[14] C. E. Gerber,[14] B. Gibbard,[4] S. Glenn,[7] B. Gobbi,[31] M. Goforth,[15] A. Goldschmidt,[22] B. Gómez,[1] G. Gomez,[23] P. I. Goncharov,[35] J. L. González Solís,[11] H. Gordon,[4] L. T. Goss,[45] A. Goussiou,[42] N. Graf,[4] P. D. Grannis,[42] D. R. Green,[14] J. Green,[30] H. Greenlee,[14] G. Grim,[7] N. Grossman,[14] P. Grudberg,[22] S. Grünendahl,[39] G. Guglielmo,[33] J. A. Guida,[2] J. M. Guida,[5] A. Gupta,[43] S. N. Gurzhiev,[35] P. Gutierrez,[33] Y. E. Gutnikov,[35] N. J. Hadley,[23] H. Haggerty,[14] S. Hagopian,[15] V. Hagopian,[15] K. S. Hahn,[39] R. E. Hall,[8] S. Hansen,[14] J. M. Hauptman,[19] D. Hedin,[30] A. P. Heinson,[9] U. Heintz,[14] R. Hernández-Montoya,[11] T. Heuring,[15] R. Hirosky,[15] J. D. Hobbs,[14] B. Hoeneisen,[1,*] J. S. Hoftun,[5] F. Hsieh,[24] Ting Hu,[42] Tong Hu,[18] T. Huehn,[9] A. S. Ito,[14] E. James,[2] J. Jaques,[32] S. A. Jerger,[25] R. Jesik,[18] J. Z.-Y. Jiang,[42] T. Joffe-Minor,[31] K. Johns,[2] M. Johnson,[14] A. Jonckheere,[14] M. Jones,[16] H. Jöstlein,[14] S. Y. Jun,[31] C. K. Jung,[42] S. Kahn,[4] G. Kalbfleisch,[33] J. S. Kang,[20] R. Kehoe,[32] M. L. Kelly,[32] C. L. Kim,[20] S. K. Kim,[41] A. Klatchko,[15] B. Klima,[14] C. Klopfenstein,[7] V. I. Klyukhin,[35] V. I. Kochetkov,[35] J. M. Kohli,[34] D. Koltick,[36] A. V. Kostritskiy,[35] J. Kotcher,[4] A. V. Kotwal,[12] J. Kourlas,[28] A. V. Kozelov,[35] E. A. Kozlovski,[35] J. Krane,[27] M. R. Krishnaswamy,[43] S. Krzywdzinski,[14] S. Kunori,[23] S. Lami,[42] H. Lan,[14,†] R. Lander,[7] F. Landry,[25] G. Landsberg,[14] B. Lauer,[19] A. Leflat,[26] H. Li,[42] J. Li,[44] Q. Z. Li-Demarteau,[14] J. G. R. Lima,[38] D. Lincoln,[24] S. L. Linn,[15] J. Linnemann,[25] R. Lipton,[14] Q. Liu,[14,†] Y. C. Liu,[31] F. Lobkowicz,[39] S. C. Loken,[22] S. Lökös,[42] L. Lueking,[14] A. L. Lyon,[23] A. K. A. Maciel,[10] R. J. Madaras,[22] R. Madden,[15] L. Magaña-Mendoza,[11] S. Mani,[7] H. S. Mao,[14,†] R. Markeloff,[30] L. Markosky,[2] T. Marshall,[18] M. I. Martin,[14] B. May,[31] A. A. Mayorov,[35] R. McCarthy,[42] J. McDonald,[15] T. McKibben,[17] J. McKinley,[25] T. McMahon,[33] H. L. Melanson,[14] M. Merkin,[26] K. W. Merritt,[14] H. Miettinen,[37] A. Mincer,[28] J. M. de Miranda,[10] C. S. Mishra,[14] N. Mokhov,[14] N. K. Mondal,[43] H. E. Montgomery,[14] P. Mooney,[1] H. da Motta,[10] C. Murphy,[17] F. Nang,[2] M. Narain,[14] V. S. Narasimham,[43] A. Narayanan,[2] H. A. Neal,[24] J. P. Negret,[1] P. Nemethy,[28] D. Nešić,[5] M. Nicola,[10] D. Norman,[45] L. Oesch,[24] V. Oguri,[38] E. Oltman,[22] N. Oshima,[14] D. Owen,[25] P. Padley,[37] M. Pang,[19] A. Para,[14] Y. M. Park,[21] R. Partridge,[5] N. Parua,[43] M. Paterno,[39] J. Perkins,[44] M. Peters,[16] H. Piekarz,[15] Y. Pischalnikov,[36] V. M. Podstavkov,[35] B. G. Pope,[25] H. B. Prosper,[15] S. Protopopescu,[4] D. Pušeljić,[22] J. Qian,[24] P. Z. Quintas,[14] R. Raja,[14] S. Rajagopalan,[4] O. Ramirez,[17] P. A. Rapidis,[14] L. Rasmussen,[42] S. Reucroft,[29] M. Rijssenbeek,[42] T. Rockwell,[25] N. A. Roe,[22] P. Rubinov,[31] R. Ruchti,[32] J. Rutherfoord,[2] A. Sánchez-Hernández,[11] A. Santoro,[10] L. Sawyer,[44] R. D. Schamberger,[42] H. Schellman,[31] J. Sculli,[28] E. Shabalina,[26] C. Shaffer,[15] H. C. Shankar,[43] R. K. Shivpuri,[13] M. Shupe,[2] H. Singh,[9] J. B. Singh,[34] P. Singh,[30] V. Sirotenko,[30] W. Smart,[14] A. Smith,[2] R. P. Smith,[14] R. Snihur,[31] G. R. Snow,[27] J. Snow,[33] S. Snyder,[4] J. Solomon,[17] P. M. Sood,[34] M. Sosebee,[44] N. Sotnikova,[26] M. Souza,[10] A. L. Spadafora,[22] R. W. Stephens,[44] M. L. Stevenson,[22] D. Stewart,[24] D. A. Stoianova,[35] D. Stoker,[8] M. Strauss,[33] K. Streets,[28] M. Strovink,[22] A. Sznajder,[10] P. Tamburello,[23] J. Tarazi,[8] M. Tartaglia,[14] T. L. T. Thomas,[31] J. Thompson,[23] T. G. Trippe,[22] P. M. Tuts,[12] N. Varelas,[25] E. W. Varnes,[22] D. Vititoe,[2] A. A. Volkov,[35] A. P. Vorobiev,[35] H. D. Wahl,[15] G. Wang,[15] J. Warchol,[32] G. Watts,[5] M. Wayne,[32] H. Weerts,[25]

 0031-9007/97/78(20)/3818(6)$10.00

A. White,[44] J. T. White,[45] J. A. Wightman,[19] S. Willis,[30] S. J. Wimpenny,[9] J. V. D. Wirjawan,[45] J. Womersley,[14] E. Won,[39] D. R. Wood,[29] H. Xu,[5] R. Yamada,[14] P. Yamin,[4] C. Yanagisawa,[42] J. Yang,[28] T. Yasuda,[29] P. Yepes,[37] C. Yoshikawa,[16] S. Youssef,[15] J. Yu,[14] Y. Yu,[41] Q. Zhu,[28] Z. H. Zhu,[39] D. Zieminska,[18] A. Zieminski,[18] E. G. Zverev,[26] and A. Zylberstejn[40]

(DØ Collaboration)

[1]*Universidad de los Andes, Bogotá, Colombia*
[2]*University of Arizona, Tucson, Arizona 85721*
[3]*Boston University, Boston, Massachusetts 02215*
[4]*Brookhaven National Laboratory, Upton, New York 11973*
[5]*Brown University, Providence, Rhode Island 02912*
[6]*Universidad de Buenos Aires, Buenos Aires, Argentina*
[7]*University of California, Davis, California 95616*
[8]*University of California, Irvine, California 92717*
[9]*University of California, Riverside, California 92521*
[10]*LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[11]*CINVESTAV, Mexico City, Mexico*
[12]*Columbia University, New York, New York 10027*
[13]*Delhi University, Delhi, India 110007*
[14]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[15]*Florida State University, Tallahassee, Florida 32306*
[16]*University of Hawaii, Honolulu, Hawaii 96822*
[17]*University of Illinois at Chicago, Chicago, Illinois 60607*
[18]*Indiana University, Bloomington, Indiana 47405*
[19]*Iowa State University, Ames, Iowa 50011*
[20]*Korea University, Seoul, Korea*
[21]*Kyungsung University, Pusan, Korea*
[22]*Lawrence Berkeley Laboratory and University of California, Berkeley, California 94720*
[23]*University of Maryland, College Park, Maryland 20742*
[24]*University of Michigan, Ann Arbor, Michigan 48109*
[25]*Michigan State University, East Lansing, Michigan 48824*
[26]*Moscow State University, Moscow, Russia*
[27]*University of Nebraska, Lincoln, Nebraska 68588*
[28]*New York University, New York, New York 10003*
[29]*Northeastern University, Boston, Massachusetts 02115*
[30]*Northern Illinois University, DeKalb, Illinois 60115*
[31]*Northwestern University, Evanston, Illinois 60208*
[32]*University of Notre Dame, Notre Dame, Indiana 46556*
[33]*University of Oklahoma, Norman, Oklahoma 73019*
[34]*University of Panjab, Chandigarh 16-00-14, India*
[35]*Institute for High Energy Physics, 142-284 Protvino, Russia*
[36]*Purdue University, West Lafayette, Indiana 47907*
[37]*Rice University, Houston, Texas 77005*
[38]*Universidade Estadual do Rio de Janeiro, Brazil*
[39]*University of Rochester, Rochester, New York 14627*
[40]*CEA, DAPNIA/Service de Physique des Particules, CE-SACLAY, France*
[41]*Seoul National University, Seoul, Korea*
[42]*State University of New York, Stony Brook, New York 11794*
[43]*Tata Institute of Fundamental Research, Colaba, Bombay 400005, India*
[44]*University of Texas, Arlington, Texas 76019*
[45]*Texas A&M University, College Station, Texas 77843*

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We report on a search for pair production of a fourth generation charge $-1/3$ quark (b') in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV by the DØ experiment at the Fermilab Tevatron using an integrated luminosity of 93 pb^{-1}. Both b' quarks are assumed to decay via flavor changing neutral currents (FCNC). The search uses the signatures $\gamma + 3$ jets $+\mu$-tag and $2\gamma + 2$ jets. We see no significant excess of events over the expected background. We place an upper limit on the production cross section times branching fraction that is well below theoretical expectations for a b' decaying exclusively via FCNC for b' masses up to $m_Z + m_b$. [S0031-9007(97)03177-3]

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The existence of three generations of quarks and leptons is well established in the standard model. There is no strong expectation of additional quark and lepton generations in an extended standard model, nor are additional generations ruled out. Several models with new generations or arguments favoring new generations have been presented [1]. In this paper, the DØ experiment reports on a search for pair production of a fourth generation charge $-1/3$ quark (b') that decays via flavor changing neutral currents (FCNC) in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron. While most standard model FCNC processes are highly suppressed, it is plausible that a light b' quark (i.e., $m_{b'} < m_t$ and $m_{b'} < m_{t'}$) could decay predominantly via FCNC if, as expected, the charged current decay of a light b' quark to a charm quark is highly suppressed by a fourth generation extension of the CKM matrix [2]. The condition for FCNC dominance is roughly $|V_{cb'}/V_{t'b}| < 10^{-2}$ to 10^{-3}, depending on the mass of the b' and t' quarks. Several e^+e^- collider experiments have explicitly searched for b' quarks decaying via FCNC [3], but until now there have been no searches for b' quarks that decay via FCNC at hadron colliders [4]. The current mass limit on a b' quark that decays via FCNC is the LEP I limit of half the Z boson mass [5].

The data used in this search were collected with the DØ detector during the 1992–1995 Tevatron collider run and represent an integrated luminosity of 93 pb^{-1}.

We assume that b' quarks are pair produced with the same cross section, for a given mass, as the top quark [6]. We consider the signatures $b'\overline{b}' \to \gamma g b\overline{b}$ and $b'\overline{b}' \to \gamma\gamma b\overline{b}$, in which the photons are observed directly and b quarks and gluons are observed as hadronic jets. For the single photon signature, we require that one of the jets be identified as a b quark jet ("b-tagged") by the presence near the jet of a muon from semileptonic decay of the b quark. For the diphoton signature, we do not require that either jet be b-tagged. We assume that b' quarks decay 100% of the time via FCNC with the relative FCNC branching fractions determined by the standard model [7], which are 13% for the single photon signature and 1.6% for the diphoton signature for a b' quark of mass 80 GeV/c^2. We have not included the contribution of three-body hadronic FCNC decay modes, such as $b' \to bq\overline{q}$, in the single photon acceptance calculation or in any quoted theoretical branching fractions. The acceptance for such modes is only slightly lower than for the two-body decay $b' \to bg$. If three-body hadronic decay modes were included in the acceptance calculation for the single photon signature, the acceptance times branching fraction might increase by 30%–50%, but with considerable theoretical uncertainty. For b' masses above $m_Z + m_b$, the decay channel $b' \to Z + b$ is expected to dominate other FCNC decay processes. Thus, the sensitivity of the photon decay channels is limited to b' masses where the Z boson decay channel is not open.

The DØ detector is described in detail in Ref. [8]. The detector consists of an iron toroid muon spectrometer, a uranium-liquid argon calorimeter, and a nonmagnetic central tracking volume containing drift chambers, a vertex chamber, and a transition radiation detector. Jets are reconstructed using a cone algorithm with radius $\mathcal{R} = 0.5$ in η-ϕ space, where η is pseudorapidity [$\eta = \tanh^{-1}(\cos\theta)$], and θ, ϕ are the polar and azimuthal angles in a laboratory coordinate system with the polar axis parallel to the beam. Muons are identified by reconstructed tracks in the muon spectrometer. Muons used for b-tagging are required to have transverse momentum $p_T > 4$ GeV/c relative to the beam axis $|\eta| < 1.1$ and to be within $\Delta\mathcal{R} < 0.5$ of a jet axis in η-ϕ space. Photon candidates are identified by the longitudinal and transverse shower shape of isolated calorimeter energy clusters and by the absence of central tracking chamber hits between the calorimeter cluster and the event vertex [9]. The photon isolation requirement is that the energy in an annular isolation cone from radius 0.2 to 0.4 in η-ϕ space be less than 10% of the photon energy.

In addition to requiring the requisite number of photons, jets, and b-tagging muons, both analyses place a cut on the quantity H_T, which is defined as the scalar sum of the transverse energies (E_T's) of the photons, jets, and any b-tagging muons in the event. Both analyses require $H_T \geq 1.6 m_{b'}$. Note that the H_T cut depends on the b' mass hypothesis. The value of the H_T cut is set to maximize expected significance, defined as acceptance divided by the square root of the expected background. The cuts used by the two analyses are summarized in Table I.

The acceptance is calculated using the HERWIG event generator [10] with a detector simulation based on the GEANT program [11]. We assign a 10% systematic error to the calculated acceptance based on comparisons between the HERWIG and ISAJET event generators [12]. The calculated acceptance for the two channels is listed in Tables II and III, respectively.

TABLE I. Kinematic cuts used in the $\gamma + 3$ jets and $2\gamma + 2$ jets analyses (energies in GeV).

	Photons			Jets				
Channel	N	$E_{T\,\min}$	$\|\eta\|_{\max}$	$N_{\min}$	$E_{T\,\min}$	$\|\eta\|_{\max}$	b-tag	$H_{T\,\min}$
$\gamma + 3$ j	1	20	1	3	15	2	yes	1.6 $m_{b'}$
$2\gamma + 2$ j	2	20	2	2	15	2.5	no	1.6 $m_{b'}$

TABLE II. The acceptance, the numbers of expected and observed events, and the measured cross section as a function of b' mass in the γ + 3 jets channel. The acceptance includes the muon semileptonic branching fraction of the b quark. The integrated luminosity is 93 pb^{-1}.

$m_{b'}$ (GeV/c^2)	Acceptance (%)	Observed signal	Events Expected ($B = 13\%$)	Expected background	$\sigma_{b'\overline{b}'} \times B(b'\overline{b}' \to \gamma g b \overline{b})$ (pb) Value	Upper limit (95% C.L.)
50	0.38 ± 0.07	71	166 ± 33	63.1 ± 6.3	22.1 ± 30.1	75.3
60	0.64 ± 0.12	70	115 ± 22	60.0 ± 6.0	17.0 ± 17.8	47.8
70	1.10 ± 0.19	60	87 ± 16	53.4 ± 5.3	6.5 ± 9.3	23.1
80	1.45 ± 0.25	46	57 ± 10	45.4 ± 4.6	0.4 ± 6.1	12.2
90	1.68 ± 0.29	30	35 ± 6	37.4 ± 3.8	−4.8 ± 4.4	6.0
100	2.16 ± 0.36	23	26 ± 5	30.1 ± 3.1	−3.5 ± 2.9	3.9
120	2.88 ± 0.46	14	13 ± 2	18.7 ± 1.9	−1.8 ± 1.6	2.2
140	3.50 ± 0.55	9	7 ± 1	12.0 ± 1.3	−1.0 ± 1.0	1.5

The primary backgrounds to the single photon channel are QCD direct photon plus multijet production and QCD multijet production with one jet misidentified as a photon. Other backgrounds that are considered are $W\gamma$ and $Z\gamma$ production with the gauge bosons decaying to quarks, and W ($\to e\nu$) + jets and Z ($\to ee$) + jets production with one electron misidentified as a photon and the second electron, if any, identified as a jet. The sum of the direct photon and multijet backgrounds is calculated using the tag rate method, in which untagged γ + 3 jet events are weighted by a per jet b-tagging probability measured in multijet (≥4 jet) data [13]. Figure 1(a) shows a test of the b-tag rate in "bad γ" + 3 jets events, in which the photon has failed one of the photon identification cuts. There is good agreement between the actual and predicted number of b-tagged bad γ + 3 jets events. We have verified that our parametrized b-tag rate is able to reproduce our observed b-tag rate in a variety of data samples within an estimated uncertainty of 10%. The estimated background obtained using the tag rate method is 62.8 ± 6.3 events before the H_T cut. The diboson background, which is expected to generate b-tags in excess of the tag rate, is estimated by a Monte Carlo calculation to be 0.7 ± 0.4 events. The total W ($\to e\nu$) + jets and Z ($\to ee$) + jets background is estimated to be 0.1 ± 0.1 events and is not included in the subtracted background. The total expected background before the H_T cut is 63.4 ± 6.3 events. We observe 71 data events. The H_T distributions of data, expected background, and expected signal are shown in Fig. 1(b).

The primary backgrounds to the diphoton channel are QCD multijet production, with two jets misidentified as photons and single direct photon plus jets production, with one jet misidentified as a photon. Other less important backgrounds are double direct photon + jets production and Z ($\to ee$) + jets events where both electrons are misidentified as photons. The sum of the single and double fake photon backgrounds is estimated from the observed number of data events having the signature photon + highly electromagnetic jet + two or more jets. The background is calculated using the measured probability for a highly electromagnetic jet to be misidentified as a photon. The background calculation includes a combinatoric correction factor of $\frac{1}{2}(1 + \mathcal{P})$, where $\mathcal{P}$ is the photon purity, which in this sample is estimated to be 38 ± 16% [9]. The sum of the two fake backgrounds is estimated to be 14.5 ± 2.2 events before the H_T cut. The double direct photon background is estimated by Monte Carlo calculation to be 1.2 ± 0.6 events. The Z ($\to ee$) + jets background is estimated to be 0.1 ± 0.1 events and is not included in the subtracted background. The total expected background before the H_T cut is 15.7 ± 2.3 events. We

TABLE III. The acceptance, the numbers of expected and observed events, and the measured cross section as a function of b' mass in the 2γ + 2 jets channel. The integrated luminosity is 79 pb^{-1}.

$m_{b'}$ (GeV/c^2)	Acceptance (%)	Observed signal	Events Expected ($B = 1.6\%$)	Expected background	$\sigma_{b'\overline{b}'} \times B(b'\overline{b}' \to \gamma\gamma b \overline{b})$ (pb) Value	Upper limit (95% C.L.)
50	2.76 ± 0.40	20	126 ± 20	15.5 ± 2.3	2.03 ± 2.33	6.11
60	5.31 ± 0.71	18	101 ± 15	14.1 ± 2.1	0.91 ± 1.14	2.91
70	8.19 ± 1.08	15	68.3 ± 9.7	11.0 ± 1.7	0.61 ± 0.66	1.76
80	10.45 ± 1.37	11	42.9 ± 6.1	8.4 ± 1.3	0.31 ± 0.44	1.08
90	11.90 ± 1.52	8	26.3 ± 3.6	6.2 ± 1.0	0.18 ± 0.32	0.76
100	13.23 ± 1.52	6	16.5 ± 2.3	4.4 ± 0.8	0.15 ± 0.25	0.59
120	15.73 ± 2.00	3	7.5 ± 1.0	2.4 ± 0.5	0.05 ± 0.15	0.32
140	16.28 ± 2.06	3	3.4 ± 0.5	1.5 ± 0.4	0.11 ± 0.14	0.36

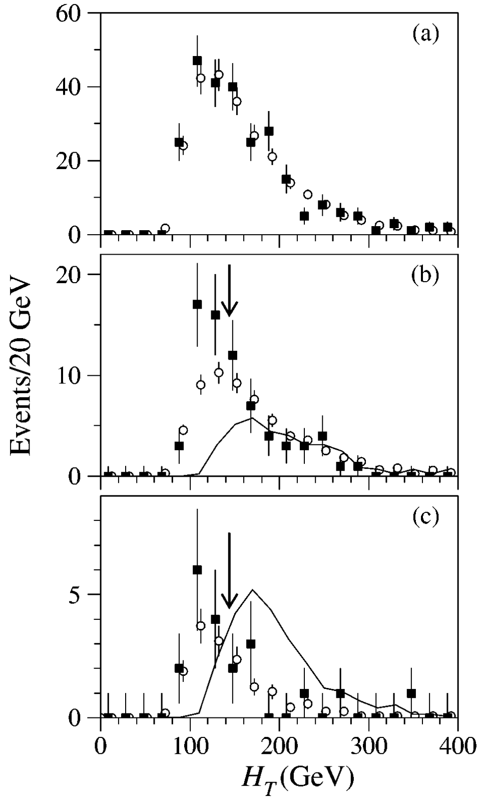

FIG. 1. H_T distributions of data (filled squares), expected background (open circles), and expected signal for 90 GeV/c^2 b' (curves) in the channels (a) "bad γ" + 3 jets, (b) γ + 3 jets, and (c) 2γ + 2 jets.

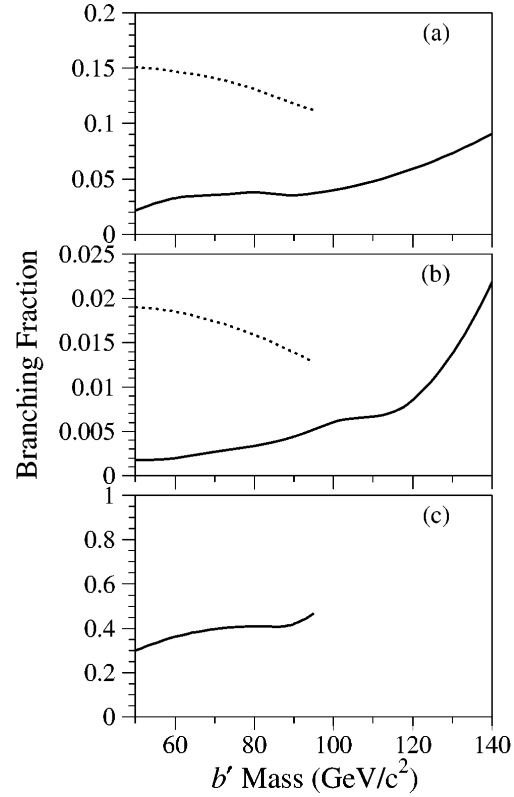

FIG. 2. Measured 95% confidence level upper limit on the branching fraction (solid line) and theoretical branching fraction (dotted line) for (a) $b'\overline{b}' \to \gamma + 3$ jets, (b) $b'\overline{p}' \to 2\gamma + 2$ jets, and (c) the total FCNC branching fraction of b'. The theoretical and FCNC branching fraction curves end at $m_{b'} = m_Z + m_b$ due to the opening of the Z boson FCNC decay channel.

observe 20 data events. The H_T distributions of data and expected background are shown in Fig. 1(c).

The acceptance, the number of data events, the expected signal and background, including the effect of the variable H_T cut, and the calculated cross section times branching fraction are shown in Tables II and III. The 95% confidence level (C.L.) upper limit on the cross section times branching fraction is calculated using Gaussian errors excluding the unphysical negative cross section region. Using the theoretical production cross section of Laenen *et al.* [6], including the quoted theoretical uncertainty, we derive an upper limit on the branching fraction for each of the two channels. The 95% confidence level upper limit for both channels is shown in Figs. 2(a) and 2(b). Using the theoretical relative FCNC branching fractions of Ref. [7], we derive an upper limit on the total FCNC branching fraction of the b' quark for both channels individually and combined [Fig. 2(c)]. For both channels the upper limit on the branching fraction is well below the theoretical branching fraction for a b' quark that decays 100% of the time via FCNC. The upper limit on the total FCNC branching fraction of the b' quark is less than 50%, for all masses up to $m_Z + m_b$, at which point the Z boson decay channel opens up.

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*Visitor from Universidad San Francisco de Quito, Ecuador.

†Visitor from IHEP, Beijing, China.

[1] G. Bhattacharyya and R.N. Mohapatra, Phys. Rev. D **54**, 4204 (1996); J.F. Gunion, D.W. McKay, and H. Pois, Phys. Rev. D **53**, 1616 (1996); 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); A. Çelikel, A.K. Çiftçi, and S. Sultansoy, Phys. Lett. B **342**, 257 (1995); N. Evans, Phys. Lett. B **340**, 81 (1994); F. Potter, Int. J. Theor. Phys. **33**, 279 (1994).

[2] W.S. Hou and R.G. Stuart, Phys. Rev. Lett. **62**, 617 (1989); W.S. Hou and R.G. Stuart, Nucl. Phys. **B320**, 277 (1989).

[3] VENUS Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **63**, 1776 (1989); AMY Collaboration, S. Eno *et al.*, Phys. Rev. Lett. **63**, 1910 (1989); TOPAZ Collaboration, I. Adachi *et al.*, Phys. Lett. B **234**, 197 (1990); Mark II Collaboration, G. S. Abrams *et al.*, Phys. Rev. Lett. **63**, 2447 (1989); ALEPH Collaboration, D. Decamp *et al.*, Phys. Lett. B **236**, 511 (1990); OPAL Collaboration, M. Z. Akrawy *et al.*, Phys. Lett. B **246**, 285 (1990).
[4] See, however, B. Mukhopadhyaya and D. P. Roy, Phys. Rev. D **48**, 2105 (1993).
[5] DELPHI Collaboration, P. Abreu *et al.*, Nucl. Phys. **B367**, 511 (1991); L3 Collaboration, O. Adriani *et al.*, Phys. Rep. **236**, 1 (1993); LEP references from Ref. [3].
[6] E. Laenen, J. Smith, and W. van Neerven, Phys. Lett. B **321**, 254 (1994); E. Berger and H. Contopanagos, Phys. Lett. B **361**, 115 (1995); Phys. Rev. D **54**, 3085 (1996); S. Catani, M. L. Mangano, P. Nason, and L. Trentadue, Phys. Lett. B **378**, 329 (1996).
[7] P. Agrawal and W. S. Hou, Phys. Rev. D **46**, 1022 (1992).
[8] DØ Collaboration, S. Abachi *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **338**, 185 (1994).
[9] DØ Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **77**, 5011 (1996).
[10] G. Marchesini *et al.*, Comput. Phys. Commun. **67**, 465 (1992).
[11] F. Carminati *et al.*, "GEANT Users Guide," CERN Program Library, 1991 (unpublished).
[12] F. Paige and S. Protopopescu, BNL Report No. BNL38034, 1986 (unpublished), release v 6.49.
[13] DØ Collaboration, S. Abachi *et al.*, Phys. Rev. D **52**, 4877 (1995).