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

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Abstract

We report on a search for pair production of a fourth generation charge $-1/3$ quark (b') in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron using an integrated luminosity of 93 pb^{-1}. Both 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 $m_Z + m_b$.

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, we report on a search for pair production of a fourth generation charge $-1/3$ quark (b') that decays via flavor changing neutral currents (FCNC) in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron. While most Standard Model FCNC processes are highly suppressed, it is quite 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 four-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 $b'\bar{b}' \rightarrow \gamma g b\bar{b}$ and $b'\bar{b}' \rightarrow \gamma\gamma b\bar{b}$, in which the photons are observed directly and b quarks and gluons are observed as hadronic jets. In the case of the single photon signature, we require that one of the b quark jets have a soft muon tag. 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 three-body hadronic FCNC decay modes, such as $b' \rightarrow bq\bar{q}$, 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 $b' \rightarrow bg$. 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 $b' \rightarrow Z + b$ 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 non-magnetic 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 and ϕ is the azimuthal angle. Muons are identified by reconstructed tracks in the muon spectrometer. Muons used for b-tagging are required to have $p_T > 4$ GeV/c, $|\eta| < 1.1$, 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 tracking chamber hits in the central tracking volume 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 explicitly 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]. The calculated acceptance for the two channels is listed in Tables II and III, respectively.

We find 71 events before the H_T cut in the single photon analysis. 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 and W and Z bosons decaying to electron(s) with one electron misidentified as a photon. 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. 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 data and background. 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 background from W and Z bosons decaying to electrons that are misidentified as photons 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. The H_T distributions of data and expected background are shown in Fig. 1(b). There is a slight, but not statistically significant, excess of data over background.

We find 20 events before the H_T cut in the diphoton channel. 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 $Z \rightarrow ee$ events where both electrons are misidentified as photons. The sum of the two fake photon backgrounds is estimated from the measured probability for a jet to be misidentified as the second photon in single photon candidate plus three jet events, corrected for the fraction of photon candidates that are actually photons (the photon purity) of the first photon. The purity of the first photon in the $2\gamma + 2$ jet sample is estimated to be $38 \pm 16\%$ [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 $Z \rightarrow ee$ 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. There is again a slight, but not statistically significant, excess of data over background. 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 (CL) 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 (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. The combined upper limit on the FCNC branching fraction of the b' quark is shown in 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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FIGURES

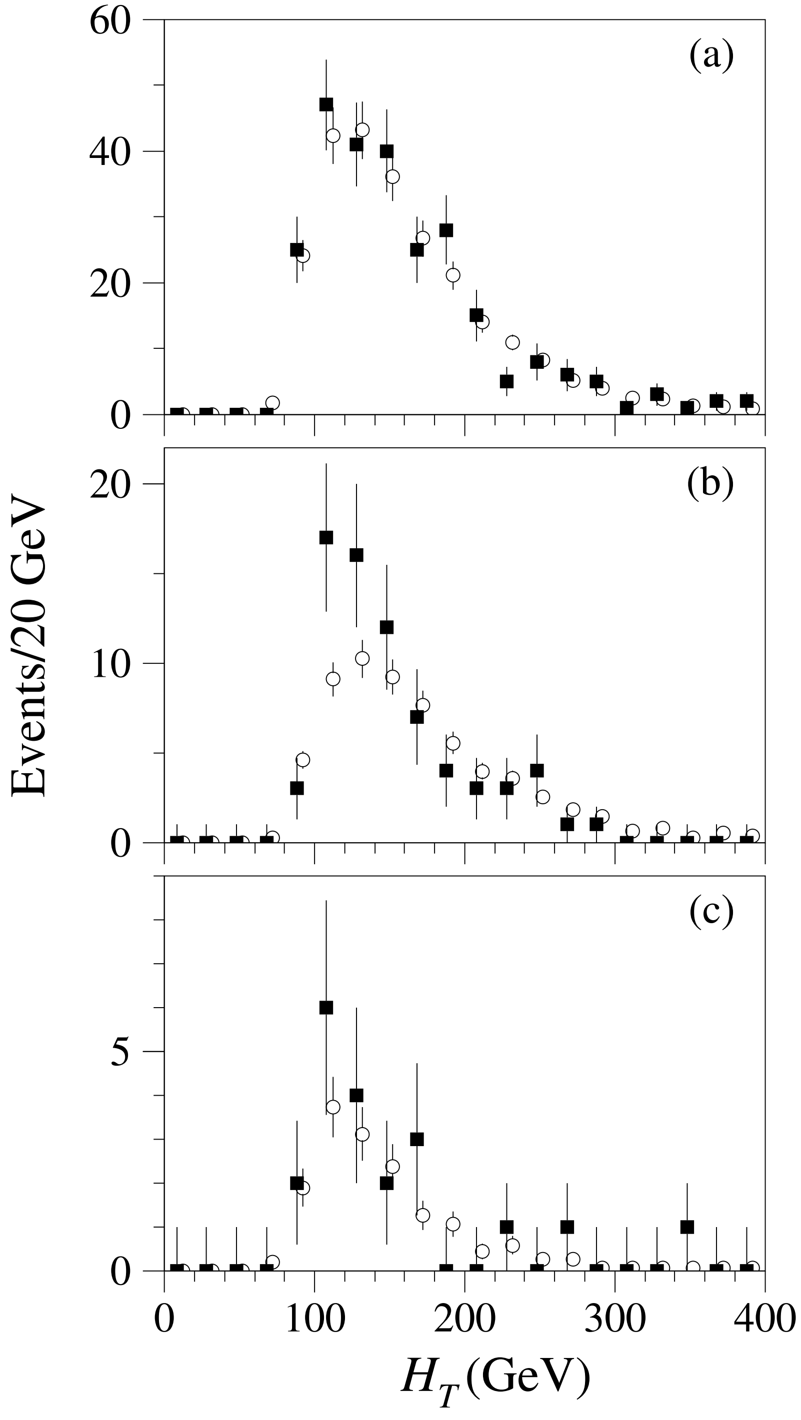

FIG. 1. H_T distributions of data (filled squares) and expected background (open circles) in the channels (a) "bad γ" + 3 jets, (b) γ + 3 jets, and (c) 2γ + 2 jets.

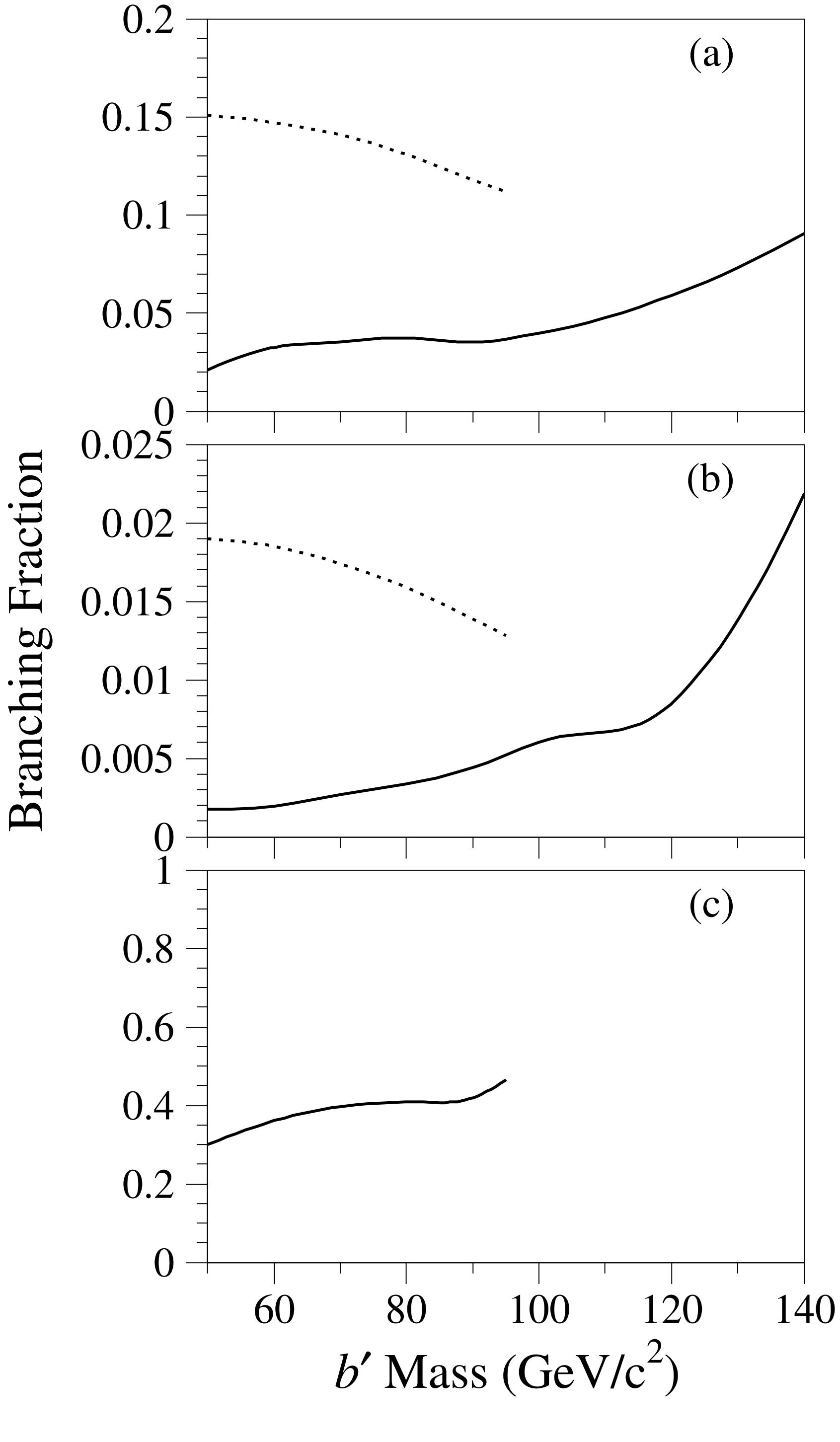

FIG. 2. Measured 95% confidence level upper limit on the branching fraction (solid line) and theoretical branching fraction (dotted line) for (a) $b'\bar{b}' \to \gamma + 3$ jets, (b) $b'\bar{b}' \to 2\gamma + 2$ jets, and (c) the total FCNC branching fraction of b'. The theoretical and FCNC branching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

TABLES

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

Channel	Photons N	Photons $E_{T\min}$	Photons $\|\eta\|_{\max}$	Jets $N_{\min}$	Jets $E_{T\min}$	Jets $\|\eta\|_{\max}$	b-tag	$H_{T\min}$
γ + 3 j	1	20	1	3	15	2	yes	1.6 $m_{b'}$
2γ + 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 $\gamma + 3$ jets channel. The acceptance includes the muon semileptonic branching fraction of the b quark. The integrated luminosity is 93 pb^{-1}.

$m_{b'}$	Acceptance	Events			$\sigma_{b'\bar{b}'} \times B(b'\bar{b}' \to \gamma g b\bar{b})$ (pb)	
			Expected	Expected		Upper limit
(GeV/c^2)	(%)	Observed	Signal ($B = 13\%$)	Background	Value	(95% CL)
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

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

$m_{b'}$	Acceptance	Events			$\sigma_{b'\bar{b}'} \times B(b'\bar{b}' \to \gamma\gamma b\bar{b})$ (pb)	
			Expected	Expected		Upper limit
(GeV/c^2)	(%)	Observed	Signal ($B = 1.6\%$)	Background	Value	(95% CL)
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 ± 1.68	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