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

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There is some likelihood that a light ($< m_t$) fourth generation charge −1/3 quark (b') would decay predominantly via loop induced flavor changing neutral currents. The charged current decay of b' to charm would be highly Cabibbo suppressed due to the fact that it changes the generation number by two. The DØ experiment has searched for b' pair production where one or both b' quarks decays via $b' \to b + \gamma$, giving signatures photon + three jets and two photons + two jets. We do not see a significant excess of such events over background. In both modes, we set an upper limit on the cross section times branching ratio that is sufficient to rule out a standard sequential b' decaying predominantly via FCNC in the mass range $m_Z/2 < m_{b'} < m_Z + m_b$. For b' masses larger than this, the dominant FCNC decay mode is expected to be $b' \to b + Z$.

Standard sequential fourth generation quarks (b', t') are pair-produced by the strong interaction with the same cross section, for a given mass, as the top quark [1,2,3]. Standard Model weak decays of either quark can proceed via the charged current (CC) or the loop-induced flavor changing current (FCNC) weak interaction. Ordinarily, FCNC decay modes are far weaker than corresponding CC decay modes, but b' decay may be an exception [4]. If the b' quark is lighter than both the t and t' quark, then the CC decay to either quark is kinematically forbidden. In that case, the dominant CC decay mechanism of b' is to the charm quark, which is Cabibbo suppressed due to changing the generation number by two. The relative strength of b' CC and FCNC decay will depend on the details of the CKM matrix and the t, b' and t' quark masses.

The FCNC scenario is relatively unconstrained by experiment. Until now, direct searches for FCNC b' quark decay signatures have been carried out only at e^+e^- colliders [5]. The LEP I data have ruled out b' with masses up to $m_Z/2$ regardless of the decay mode [6]. An indirect limit on the existence of fourth generation quarks comes from the ρ parameter ($\rho = m_W^2/(m_Z^2 \cos^2\theta_W)$). In the Standard Model, radiative corrections generate a positive contribution to ρ from each non-degenerate weak isodoublet [7]. Most of the known deviation of ρ from unity is accounted for by the large m_b-m_t mass splitting. Any additional positive contributions to $\Delta\rho$ from fourth generation quarks and leptons, or

Table 1: Calculated FCNC branching ratios of the b' quark for $m_{b'} = 80$ GeV.

Decay Mode	Branching Ratio (%)
$b' \to b\gamma$	12.6
$b' \to bg$	52.1
$b' \to be^+e^-$	1.3
$b' \to b\nu\bar{\nu}$	7.8
$b' \to bq\bar{q}$	26.2

other new particles, are limited according to the following equation [7]:

$$m_t^2 + \sum_i \frac{C_i}{3} \Delta m_i^2 \leq (210 \text{ GeV})^2 \quad (95\% \text{ CL}), \tag{1}$$

where the sum is over flavors of new particles and C_i is a color factor (*i.e.* $C_i = 3$ for quarks).

The FCNC decay modes of the b' quark are generally to a b quark and a gauge boson or fermion pair. In the present analysis we consider only modes where b' decays to a b quark and either a photon or a gluon. Some calculated branching ratios are listed in Table 1 for $m_{b'} = 80$ GeV [8]. For sufficiently heavy b' the decay mode $b' \to bZ$ is expected to dominate other modes.

The DØ detector and data collection systems are described in Ref. 9. Muons are detected and momentum-analyzed using an iron toroid spectrometer located outside of a uranium-liquid argon calorimeter and a non-magnetic central tracking system inside the calorimeter. The muons used for b-tagging are required to be within distance $\Delta\mathcal{R} < 0.5$ of any jet axis in η-ϕ space. Photons are identified by their longitudinal and transverse shower profile in the calorimeter and by the absence of matching tracking chamber hits along a road between the calorimeter cluster and any reconstructed vertex. Jets are reconstructed using a cone algorithm of radius $\mathcal{R} = 0.5$ in η-ϕ space.

Analyses were carried out to search for the two final state signatures $\gamma + 3$ jets and $2\gamma + 2$ jets, which occur when one or both b' quarks decay via $b' \to b\gamma$. In the case of the single photon signature, the second b' quark is assumed to decay via $b' \to bg$. A soft muon b tag is required in the case of the single photon signature. The acceptances for both channels were calculated using the ISAJET version 7.14 event generator. The integrated luminosities are 90 pb^{-1} for the single photon channel and 77 pb^{-1} for the diphoton channel.

The two main backgrounds to the $\gamma + 3$ jets mode are high-p_T photon + multijet production and multijet production with a fake photon. Less im-

Table 2: The number of expected and observed photon + three jet events as a function of b' mass.

$m_{b'}$ (GeV/c^2)	Events			$\sigma_{b'\bar{b}'} \times BR$ (pb)	
	Observed	Expected Signal	Expected Background	Value	Upper limit (95% CL)
50	71	134 ± 31	59 ± 11	43.1 ± 51.4	133
60	69	126 ± 26	56 ± 11	21.0 ± 21.8	58.7
70	55	92 ± 18	49 ± 9	6.3 ± 11.3	26.7
80	45	56 ± 11	41 ± 8	3.3 ± 7.9	17.7
90	33	38 ± 7	32 ± 6	0.4 ± 5.2	10.5
100	22	27 ± 5	25 ± 5	-1.7 ± 3.4	5.6
120	15	14 ± 3	15 ± 3	-0.1 ± 1.8	3.4
140	9	8 ± 1	9 ± 2	-0.1 ± 1.0	1.9

portant backgrounds are diboson ($W\gamma$ and $Z\gamma$) and single W and Z boson production with an electron misidentified as a photon.

The $\gamma + 3$ jets event selection cuts are one photon in the central cryostat ($|\eta| < 1.1$) with $E_T > 20$ GeV, three or more jets with $E_T > 15$ GeV and $|\eta| < 2$, at least one tagging muon with $|\eta| < 1.1$ and $p_T > 4$ GeV, and $H_T > 1.5 m_{b'}$. The quantity H_T used in the final cut is defined as the scalar sum of the E_T's of the photon and the jets. Note that the H_T cut depends on the b' mass hypothesis. Figure 1(a) shows H_T distributions of Monte Carlo b' events and background. The value of the H_T cut was set to maximize significance, defined as acceptance divided by the square root of background.

The major backgrounds (*i.e.* direct photon and fake photon + multijet) are calculated by the tag rate method. This method assumes that there is a universal per-jet background b-tagging rate for mixed flavor multijet processes. The tag rate function is parameterized as a function of jet E_T, jet η, instantaneous luminosity, and time. We assume that the tag rate function factorizes among these variables and is proportional to the number of jets [10].

The diboson backgrounds ($Z\gamma$ and $W\gamma$), which are expected to generate soft muon tags in excess of the background tag rate, have been estimated by a Monte Carlo calculation. The total estimated diboson background before the H_T cut is 4.6 ± 2.1 events, and is included in the background estimate.

The backgrounds from $W \rightarrow e +$ jets and $Z \rightarrow e +$ jets with the electron misidentified as a photon is estimated from the known electron-to-photon fake rate to be about 0.1 events. This background is neglected in the total background estimate.

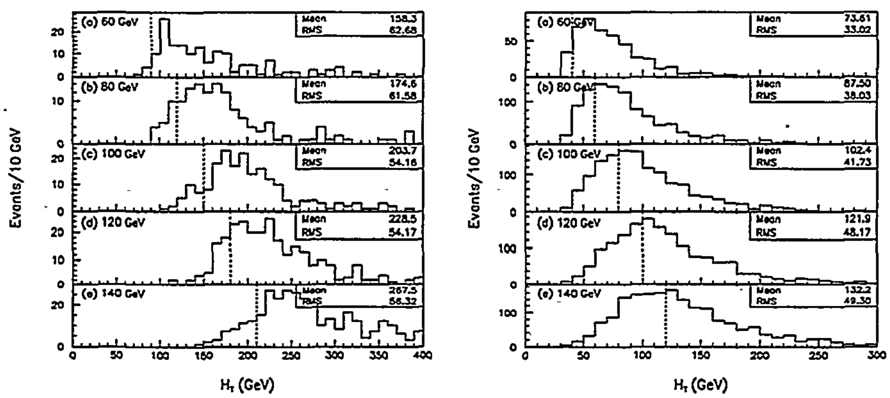


Figure 1: Monte Carlo b' and background H_T distribution for a) single photon and b) diphoton analysis for several different b' masses.

The total estimated background before the H_T cut is 59 ± 11 events with 71 events observed in the data. The H_T spectra of data and backgorund are plotted in Fig. 2(a). There is a slight (not statistically significant) excess of data over background, which is mostly at low H_T.

Table 2 shows the number of observed events, the number of events expected for signal and background, and the calculated cross section times branching ratio as a function of b' mass. The number of expected events was calculated using the central theoretical cross section of Ref. 1, and the b' branching ratios of Table 1, namely $BR(b' \to b\gamma) = 13\%$ and $BR(b' \to bg) = 52\%$, giving a combined branching ratio of 13%. The cross section times branching ratio is calculated using the equation

$$\sigma_{b'\bar{b}'} \times BR = \frac{D - B}{A\mathcal{L}}, \tag{2}$$

where D is the number of data events, B is the expected background, A is the acceptance, and $\mathcal{L}$ is the integrated luminosity. The error of the cross section times branching ratio is obtained by propagation of errors assuming Gaussian errors. The 95% CL upper limit is calculated excluding the unphysical negative cross section region of the likelihood. Figure 3(a) shows the measured branching ratio as a function of b' mass assuming that b' quarks are produced with the theoretical cross section of Ref. 1. The upper limit on the measured branching ratio is below the theoretical branching ratio up to the b' mass where the Z decay mode opens up.

The main backgrounds to the $2\gamma + 2$ jets channel are high-p_T photon +

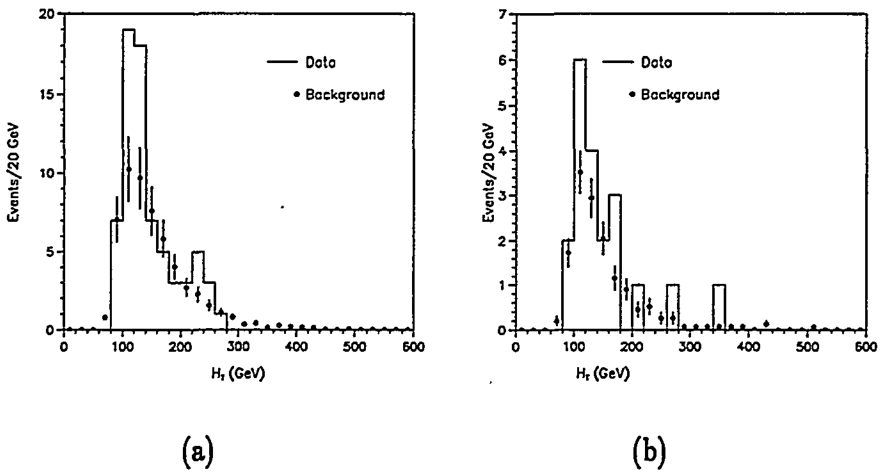


Figure 2: H_T distributions of data and background in the a) single photon and b) diphoton mode.

jets production with one fake photon, and multijet production with two fake photons. Minor backgrounds are from double direct photon production, and Drell-Yan and $Z \rightarrow ee$ with both electrons misidentified as photons.

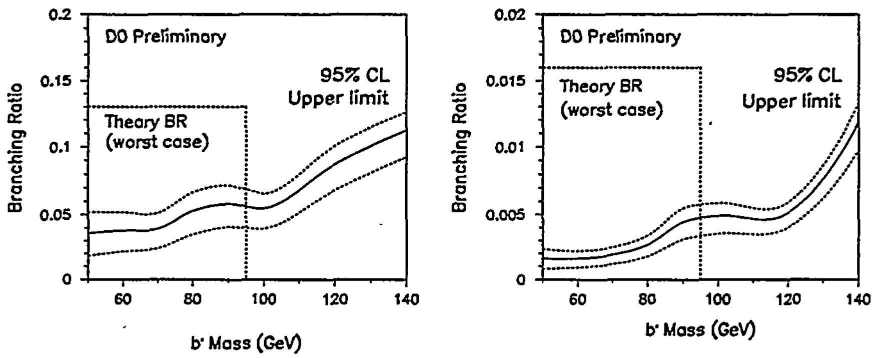
The event selection cuts for the $2\gamma + 2$ jets channel are two photons with $E_T > 20$ GeV and $|\eta| < 2.0$, two or more jets with $E_T > 15$ GeV and $|\eta| < 2.5$, and $H_T > m_{b'} - 20$ GeV. For this analysis, H_T is defined as the scalar sum of the E_T's of the jets, but not the photons. Figure 1(b) shows H_T distributions of Monte Carlo b' diphoton events and background. The value of the H_T cut was chosen to maximize significance.

The combination of the single and double fake backgrounds was estimated by the fake rate method. The fake background is the product of the number of events having a signature photon + electromagnetic cluster + two jets, times the electromagnetic cluster-to-photon fake rate. The fake rate used in this calculation is corrected for photon purity and combinatoric effects to account properly for the combination of single and double fake backgrounds.

The double direct photon background was estimated by a Monte Carlo calculation to be less than 0.05 events at 95% confidence. The double direct photon contribution to the background is neglected in the total background estimate.

The background from $Z \rightarrow ee$ + jets with both electrons faking photons is estimated from the known electron to photon fake rate to be 0.1 ± 0.1 events. This background was also neglected in the total background estimate.

The total estimated single and double fake background before the H_T cut



(a) (b)

Figure 3: Measured 95% CL upper limit on the branching ratio for a) $b'\bar{b}' \to \gamma + 3$ jets and b) $b'\bar{b}' \to 2\gamma + 2$ jets assuming the theoretical cross section of Ref. 1. The dashed curves are obtained using the author's upper and lower theory curve, rather than the central theory curve.

is 14.6 ± 2.2 events with 20 events observed in the data. The H_T distributions of data and background are shown in Fig. 2(b).

Table 3 shows the number of observed events, the number of events expected for signal and background, and the calculated cross section times branching ratio as a function of b' mass. The number of expected events was calculated using the central theoretical cross section of Ref. 1, and a branching ratio 1.6% for both b' quarks to decay to photons. Figure 3(b) shows the upper limit on the diphoton branching ratio, assuming the theoretical production cross section, as a function of b' mass.

In conclusion, the DØ experiment has searched for b' quark pair production via FCNC decay signatures where one or both b' quarks decays to a photon and a b quark. In both cases, we do not see a significant excess of events over the expected background. We set an upper limit on the cross section times branching ratio that is low enough to rule out b' quarks decaying predominantly via FCNC in the mass range $m_Z/2 < m_{b'} < m_Z + m_b$.

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Table 3: The number of expected and observed two photon + two jet events as a function of b' mass.

$m_{b'}$ (GeV/c^2)	Events			$\sigma_{b'\bar{b}'} \times BR$ (pb)	
	Observed	Expected Signal	Expected Background	Value	Upper limit (95% CL)
50	20	137 ± 19	14.6 ± 2.2	2.4 ± 2.2	6.1
60	15	101 ± 13	12.6 ± 1.9	0.6 ± 1.1	2.5
70	12	67.2 ± 8.4	10.9 ± 1.7	0.2 ± 0.6	1.3
80	9	41.7 ± 5.2	8.4 ± 1.4	0.1 ± 0.4	0.9
90	8	27.4 ± 3.4	6.0 ± 1.0	0.2 ± 0.3	0.8
100	5	16.7 ± 2.1	4.7 ± 0.8	0.0 ± 0.2	0.5
120	2	7.6 ± 0.9	2.7 ± 0.6	-0.1 ± 0.1	0.2
140	2	3.7 ± 0.4	1.6 ± 0.4	0.0 ± 0.1	0.2

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