Search for Heavy Bottomlike Quarks Decaying to an Electron or Muon and Jets in pp[over ¯] Collisions at sqrt[s]=1.96 TeV

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Phys. Rev. Lett. **106**, 141803 — Published 6 April 2011

DOI: 10.1103/PhysRevLett.106.141803

LA13338

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We report the most sensitive direct search for pair production of fourth-generation bottom-like 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 indentified as due to a b or c quark) and an imbalance of transverse momentum 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 and 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 100% branching ratio of b' to tW.

PACS numbers: 12.60.-i, 13.85.Rm, 14.65.-q, 14.80.-j

The standard model (SM) of particle physics accomodates 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-

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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 accomodate 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] bottom-like quark, b', followed by prompt decay to a t quark and a W boson with branching ratio $\mathcal{B}(b' \rightarrow Wt) = 100\%$. 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 $W \rightarrow \ell\nu$ branching ratio. We consider the mode $b'\bar{b}' \rightarrow W^+tW^-\bar{t} \rightarrow W^+W^-bW^+W^-\bar{b} \rightarrow \ell\nu qq'bqq'qq'b$ 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 four times the previous search. The larger SM 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 $4.8 \pm 0.3\,\mathrm{fb}^{-1}$.

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 offline 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 using the JETCLU [13] algorithm with a clustering radius of 0.4 in azimuth-pseudorapidity space and corrected 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 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 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 using MADGRAPH $t\bar{t}$ production with $m_t = 172.5$ GeV/c^2 in which radiation of up to three additional hard partons (including heavy flavor) are described explicitly 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 NLO cross section [28], 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 using the ALPGEN [21] program, interfaced with 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]. Multi-jet background ($\approx 5\%$), in which a jet is misreconstructed as a lepton, is modeled 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 using PYTHIA and normalized to next-to-leading order cross sections [22]. The combined background expectation is 365±194 events, including systematic and statistical uncertainties.

A b' signal would be readily separated from the background both in the number of jets and the S_{T}. To take advantage of both of these characteristics, we introduce a variable $S_{\mathrm{T}}^{N_{\mathrm{jet}}}$ which equals S_{T} for events with exactly 5 jets, $S_{\mathrm{T}}^{N_{\mathrm{jet}}} = S_{\mathrm{T}} + 1000$ GeV for events with exactly 6 jets, and $S_{\mathrm{T}}^{N_{\mathrm{jet}}} = S_{\mathrm{T}} + 2000$ GeV for events with at least 7 jets. This is equivalent to a two-dimensional analysis in N_{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 $S_{\mathrm{T}}^{N_{\mathrm{jet}}}$, 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 [23]. The 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 $S_{\mathrm{T}}^{N_{\mathrm{jet}}}$ 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 (PDF) [24, 25], 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 $S_{\mathrm{T}} > 500$ 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 $S_{\mathrm{T}}^{N_{\mathrm{jet}}}$ 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' production cross section, by performing a binned maximum-likelihood fit in the $S_{\mathrm{T}}^{N_{\mathrm{jet}}}$ variable, allowing for systematic and statistical fluctuations via template morphing [26]. We use the likelihood-ratio ordering prescription [27] 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 signal and backgrounds. The observed limits are consistent with expec-

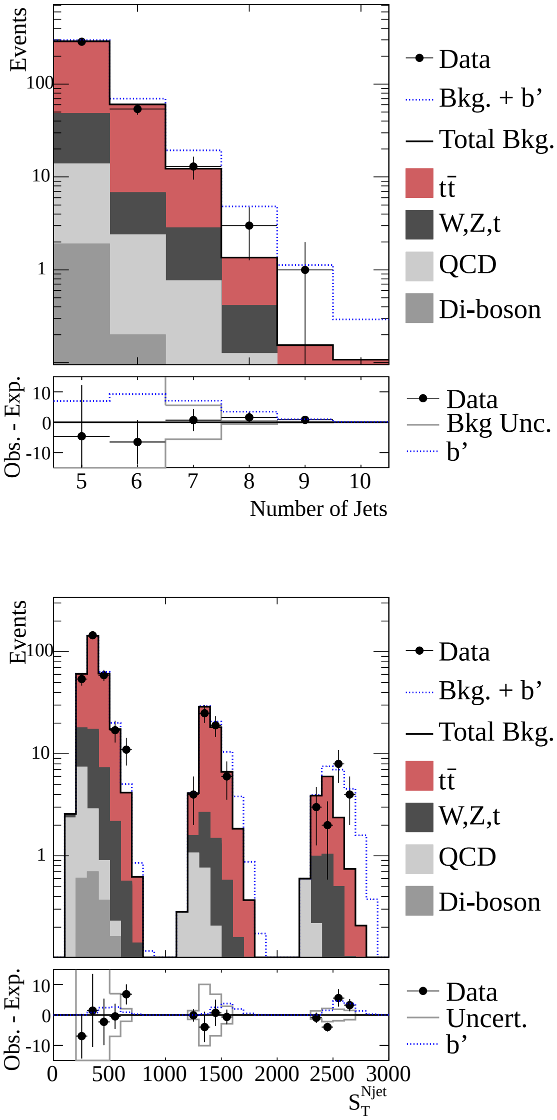

FIG. 1: Distributions in jet multiplicity and $S_{\mathrm{T}}^{N_{\mathrm{jet}}}$ (defined in the text). The example b' signal has $m_{b'} = 350$ GeV/c^2 and would have 29 ± 4.5 events expected in this sample. Top pane is log scale; bottom pane shows the difference between expected and observed events on a linear scale, as well as the total uncertainty on the expected events. The background uncertainty (Bkg Unc.) is shown as a solid grey line.

TABLE I: Expected and observed events in a background-dominated control region ($S_{\mathrm{T}} < 400, 450, 500$ for $N_{\mathrm{jet}} = 5, 6, \geq 7$, respectively) and in a signal-dominated region ($S_{\mathrm{T}} > 400, 450, 500$ for $N_{\mathrm{jet}} = 5, 6, \geq 7$) for our selection (see 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

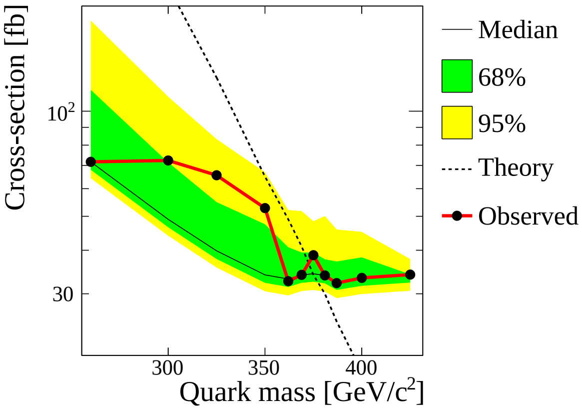

FIG. 2: Upper limits on b' production cross section at 95% C.L. assuming $\mathcal{B}(b' \rightarrow Wt)$=100%. Solid black line is the median expected upper limit in simulated experiments without b' signal; green and yellow bands represent 68% and 95% of simulated experiments, respectively; solid red line is the observed limit. Dashed black line is the NLO b' production cross section [28, 29].

tation in the background-only hypothesis and are given together with theoretical next-to-leading-order (NLO) cross sections [28, 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 ≈ 10% due to scale and PDF 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.

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, Culture, Sports, Science and Technology 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; the Bundesministerium für Bildung und Forschung, Germany; the World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

TABLE II: Theoretical cross sections (σ_{NLO} in fb [28, 29]), selection efficiency ϵ, expected b' yield (N_{exp}) after selection, median expected 95% C.L. limit (σ_{exp} in fb), and observed 95% C.L. limit (σ_{obs} in fb) for b' at varying masses. σ_{NLO} and N_{exp} have 10% uncertainties.

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

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