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Search for heavy bottom-like chiral quarks decaying to an electron or muon and jets

The CDF Collaboration
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We present a search for pair production of a heavy bottom-like chiral fourth-generation quark b' decaying via $b' \to Wt \to WWb$ in the lepton+jets channel. We observe events consistent with background expectation and exclude $m_{b'} < 385$ GeV/c^2 at 95% C.L.

I. INTRODUCTION

This paper describes a search for a fourth generation down-type chiral quark b' using the CDF detector [1]. A previous search [2] restricted the mass to $m_{b'} > 338$ GeV using a same-charge dilepton signature.

II. SIGNAL AND SELECTION

We assume that b' is pair produced and decays to Wt with 100% branching ratio for $m_{b'}$ greater than 255 GeV. If the top decays $t \to Wb$, this gives a final state of $WWWWb\bar{b}$. In particular, we search for decays in which one W decays leptonically, which leads to a high p_T lepton, two b quarks, six light quarks and a neutrino, see Figure 1.

To isolate events with this lepton plus jets final state we require:

- Exactly one good reconstructed lepton (electron or muon) with $|\eta| < 1.1$ and $p_T > 20$ GeV/c
- At least one b-tag using the SECVTX tight algorithm [3]
- At least 5 jets with $p_T > 15\ GeV/c$ and $|\eta| < 2.4$
- At least 20 GeV of missing transverse energy.

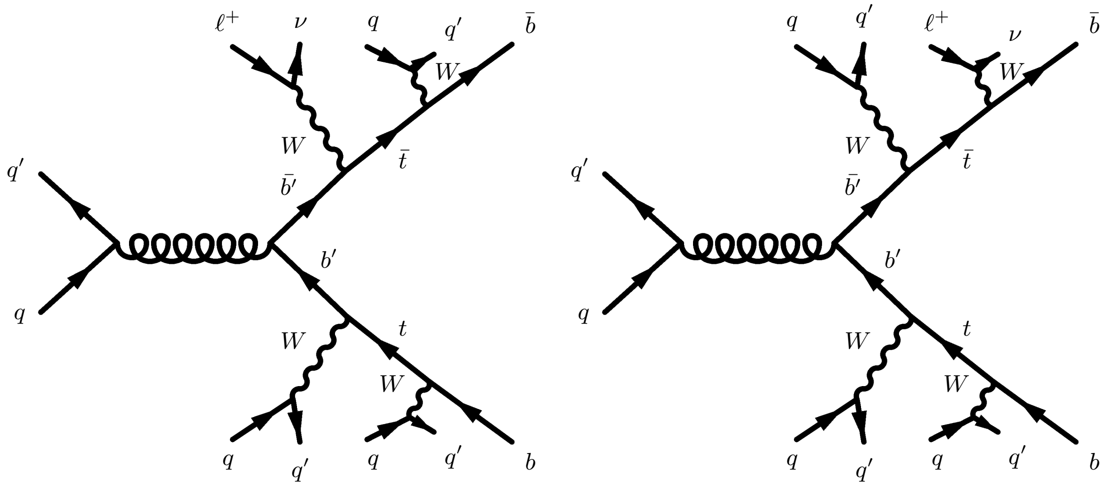

FIG. 1: Feynman diagrams for the production and decay of a generic heavy down-type fourth generation quark b'.

III. MODELING AND ACCEPTANCE

We model the b' signal using MADGRAPH [4] to describe the hard process and PYTHIA [6] for the showering. Distributions of signal event kinematics for selected events are given in Figure 2. The acceptance for b' events varies with mass, and is given in Figure 3.

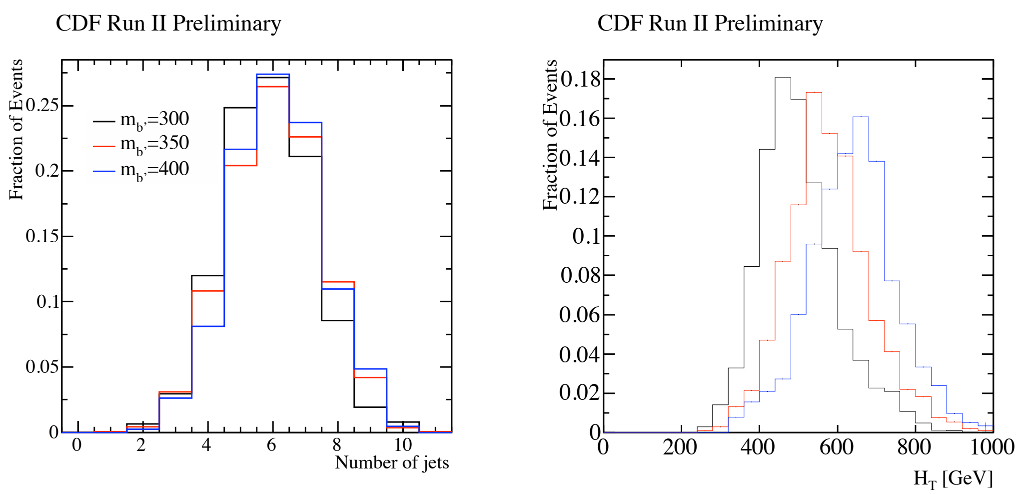

FIG. 2: For three choices of $m_{b'}$, the number of reconstructed jets, left, and the scalar sum of all event activity, H_T, right.

IV. BACKGROUNDS

When a b-tag is required, the dominant background is top quark pairs with additional jets from radiation see Figure 4 and Table IV. We describe this background using a MADGRAPH sample in which 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 [5] scheme is used to match the matrix-element and parton-shower contributions.

We consider several sources of systematic uncertainty, including jet energy scale, contributions from additional

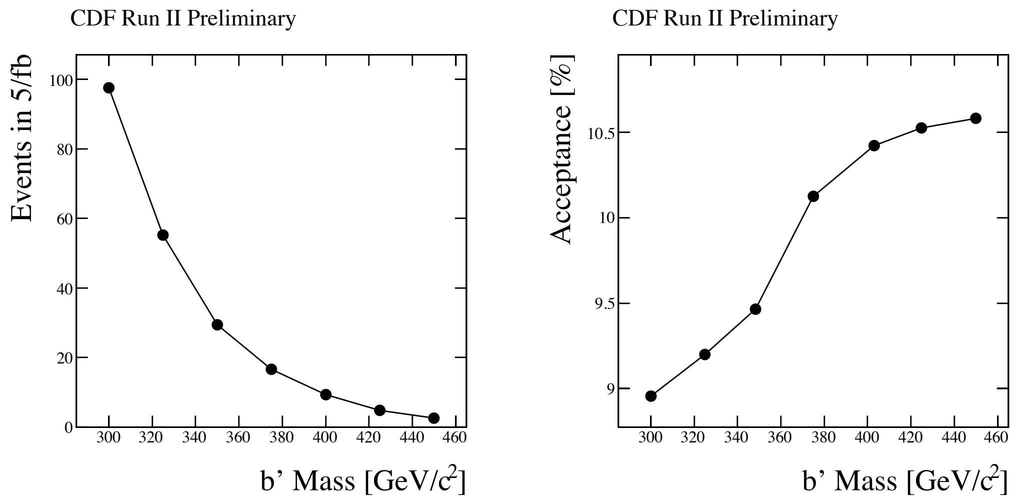

FIG. 3: Left, expected b' yield in 4.8/fb. Right, acceptance for b' events as a function of $M_{b'}$.

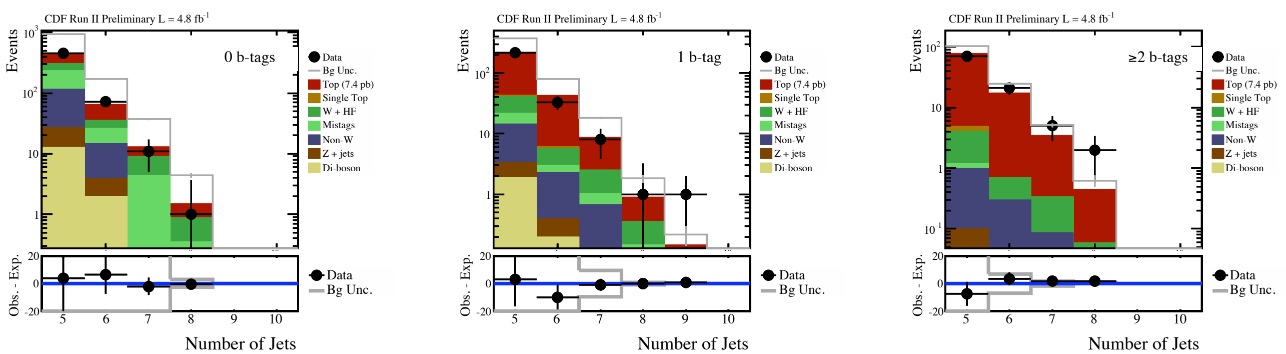

FIG. 4: Jet multiplicity in 5+ jet events with 0 (*left*), 1 (*center*) or 2+(*right*) tags. Top pane is log scale, bottom pane is difference between expected and observed.

interactions, uncertainty in descriptions of initial and final state radiation, the matching scale used between the matrix-element and the parton shower, and uncertainties in performance of the b-tagging algorithm in this topology.

V. ANALYSIS STRATEGY

Production and decay of b' would appear as events with a large number of jets and with large H_T, the scalar sum of the energy of the leptons, jets and missing transverse energy in the event, see Figure 2. The dominant $t\bar{t}$ background is expected to have fewer jets, and smaller H_T, as the additional jets would arise from initial or final state radiation. To take advantage of both of these characteristics, we introduce a variable "Jet-H_T", defined as

- if $N_{jets} == 5$, Jet-$H_T = H_T$.
- if $N_{jets} == 6$, Jet-$H_T = H_T + 1000$ GeV.
- if $N_{jets} >= 7$, Jet-$H_T = H_T + 2000$ GeV.

which effectively splits the H_T distribution by the number of jets. This is equivalent to a two-dimensional analysis in N_{jets} and H_T. Figure 5 shows the distribution of the b' signal and the backgrounds in Jet-H_T.

Figure 6 shows the data and backgrounds in the Jet-H_T variable.

	CDF Run II Preliminary $\mathcal{L} = 4.8$ fb^{-1} ≥ 5 jets, ≥ 1 b-tag	
Source	Electrons	Muons
$t\bar{t}$	136.8 ± 16.5	165.5 ± 14.0
single t	0.8 ± 0.1	1.1 ± 0.2
Z	0.9 ± 0.1	1.3 ± 0.2
W+h.f.	13.9 ± 5.1	15.2 ± 3.1
W+l.f.	4.6 ± 2.9	5.1 ± 1.5
QCD	15.2 ± 12.2	1.4 ± 0.9
WW, WZ, ZZ	1.3 ± 0.1	1.9 ± 0.2
Total	173.5 ± 21.1	191.5 ± 14.4
Observed	157	200

TABLE I: Expected backgrounds and observed ≥ 5 jet events in 4.8fb^{-1} of data with at least one b-tag.

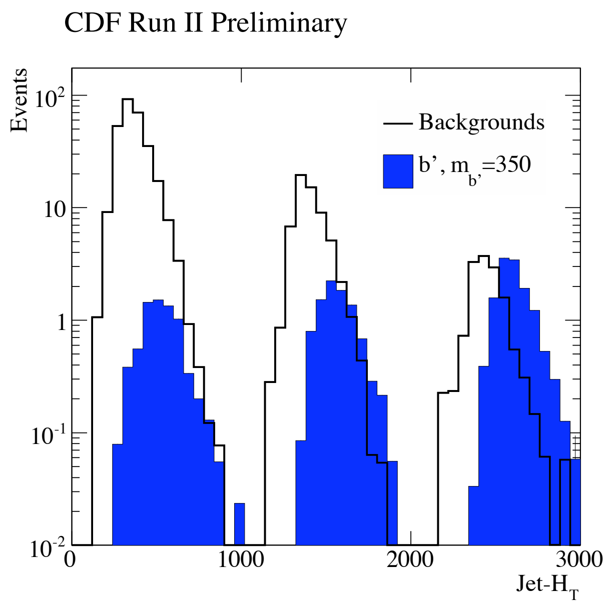

FIG. 5: Distributions of signal and expected backgrounds in the Jet-H_T analysis variable. "Jet-H_T" is defined: if $N_{jets} == 5$, Jet-$H_T = H_T$; if $N_{jets} == 6$, Jet-$H_T = H_T + 1000$ GeV; if $N_{jets} >= 7$, Jet-$H_T = H_T + 2000$ GeV.

We fit templates of the signal and background shapes in Jet-H_T to the observed events in the data, using a binned likelihood and allowing for systematic and statistical fluctuations via template morphing, to extract the most likely signal cross-section.

VI. BACKGROUND CONSISTENCY

In the ≥ 7 jet category with at least one b-tag, there are more events than expected with large H_T, though the total number of events observed in the low H_T and high H_T regions combined is consistent with expectation. The $t\bar{t}$ background description includes explicit modeling of up to three additional hard partons, or ≤ 7 jets, where we would expect a b' signal. Events with eight jets and above are described by the parton shower and therefore may be underpredicted in the nominal sample. However, systematic uncertainties in this prediction are significant.

We divide the events into low and high H_T regions, see Table II and calculate a p-value to observe this many events or more, see Figure 7. In 12% of pseudo-experiments, we see a more significant excess at large H_T than that which we observe in the data.

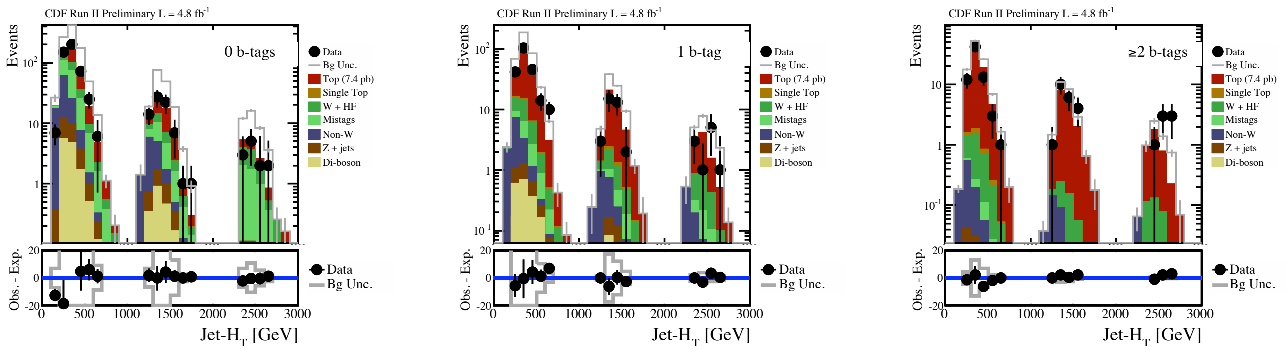

FIG. 6: Jet-H_T in 5+ jet events with 0 (*left*), 1 (*center*) or 2+(*right*) tags. Top pane is log scale, bottom pane is difference between expected and observed. "Jet-H_T" is defined: if $N_{jets} == 5$, Jet-$H_T = H_T$; if $N_{jets} == 6$, Jet-$H_T = H_T + 1000$ GeV; if $N_{jets} >= 7$, Jet-$H_T = H_T + 2000$ GeV.

	CDF Run II Preliminary $\mathcal{L} = 4.8$ fb^{-1}					
	$\geq 1b$-tag, Small H_T		$\geq 1b$-tag, Large H_T		$\geq 1b$-tag, All	
Jets	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
5	207.1 $^{\pm 62.1 \pm 107.9}$	199	83.6 $^{\pm 25.1 \pm 60.3}$	87	290.6 $^{\pm 87.2 \pm 168.2}$	286
6	42.6 $^{\pm 12.8 \pm 28.0}$	40	18.0 $^{\pm 5.4 \pm 11.1}$	14	60.5 $^{\pm 18.2 \pm 39.1}$	54
7+	10.5 $^{\pm 3.1 \pm 2.4}$	5	3.4 $^{\pm 1.0 \pm 3.3}$	12	13.9 $^{\pm 4.2 \pm 5.7}$	17

TABLE II: Expected and observed events in a background-dominated region ($H_T < 400, 450, 500$ for $N_{jet} = 5, 6, 7+$) and in a signal-dominated region ($H_T > 400, 450, 500$ for $N_{jet} = 5, 6, 7+$) for 1-tag inclusive events with at least 5 jets. Errors are statistical followed by systematic.

VII. RESULTS

We do not see evidence of a b' and construct confidence intervals [7] in the theoretical cross section by generating ensembles of simulated experiments that describe expected fluctuations of statistical and systematic uncertainties. The median expected and observed limits and theoretical next-to-leading-order (NLO) cross sections [8, 9] are shown in Fig. 8.

We convert limits on the pair-production cross sections to limits on the heavy quark mass and obtain $m_{b'} > 385\,\mathrm{GeV}/c^2$ at 95% confidence level. This is the most restrictive direct lower limit on the mass of a down-type fourth-generation quark, significantly reducing the allowed mass range.

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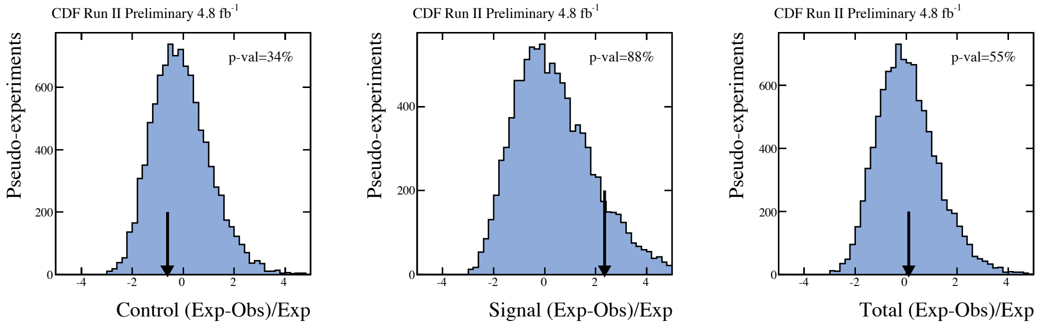

FIG. 7: Distributions in pseudo-experiments of a test statistic sensitive to excess events; the arrow shows the value in the data. Left, for control regions (low H_T); center for signal regions (large H_T); right for control+signal regions. The p value represents the fraction of pseudo-experiments that would give a smaller observed test statistic. Pseudo-experiments include statistical and systematic fluctuations.

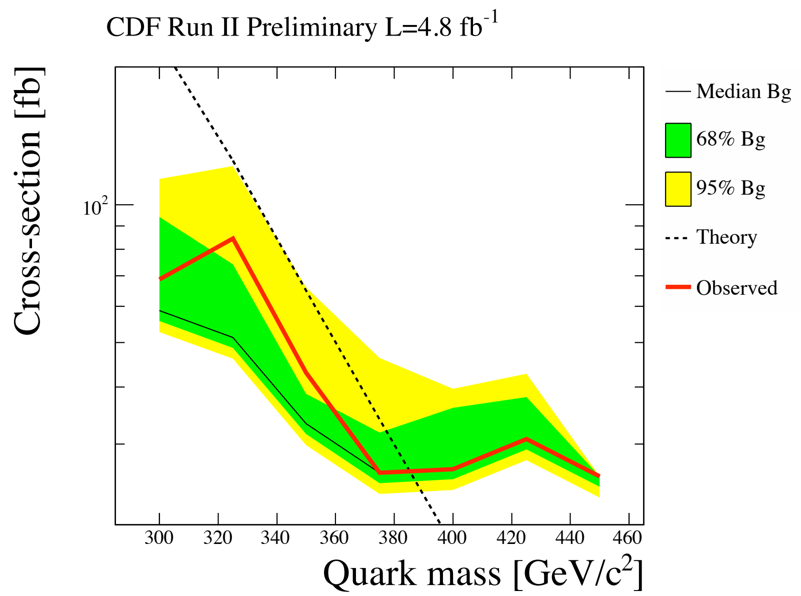

FIG. 8: Upper limits on b' production cross-section at 95% C.L. Solid black line is the median expected upper limit in pseudo-experiments without b' signal; green and yellow bands represent 68% and 95% of pseudo-experiments, respectively; solid red line is the observed limit. Dashed black line is the NLO b' production cross section [8, 9].

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