Search for Fermion-Pair Decays $Q\overline{Q} \rightarrow (tW^{\mp})(\bar{t}W^{\pm})$ in Same-Charge Dilepton Events

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We report the most restrictive direct limits on masses of fourth-generation down-type quarks b', and quark-like composite fermions (B or $T_{5/3}$), decaying promptly to $tW^{\mp}$. We search for a significant excess of events with two same-charge leptons (e, μ), several hadronic jets, and missing transverse energy. An analysis of data from $p\overline{p}$ collisions with an integrated luminosity of $2.7\,\mathrm{fb}^{-1}$ collected with the CDF II detector at Fermilab yields no evidence for such a signal, setting mass limits $m_{b'}, m_B > 338\,\mathrm{GeV}/c^2$ and $m_{T_{5/3}} > 365\,\mathrm{GeV}/c^2$ at 95% confidence level.

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The standard model (SM) of particle physics accomodates three generations of fundamental quarks and leptons, but does not prohibit a fourth. Recent measurements of charge-parity (CP) nonconservation in B-meson decays [1] have two features in common: they are more than two standard deviations from SM expectations, and they are sensitive to contributions [2] from a fourth-generation up-type quark, t'. This pattern of measurements [3–6], if genuine, warrants a search for another generation of quarks or a multiplet of quark-like objects. Another quark generation (Cf. [7]) could provide sources of particle-antiparticle asymmetries large enough to account for the baryon asymmetry of the universe [8], and accomodate a heavier Higgs boson (the source of electroweak symmetry breaking and mass generation) than a three-generation model [9].

This Letter reports a search for heavy particles Q decaying to a top quark and a W boson at a mass scale relevant to both the B-meson anomalies and the Higgs mechanism. We search for pair-production of $Q\overline{Q}$ via strong interactions, where Q is either a fourth-generation down-type quark b' or a quark-like (non-hadronic) composite fermion B or $T_{5/3}$ [10]. The B and $T_{5/3}$ (with 5/3 electron charge) that we consider might arise from symmetries, consistent with precise electroweak measurements [11, 12]. If $T_{5/3}$ exists, the existence of B is implied, doubling the expected event rate. Many additional models of new phenomena that provide a Higgs mechanism also predict particles with large couplings to the third-generation t quark and similar decay modes. For instance, models of warped extra dimensions, equivalent to models of strongly interacting composite particles, predict fermion excitations with the quantum numbers of quarks. A summary is given in [13].

In each case, $Q \to tW^{\mp}, t \to bW^{+}$ [14]. We investigate the case in which two same-charge W bosons decay leptonically (including τ decays to e or μ). This is the first search for quark-like particles in this mode [15], achieving the most sensitive direct limits on short-lived fourth-generation particles. (We do not consider long-lived particles, since displaced vertices require different analysis methods.)

We assume that Q decays exclusively to $tW^{\mp}$. This is expected for B and $T_{5/3}$, and for b' it is expected [16] under the assumptions that (a) coupling to light quarks is insignificant, (b) $m_{b'} > m_{top} + m_W = 255\,\mathrm{GeV}/c^2$, and (c) $|m_{t'} - m_{b'}| < m_W$. These assumptions are justified by experimental constraints. A search for $Q \to W$+jet [17] found $m_{t'} > 311\,\mathrm{GeV}/c^2$, implying a similar limit on $m_{b'}$ if the b' decay to this channel is significant. Combining this limit with results of a search for $Q \to Z$+jets [18] and an analysis of branching fractions for b' [16], we infer $m_{b'} > 255\,\mathrm{GeV}/c^2$. A fourth generation is most consistent with precise electroweak measurements when the mass splitting Δm between b' and t' is less than the W-boson mass but non-zero; ref. [9] gives $\Delta m \approx 50\,\mathrm{GeV}/c^2$, based on $|m_{t'} - m_{b'}| < m_W$.

We use a data sample corresponding to an integrated luminosity of $2.7\,\mathrm{fb}^{-1}$ collected with the CDF II detector [19] at the Tevatron $p\overline{p}$ collider at Fermilab. The data acquisition system is triggered by e or μ candidates with $p_T > 18\,\mathrm{GeV}/c$ [20]. We require the $\ell^{\pm}\ell^{\pm}bj\not\!\!E_T$ signature, following [21]: two same-charge reconstructed leptons (e or μ) with pseudorapidity magnitude $|\eta| < 1.1$ and $p_T > 20\,\mathrm{GeV}/c$, where at least one lepton is isolated [22]; at least two jets with $E_T > 15\,\mathrm{GeV}$ and $|\eta| < 2.4$; at least one of the jets with evidence of a long-lived particle (b-tag) using the tight SECVTX algorithm [23]; and missing transverse energy $\not\!\!E_T > 20\,\mathrm{GeV}$ [24].

The dominant background comes from events in which one of the leptons is a misidentified light-flavor jet or a lepton from the decay of a bottom or charmed hadron in a heavy flavor jet, largely from W production in association with light or heavy flavor jets or from $t\bar{t}$ production with semi-leptonic decays. This background is described using a lepton misidentification model from inclusive jet data [25] applied to W+jet events. In same-charge dilepton control regions without a b-tag requirement, this model decribes well the kinematics of observed events with large missing transverse energy. Nevertheless, the requirement of a b-tag in the final selection introduces uncertainty regarding the misidentification model, leading to a final 100% systematic uncertainty, as described in [21].

Other backgrounds include processes that produce electron-positron pairs. These may be reconstructed with the same charge due to asymmetric γ conversions in the

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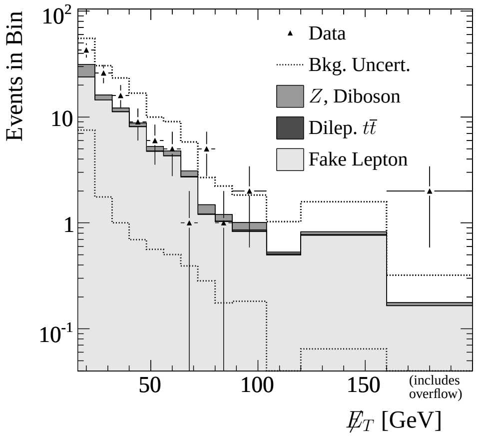

FIG. 1: Missing transverse energy in events with same-charge leptons in 2.7 fb^{-1} . The right outer-most bin includes overflow events with $\not{E}_T > 160$ GeV.

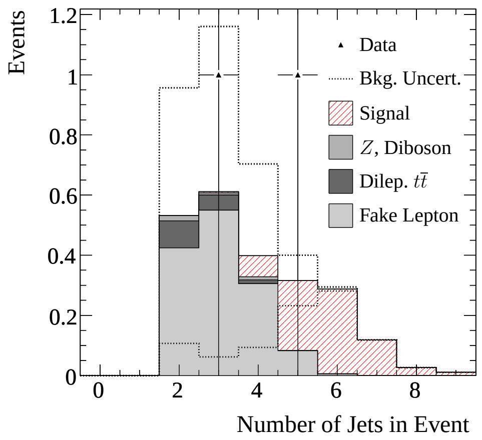

FIG. 2: Number of reconstructed jets for the expected backgrounds. The observed data and the b' (or B) signal are shown at the best-fit rate for $m_Q = 330$ GeV/c^2. The fitted size and shape for the $T_{5/3} + B$ signal is nearly identical.

process $e^-_{\rm hard} \rightarrow e^-_{\rm soft}\gamma \rightarrow e^+_{\rm hard}e^-_{\rm soft}e^-_{\rm soft}$, where hard and soft refer to large and small transverse momentum, respectively. The major contributions from this mechanism are from events with a Z or virtual γ in association with jets (Z/γ^*+jets) and $t\bar{t}$ production with fully leptonic decays.

Estimates of the backgrounds from Z/γ^*+jets processes are made with the ALPGEN [26] v2.10 simulation code interfaced with PYTHIA 6.325 [27] in the MLM scheme [26] for the hadronization and fragmentation and normalized to data in opposite-charge events in the Z mass region. The detector response for both Z+jets and $t\bar{t}$ processes is evaluated using the CDF simulation program CDFSIM [28], where, to avoid double-counting, the same-charge leptons are required to originate from the W or Z decays rather than from misidentified jets.

To validate the modeling of the rate of hard bremsstrahlung from electrons, we compare our prediction for the contribution of $Z \rightarrow e^+e^-$ to the observed sample of same-charge electrons or positrons without a b-tag or missing transverse energy requirement. The shape of the dilepton invariant mass spectrum and yield in the Z mass region ($M_{ll} = [M_Z - 20, M_Z + 20]$) agrees well with the prediction. In addition, $\mu\mu$ and $e\mu$ events have negligible contributions from hard bremsstrahlung, as predicted. Figure 1 shows that the missing transverse energy in inclusive same-charge dilepton events is well described.

TABLE I: Expected background contributions to the ee, $e\mu$, and $\mu\mu$ channels in 2.7 fb^{-1} from (a) Z and diboson, (b) $t\bar{t} \rightarrow \ell^+\nu b\ell^-\nu\bar{b}$, and (c) misidentified lepton.

Source	ee	$\mu\mu$	$e\mu$	Total $\ell\ell$
(a)	0.01 ± 0.01	0	0.02 ± 0.02	0.03 ± 0.03
(b)	0.06 ± 0.04	0	0.09 ± 0.03	0.15 ± 0.05
(c)	0.6 ± 0.6	0.3 ± 0.3	0.5 ± 0.5	1.4 ± 1.4
Total	0.7 ± 0.6	0.3 ± 0.3	0.6 ± 0.5	1.6 ± 1.4
Data	0	1	1	2

The $t\bar{t} \rightarrow \ell^+\nu b\ell^-\nu\bar{b}$ backgrounds are estimated using events generated in PYTHIA 6.216 at $m_t = 172.5\,{\rm GeV}/c^2$, assuming a $t\bar{t}$ production cross-section of 7.2 pb. Modeling of the $t\bar{t}$ contribution is validated by comparing predicted and observed rates of events with opposite-charge leptons, large $\not{E}_T$, and at least one b-tagged jet, where $t\bar{t}$ is expected to dominate.

Backgrounds to the $\ell^\pm\ell^\pm bj\not{E}_T$ signature with real same-charge leptons are rare in the SM; they are largely from WZ and ZZ production and are highly suppressed by the requirement of a b-tag. Backgrounds from diboson production WW, WZ, ZZ, $W\gamma$, and $Z\gamma$ in association with b jets are modeled with PYTHIA 6.216 and BAUR [29] generators.

Backgrounds from charge mismeasurement are insignificant, as the charge of a particle with $p_T \approx 100\,{\rm GeV}/c$ is typically determined with more than 5σ significance [30]. Charge mismeasurement is very rare in this range, confirmed by the absence of any strong fea-

TABLE II: Theoretical cross-sections ($\sigma_{\rm NLO}$ in fb [36, 37]), expected yield (N), median expected 95% C.L limit ($\sigma_{\rm exp'd}$ in fb), and observed 95% C.L limit ($\sigma_{\rm obs}$ in fb) for b' (or B) and ($T_{5/3}$ +B) signals at varying masses.

Mass [GeV/c^2]		300	310	320	330	340	350	375	400
	$\sigma_{\rm NLO}$	227	176	137	106	83	64	34	18
$b'\,or\,B$	N	13.4	9.6	7.5	5.9	4.6	3.5	1.9	1.0
	$\sigma_{\rm exp'd}$	67	63	63	62	63	63	63	57
	$\sigma_{\rm obs}$	67	96	83	94	85	83	78	67
	$\sigma_{\rm NLO}$	454	352	274	212	166	128	68	36
$T_{5/3}$	N	27.0	19.5	15.3	11.9	9.4	7.1	3.6	2.1
$+B$	$\sigma_{\rm exp'd}$	86	89	69	62	59	65	66	60
	$\sigma_{\rm obs}$	86	89	69	98	91	83	83	79

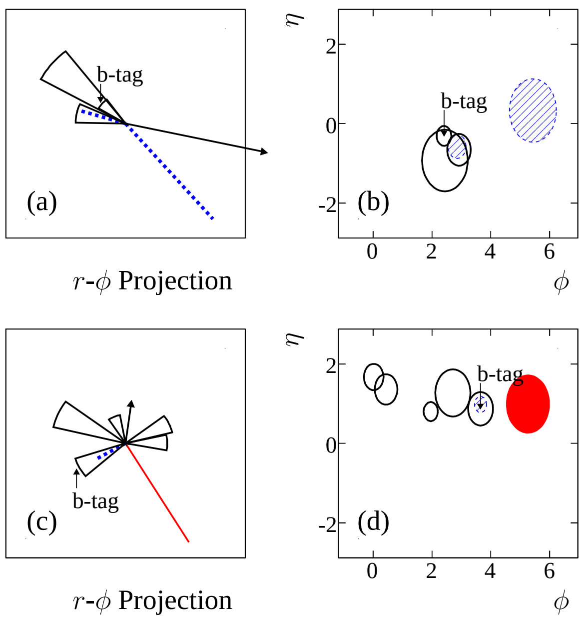

FIG. 3: Event displays for the observed three-jet, $\mu\mu$ event (a,b) and the five-jet, $e\mu$ event (c,d). Shown in (a) and (c) are views of the events along the beam axis; jets shown as cones, electrons as solid lines, muons as dotted lines and missing transverse energy as an arrow; lengths are proportional to p_T (see Table III). Shown in (b) and (d) are views of the events in $\eta - \phi$; jets shown as open circles, electrons as filled circles and muons as dashed circles; radii are proportional to p_T.

tures in dilepton invariant mass in the Z mass region in same-charge muon events. The largest potential source comes from $t\bar{t}$ events, in which the lepton momenta are typically smaller than 100 GeV/c. The final background estimates are given in Table I.

The b' and $T_{5/3}$ $+B$ signals are modeled with the MADGRAPH simulation program following the minimal composite Higgs model described in [10] and paired with PYTHIA for hadronization and fragmentation. The acceptance is approximately 2.2%, nearly independent of heavy quark masses in the range 300–400 GeV/c^2. The expected numbers of events for b' (or B), and $T_{5/3}$ $+B$ are given in Table II.

We observe two events in the signal region, in agreement with the expected backgrounds (see Table I). To calculate the most likely signal cross section, we perform a binned maximum-likelihood fit to the number of reconstructed jets. Figure 2 shows the number of reconstructed jets in the observed events, as well as the signal distribution with the best-fit value of the signal cross section. Kinematics of the two signal events is shown in Fig. 3 and the p_T values are given in Table III.

TABLE III: Transverse momentum (in GeV/c) of leptons and transverse energy (in GeV) of jets in the two events with the $\ell^\pm \ell^\pm b j \not\!\!E_T$ signature.

Event	ℓ_1	ℓ_2	jet$_1$	b-jet	$\not\!\!E_T$	other jets
$\mu^+\mu^+$	80	31	78	25	87	40
$e^+\mu^+$	73	21	60	42	27	39, 33, 24

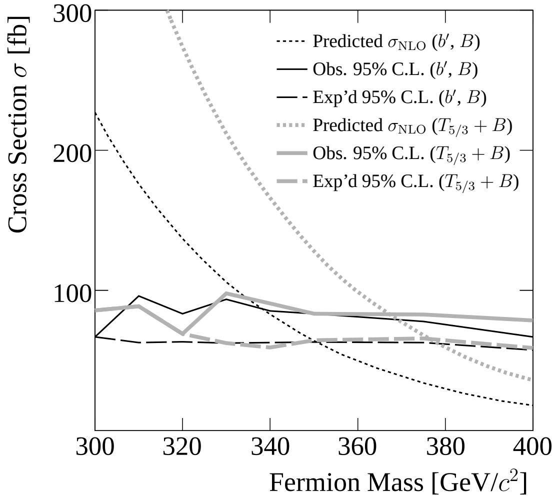

FIG. 4: Theoretical cross sections for b' (or B) and $T_{5/3}+B$ with expected and observed 95% C.L. limits overlaid.

We construct confidence intervals [31] in the theoretical cross section by generating ensembles of simulated experiments that describe expected fluctuations of statistical and systematic uncertainties, including uncertainties in the jet-energy scale [32], gluon radiation [33], signal and background normalization, and parton distribution functions [34, 35]. The median expected and observed limits along with the theoretical next-to-leading-order (NLO) cross section [36, 37] are given in Table II and shown in Fig. 4.

We convert limits on the pair-production cross sections to limits on the fermion masses and obtain $m_{b'}, m_B >$ 338 GeV/c^2 and $m_{T_{5/3}} > 365$ GeV/c^2 at 95% confidence level. The two events observed are consistent with the predicted number of background events, although we note that the $e\mu$ event has a number of jets characteristic of the signal, reducing the observed lower limits from what is expected. This is the most restrictive direct lower limit on the mass of a down-type fourth-generation quark, significantly reducing the allowed SM mass range, and the first lower limits on the masses of an exotic doublet $T_{5/3}+B$, which may figure prominently in future searches.

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[1] Specifically, we refer to the mixing-induced *CP* asymmetry in the decays $B_s \to J/\psi\,\phi$ [3], the difference between direct *CP* asymmetries in the decays $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ [4, 6], and the values of mixing-induced *CP* asymmetry obtained from $B^0 \to J/\psi\,K^0_S$ or $B^0 \to (\phi, \eta', K^0_S K^0_S) K^0_S$ [5, 6].

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