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# Search for fermion-pair decays $Q\bar{Q} \to (tW^{\pm})(\bar{t}W^{\mp})$ in same-charge dilepton events with 2.7 fb$^{-1}$

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*URL http://www-cdf.fnal.gov*
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We report a search for a heavy fourth-generation down-type quark ($b'$) which decays with 100% branching ratio $b' \to tW$, giving a significant number of same-charge dilepton events. In addition, we search for exotic top partners ($B, T_{5/3}$) which have similar decays. We select events with two same-charge leptons, missing transverse energy, at least two jets and a positive $b$-tag. We set a limit on the mass of the $b'$ to be $> 325$ GeV and on the mass of the $B, T_{5/3}$ to be $> 351$ GeV at 95% C.L.

## I. INTRODUCTION

This paper describes a search for a generic fourth generation down-type quark $b'$, which covers at the same time a specific model of new physics that predicts a new heavy down-type quark $B$ and an exotic new fermion $T_{5/3}$ with charge 5/3.

This particular model [1] belongs to a class of models which offer an alternative solution of the hierarchy problem of a light Higgs boson. In these models, the Higgs is a pseudo Goldstone boson of a spontaneously broken global symmetry. Since this implies that the Higgs is a bound state of fundamental constituents of the theory, they are also often referred to as composite Higgs models. They overcome the hierarchy problem by balancing the radiative correction of the top quark to the Higgs mass with contributions of new heavy fermionic partners, which are expected to have masses up to 1 TeV.

One possibility of the spontaneous breaking of the global symmetry is due to a new strong sector, in which case new heavy resonances are predicted. The particular model that motivated in parts the work presented here places the strong sector that generates a light composite Higgs into the bulk of a warped extra dimension. In this case the new heavy resonances are Kaluza-Klein excitations. Namely, taking symmetry constraints to obey the LEP electroweak precision data into account, two heavy quarks with the same quantum numbers as the third generation of Standard Model quarks are predicted, the $T$ and $B$, as well as fermions with exotic charges, the $T_{5/3}$ and $T_{2/3}$, with charges

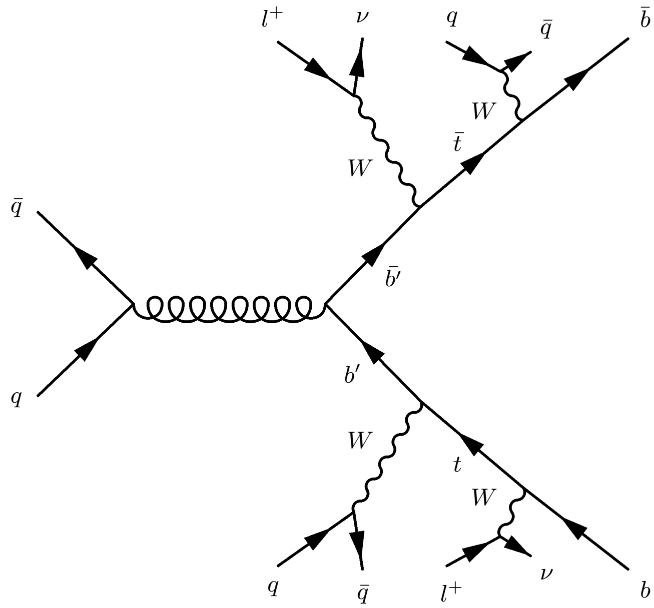


**FIG. 1:** Feynman diagrams for the production and decay of a generic fourth generation heavy down-type quark $b'$.

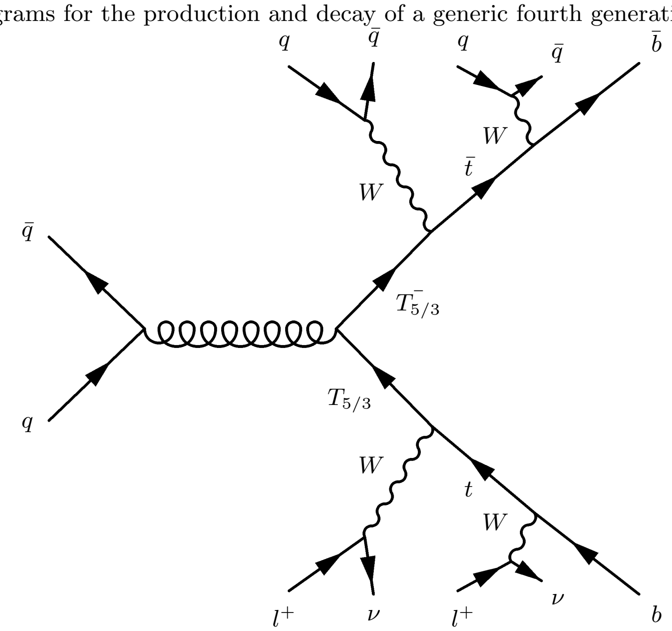


**FIG. 2:** Feynman diagrams for the production and decay of a heavy top partner $T_{5/3}$ with charge 5/3.

2/3 and 5/3, respectively.

In the following, we are performing a same-charge dilepton analysis, hence search for pair production of the $B$ and $T_{5/3}$ in the context of the composite Higgs model, and for pair production of $b'$ in the context of a generic fourth generation down-type quark. Note that we will distinguish the two cases only when quoting the results of the analysis.

## II. SIGNAL AND SELECTION

We assume that the $b'$ is pair produced and decays to $Wt$ with 100% branching ratio for a mass greater than 255 $GeV$. If the top in turn decays like $t \to Wb$, this results in a final state of $WWWWb\bar{b}$. In the case of the $B$ and $T_{5/3}$, we assume the mass splitting is small.

In particular, we are interested in specific $W$ decays which lead to a pair of same-charge leptons, two $b$ jets and neutrinos. For the $b'$ or $B$ the decay chain is shown in Figure 1: $b' \to W^+t \to \bar{q}ql^+\nu b$ and $\bar{b}' \to W^-\bar{t} \to l^+\nu\bar{q}q\bar{b}$. Figure 2 shows similarly the decay of the $T_{5/3}$: $T_{5/3} \to W^+t \to l^+\nu l^+\nu b$ and $\bar{T}_{5/3} \to W^-\bar{t} \to \bar{q}q\bar{q}q\bar{b}$.

To isolate events with this same-charge dilepton final state we define the $l^{\pm}l^{\pm}bE_t$ signature by requiring:

- Two same-charge reconstructed leptons (electrons or muons) with $|\eta| < 1.1$ and $p_T > 20$ GeV/$c$
- At least one b-tag using the SECVTX tight algorithm [9]
- At least 2 jets with $p_T > 15$ $GeV/c$ and $|\eta| < 2.4$
- At least 20 GeV of missing transverse energy.

## III. BACKGROUNDS

Backgrounds to the $l^{\pm}l^{\pm}bE_t$ signature mainly come from two sources: when the second lepton is faked and when it is real. When the second lepton is faked, it primarily comes from:

- A jet faking a lepton that is then paired with an identified real lepton (mainly due to $W$+jets.)

Backgrounds where the 2nd lepton is real primarily come from:

- $Z \to e^+e^-$ reconstructed as $Z \to e^{\pm}e^{\pm}$ due to a lepton emitting a hard photon leading to an asymmetric conversion.
- $t\bar{t} \to e^{\pm}e^{\pm}b\bar{b}$ through the same hard photon emission process.

Backgrounds in which the second lepton arises from a misidentified jet or the decay of a heavy quark are largely due to production of $W$+jets or semi-leptonic $t\bar{t}$ decays and are described using a model from jet data [8] in which the rate of lepton reconstruction in inclusive jets is measured and applied to $W$+jet events. The misidentification model is validated for light-quark jets by comparing the predicted and observed rates of same-charge events as a function of the missing transverse energy without a $b$-tag requirement. Discrepancies in rates in control regions motivate a 40% uncertainty. The selected sample may have a larger heavy flavor fraction than the jets from which the lepton misidentification model was derived. Studies in simulated events show that the rate of misidentified leptons in a heavy-flavor enriched sample may be $50 - 75\%$ higher, and examination of the equivalent opposite-charge sample motivate a 100% total uncertainty on the background prediction from lepton misidentification. The final uncertainty is 100%.

Backgrounds in which the same-charge lepton is due to a hard photon emission come from $Z/\gamma^*$+jets and top-quark pairs with electron-positron decays. Estimates of the backgrounds from $Z/\gamma^*$+jets processes are made with the ALPGEN [12] simulation code matched with PYTHIA in the MLM scheme [12] for the hadronization and fragmentation and normalized to data in opposite-sign events. The detector response for both $Z$+jets and $t\bar{t}$ processes is evaluated using CDFSIM, where, to avoid double-counting, the same-charge leptons are required to originate from the $W$ or $Z$ decays rather than from misidentified jets.

Backgrounds from charge-mismeasurement are insignificant, as the charge of a particle with momentum of 100 GeV/$c$ is typically determined with a significance greater than $5\sigma$ [6]. The largest potential source comes from top quark pair events, in which the lepton momenta are typically softer. Charge mismeasurement is very rare in this range, confirmed by the absence of a significant signal near the $Z$ mass in observed same-charge muon events.

Backgrounds from diboson production $WW$,$WZ$, $ZZ$, $W\gamma$, and $Z\gamma$ in association with $b$ jets are modeled with PYTHIA and BAUR [7] generators.

### A. Z normalization

To cross-check our understanding of leptons, we examine the opposite-charge lepton data-set, which should be dominated by $Z$ events. We extract an overall normalization for the $Z$ cross-section and confirm that the predicted and observed number of events agree as a function of the invariant mass of the lepton pair, see Figure 3.

### B. $Z \to l^{\pm}l^{\pm}$

To validate the modeling of the rate of hard emission, we compare our prediction for the contribution of $Z \to e^+e^-$ to the observed sample of same-charge electrons or positron without a $b$-tag or missing transverse energy requirement. Note that the overall $Z$ cross-section uses the normalization extracted in the opposite-charge lepton sample. The shape and yield of the observed signal at the $Z$ mass agrees well with the prediction, see Figure 4. In addition, no such peak is observed in $\mu\mu$ or $e\mu$ events.

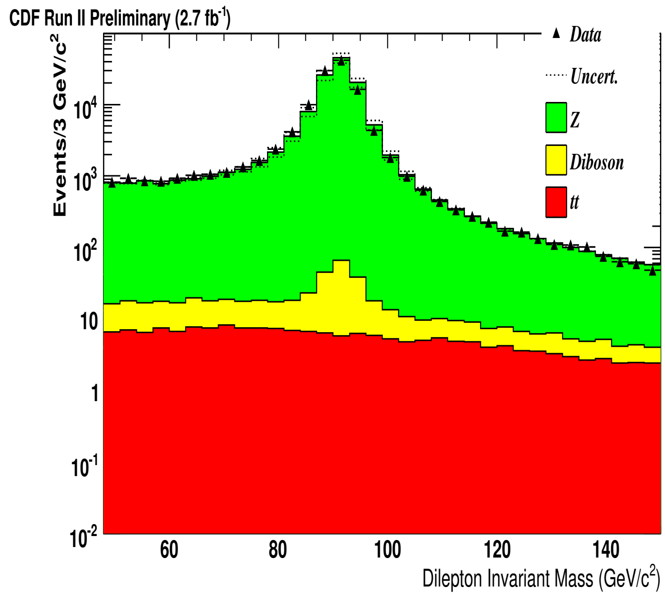


**FIG. 3:** Reconstructed mass of two opposite sign leptons.

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| Source | $ee$ | $mm$ | $em$ | $ll$ |
|---|---|---|---|---|
| $Z, diboson$ | 0.03 ± 0.02 | 0.02 ± 0.01 | 0.04 ± 0.02 | 0.10 ± 0.05 |
| $tt$ | 0.17 ± 0.02 | 0.06 ± 0.01 | 0.22 ± 0.02 | 0.50 ± 0.05 |
| $W + jets$ | 0.56 ± 0.56 | 0.34 ± 0.34 | 0.47 ± 0.47 | 1.4 ± 1.4 |
| Total | 0.8 ± 0.6 | 0.4 ± 0.3 | 0.7 ± 0.5 | 1.9 ± 1.4 |

**TABLE I:** Number of expected background events from each source at the final cut level.

### C. Missing transverse energy

We examine the inclusive same-charge events as a function of missing transverse energy, see Figure 5.

### D. $t\bar{t}$

The $t\bar{t}$ backgrounds are estimated using events generated in PYTHIA at $m_t = 172$ GeV/c$^2$, assuming a cross-section of 7.2 pb. Modeling of the $t\bar{t}$ contribution is validated by comparing predicted and observed rates of opposite-sign leptons with $\not\!\!E_T$ and a $b$ tag, where $t\bar{t}$ is expected to dominate, see Figure 6.

### E. Total Background Estimate

The final background estimates are given in Table I.

## IV. SIGNAL EFFICIENCY

The $b'$ signal is modeled with the MADGRAPH simulation code paired with PYTHIA for hadronization and fragmentation. The detector response is simulated with CDFSim. To avoid double-counting, the same-charge leptons

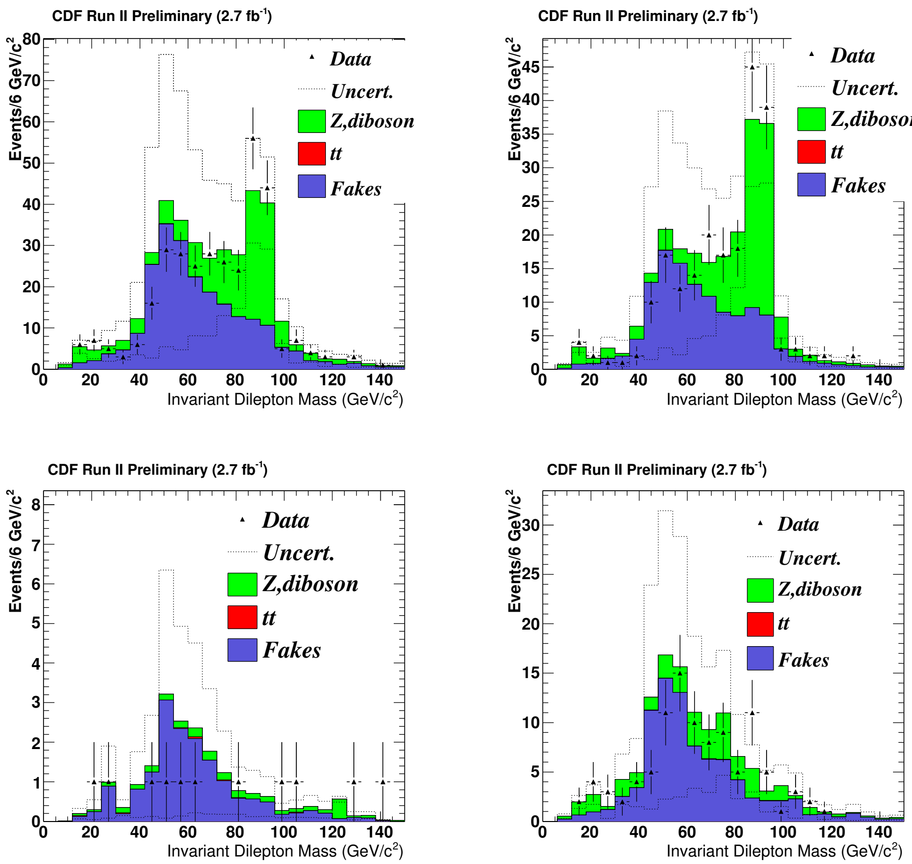


**FIG. 4:** Reconstructed mass of two same-charge leptons with $|\eta| < 1.1$. Top plot contains total channel. Clockwise: $ll$,$ee$,$e\mu$,$\mu\mu$.

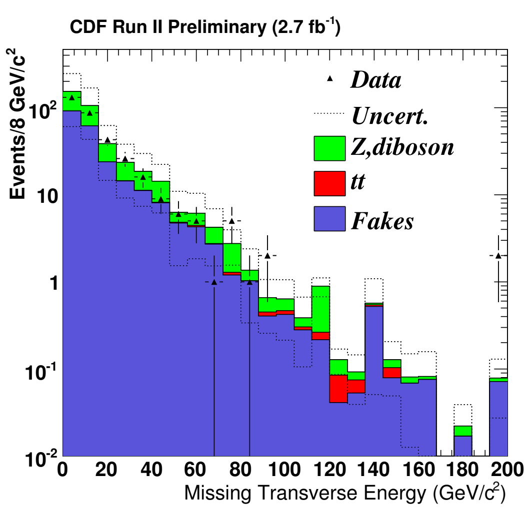


**FIG. 5:** Missing transverse energy (M$E_T$) with same sign leptons with $|\eta| < 1.1$. Note that the last bin contains the high M$E_T$ overflow.

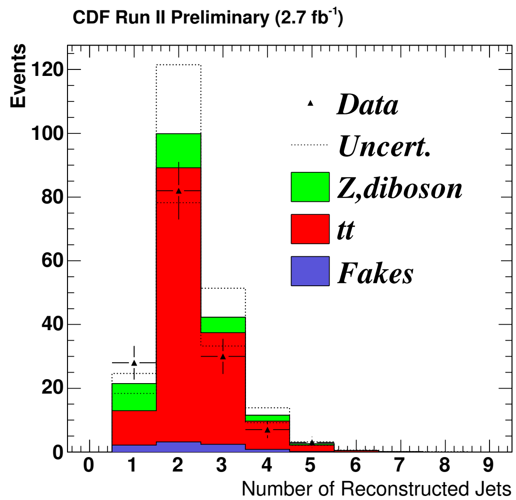


**FIG. 6:** Number of observed jets with opposite-sign leptons, $|\eta| < 1.1$, MET$> 20\ GeV/c$, and at least one positive SECVTX b-tag.

CDF Run II Preliminary 2.7 fb $^{-1}$

| Mass ($GeV/c^2$) | $N_{exp} b'/B$ | Acceptance $b'/B$ | $N_{exp} T_{5/3}$ | Acceptance $T_{5/3}$ |
|---|---|---|---|---|
| 260 | 24.9 ± 2.5 | .026 ± .003 | 26.6 ± 2.7 | .028 ± .003 |
| 300 | 8.99 ± .90 | .027 ± .003 | 8.95 ± .99 | .027 ± .003 |
| 310 | 6.72 ± .67 | .026 ± .003 | 6.70 ± .67 | .026 ± .003 |
| 320 | 5.30 ± .53 | .027 ± .003 | 5.33 ± .53 | .027 ± .003 |
| 330 | 4.08 ± .40 | .027 ± .003 | 4.10 ± .41 | .027 ± .003 |
| 340 | 2.97 ± .30 | .025 ± .003 | 3.19 ± .32 | .027 ± .004 |
| 350 | 2.38 ± .24 | .026 ± .003 | 2.39 ± .24 | .026 ± .003 |
| 375 | 1.26 ± .13 | .026 ± .003 | 1.18 ± .12 | .024 ± .004 |
| 400 | .671 ± .067 | .027 ± .003 | .664 ± .066 | .027 ± .003 |

**TABLE II:** Acceptance and expected number of events for $b'$, $B$, and $T_{5/3}$.

are required to originate from the $W$ or $Z$ decays rather than from misidentified jets. The $T_{5/3}$ signal is modeled in the same manner.

The acceptance and expected number of events for the $b'$, $B$, and $T_{5/3}$ are given in Table II. Acceptance breakdown by channel is given in Table III.

## V. FITTING

From the observed number of events, one could perform a counting experiment. However, we can improve our sensitivity by simultaneously fitting the observed jet multiplicity spectrum for the number of signal and background events in the data. This exploits the different number of jets expected in signal and background events In each case,

CDF Run II Preliminary 2.7 fb $^{-1}$

| Source | $ee$ | $mm$ | $em$ | $ll$ |
|---|---|---|---|---|
| 300 $GeV/c^2$ $b'$ | 1.97 ± .20 | 2.14 ± .21 | 4.88 ± .49 | 9.0 ± .90 |
| 300 $GeV/c^2$ $T_{5/3} + B$ | 4.17 ± .42 | 4.22 ± .42 | 9.56 ± .96 | 17.9 ± 1.8 |

**TABLE III:** Acceptance for $b'$ and $B$, $T_{5/3}$ at mass of 350 $GeV/c^2$ in $ee$, $e\mu$ and $\mu\mu$ events.

| Mass ($GeV/c^2$) | $-2\sigma$ | median | $+2\sigma$ |
|---|---|---|---|
| 260 | 0.21 | 0.21 | 0.21 |
| 300 | 0.38 | 0.38 | 0.63 |
| 310 | 0.53 | 0.53 | 0.78 |
| 320 | 0.63 | 0.63 | 1.01 |
| 330 | 0.86 | 0.86 | 1.45 |
| 340 | 1.18 | 1.18 | 1.76 |
| 350 | 1.41 | 1.41 | 2.27 |

**TABLE IV:** Expected limits on the scale factor in background-only pseudo-experiments. $\pm 2\sigma$ deviations in the expected limits are also shown.

| Mass ($GeV/c^2$) | $-2\sigma$ | median | $+2\sigma$ |
|---|---|---|---|
| 260 | 0.15 | 0.15 | 0.15 |
| 300 | 0.27 | 0.27 | 0.40 |
| 310 | 0.29 | 0.29 | 0.42 |
| 320 | 0.32 | 0.32 | 0.50 |
| 330 | 0.42 | 0.42 | 0.67 |
| 340 | 0.55 | 0.55 | 0.84 |
| 350 | 0.74 | 0.74 | 1.18 |
| 375 | 0.39 | 1.39 | 2.06 |
| 400 | 0.42 | 2.42 | 3.90 |
| 425 | 0.16 | 5.16 | 7.41 |

**TABLE V:** Expected limits on the $B$, $T_{5/3}$ scale factor in background-only pseudo-experiments. $\pm 2\sigma$ deviations in the expected limits are also shown.

we fit for the *scale factor* which is the ratio of the measured and theoretical signal cross-sections.

Following the Feldman-Cousins prescription [13], we use simulated experiments to construct bands which contain 95% of the fitted values of scale factor at various true values of scale factor for a mass of $b'$. The simulated experiments include fluctuations in the nuisance parameters, including the uncertainty in the jet energy scale, initial and final state radiation, parton distribution functions and signal and background normalization uncertainties.

### A. Sensitivity to $b'$

We measure our sensitivity via the median expected scale-factor in background-only pseudo-experiments. Table IV shows these values, which indicates that we can expect to set a limit $m_{b'} >\approx 335$ GeV. Figure 7 shows these limits in terms of the theoretical cross-section.

### B. Sensitivity to $B, T_{5/3}$

We measure our sensitivity via the median expected scale-factor in background-only pseudo-experiments. Table V shows these values, which indicates that we can expect to set a limit $m_{B,T_{5/3}} >\approx 375$ GeV. Figure 9 shows these limits in terms of the theoretical cross-section.

## VI. RESULT

In 2.7 fb$^{-1}$ of data, we see two events (see Table VI) in excellent agreement with the predictions. We set a limit on the mass of the $b'$ to be $> 325.5$ GeV and on the mass of the $B, T_{5/3}$ to be $> 351.6$ GeV at 95% C.L. See Figures 7- 12 for details and event displays.

| Source | $ee$ | $\mu\mu$ | $e\mu$ | $ll$ |
|---|---|---|---|---|
| $Z, diboson$ | $0.03 \pm 0.02$ | $0.02 \pm 0.01$ | $0.04 \pm 0.02$ | $0.10 \pm 0.05$ |
| $tt$ | $0.17 \pm 0.02$ | $0.06 \pm 0.01$ | $0.22 \pm 0.02$ | $0.50 \pm 0.05$ |
| $W + jets$ | $0.56 \pm 0.56$ | $0.34 \pm 0.34$ | $0.47 \pm 0.47$ | $1.40 \pm 1.40$ |
| Total | $0.8 \pm 0.6$ | $0.4 \pm 0.3$ | $0.7 \pm 0.5$ | $1.9 \pm 1.4$ |
| Data | 0 | 1 | 1 | 2 |

**TABLE VI:** List of the backgrounds at final cut level with observed values in the data.

| CDF Run II Preliminary 2.7 fb $^{-1}$<br>Mass $b'$ $(GeV/c^2)$ | Measured $\sigma/\sigma_{Theory}$ |
|---|---|
| 260 | .028 |
| 300 | .073 |
| 310 | .095 |
| 320 | .120 |
| 330 | .160 |
| 340 | .225 |
| 350 | .276 |

**TABLE VII:** Best-fit signal cross sections for $b'$, relative to theoretical prediction, measured at varying masses.

| CDF Run II Preliminary 2.7 fb $^{-1}$<br>Mass $b'$ $(GeV/c^2)$ | 95% CL upper limit $\sigma/\sigma_{Theory}$ |
|---|---|
| 260 | 0.21 |
| 300 | 0.57 |
| 310 | 0.67 |
| 320 | 0.86 |
| 330 | 1.11 |
| 340 | 1.51 |
| 350 | 1.85 |

**TABLE VIII:** 95% CL upper limits on the $b'$ cross section, relative to the theoretical prediction, as a function of mass.

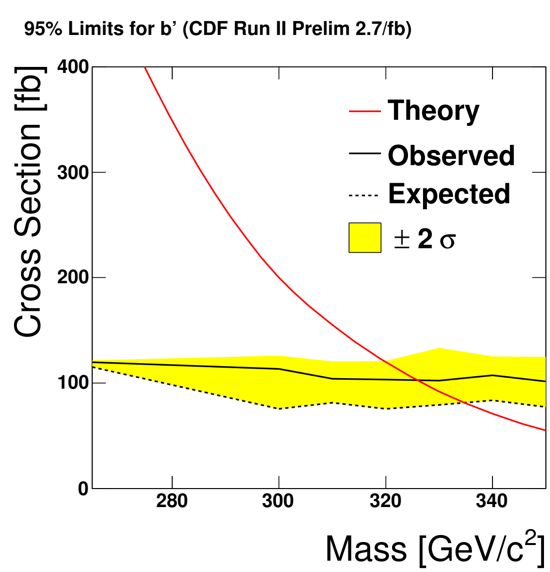


**FIG. 7:** Plot of expected and measured sensitivity for b' with 1 and 2 sigma regions. Note that due to the small number of events, approximately half of simulated experiments yield a measured signal rate of zero; therefore both the median and -2 sigma deviations correspond to the same measured rate, of zero signal events.

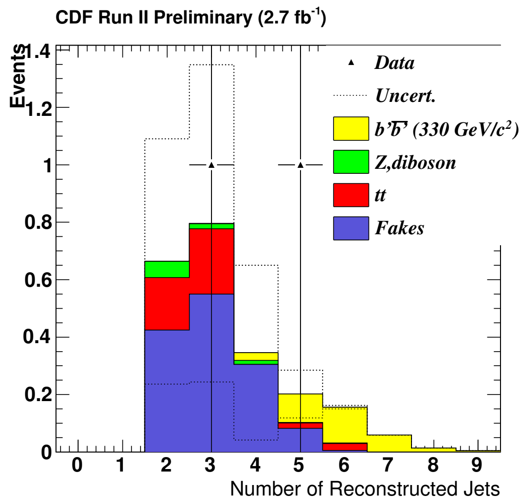


**FIG. 8:** Plot of the best fit scale factor for b' at 330 GeV

| CDF Run II Preliminary 2.7 fb $^{-1}$ | |
|---|---|
| Mass $B + T_{5/3} (GeV/c^2)$ | Measured $\sigma/\sigma_{Theory}$ |
| 260 | .014 |
| 300 | .037 |
| 310 | .049 |
| 320 | .061 |
| 330 | .081 |
| 340 | .105 |
| 350 | .133 |
| 375 | .262 |
| 400 | .491 |
| 425 | .907 |

**TABLE IX:** Best-fit signal cross sections for $B + T_{5/3}$, relative to theoretical prediction, measured at varying masses.

### Acknowledgments

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[3] A. Abulencia *et al.*, J. Phys. G **34**, 2457 (2007).,
[4] `http://www-cdf.fnal.gov/internal/physics/joint_physics/instructions/`
[5] CDF 8741, CDF 9247
[6] W and Z cross-sections

| CDF Run II Preliminary 2.7 fb $^{-1}$ | |
|---|---|
| Mass $B + T_{5/3} (GeV/c^2)$ | 95% CL upper limit $\sigma/\sigma_{Theory}$ |
| 260 | 0.15 |
| 300 | 0.27 |
| 310 | 0.29 |
| 320 | 0.50 |
| 330 | 0.59 |
| 340 | 0.74 |
| 350 | 0.95 |
| 375 | 1.76 |
| 400 | 2.86 |
| 425 | 5.84 |

**TABLE X:** 95% CL upper limits on the $B+T_{5/3}$ cross section, relative to the theoretical prediction, as a function of mass.

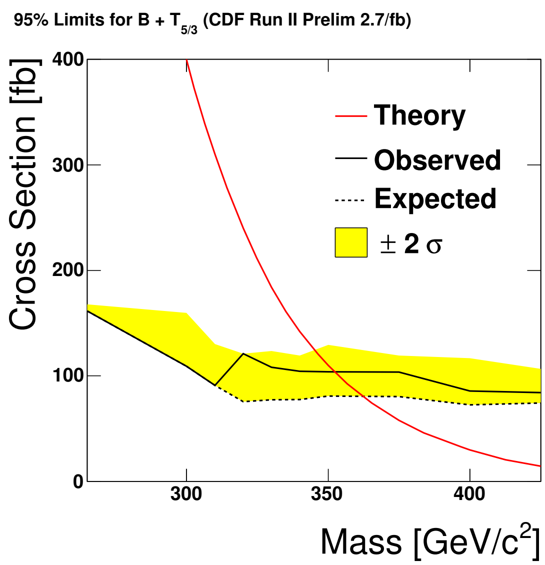


**FIG. 9:** Plot of expected and measured sensitivity for $B+T_{5/3}$ with 1 and 2 sigma regions.

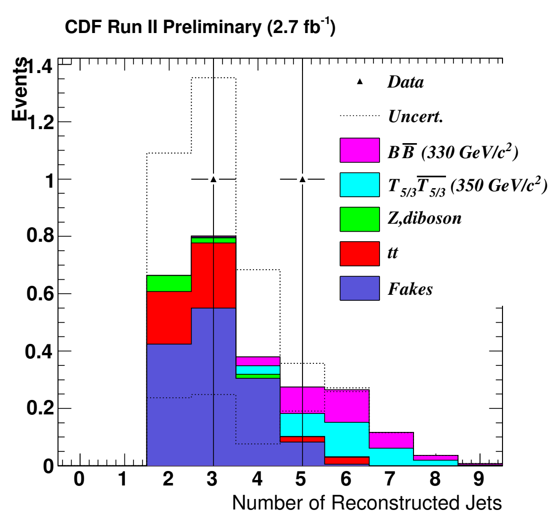


**FIG. 10:** Plot of the best fit scale factor for $B+T_{5/3}$ at 350 GeV

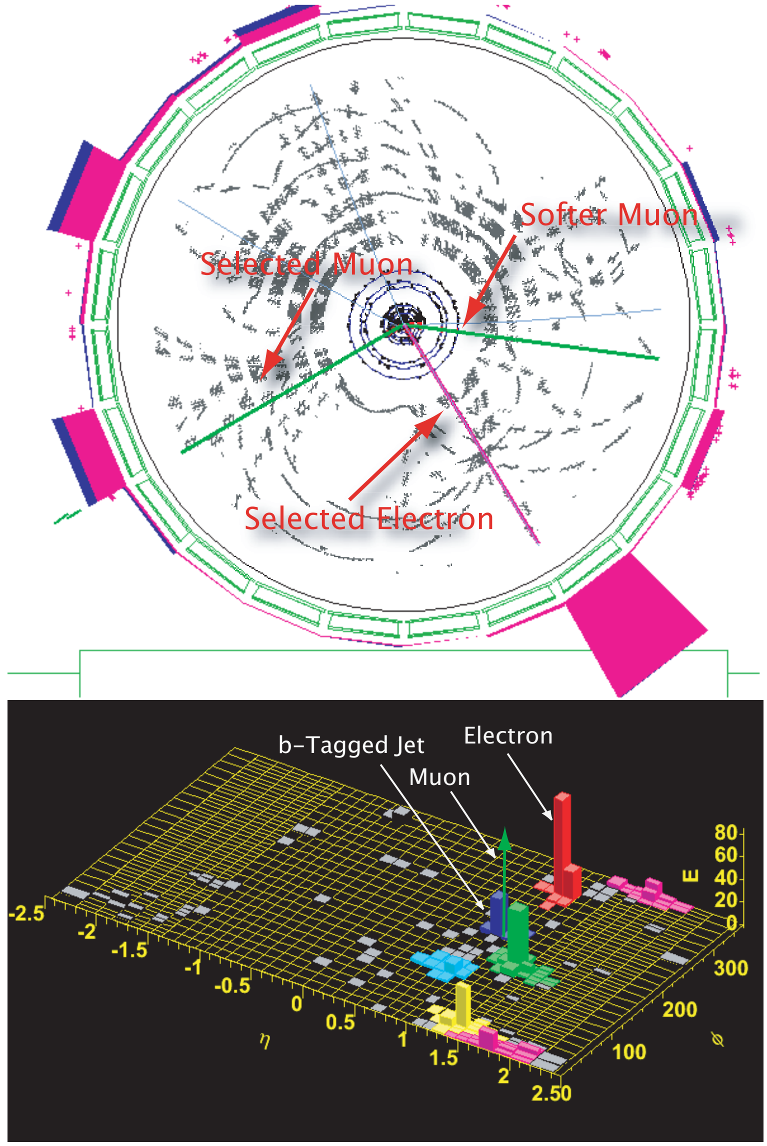


**FIG. 11:** Event display for $e\mu$ 5-jet event (run 198843 event 15281816).


[7] BAUR generator

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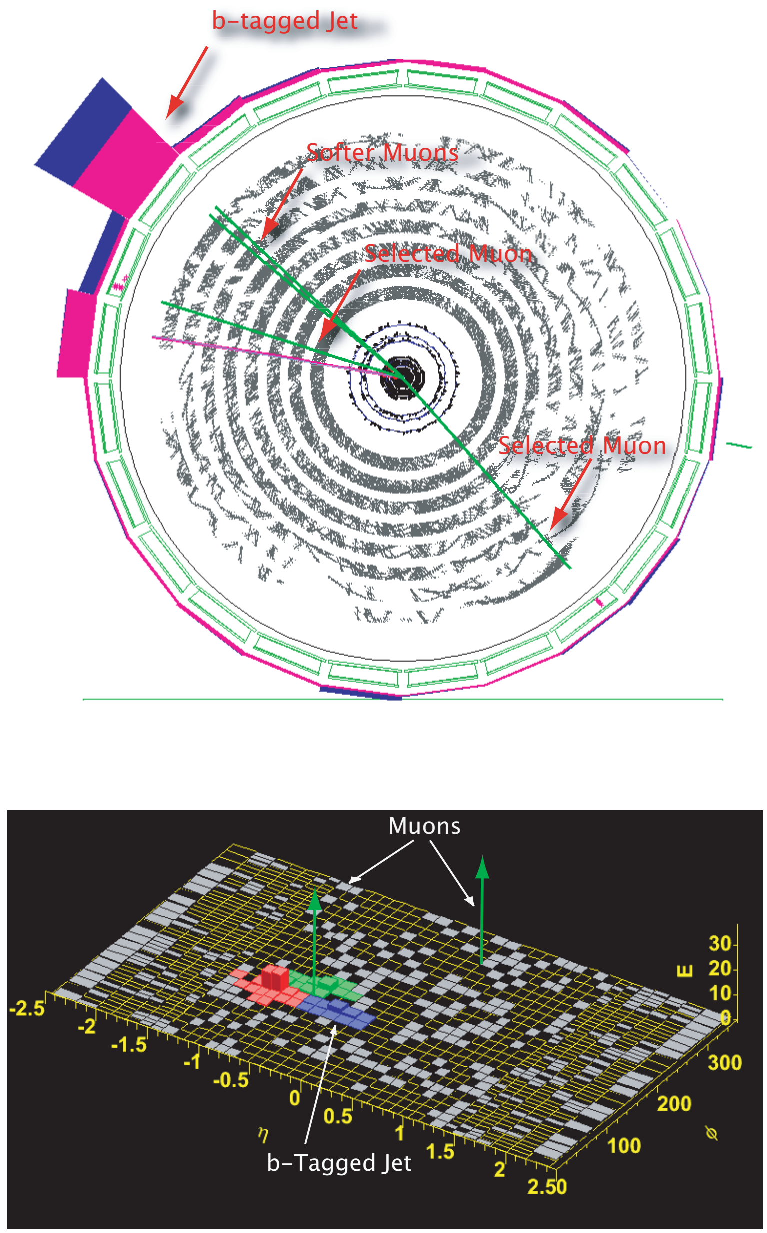


**FIG. 12:** Event display for $\mu\mu$ 3-jet event (run 185637 event 3178143)