Search for down-type fourth generation quarks with the ATLAS detector in events with one lepton and hadronically decaying $W$ bosons

The ATLAS Collaboration

This Letter presents a search for pair production of heavy down-type quarks decaying via $b' \rightarrow Wt$ in the lepton+jets channel, as $b'b' \rightarrow WtW^+ \bar{t}' \rightarrow b\bar{b}W^+W'^-W'^- \rightarrow l^{\pm}b\bar{b}qqqqqq$. In addition to requiring exactly one lepton, large missing transverse momentum and at least six jets, the invariant mass of nearby jet pairs is used to identify high transverse momentum $W$ bosons. In data corresponding to an integrated luminosity of 1.04 fb$^{-1}$ from $pp$ collisions at $\sqrt{s} = 7$ TeV recorded with the ATLAS detector, a heavy down-type quark with mass less than 480 GeV is excluded at the 95% confidence level.

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the same bunch crossing as the selected event (in-time pileup) and, to a lesser extent, collisions during adjacent bunch crossings, within the time the detectors are sensitive for each trigger (out-of-time pileup). The simulation takes both kinds of pileup into account.

The signal and SM backgrounds are modeled using a variety of generators. Pair-production of $b'$ quarks decaying to $Wt$ with subsequent showering and hadronization is generated with PYTHIA [12] using the MRST2007 LO* parton distribution function (PDF) set [13]. Seven samples with $m_{W'}$ masses ranging from 300 to 600 GeV are used. The cross section for each $b'$ mass is calculated at approximate next-to-next-to-leading order (NNLO) using Hather [14]. For a $b'$ quark with a mass of 350 GeV, the cross section is $3.20^{+0.10+0.12}_{-0.19-0.12}$ pb, where the first uncertainty comes from varying the renormalization and factorization scales by a factor of two, and the second one from the PDFs. For a 500 GeV $b'$ quark, the cross section is $0.33^{+0.02}_{-0.01}$ pb.

Top quark pair production is modeled using ALPGEN [15] where hard emission of up to three partons is described using QCD matrix elements, HERWIG [16] is used to model the parton shower, and JIMMY [17] describes multiple parton interactions. The rate of top quark production predicted by the simulation is validated with data using an event sample with three, four or five jets, where little or no $b'$ signal is expected.

Production of a $W$ or $Z$ boson in association with many jets is described in ALPGEN with hard parton emission of up to five partons and HERWIG for the parton shower. The $W$+jets background is normalized using a data-driven method which fits templates from simulated events to a data sample dominated by $W$ decays [18]. The $Z$+jets background is normalized to a NNLO calculation [19].

Other processes considered are the production of di-bosons ($WW, WZ, ZZ$), modeled with ALPGEN and HERWIG and normalized to next-to-leading order (NLO) calculations [20]; single top, modeled with MC@NLO [21] and HERWIG; and $ttW, ttZ, ttWW, tWj, tZj$, and $WWjj$, all modeled with MADGRAPH [22] and PYTHIA.

The multijet background is strongly suppressed by the requirements described below. The residual contribution is estimated using a data-driven technique called the matrix method, described in detail in Ref. [23]. Validation of this background estimate is done by reversing these requirements to enhance the multijet contribution.

Electrons, jets, muons, and missing transverse momentum are used to select events for this search. Electrons are required to have $E_T > 25$ GeV and be within the pseudorapidity range $|\eta| < 2.47$, excluding the barrel-endcap transition region $1.37 < |\eta| < 1.52$. Electrons must pass tight identification requirements [11] and also satisfy calorimeter isolation: the energy not associated to the electron cluster inside a cone of size $\Delta R = 0.2$ around the electron direction must be smaller than 3.5 GeV after the correction for the contributions from interactions additional to the hard process.

Jets are reconstructed from topological calorimeter clusters using the anti-$k_T$ algorithm [24] with radius parameter 0.4. These jets are then calibrated to the hadronic energy scale using $p_T$- and $\eta$-dependent correction factors obtained from simulation and validated with collision data [25]. For this analysis, jets are required to satisfy $p_T > 25$ GeV and $|\eta| < 2.5$. The closest jet within an $\eta-\phi$ cone of 0.2 around an electron candidate is removed.

Muon candidates must satisfy $p_T > 20$ GeV and $|\eta| < 2.5$ and pass tight identification requirements [23]. Muons must also satisfy calorimeter isolation, which requires that the energy, excluding the estimated energy deposited by the muon, is smaller than 4 GeV in a cone of size $\Delta R = 0.3$ around the muon direction, and track isolation, which requires that the summed momentum of all tracks excluding the muon track is smaller than 4 GeV in a cone of size $\Delta R = 0.3$. Finally, all muons within a cone of size $\Delta R = 0.4$ around any jet with $p_T > 20$ GeV are removed.

The missing transverse momentum ($E^{\text{miss}}_T$) is constructed from the vector sum of topological calorimeter energy deposits and muon momenta, projected onto the transverse plane [26].

If each $b'$ quark decays to a top quark and a $W$ boson, the resulting final state is $tWtW^-$. In the lepton + jets decay channel, the final state contains one lepton, $E^{\text{miss}}_T$ from the undetected neutrino, and many jets from the eight quarks. Exactly one lepton ($e$ or $\mu$) must pass the selection described above. Since not all jets are expected to satisfy the momentum and rapidity requirements, at least six jets are required.

To reduce the multijet background, additional requirements are placed on the $E^{\text{miss}}_T$ and the transverse mass of the leptonically decaying $W$ boson, $m_T^W = \sqrt{2E^{\text{miss}}_T p^\ell_T (1 - \cos(\Delta \phi(E^{\text{miss}}_T, p^\ell_T)))}$. In the electron channel, $E^{\text{miss}}_T > 35$ GeV and $m_T^W > 25$ GeV are required, and in the muon channel, $E^{\text{miss}}_T > 20$ GeV and $E^{\text{miss}}_T + m_T^W > 60$ GeV are required. Only events with six or more jets are considered. For a $b'$ quark with a mass of 350 GeV, $11.2 \pm 1.7\%$ of signal events are accepted with this selection. For a $b'$ quark with a mass of 500 GeV, $13.5 \pm 2.0\%$ of signal events are retained.

At this stage of the selection, pair production of $b'$ quarks is distinguished mostly by the large number of energetic jets, as shown in Fig. 1. Events with $b'$ decays contain jets from three hadronic $W$ decays, while $t\bar{t}$ background events contain only one hadronic $W$ decay.

To identify these hadronic $W$ decays, pairs of jets separated by $\Delta R < 1.0$ are examined. This choice of $\Delta R$ selects $W$ bosons with high $p_T$ and reduces the combinatorial background in events with large jet multiplicity. The number of reconstructed $W$ bosons ($N_{W^\pm}$) is defined as the number of such jet pairs with an invariant mass in the range $70 - 100$ GeV. This range is not symmetric around the $W$ boson mass as additional energy is often included in the cone. Each jet may contribute to only
one identified hadronic $W$ decay. In Fig. 2, the invariant masses of dijet pairs in a control sample of events with only three to five jets are shown. Good agreement is observed between the data and simulation across the entire spectrum including the region close to the $W$ boson mass, where a bump can be seen in the $t\bar{t}$ simulation.

The efficiency of finding a simulated $W$ decay with both quarks matched to separate reconstructed jets depends on the $W$ boson $p_T$. For simulated $t\bar{t}$ and $b'$ events passing the selection described above and containing a $W$ boson with a $p_T$ of about 250 GeV the two jets from the $W$ boson are found approximately 80% of the time. Once both jets are found, the efficiency that the jets have $\Delta R < 1.0$ and a dijet mass within the specified invariant mass range is approximately 70%, as can be seen in Fig. 3.

To further distinguish the potential $b'$ signal from the backgrounds, nine exclusive bins are examined, defined as a function of the multiplicity of hadronic $W$ decays ($N_W = 0, 1, \geq 2$) and jet multiplicity ($N_{\text{jet}} = 6, 7, \geq 8$).

The agreement between data and simulation for the description of the number of jets is validated in events to have exactly six jets. The efficiency of finding a simulated $W$ boson decay to have $\Delta R < 1.0$ and a dijet mass within the specified invariant mass range is approximately 70%, as can be seen in Fig. 3.

![Graph](image1)

**FIG. 1:** Jet multiplicity distribution for signal and backgrounds for events with at least one jet. The shaded SM backgrounds are stacked on one another, while the $b'$ signal histograms are not. In this figure and those following, the bottom plot shows the relative difference between the SM prediction and the data together with the uncertainty (shaded band) due to statistics, jet energy scale, and $W$+jets normalization.

![Graph](image2)

**FIG. 2:** The invariant mass distribution of jet pairs with $\Delta R < 1.0$ for data and simulation in a control sample of events with exactly three to five jets.

![Graph](image3)

**FIG. 3:** The efficiency for jet pairs from a simulated $W$ boson decay to have $\Delta R < 1.0$ and a dijet mass within $70 - 100$ GeV, for simulated $t\bar{t}$ and signal events. Events are required to have exactly six jets.

**TABLE I:** Systematic uncertainties in the predicted total background in the signal region. Some of the uncertainties have been constrained in background-dominated regions, ‘profiled’ as described in the text. Smaller systematic uncertainties, such as those related to lepton identification and theory, and small uncertainties on the rate, are not profiled and are not included here. For the profiled systematics, the uncertainty before profiling is given in parentheses.

<table>
<thead>
<tr>
<th>Uncertainty on Background</th>
<th>Uncertainty on Background</th>
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</thead>
<tbody>
<tr>
<td>Profied Uncertainties</td>
<td>Not-profiled Uncertainties</td>
</tr>
<tr>
<td>$W$+jets Normalization</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>$\pm5% \pm16%$</td>
<td>$\pm31%$</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>$t\bar{t}$ Simulation Generator</td>
</tr>
<tr>
<td>$\pm12% \pm17%$</td>
<td>$\pm6%$</td>
</tr>
<tr>
<td>Jet Energy Resolution</td>
<td>$t\bar{t}$ Showering Model</td>
</tr>
<tr>
<td>$\pm3% \pm6%$</td>
<td>$\pm3%$</td>
</tr>
<tr>
<td>Jet Reconstruction Efficiency</td>
<td>$\pm2% \pm3%$</td>
</tr>
<tr>
<td>$\pm17% \pm16%$</td>
<td></td>
</tr>
</tbody>
</table>

The main contributions to uncertainty in the
modeling of the backgrounds and $b'$ signal come from the jet energy scale and the level of initial and final state radiation (ISR/FSR) in the top quark pair background. The jet energy scale uncertainty is extracted from dijet events and validated with $\gamma + \text{jet}$ events as discussed in Ref. [28], with an additional uncertainty due to time pileup. The amounts of simulated ISR and FSR are varied according to their uncertainties for both background and signal events. Jet reconstruction efficiency and jet energy resolution lead to smaller uncertainties in the predicted background.

For the largest background source, $t\bar{t}$ with additional jets, uncertainties in the description of the parton shower and fragmentation model are estimated by comparing predictions of POWHEG [27] with PYTHIA to POWHEG with HERWIG. Uncertainties in the modeling of the production and decay of the top quark are estimated by comparing the predictions from POWHEG with HERWIG and ALPGEN.

The $W$+jets normalization uncertainty is 4%, plus 24% per jet added in quadrature [18]. The uncertainties in lepton reconstruction efficiency and energy scale are derived in dilepton samples dominated by $Z \rightarrow \ell\ell$ decays and applied to the simulated background and signal samples.

The systematic uncertainties are treated as correlated between signal and background, and between electron and muon channels, except where they are specific to the background model (e.g. $W$+jets normalization) or to a channel (e.g. electron or muon efficiencies).

To extract the most likely value of the $b\bar{b}$ cross section in the nine bins of ($N_W, N_{\text{jet}}$) multiplicity, a binned maximum likelihood fit using a profile likelihood ratio is performed, varying each background rate within its uncertainty, and allowing shape and rate variation due to the systematic uncertainties described above. The signal and background rates are fitted simultaneously.

Events in the final selection which have low hadronic $W$ boson or jet multiplicity ($N_W < 2$ and $N_{\text{jet}} < 8$) are dominated by background processes and serve to constrain some of the systematic uncertainties. The likelihood is maximized with respect to the variation due to the systematic uncertainties. This procedure serves to reduce some of the systematic uncertainties, those listed as ‘profiled’ in Table 4.

The expected background and signal contributions, as well as the observed numbers of events in the data, are shown in Fig. 4 and given in Table 4. No evidence for the production of $b'$ quarks is observed. The CLs method [28] is used to set 95% confidence level (C.L.) cross section upper limits for the pair production of fourth generation quarks, $b'$. The median expected upper limit is extracted in the background-only hypothesis. The results are shown in Fig. 5 as a function of the $b'$ mass. Systematic uncertainties are taken into account and it is assumed that the branching ratio (BR) for $b' \rightarrow Wt$ is 100%. These cross section limits are interpreted as limits on the $b'$ mass by finding the intersection of the limit curves with the theoretical cross section curve. Uncertainty in the theoretical cross section includes renormalization and factorization scale and PDF uncertainties calculated with Hathor [14].

Masses below 480 GeV are excluded at the 95% confidence level, while the expected limit is $m_{b'} > 470$ GeV. For a particle with a mass of 480 GeV, the expected exclusion limit on the pair production cross section is $\sigma < 0.54^{+0.45}_{-0.22}$ pb, while the observed exclusion is $\sigma < 0.47$ pb.

In conclusion, a search for pair production of heavy down-type quarks decaying via $b' \rightarrow Wt$ in the lepton

<table>
<thead>
<tr>
<th>$N_{\text{jet}}$, $N_W$</th>
<th>Background</th>
<th>Events</th>
<th>$E_b$</th>
<th>$E_{b'}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0, 0</td>
<td>2060 $^{+104}_{-75}$</td>
<td>1839</td>
<td>80</td>
<td>5</td>
</tr>
<tr>
<td>1, 0</td>
<td>410 $^{+104}_{-150}$</td>
<td>410</td>
<td>47</td>
<td>8</td>
</tr>
<tr>
<td>2, 0</td>
<td>28 $^{+10}_{-8}$</td>
<td>32</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>3, 0</td>
<td>570 $^{+320}_{-230}$</td>
<td>521</td>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>4, 1</td>
<td>166 $^{+49}_{-68}$</td>
<td>142</td>
<td>46</td>
<td>7</td>
</tr>
<tr>
<td>5, 2</td>
<td>17.9 $^{+6.8}_{-6.8}$</td>
<td>21</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>6, 3</td>
<td>170 $^{+180}_{-70}$</td>
<td>173</td>
<td>56</td>
<td>3</td>
</tr>
<tr>
<td>7, 4</td>
<td>69 $^{+33}_{-27}$</td>
<td>57</td>
<td>50</td>
<td>8</td>
</tr>
<tr>
<td>8, 5</td>
<td>12 $^{+8.6}_{-5.2}$</td>
<td>11</td>
<td>22</td>
<td>6</td>
</tr>
</tbody>
</table>

**FIG. 4:** Distribution of the numbers of events observed in the data and expected from SM processes for jet multiplicity $N_{\text{jets}} = 6, 7, \geq 8$ with hadronic $W$ multiplicity $N_W = 0, 1, \geq 2$. The expected $b'$ signals for two masses are also shown, stacked on top of the backgrounds.
+ jets channel has been performed using 1.04 fb$^{-1}$ of $\sqrt{s} = 7$ TeV pp collision data recorded with the ATLAS detector, selecting events based on the number of jets and hadronic $W$ decays. A heavy down-type quark with mass less than 480 GeV is excluded at the 95% confidence level, improving significantly on previous limits.

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FIG. 5: Expected and observed cross section exclusion upper limits at 95% C.L. for a fourth-generation $b'$ quark. Systematic uncertainties on the expected limit are shown with shaded bands. Previously published limits from CDF [3, 4], CMS [5], and ATLAS [7] are also shown.

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007 (2003); S. Frixione et al., JHEP 0603, 092 (2006); S. Frixione et al., JHEP 0807, 029 (2008).


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