Search for Pair Production of a New $b'$ Quark that Decays into a $Z$ Boson and a Bottom Quark with the ATLAS Detector

G. Aad et al.*

(ATLAS Collaboration)

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A search is reported for the pair production of a new quark $b'$ with at least one $b'$ decaying to a $Z$ boson and a bottom quark. The data, corresponding to 2.0 fb$^{-1}$ of integrated luminosity, were collected from $p\bar{p}$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector at the CERN Large Hadron Collider. Using events with a $b$-tagged jet and a $Z$ boson reconstructed from opposite-charge electrons, the mass distribution of large transverse momentum $b'$ candidates is tested for an enhancement. No evidence for a $b'$ signal is detected in the observed mass distribution, resulting in the exclusion at a 95% confidence level of $b'$ quarks with masses $m_{W'} < 400$ GeV that decay entirely via $b' \rightarrow Z + b$. In the case of a vectorlike singlet $b'$ mixing solely with the third standard model generation, masses $m_{W'} < 358$ GeV are excluded.

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The matter sector of the standard model (SM) consists of three generations of chiral fermions, with each generation containing a quark doublet and a lepton doublet. A natural question is whether quarks and leptons exist beyond the third generation [1]. In this Letter, we present a search for the pair production of a new quark with electric charge $-1/3$, denoted $b'$, using data collected by the ATLAS experiment at the Large Hadron Collider. New quarks appear in a variety of models that address shortcomings of the SM [1–5]. In addition to signaling a richer matter content at high energy, their existence would impact lower-energy experiments. In particular, the branching ratios of $W$ and $Z$ boson decays [10], excluding, for example, $b'$ masses below 180 GeV for $c\tau = 20$ cm [11]. More recently, CDF [12], CMS [13], and ATLAS [14] have searched for the prompt charged-current decay $b' \rightarrow W + t$. This decay mode is dominant for a chiral $b'$ with mass in excess of $m_W + m_t$, as the neutral-current modes only occur through loop diagrams [1]. The ATLAS result excludes chiral $b'$ quarks with masses below 480 GeV.

Extensions to the SM often propose new quarks transforming as vectorlike representations of the electroweak gauge groups [2–5]. The decay of a vectorlike $b'$ to a $Z$ boson and a bottom quark is a tree-level process with a branching ratio comparable to that of the decay $b' \rightarrow W + t$. In particular, the branching ratios $Wt:Zb:Hb$ approach the proportion 2:1:1 in the limit of a large $b'$ mass as a consequence of the Goldstone boson equivalence theorem [2,5]. Furthermore, if a signal were observed in the $WtWt$ final state, a search for a resonant $Z + b$ signal would aid in establishing the charge of the new quark. In light of these observations, this search explores the $Z + b$ jet final state for the presence of a $b'$ quark.

The ATLAS detector [15] consists of particle-tracking detectors, electromagnetic and hadronic calorimeters, and a muon spectrometer. At small radii transverse to the beam line, the inner tracking system utilizes fine-granularity pixel and microstrip detectors designed to provide precision track impact parameter and secondary vertex measurements. These silicon-based detectors cover the pseudorapidity [16] range $|\eta| < 2.5$. A gas-filled straw tube tracker complements the silicon tracker at larger radii. The tracking detectors are immersed in a 2 T magnetic field produced by a thin superconducting solenoid located in the same cryostat as the barrel electromagnetic (EM) calorimeter. The EM calorimeters employ lead absorbers and utilize liquid argon as the active medium. The barrel EM calorimeter covers $|\eta| < 1.5$, and the end-cap EM calorimeters cover $1.4 < |\eta| < 3.2$. Hadronic calorimetry in the region $|\eta| < 1.7$ is achieved using steel absorbers and scintillating tiles as the active medium. Liquid argon calorimetry with copper absorbers is employed in the hadronic end-cap calorimeters, which cover the region $1.5 < |\eta| < 3.2$.

The search for the decay $b' \rightarrow Z + b$ is performed in the final state with the $Z$ boson decaying to an electron-positron pair ($e^+e^-$) using a dataset collected in 2011 corresponding to an integrated luminosity of...
The selected events were recorded with a single-electron trigger that is over 95% efficient for reconstructed electrons [18] with momentum transverse to the beam direction, $p_T$, exceeding 25 GeV. At least two opposite-charge electron candidates are required, each satisfying $p_T > 25$ GeV and reconstructed in the pseudorapidity region $|\eta| < 2.47$, excluding the barrel to end-cap calorimeter transition region, $1.37 < |\eta| < 1.52$. In addition, the electron candidates satisfy medium quality requirements [18] on the reconstructed track and properties of the electromagnetic shower. The two opposite-charge electron candidates yielding an invariant mass $m_{ee}$ that satisfies $|m_{ee} - m_Z| < 15$ GeV and is closest to the $Z$ boson mass define the $Z$ candidate. Approximately 475,000 events pass the $Z \rightarrow e^+e^-$ selection criteria.

Jets are reconstructed using the anti-$k_t$ clustering algorithm [19] with a distance parameter of 0.4. The inputs to the algorithm are three-dimensional clusters formed from calorimeter energy deposits. Jets are calibrated using $p_T$- and $\eta$-dependent factors determined from simulation and validated with data [20]. Jets are rejected if they do not satisfy quality criteria to suppress noise and noncollision backgrounds, as are jets whose axis is within $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.5$ of a reconstructed electron associated with the $Z$ candidate. A requirement is made to ensure at least 75% of the total $p_T$ of all tracks associated with the jet be attributed to tracks also associated with the selected $pp$ collision vertex [21]. Finally, jets in this analysis are restricted to the region covered by the tracking detectors, $|\eta| < 2.5$, and satisfy $p_T > 25$ GeV. Approximately 81,000 events pass the $Z \rightarrow e^+e^-$ candidate selection and contain at least one selected jet.

The SM production of $Z$ bosons in association with jets accounts for most events passing the $Z+ \geq 1$ jet selection. Two leading-order Monte Carlo (MC) generators, ALPGEN [22] and SHERPA [23], are used to assess the background arising from this process, with ALPGEN providing the baseline prediction. A description of the generation of these samples, in particular, in regard to differences between ALPGEN and SHERPA in the modeling of $Z$ boson production in association with $b$ jets, is detailed in Ref. [24]. The predictions of both are normalized such that the inclusive $Z$ boson cross section is equal to a next-to-next-to-leading-order (NNLO) calculation [25]. All MC samples fully simulate the ATLAS detector [26] and are reconstructed with the same algorithms as those applied to data. The $Z + b$ jet background category comprises simulated $Z + j$ events in which a generated $p_T > 5$ GeV bottom quark is matched to a selected reconstructed jet. Similarly, events with a jet matched to a charm quark, but not a bottom quark, constitute the $Z + c$ quark category. In the $Z + l$ category, none of the selected jets are matched to a bottom or charm quark.

Additional SM backgrounds modeled with MC events include top quark pair production ($t\bar{t}$), single top production, heavy vector boson pair (diboson) production, $Z(\rightarrow \tau\tau) + j$ events, and $W(\rightarrow e\nu) + j$ events. Processes with a top quark are simulated with MC@NLO [27,28]. The $t\bar{t}$ cross section is used as the HATHOR [29] approximate NNLO value, while MC@NLO [28] values are used for the single top processes. HERWIG [30] models the contribution of diboson events, with the cross sections set by the MC@NLO predictions. The remaining $W/Z + j$ backgrounds are simulated with ALPGEN, and normalized using single vector boson production NNLO cross sections [25]. The multijet background is estimated using a data sample with both electron candidates passing loose criteria [18] but failing the slightly tighter medium criteria. This sample is normalized to the difference in the inclusive $Z$ sample between the data and all other backgrounds in the region $50 < m_{ee} < 65$ GeV. The small single top, diboson, $Z \rightarrow \tau\tau$, $W \rightarrow e\nu$, and multijet contributions are combined and denoted Other SM.

Figure 1 presents the $e^+e^-$ invariant mass distribution for events passing the $Z+ \geq 1$ jet selection, before imposing the $|m_{ee} - m_Z| < 15$ GeV requirement, together with the SM prediction. The observed and predicted number of events are listed in Table I for this and two other stages of the event selection. Most events passing the $Z+ \geq 1$ jet selection arise from the $Z+ l$ category. The appreciable lifetime of the $b$ hadron originating from the bottom quark in the decay $b' \rightarrow Z + b$ provides a means to reduce this background source. A $b$ jet tagging algorithm referred to as IP3D + SV1 [32] is utilized to select events with at

![Figure 1](https://example.com/figure1.png)
Figure 2 presents the simulated properties of a reconstructed secondary vertex. In a transverse track impact parameters, while the second utilizes properties of a reconstructed secondary vertex. In a simulated $\tilde{t}$ sample, the requirement on the discriminant defining a $b$ jet is 60% efficient for jets with a $b$ hadron, and yields a light flavor jet rejection rate of 300 [32].

A total of 3466 events satisfy the $Z + \geq 1$ jet selection. Figure 2 presents the $e^+ e^-$ invariant mass distribution in this sample and the SM prediction, before imposing the $|m_{ee} - m_Z| < 15$ GeV requirement. The accurate modeling of the mass distribution for values beyond the $Z$ boson mass supports the prediction of $t\tilde{t}$ and Other SM background events. Within the window around the $Z$ boson mass, ALPGEN and SHERPA agree to within 1% and 7% in the prediction of the number of $Z$ + light and $Z$ + charm events, respectively. However, ALPGEN and SHERPA disagree in the prediction of the $Z$ + bottom contribution, a fact previously reported in an ATLAS cross section measurement of $Z$ bosons produced in association with $b$ jets using a smaller dataset [24]. The ALPGEN and SHERPA $Z$ + bottom predictions are scaled to account for the difference between data and all other predicted backgrounds in a subsample of the $Z + \geq 1$ jet sample that contains events failing the requirement discussed below on the transverse momentum of the $b'$ candidate. The scale factors are consistent with those measured in Ref. [24], and the invariant mass distribution of secondary vertex tracks is used to confirm the validity of the resulting prediction for the flavor composition in the $Z + \geq 1$ jet sample [24].

Simulated $b'b'$ events are generated for a range of $b'$ masses using MADGRAPH [33] with the G4LHC extension [6]. PYTHIA [34] performs fragmentation and hadronization of the parton-level events. The signal cross sections are obtained with HATHOR [29], and vary from 80 pb to 30 fb over the range $m_{b'} = 200–700$ GeV. In each sample, one $b'$ decays in the mode $b' \rightarrow Z + b$, with the $Z$ boson decaying via $Z \rightarrow e^+ e^-$. Two separate samples are produced for each mass value, with the other $b'$ decaying either via $b' \rightarrow Z + b$ or $b' \rightarrow W + t$, and with all decay modes of the $Z$ and $W$ bosons allowed. The factor $\beta = 2 \times \text{BR}(b' \rightarrow Zb) - \text{BR}(b' \rightarrow Zb)^2$ characterizes the fraction of signal events with at least one $b' \rightarrow Z + b$ decay as a function of the branching ratio. The case $\beta = 1$ is equivalent to previous measurements [9] which assumed $\text{BR}(b' \rightarrow Zb) = 1$. The case of a vectorlike singlet (VLS) mixing solely with the third SM generation is also considered by computing $\beta$ as a function of the $b'$ mass [5]. Over the range $m_{b'} = 200–700$ GeV, $\beta$ varies from 0.9 to 0.5. A SM Higgs of mass 125 GeV is assumed.

<table>
<thead>
<tr>
<th>Source</th>
<th>$Z + \geq 1$ jet</th>
<th>$Z + \geq 1$ b jet</th>
<th>$p_T(Zb) &gt; 150$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z + \text{light}$</td>
<td>$74,400 \pm 7300$</td>
<td>$590 \pm 140$</td>
<td>$19 \pm 7$</td>
</tr>
<tr>
<td>$Z + \text{charm}$</td>
<td>$5340 \pm 520$</td>
<td>$870 \pm 210$</td>
<td>$18 \pm 7$</td>
</tr>
<tr>
<td>$Z + \text{bottom}$</td>
<td>$2540 \pm 250$</td>
<td>$1710 \pm 270$</td>
<td>$52 \pm 17$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$320 \pm 40$</td>
<td>$220 \pm 40$</td>
<td>$20 \pm 4$</td>
</tr>
<tr>
<td>Other SM</td>
<td>$1010 \pm 280$</td>
<td>$70 \pm 20$</td>
<td>$1.6 \pm 0.4$</td>
</tr>
<tr>
<td>Total SM</td>
<td>$83,600 \pm 8100$</td>
<td>$3460 \pm 580$</td>
<td>$110 \pm 30$</td>
</tr>
<tr>
<td>Data</td>
<td>$80,519$</td>
<td>$3466$</td>
<td>$100$</td>
</tr>
<tr>
<td>$m_{b'} = 350$ GeV</td>
<td>$110 \pm 12$</td>
<td>$93 \pm 11$</td>
<td>$55 \pm 7$</td>
</tr>
<tr>
<td>$m_{b'} = 450$ GeV</td>
<td>$27 \pm 3$</td>
<td>$20 \pm 2$</td>
<td>$14 \pm 2$</td>
</tr>
</tbody>
</table>
The $b'$ candidate is formed from the $e^+e^-$ pair and the highest $p_T$ $b$ jet. The mass of the $b'$ candidate, $m(Zb)$, is the discriminant distinguishing the background-only and signal-plus-background hypotheses. In $b'$ pair production, the new quarks are typically produced with large transverse momentum, $p_T(Zb)$. Therefore, a $p_T(Zb) > 150$ GeV requirement is applied to increase the signal sensitivity. Figure 3 presents the $p_T(Zb)$ distribution for data and the predicted SM backgrounds. Additionally, the signal distribution is overlaid for a $b'$ mass of 350 GeV, assuming the VLS scenario value $\beta = 0.63$, and for a mass of 450 GeV, assuming $\beta = 1$.

The fraction of signal events passing all requirements varies from 7% to 43% between $m_{V'} = 200–700$ GeV, assuming $\beta = 1$, with the efficiency to pass the minimum $p_T(Zb)$ requirement contributing most to the degree of variation. The requirement $p_T(Zb) > 150$ GeV was determined by assessing the signal sensitivity for different minimum $p_T(Zb)$ values, as quantified by the expected cross section exclusion limit. The limit is computed using a binned Poisson likelihood ratio test [35] of the $m(Zb)$ distribution for different $m_{V'}$ hypotheses. Pseudoexperiments are generated according to the background-only and signal-plus-background hypotheses, and incorporate the impact of systematic uncertainties. The cross section limit is evaluated using the CL$_s$ modified frequentist approach [35].

The impact of each systematic uncertainty on the normalization and shape of the $m(Zb)$ distribution is assessed for each SM background source and the expected $b'$ signal. The fractional uncertainty on the total number of background events passing the $p_T(Zb) > 150$ GeV requirement is 27%. Significant contributions arise from uncertainties in the $p_T(Zb)$ distribution shape in $Z + jet(s)$ events. Such sources of uncertainty include the renormalization and factorization scale choice (14%, evaluated using MCFM [36]), shape differences observed between ALPGEN and SHERPA (12%), and variations in the degree of initial and final state QCD radiation (9%). The uncertainty in the efficiency of the $b$-tagging requirement contributes an additional 12%. Other sources of uncertainty contributing at the level of 6% or less include the jet energy scale [20], parton distribution functions (PDF), MC sample sizes, electron identification efficiency, $Z$ boson cross section, luminosity, $b$ jet mistag rate, $t\bar{t}$ cross section, jet energy resolution, trigger efficiency, and the Other SM event yield. Most of the above uncertainties, with the notable exception of the $p_T(Zb)$ modeling uncertainties in $Z + jet(s)$ events, contribute to the total uncertainty on the signal normalization, which varies between 11% and 14% depending on the $b'$ mass.

Figure 4 presents the $b'$ candidate mass distribution after requiring $p_T(Zb) > 150$ GeV and the predicted SM background. The distributions for the signal scenarios depicted in Fig. 3 are shown overlaid. The data are in agreement with the SM prediction over the full range of $m(Zb)$ values. In the absence of evidence of an enhancement, 95% confidence level (C.L.) cross section exclusion limits are derived. Figure 5 presents the expected and observed cross section limits as a function of $m_{V'}$, computed under the assumption $\beta = 1$. The expected cross section limit was checked to be stable to within 15% over the full mass range considered using the signal samples in which one $b'$ quark...
decays via $b' \rightarrow Z + b$ and the other decays via $b' \rightarrow W + t$.

The approximate NNLO $b'b'$ cross section prediction is shown multiplied by $\beta = 1$, as well as by the VLS $\beta$ value, with the shaded region representing the total uncertainty arising from PDF uncertainties and the factorization and renormalization scale choice. From the intersection of the observed cross section limit and the theoretical prediction, $b'$ quarks with masses $m_{b'} < 400$ GeV decaying entirely via $b' \rightarrow Z + b$ are excluded at 95% C.L., representing a significant improvement with respect to the previous best limit of 268 GeV [9]. In the case of a vectorlike singlet $b'$ mixing solely with the third SM generation, masses $m_{b'} < 358$ GeV are excluded.

In conclusion, a search with 2.0 fb$^{-1}$ of ATLAS data is presented for $b'$ quark pair production, with at least one $b'$ decaying to a $Z$ boson and a bottom quark. This decay mode is particularly relevant in the context of vectorlike quarks and is an essential complement to searches in the mode with both $b'$ decaying to a $W$ boson and a top quark. No evidence for a $b'$ is observed in the $Z + b$ jet final state, and new limits are derived on the mass of a $b'$ quark decaying via $b' \rightarrow Z + b$.

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ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the $z$ axis coinciding with the axis of the beam pipe. The $x$ axis points from the interaction point to the center of the LHC ring, and the $y$ axis points upward. Cylindrical coordinates $(r, \phi)$ parametrize the transverse plane, with $\phi$ as the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. 

071801-5
145a Department of Physics, Stockholm University, Sweden  
145b The Oskar Klein Centre, Stockholm, Sweden

146 Physics Department, Royal Institute of Technology, Stockholm, Sweden

147 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook New York, USA

148 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

149 School of Physics, University of Sydney, Sydney, Australia

150 Institute of Physics, Academia Sinica, Taipei, Taiwan

151 Department of Physics, Technion: Israel Inst. of Technology, Haifa, Israel

152 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

153 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

154 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

155 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

156 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

157 Department of Physics, University of Toronto, Toronto Ontario, Canada

158a TRIUMF, Vancouver British Columbia, Canada

158b Department of Physics and Astronomy, York University, Toronto Ontario, Canada

159 Institute of Pure and Applied Sciences, University of Tsukuba, I-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan

160 Science and Technology Center, Tufts University, Medford Massachusetts, USA

161 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

162 Department of Physics and Astronomy, University of California Irvine, Irvine California, USA

163a INFN Gruppo Collegato di Udine, Italy

163b ITP, Trieste, Italy

163c Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

164 Department of Physics, University of Illinois, Urbana Illinois, USA

165 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

166 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

167 Department of Physics, University of British Columbia, Vancouver British Columbia, Canada

168 Department of Physics and Astronomy, University of Victoria, Victoria British Columbia, Canada

169 Waseda University, Tokyo, Japan

170 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

171 Department of Physics, University of Wisconsin, Madison Wisconsin, USA

172 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

173 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

174 Department of Physics, Yale University, New Haven Connecticut, USA

175 Yerevan Physics Institute, Yerevan, Armenia

176 Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

a Deceased.
b Also at Laboratorio de Instrumentaciao e Física Experimental de Particulas—LIP, Lisboa, Portugal.
c Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
d Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
e Also at TRIUMF, Vancouver BC, Canada.
f Also at Department of Physics, California State University, Fresno CA, USA.
g Also at Novosibirsk State University, Novosibirsk, Russia.
h Also at Fermilab, Batavia IL, USA.
i Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
j Also at Università di Napoli Parthenope, Napoli, Italy.
k Also at Institute of Particle Physics (IPP), Canada.
l Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
m Also at Louisiana Tech University, Ruston LA, USA.

n Also at Department of Physics and Astronomy, University College London, London, United Kingdom.
o Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada.
p Also at Department of Physics, University of Cape Town, Cape Town, South Africa.
q Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
r Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
s Also at Manhattan College, New York NY, USA.
t Also at School of Physics, Shandong University, Shandong, China.
u Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France.

Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at Departamento de Física, Universidade de Minho, Braga, Portugal.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at California Institute of Technology, Pasadena CA, USA.

Also at Institute of Physics, Jagiellonian University, Krakow, Poland.

Also at LAL, Univ. Paris-Sud and CNRS/IN2P3, Orsay, France.

Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

Also at Department of Physics, Oxford University, Oxford, United Kingdom.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.