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Search for pair-produced heavy quarks decaying to Wq in the two-lepton channel at \(\sqrt{s} = 7\) TeV
with the ATLAS detector

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A search is presented for heavy-quark pair production ($Q\bar{Q}$) under the decay hypothesis $Q\bar{Q} \rightarrow W^+ q W^- \bar{q}$ with $q = d, s, b$ for up-type $Q$ or $q = u, c$ for down-type $Q$. The search is performed with 1.04 fb$^{-1}$ of integrated luminosity from $pp$ collisions at $\sqrt{s} = 7$ TeV collected by the ATLAS detector at the CERN LHC. Dilepton final states are selected, requiring large missing transverse momentum and at least two jets. Mass reconstruction of heavy-quark candidates is performed by assuming that the $W$ boson decay products are nearly collinear. The data are in agreement with standard model expectations; a heavy quark with mass less than 350 GeV is excluded at 95% confidence level.

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The addition of one or more heavy quarks is a natural extension to the standard model, capable of providing an additional source of $CP$ violation in $B_i$ decays and accommodating a heavy Higgs boson [1,2]. Searches for heavy quarks with the Collider Detector at Fermilab (CDF) constrain the mass of heavy quarks ($Q$) that decay as $Q \rightarrow W q$, where $q = d, s, b$ for up-type $Q$ or $q = u, c$ for down-type $Q$, to be $m_Q > 340$ GeV [3]. More specific searches have also constrained the mass of up-type heavy quarks ($t'$) that decay as $t' \rightarrow W b$ to be $m_{t'} > 358$ GeV [3] and the mass of down-type heavy quarks ($b'$) decaying via $b' \rightarrow W t$ to be $m_{b'} > 372$ GeV [4].

The D0 experiment at Fermilab has set a mass limit of $m_Q > 285$ GeV [5] on heavy quarks that decay as $Q \rightarrow W q$. All previous searches used the “lepton + jets” channel, where only one of the produced $W$ bosons decays hadronically.

In this article, a search is presented for pair production of a heavy quark ($Q\bar{Q}$) in data corresponding to an integrated luminosity of 1.04 fb$^{-1}$ from proton-proton collisions at $\sqrt{s} = 7$ TeV collected by the ATLAS experiment. The heavy quark is assumed to decay via $Q \rightarrow W q$ where $q = d, s, b$ for up-type $Q$ or $q = u, c$ for down-type $Q$. This search does not include states with $q = t$, i.e. $d' \rightarrow W t$ decays are assumed not to happen. The search is performed in the dilepton channel, where both $W$ bosons decay leptonically. Fourth-generation up-type quarks ($t'$) decaying through weak charged currents ($t' \rightarrow W b$, $t' \rightarrow W s$, and $t' \rightarrow W d$) are used as a benchmark.

Three complementary searches for fourth-generation quarks were performed with the ATLAS detector using 1.04 fb$^{-1}$ of 2011 data. These searches all implement $b$-quark identification algorithms and are thus targeted towards more specific heavy-quark decay modes. The channels considered are $t't' \rightarrow W^+ W^- b\bar{b}$ in the lepton plus jets channel (setting a limit $m_{t'} > 404$ GeV [6]), $b'b' \rightarrow W^+ W^- t\bar{t} \rightarrow W^+ W^- W^+ W^- b\bar{b}$ in the lepton plus jets channel ($m_{b'} > 480$ GeV [7]), and $b'b' \rightarrow W^+ W^- t\bar{t} \rightarrow W^+ W^- W^+ W^- b\bar{b}$ with two same sign leptons in the final state ($m_{b'} > 450$ GeV [8]).

The dileptonic final state arises in a way similar to that of pair-produced top quarks: $Q\bar{Q} \rightarrow \ell^+ \ell^- q\ell^+ \ell^- \bar{q}$, where $\ell$ is either $e$ or $\mu$. Leptonically decaying intermediary $\tau$ leptons are able to contribute to this final state if additional neutrinos are considered. The signature is at least two jets, two oppositely charged leptons, and missing transverse momentum ($E_T^{\text{miss}}$) from undetected neutrinos. Top quark pair production is the dominant source of background. To distinguish a potential heavy-quark signal, heavy-quark mass reconstruction is performed by taking advantage of the larger boost each $W$ boson receives from the decay of a heavy quark compared to the decay of a top quark. This large boost makes each undetected neutrino approximately collinear with an observed charged lepton.

The following sections contain descriptions of the ATLAS detector (Sec. I), simulated samples (Sec. II), object reconstruction (Sec. III), baseline event selection (Sec. IV), data-driven background estimates (Sec. V), mass reconstruction strategy (Sec. VI), validation of background modeling (Sec. VII), final event selection (Sec. VIII), binned maximum-likelihood fit using the reconstructed mass (Sec. IX and X), and final results (Sec. XI).

I. THE ATLAS DETECTOR

The ATLAS detector [9] is a multipurpose particle detector with precision trackers, calorimeters, and muon spectrometers. The momenta of charged particles with
subject to the same reconstruction algorithms as the data.

Events are showered and hadronized with HERWIG v6.5 unless otherwise noted, using JIMMY [13] for the underlying event model. Muon trigger candidates must have transverse momentum \( p_T \) > 18 GeV and matching tracks in the ID and MS.

The ATLAS detector uses a three-level trigger system to select events for offline analysis. For this search, events are required to have at least one lepton satisfying trigger requirements. Electron trigger candidates must have transverse energy \( E_T \) > 20 GeV, must satisfy shower-shape requirements [10], and must have an ID track matched to the EM shower. Muon trigger candidates must have transverse momentum \( p_T \) > 18 GeV and matching tracks in the ID and MS.

II. SIMULATED SIGNAL AND BACKGROUND SAMPLES

Simulated samples are used to evaluate the contributions from the \( Q\bar{Q} \) signal (assuming an up-type heavy quark) and most background processes. Unless otherwise noted, all events are showered and hadronized with HERWIG v6.5 [11,12], using JIMMY [13] for the underlying event model. After event generation, all samples are processed with the GEANT4-based [14] simulation of the ATLAS detector [15] and subject to the same reconstruction algorithms as the data.

The CERN LHC instantaneous luminosity varied during data-taking from about 2 \( \times 10^{32} \) cm\(^{-2}\) s\(^{-1}\) to 1 \( \times 10^{33} \) cm\(^{-2}\) s\(^{-1}\) [16,17]. At maximum luminosity numerous proton-proton (\( pp \)) interactions were superimposed in each bunch crossing. This pileup background produces additional activity in the detector, affecting variables such as jet reconstruction and isolation energies. Monte Carlo (MC) events simulate the pileup background by adding minimum bias events on top of the hard scatter. The MC events are later reweighted such that the simulated instantaneous luminosity distribution matches that in data.

A. Heavy-quark pair production

Production and decay of heavy-quark pairs (\( Q\bar{Q} \)) is modeled with the leading-order (LO) generator PYTHIA 6.421 [18] using MRST 2007 LO* [19] parton distribution functions (PDFs). The production cross section is calculated using HATHOR [20] with approximate next-to-next-to-leading-order (NNLO) QCD calculations with CTEQ6.6 PDFs [21] for several heavy-quark masses \( (m_Q) \). In addition, scale uncertainties are evaluated in the range \( m_Q/2 \) to \( 2 \times m_Q \) and PDF uncertainties are calculated from the CTEQ6.6 error eigenvectors. The cross sections and uncertainties for each heavy-quark mass considered in this analysis are shown in Table I. Samples are generated with either \( t' \rightarrow Wb, t' \rightarrow Ws, \) or \( t' \rightarrow Wd \) final states; final results are verified with all three decay modes.

B. Top quark pair production

The background due to \( t\bar{t} \) production is modeled using the next-to-leading-order (NLO) generator MC@NLO v3.41 [22] with an assumed top quark mass of 172.5 GeV and the NLO PDF set CTEQ6.6. The cross section for \( t\bar{t} \) production is normalized to the value obtained from an approximate NNLO calculation [20].

C. Z boson, diboson, and single-top quark production

The background from Z/\( \gamma \)∗ boson production in association with jets is modeled with the LO generator ALPGEN

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\(^1\)ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the \( \varepsilon \) axis along the beam pipe. The \( x \) axis points from the IP to the center of the Large Hadron Collider (LHC) ring and the \( y \) axis points upward. Cylindrical coordinates \( (r, \phi) \) are used in the transverse plane, \( \phi \) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = -\ln \tan(\theta/2) \).
between the EM calorimeter barrel and endcap. These jets are calibrated to the hadronic energy scale using NLO calculations with MC@NLO. The cross sections for single-top samples are normalized to an approximate NNLO prediction [28,29].

III. OBJECT SELECTION

Electrons are found by a calorimeter-seeded reconstruction algorithm and must have a track that matches an energy deposit in the calorimeter. They are required to satisfy 

\[
E_{\text{cluster}}/\cosh(\eta_{\text{track}}) > 25 \text{ GeV},
\]

where \(E_{\text{cluster}}\) is the energy deposited in the calorimeter cluster and \(\eta_{\text{track}}\) is the pseudorapidity of the matching track. Electrons are required to be in a pseudorapidity range \(|\eta_{\text{cluster}}| < 2.47\), excluding the transition region \(1.37 < |\eta_{\text{cluster}}| < 1.52\) between the EM calorimeter barrel and endcap. They must also satisfy a calorimeter isolation \(I_{\text{cal}} < 3.5 \text{ GeV}\) requirement in \(\Delta R < 0.2\), where \(\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}\). Calorimeter isolation is defined as the energy reconstructed within a cone of a certain radius around the lepton that is not associated with that lepton, and it is represented by \(I_{\text{cal}}\). The calorimeter shower shape is required to closely resemble what is expected for electrons [10].

Jets are reconstructed from topological clusters of energy deposits in the calorimeter [30] using the anti-\(k_t\) algorithm with distance parameter \(R = 0.4\) [31,32]. These jets are calibrated to the hadronic energy scale using a correction factor obtained from simulation that depends on \(p_T\) and \(\eta\) [33]. They are required to satisfy \(p_T > 25 \text{ GeV}\) and \(|\eta| < 2.5\). Jets that fall within \(\Delta R < 0.2\) of accepted electrons are rejected.

Muons are found by requiring that a track reconstructed in the MS has a matching track in the ID. A loose cosmic ray rejection is applied by removing all muon pairs that are back-to-back azimuthally \((\Delta \phi(\mu, \mu') > 3.1)\) and whose transverse impact parameter with respect to the beam line is greater than 0.5 mm. Muon candidates must satisfy \(p_T > 20 \text{ GeV}\) and \(|\eta| < 2.5\). The muon must be isolated, satisfying calorimeter isolation \(I_{\text{cal}} < 4 \text{ GeV}\) in \(\Delta R < 0.3\) and tracking isolation \(I_{\text{trk}} < 4 \text{ GeV}\) in \(\Delta R < 0.3\). Tracking isolation is defined as the sum of track momenta within a cone of a certain radius around the lepton vertex, and it is represented by \(I_{\text{trk}}\). The muon must also not fall within \(\Delta R < 0.4\) of any jet with \(p_T > 20 \text{ GeV}\).

The \(E_T^{\text{miss}}\) is constructed from the vector sum of calorimeter topological cluster energies projected onto the transverse plane [34]. Calorimeter deposits not associated with a jet are calibrated at the EM energy scale. Deposits associated with selected jets contribute at the corrected hadronic energy scale. Muon transverse momenta are included after correcting for muon energy losses in the calorimeters.

IV. BASELINE EVENT SELECTION

The \(Q\bar{Q}\) pair decay yields two charged leptons, two jets, and \(E_T^{\text{miss}}\) from the undetected neutrinos. An initial dilepton selection is applied to validate the modeling of the \(Z/\gamma^*\) boson production background as well as the identification of leptons, reconstruction of jets, and measurement of \(E_T^{\text{miss}}\).

The initial dilepton selection [35,36] first requires that an event contains a high-quality reconstructed primary vertex. The event must also have exactly two leptons (\(e\) or \(\mu\)) with opposite charges, at least one of which must be associated with the object that triggered the event. The two leptons must not share a track in the ID. At this stage, the data sample is dominated by \(Z/\gamma^* \rightarrow \ell\ell\) decays (the Drell-Yan process), although the contribution from \(t\bar{t}\) production is evident at large jet multiplicity, as can be seen in Figs. 1 and 2. These figures show good agreement between the data and background expectation.

To reduce the background from \(Z/\gamma^* \rightarrow \ell\ell\) decays, the baseline selection requires:

(i) all events must have at least two jets, each with \(p_T > 25 \text{ GeV}\) and \(|\eta| < 2.5\);

(ii) same-flavor events (\(ee\) and \(\mu\mu\)) must satisfy a missing transverse momentum requirement, \(E_T^{\text{miss}} > 60 \text{ GeV}\);

(iii) the dilepton invariant mass of same-flavor events (\(ee\) and \(\mu\mu\)) must be greater than 15 \text{ GeV} and must fall outside a window around the \(Z\) boson mass, defined as \(81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}\);

(iv) in different-flavor events (\(e\mu\)), \(H_T\), defined as the scalar sum of \(E_T\) from every lepton and jet passing the object selection criteria, must exceed 130 \text{ GeV}. The \(H_T\) requirement reduces the \(Z/\gamma^* \rightarrow \tau\tau\) background, where an \(E_T^{\text{miss}}\) requirement is insufficient due to the presence of neutrinos.

V. DATA-DRIVEN ESTIMATES

A. Drell-Yan events

The total number of Drell-Yan \(ee\) and \(\mu\mu\) events remaining after the baseline selection has been applied is estimated with a data-driven technique that extrapolates from a control region (CR) [37]. Events in the CR have dilepton invariant mass in the range 81–101 \text{ GeV} with at least two jets and \(E_T^{\text{miss}} > 30 \text{ GeV}\). The number of data
events in the control region, data (CR), and MC $Z/\gamma^* + \text{jets}$ events in the control region, MC$_{DY}$ (CR), are used to scale the prediction of $Z/\gamma^* + \text{jets}$ events in the signal region, MC$_{DY}$. Non-$Z/\gamma^*$ background processes in the control region, MC$_{other}$ (CR), are subtracted from the data using MC predictions. The estimated number of $Z/\gamma^* + \text{jets}$ events in the signal region, $N_{DY}$, in the $ee$ and $\mu\mu$ channels is calculated with Eq. (1):

$$\begin{align*}
N_{DY} &= \frac{(\text{Data(CR)} - \text{MC}_{other(CR)})}{\text{MC}_{DY}(\text{CR})} \\
&= \frac{(\text{Data(CR)} - \text{MC}_{other(CR)})}{\text{MC}_{DY}(\text{CR})}.
\end{align*}$$

FIG. 1 (color online). Jet multiplicity after initial dilepton selection in (a) $ee$, (b) $\mu\mu$, and (c) $e\mu$ channels. The shaded region indicates the magnitude of cross section and luminosity uncertainties. Samples are stacked in the same order as they are presented in the legend, from left to right; the first entry in the legend is at the bottom of the stack. The data-driven Drell-Yan estimate defined in Sec. VA has not been applied here.

FIG. 2 (color online). Dilepton mass after initial dilepton selection in (a) $ee$, (b) $\mu\mu$, and (c) $e\mu$ channels. The shaded region indicates the magnitude of cross-section and luminosity uncertainties. The last bin contains overflow events, and the first bin contains underflow events. Samples are stacked in the same order as they are presented in the legend, from left to right; the first entry in the legend is at the bottom of the stack. The data-driven Drell-Yan estimate defined in Sec. VA has not been applied here.
B. Fake lepton events

A small fraction of the background consists of events in which a jet or a nonprompt lepton is misidentified as a prompt lepton from W boson decay. Prompt leptons and misidentified nonprompt leptons are referred to as real and fake leptons, respectively. Fake muons are predominantly produced from semileptonic $b$ or $c$ quark decays in which the muon passes the isolation requirements despite being produced in association with a jet. There are three principal mechanisms for producing fake electrons: heavy-flavor produced in association with a jet. There are three principal

The method explicitly accounts for the presence of events with two fake leptons.

The probability ($r_\ell$) for a real loose lepton to pass the tight criteria is measured in $Z \rightarrow \ell \ell$ events in data with a tag-and-probe method. The probability for a fake loose electron to satisfy the tight requirements ($f_\ell$) is measured by requiring exactly one loose electron in an event with

$E_T^{\text{miss}} < 10$ GeV. The probability for a fake loose muon to satisfy the tight requirements ($f_\mu$) is measured in a control region obtained by requiring exactly one loose muon with $|\Delta \phi (\mu, E_T^{\text{miss}})| < 0.5$. The baseline selection requirements from Sec. IV are not applied when checking these control regions.

VI. MASS RECONSTRUCTION

After the baseline selection has been applied, mass reconstruction of heavy-quark candidates is performed in order to discriminate the heavy-quark decays from the dominant $t\bar{t}$ background. Direct reconstruction is not possible, as two neutrinos escape the detector. However, a unique feature of the heavy quark is the large momentum of the daughter $W$ boson, which makes its decay products approximately collinear in the detector as seen in Fig. 3.

Both neutrino momentum vectors are reconstructed by assuming that the neutrinos are the sole contributors to $E_T^{\text{miss}}$ and that they are approximately collinear with the leptons. The optimal values of each $|\Delta \eta (\nu, \ell)|$ and each $|\Delta \phi (\nu, \ell)|$ are fit by minimizing the mass difference between the two reconstructed heavy quarks using MINUIT [38]. The fitted direction of each neutrino is constrained to be within $\Delta R < 2.5$ of the direction taken by the neutrino’s leptonic partner from the $W$ boson decay, and all jet combinations are considered during each step of the mass difference minimization. A solution of the minimization procedure is penalized if the scalar sum of neutrino momenta exceeds the scalar sum of lepton momenta by at least 30%. The square of the difference between each reconstructed $W$ boson mass and 80.4 GeV is added to the square of the heavy-quark mass difference in the minimized function; the preferred solutions produce $W$ bosons with reconstructed masses that are close to the $W$ boson mass. The full minimization function is $f_{\text{min}} = (m_Q - m_Q^\text{gen})^2 + (m_W - (80.4\text{GeV}))^2 + (m_W - (80.4\text{GeV}))^2$.
The two reconstructed mass values tend to be more correlated for signal than background, as shown in Fig. 4. This is because the collinear approximation does not work well for single-top, diboson, Drell-Yan, and fake lepton events. An event is only kept if the two values of reconstructed mass are within 25 GeV of each other. The selection efficiency for this requirement is greater than 99% for $t\bar{t}$, and only 75%–90% for other backgrounds.

The final reconstructed mass ($m_{\text{Collinear}}$) is taken to be the average of the two reconstructed masses in the event. Distributions of $m_{\text{Collinear}}$ for various simulated $Q\bar{Q}$ samples and the $t\bar{t}$ background are shown in Fig. 5.

The expected background yields and number of observed events after the baseline selection are given in Table II. Distributions of $H_T$ and $m_{\text{Collinear}}$ are shown in Fig. 6.

![Figure 4](image1.png)

**FIG. 4.** Correlation between reconstructed masses for $Q\bar{Q}$ pairs produced with $m_Q = 350$ GeV and for background samples. The fitting method selects solutions with correlated mass values; however, this correlation is smaller for background events. Events within $|m_{\text{Collinear}} - m_{\text{Collinear}}| < 25$ GeV are kept; this region is found between the two lines in the figure.

![Figure 5](image2.png)

**FIG. 5 (color online).** $m_{\text{Collinear}}$ for simulated heavy-quark pairs produced with masses of 350 GeV, 400 GeV, and 450 GeV and for top quark pairs. Each histogram is normalized to unit area. The distributions have long tails that are produced by wrong jet assignment in events where at least one of the correct jets fails selection requirements.

![Figure 6](image3.png)

**FIG. 6 (color online).** Expected and observed distributions of (a) $H_T$ and (b) $m_{\text{Collinear}}$ for the sum of $ee$, $\mu\mu$, and $e\mu$ channels after the baseline selection. The last bin contains overflow events. Samples are stacked in the same order as they are presented in the legend, from left to right; the first entry in the legend is at the bottom of the stack. The signal has been amplified to 20 times the expected rate.

<table>
<thead>
<tr>
<th>Process</th>
<th>$ee$</th>
<th>$e\mu$</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>$190^{+40}_{-30}$</td>
<td>$1140^{+250}_{-200}$</td>
<td>$370^{+80}_{-70}$</td>
</tr>
<tr>
<td>Single-top</td>
<td>$9.4^{+2.2}_{-1.9}$</td>
<td>$60^{+14}_{-11}$</td>
<td>$24^{+5}_{-5}$</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow ee$</td>
<td>$6.3^{+2.0}_{-1.9}$</td>
<td>$0.0^{+0.1}_{-0.0}$</td>
<td>$0.0^{+0.1}_{-0.0}$</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \mu\mu$</td>
<td>$0.0^{+0.1}_{-0.0}$</td>
<td>$2.2^{+1.1}_{-1.1}$</td>
<td>$17^{+4}_{-4}$</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \tau\tau$</td>
<td>$7.3^{+2.4}_{-2.2}$</td>
<td>$62^{+15}_{-12}$</td>
<td>$16^{+4}_{-4}$</td>
</tr>
<tr>
<td>$WW, WZ, ZZ$</td>
<td>$8.7^{+2.2}_{-1.9}$</td>
<td>$49^{+11}_{-10}$</td>
<td>$12^{+3.0}_{-2.6}$</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>$3.7 \pm 2.8$</td>
<td>$70 \pm 40$</td>
<td>$0.5 \pm 0.8$</td>
</tr>
<tr>
<td>Total Bg</td>
<td>$230^{+20}_{-40}$</td>
<td>$1380^{+310}_{-250}$</td>
<td>$440^{+90}_{-80}$</td>
</tr>
<tr>
<td>Observed</td>
<td>243</td>
<td>1410</td>
<td>460</td>
</tr>
</tbody>
</table>

TABLE II. Expected and observed number of events after baseline selection. Uncertainties shown are statistical and systematic, added in quadrature.
VII. BACKGROUND VALIDATION

Event samples with the baseline selection and low \(H_T\), low lepton \(p_T\), low jet \(p_T\), or low \(E_T^{\text{miss}}\) are examined to validate the modeling of the background (Fig. 7). These conditions cause the distributions to be depleted of signal. In each case, the data is described well by the background model, within uncertainties.

VIII. FINAL EVENT SELECTION

The baseline selection provides excellent discrimination against \(Z/\gamma^*\) production and other backgrounds, but additional selection requirements are necessary to suppress the dominant \(t\bar{t}\) background. A triangular selection in \(H_T + E_T^{\text{miss}}\) versus \(m_{\text{collinear}}\), \(H_T + E_T^{\text{miss}} > X - 0.4 \times m_{\text{collinear}}\) with \(X\) dependent on the assumed signal mass, is applied. Mass-dependent requirements on \(E_T^{\text{miss}}\) and leading jet \(p_T\) are imposed as well. These selection requirements are optimized in MC simulation by seeking a point of maximum significance, \(S/\sqrt{S+B}\), while simultaneously varying all of the selection requirement parameters. Distributions of \(H_T + E_T^{\text{miss}}\) versus \(m_{\text{collinear}}\) for background and signal are shown in Fig. 8. Tables III and IV list the full set of optimized selection requirements at each mass point. Table V lists the expected backgrounds, expected signal, and observed data for each mass point after this final selection. Figure 9 shows the distributions in \(m_{\text{collinear}}\) for two signal samples after the final selection.

IX. SYSTEMATIC UNCERTAINTIES

The major sources of systematic uncertainty are due to modeling of the signal and most sources of background.

The uncertainties due to simulation of the lepton trigger, reconstruction, and selection efficiencies are assessed using leptons from \(Z\rightarrow ee\) and \(Z\rightarrow \mu\mu\) in data [36]. MC events are corrected for differences in data and simulation. The statistical and systematic uncertainties in these corrections are included in the uncertainties on the acceptance values. Uncertainties in the modeling of the lepton energy scale and resolution are studied using reconstructed \(Z\) boson mass distributions. The jet energy scale (JES) and its uncertainty are derived by combining information from test-beam data, LHC collision data, and simulation [33]. The JES uncertainty varies as a function of jet \(p_T\) and \(\eta\) and also accounts for the presence of nearby jets and event pileup. There is additional uncertainty associated with jets originating from \(b\) quarks in simulation. Smaller uncertainties are associated with the jet energy resolution and jet finding efficiency.

Uncertainties related to the \(E_T^{\text{miss}}\) arise due to uncertainties associated with low momenta jets, event pileup, and calorimeter energy not associated with reconstructed leptons or jets [34]. There is also some uncertainty in estimating the effect of a readout problem affecting a subset of the LAr calorimeter channels in a part of the data set.

FIG. 7 (color online). Distributions of \(m_{\text{collinear}}\) in events that have (a) \(H_T < 400\) GeV, (b) two leptons with \(p_T < 60\) GeV, (c) all jets with \(p_T < 60\) GeV, or (d) \(E_T^{\text{miss}} < 80\) GeV. Each histogram contains the sum of the \(ee, \mu\mu,\) and \(e\mu\) channels. The last bin contains overflow events. Samples are stacked in the same order as they are presented in the legend, from left to right; the first entry in the legend is at the bottom of the stack.

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The uncertainty due to the choice of generator for PYTHIA, varying the parameters controlling ISR and FSR in a range consistent with experimental data [41]. For $Z/\gamma^* +$ jets events, the generator uncertainty is evaluated by comparing the predictions of ALPGEN with the PDF set CTEQ6.1 and SHERPA [42] with the PDF set CTEQ6.6. Finally, the uncertainty in the PDFs used to generate signal, $t\bar{t}$, and single-top events is evaluated using the procedure adopted in a measurement of the $t\bar{t}$ cross section [36].

The integrated luminosity measurement carries a 3.7% uncertainty [16,17]. Each sample also has an uncertainty associated with its theoretical cross section or with its data-driven rate. For $t\bar{t}$ [20], single-top [28,29], and $Z/\gamma^* \rightarrow \ell \nu$ events, the rate uncertainty is estimated from theoretical calculations. $Z/\gamma^* \rightarrow ee$, $Z/\gamma^* \rightarrow \mu\mu$, and fake lepton event rate uncertainties are evaluated with the data-driven fitting described in Sec. V. The cross section uncertainty for each signal point comes from HATHOR NNLO calculations and can be found in Table I. The background normalization uncertainties are listed in Table VI.

The effects of the systematic uncertainties on the overall background yield are summarized in Table VII for the cuts used for $m_Q = 350$ GeV.

Table: X. RESULTS AND DISCUSSION

A binned maximum-likelihood ratio technique is used to fit distributions of $m_{\text{Collinear}}$ to the observed data in order to measure the most likely $Q\bar{Q}$ production cross section,
FIG. 9 (color online). Distributions of \( m_{\text{Collinear}} \) for the sum of \( ee, \mu\mu, \) and \( e\mu \) channels after applying the final selection for (a) \( m_Q = 350 \text{ GeV} \) and (b) \( m_Q = 400 \text{ GeV} \). The last bin contains overflow events. The uncertainty bands include all statistical and systematic background uncertainties. The signal samples are normalized using the cross sections in Table I. Samples are stacked in the same order as they are presented in the legend, from left to right; the first entry in the legend is at the bottom of the stack.

\( \sigma(pp \rightarrow Q\bar{Q}) \). In the fitting technique, all events with \( m_{\text{Collinear}} > 760 \text{ GeV} \) are considered to belong in the same bin. A shape fit is performed on background and signal simultaneously; this allows the background normalization to float, but maintains the bin-to-bin relationships that define the background and signal shapes in \( m_{\text{Collinear}} \).

This fitting procedure allows for the possibility of an underestimated or overestimated background in the signal region. To take into account systematic uncertainties, the signal and background shapes are smoothly deformed in generated samples of pseudodata by random variations consistent with these uncertainties as shown in Tables VI and VII; these fluctuations are not constrained by the data. Most of the systematic uncertainties are assumed to be correlated between signal and background; the uncertainties due to cross section or data-driven estimates, Drell-Yan modeling, \( t\bar{t} \) modeling, and \( t\bar{t} \) generation are uncorrelated between signal and background.

A small excess is observed over the background expectation for each hypothetical \( Q \) mass.

Since the statistical interpretation uses the full shape of the signal and background distributions, the results in Table V do not entirely determine the results; only a signal-like excess would weaken the observed limits. The excess shape in the \( m_{\text{Collinear}} \) distribution is not particularly signal-like and the data are found to be in better agreement with the background-only than the signal + background hypothesis.

Statistical interpretation of the fitted cross section \( \sigma \) is made using the CLs technique [44,45]. This technique performs fits in pseudodata generated from the background model and varying levels of injected signal to measure the ability of the fit to distinguish between the background-only and background-plus-signal hypotheses. In the case that the data are in better agreement with the background-only hypothesis, 95% C.L. upper limits on the signal cross section \( \sigma_{95} \) are derived. The limit \( \sigma_{95} \) is chosen so that

<table>
<thead>
<tr>
<th>Source</th>
<th>(+1\sigma) Unc.</th>
<th>(-1\sigma) Unc.</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1%</td>
</tr>
<tr>
<td>Lepton ID and reconstruction</td>
<td>2%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Jet reconstruction</td>
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<td>3%</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>13%</td>
<td>11%</td>
</tr>
<tr>
<td>( \mu ) momentum resolution</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>( \mu ) momentum scale</td>
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<td>( e ) energy resolution</td>
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<td>( e ) isolation pileup term</td>
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<tr>
<td>( e ) isolation ( p_T ) term</td>
<td>&lt;1%</td>
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<tr>
<td>Drell-Yan uncertainties</td>
<td>1%</td>
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</tr>
<tr>
<td>LAr readout problem</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>ISR/FSR: ( t\bar{t} )</td>
<td>8%</td>
<td>5%</td>
</tr>
<tr>
<td>MC generator: ( t\bar{t} )</td>
<td>1%</td>
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<tr>
<td>MC fragmentation/model: ( t\bar{t} )</td>
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</tr>
<tr>
<td>Drell-Yan model</td>
<td>7%</td>
<td>7%</td>
</tr>
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</table>

TABLE VI. Overall normalization uncertainties for each background, which are either due to cross section uncertainties or uncertainties related to data-driven methods.

<table>
<thead>
<tr>
<th>Background</th>
<th>(+1\sigma) Unc.</th>
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<tbody>
<tr>
<td>( t\bar{t} )</td>
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<td>10%</td>
</tr>
<tr>
<td>Single-top</td>
<td>7%</td>
<td>7%</td>
</tr>
<tr>
<td>ZZ, WW, WZ, ZZ</td>
<td>60%</td>
<td>30%</td>
</tr>
<tr>
<td>Z/\gamma \rightarrow \mu\mu</td>
<td>60%</td>
<td>30%</td>
</tr>
<tr>
<td>Z/\gamma \rightarrow \tau\tau</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>Z/\gamma \rightarrow e\mu</td>
<td>40%</td>
<td>30%</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>50%</td>
<td>50%</td>
</tr>
</tbody>
</table>

TABLE VII. The effects of the \( \pm 1\sigma \) systematic uncertainties on the overall background yield.

<table>
<thead>
<tr>
<th>Source</th>
<th>(+1\sigma) Unc.</th>
<th>(-1\sigma) Unc.</th>
</tr>
</thead>
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<td>1%</td>
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</tr>
</tbody>
</table>
This article presents a search for pair production of heavy quarks decaying to $Wq$ in the dilepton channel at the CERN LHC. This search allows $q = d, s, b$ for up-type $Q$ final states or $q = u, c$ for down-type $Q$ final states. The analyzed data correspond to an integrated luminosity of 1.04 fb$^{-1}$ collected by the ATLAS detector in $pp$ collisions at $\sqrt{s} = 7$ TeV. To enhance the sensitivity to a new quark, mass reconstruction is performed by exploiting the boost received by the heavy-quark decay products. The reconstructed mass is used for binned maximum-likelihood ratio fitting.

The data are found to be in agreement with the expectation from the standard model. A lower limit is set on the mass $m_Q > 350$ GeV at 95% confidence level. This limit assumes $\text{BR}(Q \rightarrow Wq) = 100\%$ and is applicable to many exotic models [46,47], including up-type fourth-generation quarks $t'$, down-type fourth-generation quarks $b'$, and quarks with exotic charges (such as $-4/3$) decaying to light quarks.

**ACKNOWLEDGMENTS**

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; STFC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST, and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR, and VSC CR, Czech Republic; DPLF, DNSRC, and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG, and AvH Foundation, Germany; GSRT, Greece; ISF, MINEVA, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRSRT, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MÆRYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; AARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF, and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; and DOE and NSF, USA. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular, from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK), and BNL (USA) and in the Tier-2 facilities worldwide.
SEARCH FOR PAIR-PRODUCED HEAVY QUARKS . . .

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