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Search for pair production of a new heavy quark that decays into a W boson and a light quark in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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A search is presented for pair production of a new heavy quark (Q) that decays into a W boson and a light quark (q) in the final state where one W boson decays leptonically (to an electron or muon plus a neutrino) and the other W boson decays hadronically. The analysis is performed using an integrated luminosity of 20.3 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV collected by the ATLAS detector at the LHC. No evidence of $Q\bar{Q}$ production is observed. New chiral quarks with masses below 690 GeV are excluded at 95% confidence level, assuming $\mathrm{BR}(Q \to Wq) = 1$. Results are also interpreted in the context of vectorlike quark models, resulting in the limits on the mass of a vectorlike quark in the two-dimensional plane of $\mathrm{BR}(Q \to Wq)$ versus $\mathrm{BR}(Q \to Hq)$.

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I. INTRODUCTION

The recent observation of the long-predicted Higgs boson by the ATLAS [1] and CMS [2] collaborations now completes the Standard Model (SM). In spite of its success, the SM cannot account for dark matter and the matter/antimatter asymmetry in the Universe and also fails to provide insight into the fermion mass spectrum, nonzero neutrino masses, why there are three generations of fermions, or why parity is not violated in the strong interaction. Furthermore, the observed Higgs boson is unnaturally light, requiring fine-tuning to cancel radiative corrections that would naturally result in a mass many orders of magnitude larger, a discrepancy known as the hierarchy problem [3].

A variety of models has been proposed to address the various shortcomings of the SM. For example, a primary motivation for supersymmetry (SUSY) is to solve the hierarchy problem [4]. In SUSY models, the quadratically divergent radiative corrections to the Higgs-boson mass due to SM particles are automatically canceled by the corrections from the supersymmetric partners. Models such as little Higgs, composite Higgs, and topcolor take a different approach, proposing that electroweak symmetry breaking happens dynamically as the result of a new strong interaction [5–9]. Grand unified theories (GUTs) go further, unifying the electroweak and strong forces by proposing that the SM gauge symmetry $SU(3)_\mathrm{C} \times SU(2)_\mathrm{L} \times U(1)_\mathrm{Y}$ is the low-energy limit of a single fundamental symmetry group such as $SO(10)$ or E_6 [10,11], which could potentially explain the observed spectrum of fermions and even provide insight into the unification of the electroweak and strong forces with gravity. A feature in many of these, and other models [12–14], is the prediction of vectorlike quarks (VLQs), hypothetical spin-$\frac{1}{2}$ particles that are triplets under the color gauge group and have identical transformation properties for both chiralities under the electroweak symmetry group. Furthermore, massive VLQs would respect gauge invariance without coupling to the Higgs field. This allows VLQs to avoid constraints from Higgs-boson production [15]; if the Higgs sector is minimal, these constraints rule out additional chiral quarks. However, some two-Higgs-doublet models are able to avoid those constraints and accommodate a fourth generation of quarks [16].

In the models of interest, the VLQs have some mixing with the SM quarks, allowing them to decay to SM quarks and either a W, Z, or Higgs boson; however, the exact nature of the coupling depends on the model. For example, in composite Higgs models, the VLQs are involved in a seesaw mechanism with the SM quarks, so the lightest VLQ couples almost exclusively to the heaviest SM quarks (t- and b-quarks) [6]. However, there are also models that predict TeV-scale VLQs that could preferentially decay to light SM quarks ($q = u, d, s$, or c) [10,11,17]. For example, the left-right mirror model (LRMM) [17] predicts three generations of heavy “mirror” quarks, with the lightest mirror generation coupling to the lightest SM generation. The two lightest mirror quarks could be pair-produced at the LHC via the strong interaction and would then decay to Wq, Zq, or Hq ($q = u$ or d). The LRMM would provide an explanation for tiny neutrino masses, parity violation in weak interactions, parity conservation in strong interactions, and could be the first step toward uncovering the symmetry structure of a GUT. Another model predicting VLQs that decay to light quarks is the E_6 GUT with

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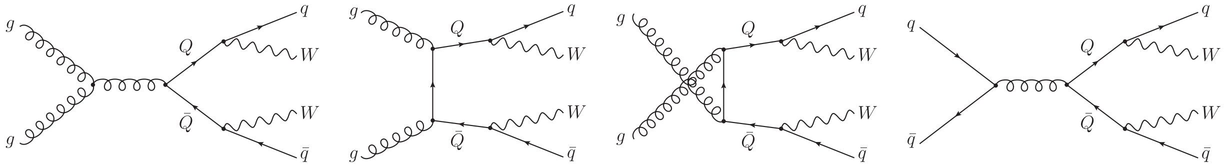

FIG. 1. Leading-order Feynman diagrams for $Q\bar{Q} \to WqW\bar{q}$ production at the LHC.

isosinglet quarks [10,11]. In this model, after the E_6 symmetry is broken down to the SM group structure, VLQ partners to the *d*-, *s*-, and *b*-quarks are predicted. If the VLQs have the same mass ordering as their SM partners, the lightest VLQ would couple predominately to first-generation SM quarks ($q = u$ or d). The values for the branching ratios to the three decay modes (Wq, Zq, Hq) depend on parameters in the model. The values in the E_6 isosinglet model range from approximately (0.6, 0.3, 0.1) to (0.5, 0.25, 0.25), while the LRMM allows branching ratios from approximately (0.6, 0.4, 0) to (0, 0, 1), depending on the VLQ mass and mixing angles.

If such new quarks exist, they are expected to be produced predominantly in pairs via the strong interaction for masses up to $O(1\ \text{TeV})$ in LHC collisions with a center-of-mass energy of 8 TeV. Single production of a new heavy quark, Q, would be dominant for very high quark masses, but the production rate is model dependent and could be suppressed if the coupling to SM quarks is small. To date, there have been two analyses of LHC data sensitive to VLQs that decay to light quarks, both using 1.04 fb^{-1} of ATLAS data at $\sqrt{s} = 7$ TeV: one search for pair-production [18] and one for single production [19]. The pair-production search set a lower limit on the Q mass of 350 GeV at 95% confidence level, assuming $\text{BR}(Q \to Wq) = 1$. Such a signal was also ruled out by the Tevatron for masses up to 340 GeV [20].

This paper presents a search for new heavy quarks that couple to light SM quarks using data collected by the ATLAS detector. The analysis focuses on model-independent pair production of a new heavy quark and its antiparticle, which then decay through a charged-current interaction to a final state with a single electron or muon, missing transverse momentum and light SM quarks, making it complementary to searches for VLQs that decay to third-generation quarks [21–28]. The dominant Feynman diagrams for the signal process are shown in Fig. 1. Background rejection is achieved through event topology and kinematic requirements. In particular, a kinematic variable motivated by the splitting scale of a heavy object into daughter particles [29,30] is used to reduce the background when selecting the pair of jets consistent with a hadronically decaying W boson. The statistical interpretation of the data uses the invariant mass distribution of the Q candidate formed from the hadronically decaying W boson and a light quark. The results are interpreted both in the context of VLQs and a chiral fourth-generation quark.

II. THE ATLAS DETECTOR

The ATLAS detector [31] at the LHC covers nearly the entire solid angle around the interaction point (IP)[1]. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroid magnets.

The inner tracking detector system is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$. A high-granularity silicon pixel detector covers the interaction region and typically provides three measurements per track. It is followed by a silicon microstrip tracker, which usually provides four two-dimensional measurement points per track. These silicon detectors are complemented by a transition radiation tracker, which enables radially extended track reconstruction up to $|\eta| = 2.0$. The transition radiation tracker also provides electron identification information based on the fraction of hits (typically 30 in total) above a higher threshold for energy deposits corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$, to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters with $|\eta| < 3.2$. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimized for electromagnetic and hadronic measurements respectively.

The muon spectrometer comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by superconducting air-core toroids. The precision chamber system covers the region $|\eta| < 2.7$ with three layers of monitored drift tubes,

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal IP in the center of the detector and the z axis along the beam pipe. The x axis points from the IP to the center of the LHC ring, and the y axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

complemented by cathode strip chambers in the forward region, where the background is highest. The muon trigger system covers the range $|\eta| < 2.4$ with resistive plate chambers in the barrel, and thin-gap chambers in the endcap regions.

A three-level trigger system [32] is used to select events for offline analysis. The level-1 trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to at most 75 kHz. This is followed by two software-based trigger levels that together reduce the event rate to about 400 Hz.

III. SIGNAL AND BACKGROUND SAMPLES

The pair-production cross section for a new heavy quark ranges from 12 pb for a 300 GeV quark to 21 fb for an 800 GeV quark. It was calculated at next-to-next-to-leading order (NNLO) in QCD, including resummation of next-to-next-to-leading-logarithmic (NNLL) soft gluon terms, with Top ++ 2.0 [33–38], using the MSTW2008 NNLO [39,40] set of parton distribution functions (PDFs) and $\alpha_S = 0.117$. The PDF and α_S uncertainties were calculated using the PDF4LHC prescription [41] with the MSTW2008 68% CL NNLO, CT10 NNLO [42], and NNPDF2.3 5f FFN [43] PDF sets. The uncertainties in the prediction stem from scale variations and the PDF + α_S uncertainty and range from approximately 11% to 12% for masses from 300 to 800 GeV.

VLQ signal samples were simulated with the tree-level event generator CompHEP v4.5.1 [44] at the parton level with the CTEQ6L1 LO PDF set [45] and with the QCD scale set to the mass of the heavy quark, m_Q. The generated events were then passed into Pythia v8.165 [46,47] for hadronization and parton showering. The VLQ signal samples were produced for values of m_Q ranging from 300 to 800 GeV in 100 GeV steps. This range is motivated by the previous limit at 350 GeV and the expected sensitivity of this analysis to masses up to approximately 700 GeV. Although the analysis is targeting the $Q \to Wq$ decay, there is also sensitivity to the neutral-current decays $Q \to Zq$ and $Q \to Hq$ (e.g., $Q\bar{Q} \to WqZ\bar{q} \to \ell\nu qq\bar{q}\,\bar{q}$) and events were generated for all six decay combinations. In addition to the VLQ signal samples, a set of fourth-generation chiral-quark signal samples was generated with Pythia v8.1 using the MSTW 2008 LO PDF set. The kinematics of the chiral-quark signal samples, which only contain $Q\bar{Q} \to WqW\bar{q}$, are compatible with the VLQ samples when requiring $\mathrm{BR}(Q \to Wq) = 1$. Therefore, the more generic VLQ samples are used for the statistical analysis, with the sample corresponding to $m_Q = 700$ GeV and $\mathrm{BR}(Q \to Wq) = 1$ used to represent the signal in tables and figures, unless noted otherwise.

The background originates mainly from W-boson production in association with jets, W + jets, with lesser contributions from top quark pair production ($t\bar{t}$), Z + jets, single-top, diboson, and multijet events. The W + jets and Z + jets samples were produced using Sherpa v1.4.1 [48] with the CT10 PDF set, taking the c- and b-quarks as massive. Samples of $t\bar{t}$ and single-top events were generated with Powheg-Box 3.0 [49,50] interfaced to Pythia v6.426 [47] using the Perugia2011C set of tunable parameters [51] for the underlying event and the CTEQ6L1 PDF set. Diboson production was modeled using Alpgen v2.13 [52] interfaced to Herwig v6.520 [53] with the CTEQ6L1 PDF set, except for the lepton + jets final state ($WV \to \ell\nu qq$ with $V = W, Z$), which used the Sherpa v1.4.1 event generator with the CT10 PDF set. The contribution from multijet events originates from the misidentification of a jet or a photon as an electron, or from the semileptonic decay of a b- or c-quark, and the matrix method [54] is used to determine the kinematic distributions for the multijet background.

The W/Z + jets and multijet backgrounds are normalized to data and a data-driven correction is applied to the transverse momentum p_T of the boson as described in Sec. V A. The $t\bar{t}$ cross section is determined by the Top ++ prediction, with the top-quark mass taken to be 172.5 GeV. The single-top samples are normalized to the approximate NNLO theoretical cross sections [55–57] calculated using the MSTW 2008 NNLO PDF set. The diboson background processes are normalized to NLO theoretical cross sections [58].

All simulated samples include multiple pp interactions per bunch crossing and simulated events are weighted such that the distribution of the average number of interactions per bunch crossing agrees with data. The generated samples are processed through a simulation [59] of the detector geometry and response using Geant4 [60], then reconstructed using the same software as used for data. Simulated events are corrected so that the object identification efficiencies, energy scales, and energy resolutions match those determined in data control samples.

IV. EVENT SELECTION

The data analyzed in this search were collected with the ATLAS detector in 2012 and correspond to an integrated luminosity of 20.3 fb^{-1}. Data quality requirements are applied to remove events with incomplete, corrupted, or otherwise compromised subdetector information. Events are required to pass a single-electron or single-muon trigger. The p_T thresholds are 24 GeV and 60 GeV for the electron triggers and 24 GeV and 36 GeV for the muon triggers. The lower-threshold triggers include isolation requirements on the candidate leptons, resulting in inefficiencies at higher p_T that are recovered by the higher-threshold triggers without an isolation requirement.

A. Preselection

The basic object selection is called preselection and requires exactly one charged lepton (electron or muon), at

TABLE I. Observed and expected event yields after preselection. The quoted uncertainties include both the statistical and systematic contributions, with the latter being dominant. The sources of systematic uncertainty are discussed in Sec. VI.

	Electron	Muon
$W+\text{jets}$	110000^{+15000}_{-21000}	145000^{+20000}_{-28000}
$Z+\text{jets}$	28000^{+14000}_{-15000}	15200^{+7700}_{-7800}
$t\bar{t}$	19200^{+2800}_{-2900}	23700^{+3400}_{-3500}
Diboson	3900 ± 1900	4400 ± 2200
Single top	3750^{+540}_{-560}	4500^{+630}_{-710}
Multijet	22000 ± 8800	13300 ± 5300
Total background	183000^{+27000}_{-33000}	206000^{+27000}_{-34000}
Signal ($m_Q = 700$ GeV)	79 ± 10	79 ± 10
Data	182075	208641

least four jets, and large missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$), as described below. The criteria are similar to those used in recent ATLAS top-quark studies [61], except that this analysis requires that there are no jets identified as originating from a b-quark. The expected and observed numbers of events after preselection are shown in Table I. There is negligible sensitivity to heavy quark production because the signal expectations for all masses are much smaller than the uncertainty on the background, dominated at this stage by systematic uncertainties.

1. Charged-lepton requirements

Electron candidates are required to have $p_{\mathrm{T}} > 25$ GeV and either $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ to exclude the transition between the barrel and endcap calorimeters. Muon candidates are required to have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$. Nonprompt leptons and nonleptonic particles may be reconstructed as leptons and satisfy the selection criteria, giving rise to nonprompt and fake lepton backgrounds. In the case of electrons, these include contributions from semileptonic decays of b- and c-quarks, photon conversions, and jets with a large electromagnetic energy fraction. Nonprompt or fake muons can originate from semileptonic decays of b- and c-quarks, from charged-hadron decays in the tracking volume or in hadronic showers, or from punchthrough particles emerging from high-energy hadronic showers [54]. The nonprompt and fake lepton backgrounds are reduced by requiring the lepton candidates to be isolated from other energy deposits or high-p_{T} tracks. The tracks used in the isolation calculation are required to originate from the primary interaction vertex and have $p_{\mathrm{T}} > 1$ GeV. For electrons, an η-dependent limit is placed on the amount of energy measured in the calorimeter within a $\Delta R = 0.2$ cone around the candidate which is neither from the electron candidate itself nor from additional pp interactions. A similar requirement is placed on the scalar sum of the p_{T} of tracks within a $\Delta R = 0.3$ cone around the track of the electron candidate. Each requirement has an average efficiency of 90% for electrons from $Z \to ee$. Muons are required to have a p_{T} -dependent track isolation [62], requiring the scalar sum of the p_{T} from tracks with $\Delta R < 10\ \mathrm{GeV}/p_{\mathrm{T}}^{\mu}$ to be less than $0.05 \cdot p_{\mathrm{T}}^{\mu}$, where p_{T}^{μ} is the p_{T} of the candidate muon track. This requirement has an efficiency of approximately 95% for muons from $W \to \mu\nu$.

In this analysis, τ leptons are not explicitly reconstructed. Because of the high p_{T} threshold, only a small fraction of τ leptons decaying leptonically are reconstructed as electrons or muons, while the majority of τ leptons decaying hadronically are reconstructed as jets.

2. Jet requirements

Events must contain at least four jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$ reconstructed using the anti-k_t algorithm [63] with a radius parameter $R = 0.4$. The jets are constructed from calibrated topological clusters built from energy deposits in the calorimeters, and they are calibrated to the hadronic scale [64]. Prior to jet finding, a local cluster calibration scheme [65] is applied to correct the topological cluster energies for the effects of calorimeter noncompensation, dead material and out-of-cluster leakage. The jet energy scale was determined using information from test-beam data, LHC collision data, and simulation [64,66]. All jets are required to have at least two tracks that originate from the primary interaction vertex. In order to suppress jets that do not originate from the primary vertex, jets with $p_{\mathrm{T}} < 50$ GeV and $|\eta| < 2.4$ are required to have a jet vertex fraction (JVF) above 0.5, where JVF is the ratio of the summed scalar p_{T} of tracks originating from the primary vertex to that of all tracks associated with the jet. An overlap removal procedure [61] is applied to remove jets that were already identified as electrons.

To identify jets originating from the hadronization of a b-quark (“b-tagging”), a continuous discriminant is produced by an algorithm using multivariate techniques [67] to combine information from the impact parameter of displaced tracks and topological properties of secondary and tertiary vertices reconstructed within the jet. The efficiency for a jet containing a b-hadron to be b-tagged is 70%, while the light-jet (c-jet) efficiency is less than 1% (20%) as determined in simulated $t\bar{t}$ events, where light jets are jets initiated by a u-, d-, s-quark, or gluon. If any jets are b-tagged, the event is rejected.

3. Missing transverse momentum requirements

The $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ is constructed from the vector sum of calibrated energy deposits in the calorimeter and reconstructed muons [68]. Events that do not contain a leptonically decaying W boson are suppressed by requiring $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV and $(E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W}) > 60$ GeV, where m_{T}^{W} is the transverse mass of the W boson defined as $m_{\mathrm{T}}^{W} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$, where $\Delta\phi$ is the azimuthal

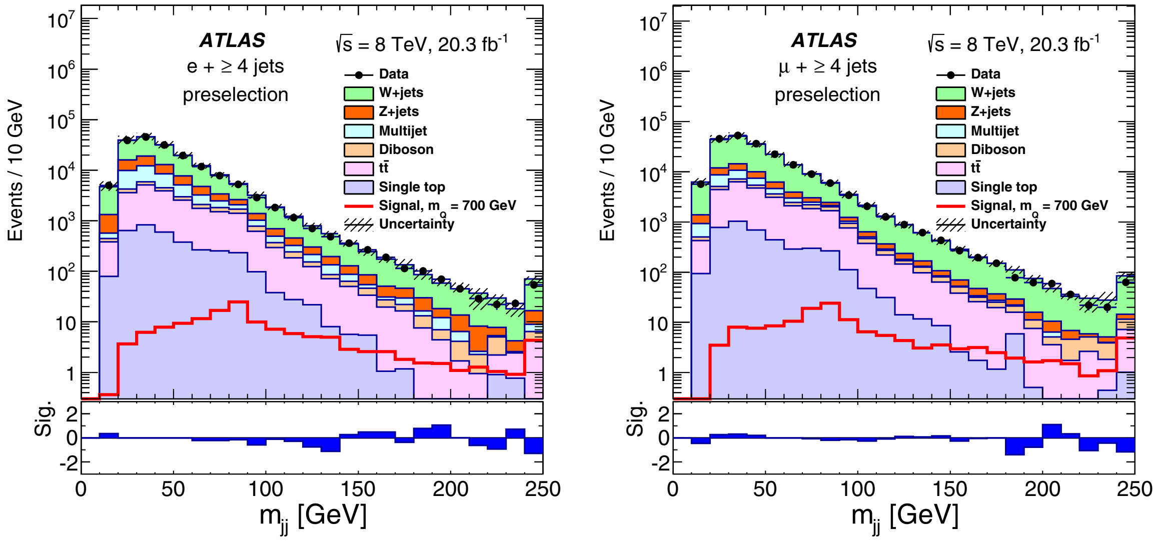

FIG. 2 (color online). Invariant mass distributions for dijet systems with $p_{\mathrm{T}} > 200$ GeV, angular separation $\Delta R < 1.0$, and an invariant mass closest to the W boson mass, for the (left) electron and (right) muon channels after the preselection requirements. W_{had} candidates correspond to the mass range 65–100 GeV. The highest bin includes all events with $m_{jj} > 240$ GeV. The shaded band shows the total uncertainty on the background prediction. The lower panel shows the significance of the difference between data and expectation in units of normal standard deviations as explained in Ref. [70].

angle between the charged-lepton transverse momentum vector and $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$.

B. Final selection

With the final-state objects identified, additional kinematic requirements are applied to exploit the distinct features of the signal, assumed to be heavier than the previously excluded mass of 350 GeV. The W boson and light quark originating from $Q \to Wq$ would be very energetic and have a large angular separation due to the large mass of the Q quark. On the other hand, the decay products of the W boson would tend to have a small separation due to the W boson's boost. By selecting only events that are consistent with these properties, the $W +$ jets background yield is reduced by orders of magnitude. To facilitate the discussion of the kinematic selection, the following objects are defined:

(i) W_{had} is the candidate for a W boson in the decay $Q \to Wq \to qqq$;

(ii) W_{lep} is the candidate for a W boson in the decay $Q \to Wq \to \ell\nu q$;

(iii) q-jet is a candidate for the jet originating from the q in $Q \to Wq$ (i.e., from the decay of the heavy quark, not the hadronically decaying W boson). There are two q-jets per event, so q_1 (q_2) is used to denote the one with higher (lower) p_{T}.

The W_{had} candidate is defined as a dijet system with $p_{\mathrm{T}} > 200$ GeV, angular separation $\Delta R < 1.0$, and an invariant mass in the range of 65 to 100 GeV. All possible jet combinations are considered and, if multiple pairs satisfy the above requirements, the pair with the mass closest to that of the W boson [69] is chosen. If no W_{had} candidate is found, the event is removed. This requirement results in 94% background rejection while keeping 53% of the signal if $m_Q = 700$ GeV. The mass distribution of the W_{had} candidates prior to the mass requirement is shown in Fig. 2.

The W_{lep} candidate is reconstructed using the lepton and $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$, which is taken to be the neutrino $\vec{p}_{\mathrm{T}}$. The longitudinal momentum of the neutrino is determined up to a two-fold ambiguity by requiring the invariant mass of the lepton–neutrino system to equal the mass of the W boson. When no real solution exists, the neutrino pseudorapidity is set equal to that of the lepton because the decay products of the W boson tend to be nearly collinear for the kinematic regime of interest. In simulated samples, the rate of events with no real solution is approximately 35%. Signal events are expected to have energetic W bosons, so the W_{lep} candidate is required to have $p_{\mathrm{T}} > 125$ GeV.

The W candidates (W_{had} and W_{lep}) are then each paired with a different one of the remaining jets to create the two heavy quark candidates, $Q1$ and $Q2$. This step involves testing all possible pairings of q-jet candidates with the W_{had} and W_{lep} candidates. In addition, the W_{lep} candidate may have two real solutions for the longitudinal momentum of the neutrino. Among the possible combinations of neutrino momentum solutions and Wq pairings, the one yielding the smallest absolute difference between the two reconstructed heavy quark masses is chosen. In simulated samples, the rate of correct Wq pairing is approximately 40% (48%) for a signal of mass 400 GeV (800 GeV). Once the heavy quark candidates are determined, the q-jets are required to have $p_{\mathrm{T}}(q_1) > 160$ GeV and $p_{\mathrm{T}}(q_2) > 120$ GeV and the difference between the reconstructed heavy quark masses must be less than 120 GeV.

With candidate objects identified for two heavy quarks and their decay products, the following additional kinematic criteria are applied. Each event must have $H_{\mathrm{T}} > 1100$ GeV, where H_{T} is the scalar sum of the transverse momenta of the lepton, neutrino, W_{had}, and the two q-jets. The angular separation between the lepton and neutrino candidates must satisfy $\Delta R(\ell, \nu) < 1.4$. The heavy quarks would tend to be central and back-to-back, so the angular separation between the two reconstructed heavy quarks is required to satisfy $2.0 < \Delta R(Q1, Q2) < 4.2$.

To further capitalize on the presence of a hadronically decaying W boson with high p_{T} in the signal, the analysis makes use of a splitting variable [30] defined as

$$y_{12} = \frac{\min(p_{\mathrm{T}j1}, p_{\mathrm{T}j2})^2 \times \Delta R(j_1, j_2)^2}{m^2_{j1j2}};$$

where j_1 and j_2 are the two jets from the W_{had} candidate and m_{j1j2} is the mass of the W_{had} candidate. The two jets from a hadronically decaying W boson tend to have roughly equal energies, while dijets from QCD processes are likely to be asymmetric in energy. Furthermore, jets from $W \to qq$ tend to have a larger opening angle due to the mass of the W boson. Dividing by the dijet mass provides discrimination

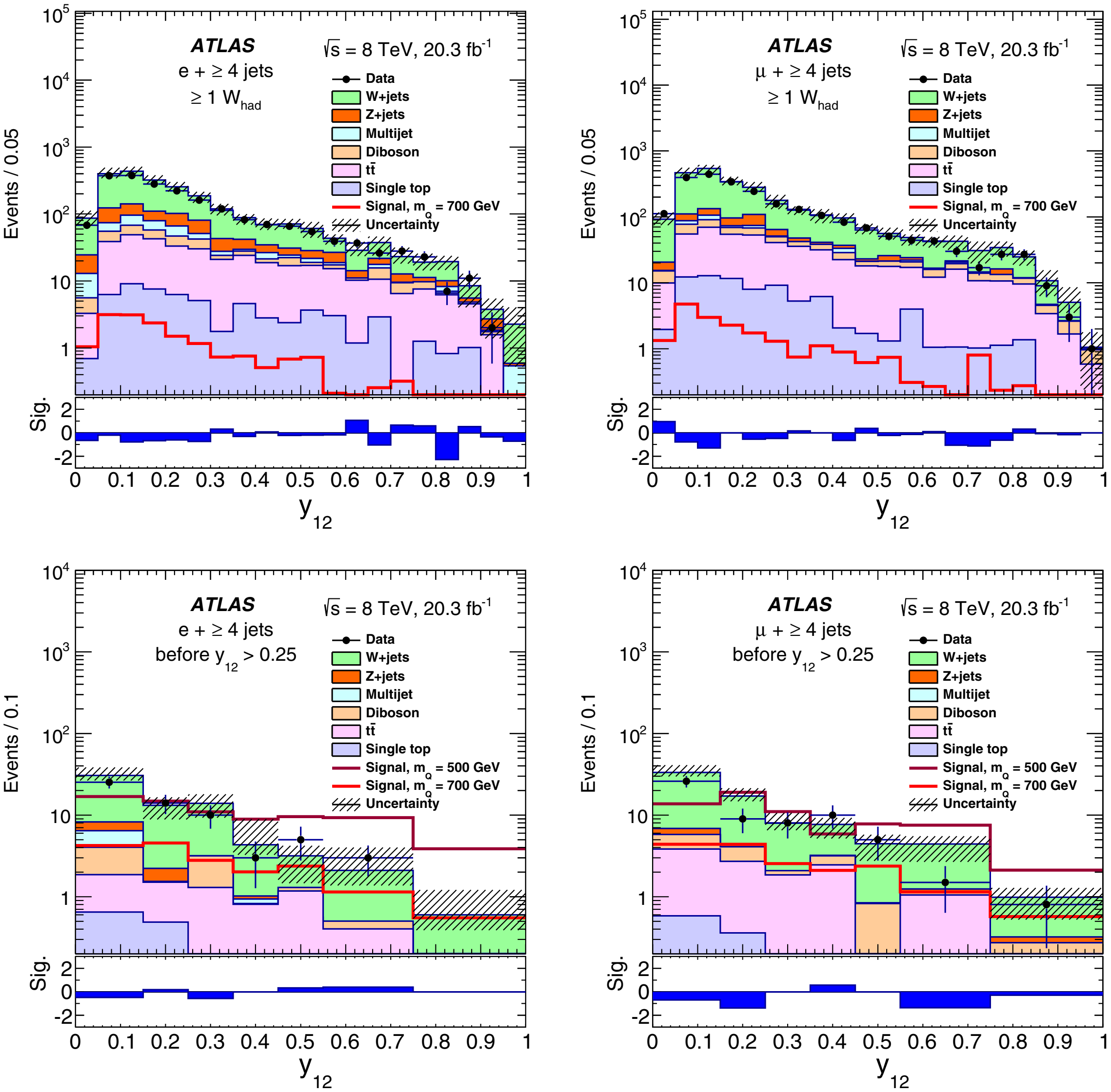

FIG. 3 (color online). The splitting variable y_{12} between the decay products of the hadronic W boson (top) after preselection and requiring a hadronic W boson candidate and (bottom) immediately before applying the requirement $y_{12} > 0.25$, for the (left) electron and (right) muon channels. The shaded band shows the total uncertainty on the background prediction. The lower panel shows the significance of the difference between data and expectation in units of normal standard deviations.

TABLE II. Expected yields for the backgrounds and the VLQ signal with $m_Q = 700$ GeV, along with the observed number of data events, after applying all selection criteria. The uncertainties on the predicted yields correspond to the statistical uncertainty due to finite sample size and the systematic uncertainty, respectively.

	Electron	Muon
$W+\text{jets}$	$5.6 \pm 1.5^{+1.5}_{-1.2}$	$6.0 \pm 1.0^{+2.2}_{-1.6}$
Non-$W+\text{jets}$	$1.2 \pm 0.5^{+1.0}_{-0.4}$	$1.2 \pm 0.4^{+0.8}_{-1.0}$
Total background	$6.8 \pm 1.6^{+2.4}_{-1.5}$	$7.2 \pm 1.1^{+2.5}_{-2.3}$
Signal ($m_Q = 700$ GeV)	$7.0 \pm 0.6^{+1.1}_{-1.3}$	$6.9 \pm 0.6^{+1.0}_{-1.0}$
Data	9	11

for cases in which a QCD dijet system happens to have large values for $\min(p_{\mathrm{T}j1}, p_{\mathrm{T}j2})^2$ and $\Delta R(j_1, j_2)^2$, as such systems are likely to have a very large mass. The background is reduced by a factor of 3.2 by requiring $y_{12} > 0.25$. This requirement has a signal efficiency of approximately 50%, although the precise value depends on the mass of the heavy quark. The modeling of the splitting variable with a large number of events can be seen in the top histograms of Fig. 3, which depict the y_{12} distribution after preselection and requiring a W_{had} candidate. The bottom of Fig. 3 contains the distributions of y_{12} immediately before the $y_{12} > 0.25$ requirement is applied.

The final selection criteria are motivated by the fact that the decay products from the Q quark are well separated. The final requirements are $\Delta R(W_{\text{had}}, q_1) > 1.0$, $\Delta R(W_{\text{had}}, q_2) > 1.0$, $\Delta R(W_{\text{lep}}, q_1) > 1.0$, and $\Delta R(W_{\text{lep}}, q_2) > 1.0$. Table II presents a summary of the expected and observed numbers of events after the final selection, for which the signal (background) efficiency compared to preselection is approximately 8% (0.004%). The small contributions from $t\bar{t}$, $Z+\text{jets}$, dibosons, single-top, and multijet events are combined into a single background source referred to as "non-$W+\text{jets}$." Uncertainties on the yields include the uncertainty due to the size of the signal and background samples and the cumulative effect of the systematic uncertainty described in Sec. VI.

The final discriminant variable used in this search is m_{reco}, the reconstructed heavy quark mass built from the W_{had} candidate and the paired q-jet candidate.

V. BACKGROUND MODELING

A. Correction to $W+\text{jets}$ modeling

It is observed after applying the preselection criteria that the simulated $W+\text{jets}$ sample does not accurately model the p_{T} spectrum of the leptonically decaying W boson candidate. This mismodeling leads to an overestimation of the $W+\text{jets}$ yields in the high-momentum tails of the $E_{\mathrm{T}}^{\text{miss}}$, lepton p_{T}, jet p_{T}, and H_{T} distributions. The dominant background for this analysis is $W+\text{jets}$ events in which the transverse momentum of the W boson, $p_{\mathrm{T}}(W)$, is high. Therefore, it is important to have accurate predictions for both the overall normalization and the $p_{\mathrm{T}}(W)$ distribution. This section describes the procedure used to derive the $W+\text{jets}$ and multijet normalizations and a reweighting function to correct the vector-boson p_{T} in the $W+\text{jets}$

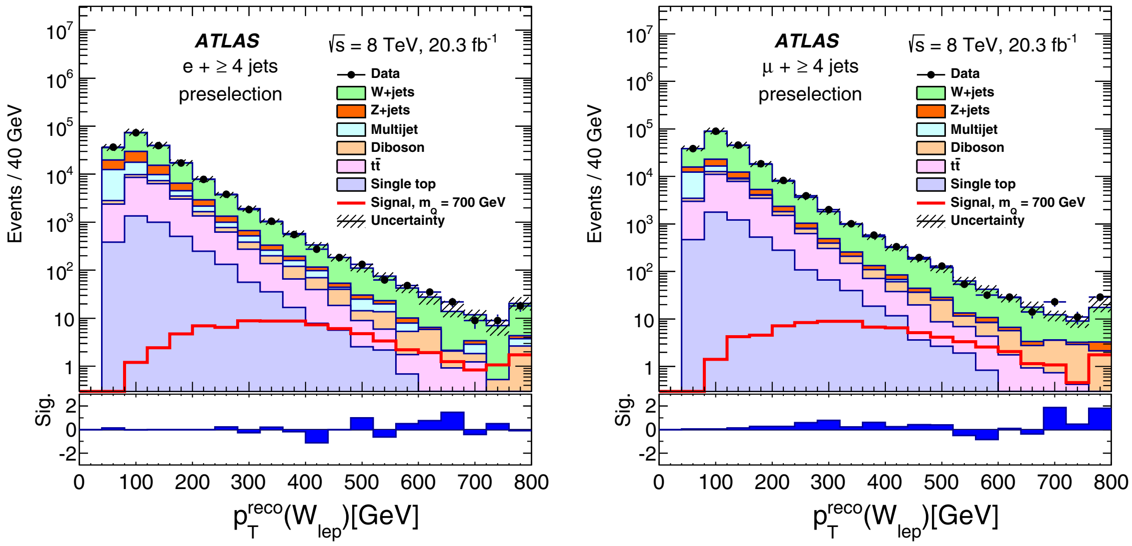

FIG. 4 (color online). The transverse momentum distributions for the leptonic W boson candidate after the $p_{\mathrm{T}}^{\text{truth}}(V)$ correction and final normalization for the (left) electron and (right) muon channels. All overflows are included in the rightmost bin. The shaded band shows the total uncertainty on the background prediction. The lower panel shows the significance of the difference between data and expectation in units of normal standard deviations.

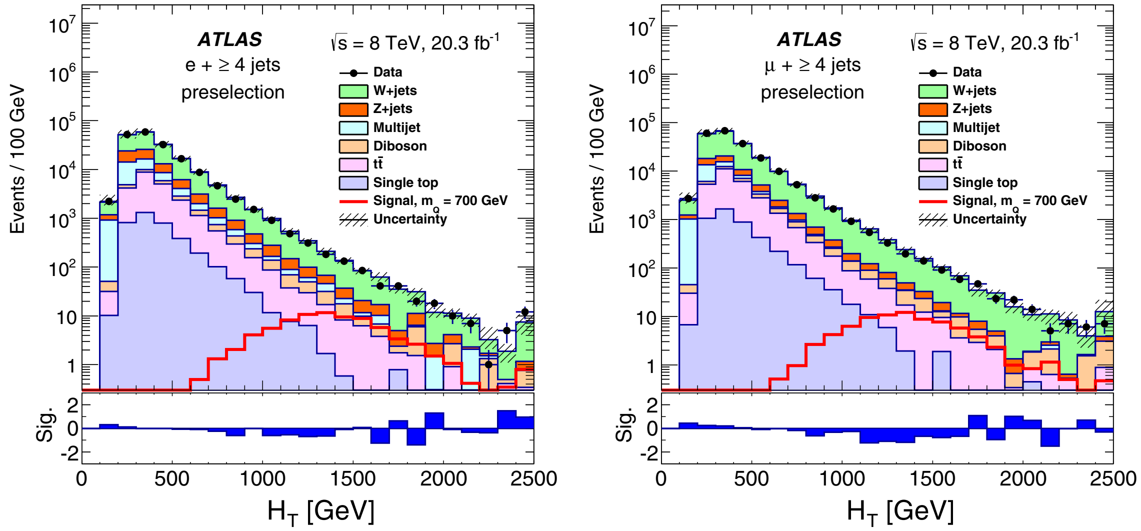

FIG. 5 (color online). Distributions of the scalar sum of the transverse momenta of the lepton, neutrino, W_{had}, and the two q-jets (H_{T}) after the $p_{\mathrm{T}}^{\mathrm{truth}}(V)$ correction and final normalization for the (left) electron and (right) muon channels. All overflows are included in the rightmost bin. The shaded band shows the total uncertainty on the background prediction. The lower panel shows the significance of the difference between data and expectation in units of normal standard deviations.

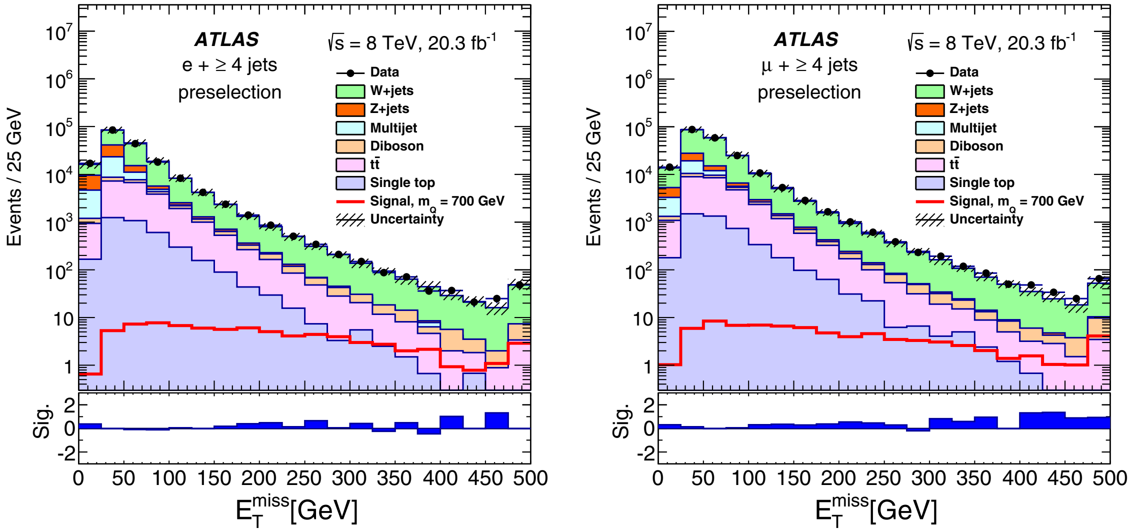

FIG. 6 (color online). Distributions of the missing transverse momentum after the $p_{\mathrm{T}}^{\mathrm{truth}}(V)$ correction and final normalization for the (left) electron and (right) muon channels. All overflows are included in the rightmost bin. The shaded band shows the total uncertainty on the background prediction. The lower panel shows the significance of the difference between data and expectation in units of normal standard deviations.

and $Z+\mathrm{jets}$[2] simulated amples. All steps in the procedure rely on fits to the data using the p_{T} distribution of the W_{lep} candidate, $p_{\mathrm{T}}^{\mathrm{reco}}(W_{\mathrm{lep}})$, after applying the preselection requirements.

First, the normalizations for the $W+\mathrm{jets}$ templates and the multijet templates are fit to the data, with all other background processes fixed at their expectations. The difference between the observed and predicted number of $W+\mathrm{jets}$ events is assumed to be due to the cross section differing from its predicted value, so the electron and muon channels are fit simultaneously to determine a single $W+\mathrm{jets}$ scale factor of 0.82. A correction for $p_{\mathrm{T}}^{\mathrm{truth}}(V)$ is then derived that minimizes the χ^2 between data and simulation for the $p_{\mathrm{T}}^{\mathrm{reco}}(W_{\mathrm{lep}})$ distribution, where $p_{\mathrm{T}}^{\mathrm{truth}}(V)$ is the p_{T} of the generated vector boson in the $W+\mathrm{jets}$ or $Z+\mathrm{jets}$

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[2] The correction is primarily motivated by the dominant $W+\mathrm{jets}$ background but is also applied to the $Z+\mathrm{jets}$ background.

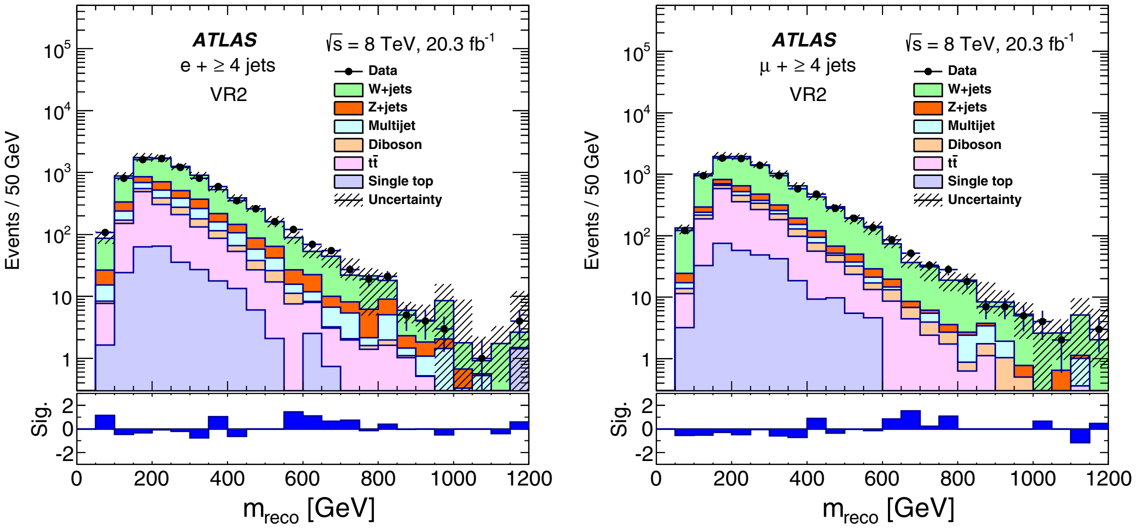

FIG. 7 (color online). Comparison between data and simulation for the distribution of $m_{\rm reco}$, the reconstructed heavy quark mass built from the $W_{\rm had}$ candidate and the paired q-jet candidate, in validation region VR2 for the (left) electron and (right) muon channels. All overflows are included in the rightmost bin. The shaded band shows the total uncertainty on the background prediction. The lower panel shows the significance of the difference between data and expectation in units of normal standard deviations.

sample just before its leptonic decay. The reweighting is approximately unity for low $p_{\rm T}^{\rm truth}(V)$, decreasing to 0.86 for $p_{\rm T}^{\rm truth}(V) = 200$ GeV and 0.65 for $p_{\rm T}^{\rm truth}(V) = 500$ GeV. Finally, the normalizations for the multijet samples and the *corrected* $W +$ jets samples are fit to the data, with all other background processes fixed. The fit is done simultaneously in the electron and muon channels. Figure 4 shows the $p_{\rm T}^{\rm reco}(W_{\rm lep})$ distribution in the electron and muon channels after applying the $p_{\rm T}^{\rm truth}(V)$ correction and scale factors. The corresponding distributions for $H_{\rm T}$ and $E_{\rm T}^{\rm miss}$ are shown in Figs. 5 and 6. The uncertainties on the normalizations and $p_{\rm T}^{\rm truth}(V)$ reweighting are described in Sec. VI.

B. Validation regions

The following validation regions are used to verify the modeling of the background processes:

(i) VR1: preselection, plus one $W_{\rm had}$ and $m_{\rm reco} <$ 350 GeV;
(ii) VR2: preselection, plus one $W_{\rm had}$ and $H_{\rm T} <$ 800 GeV;
(iii) VR3: final selection, but with the requirements on $p_{\rm T}(q_1)$, $p_{\rm T}(q_2)$, and $H_{\rm T}$ changed to $p_{\rm T}(q_1) <$ 160 GeV, $p_{\rm T}(q_2) < 80$ GeV, and $H_{\rm T} < 800$ GeV and with no requirements on $\Delta R(W_{\rm had}, q_1)$, $\Delta R(W_{\rm had}, q_2)$, $\Delta R(W_{\rm lep}, q_1)$, and $\Delta R(W_{\rm lep}, q_2)$.

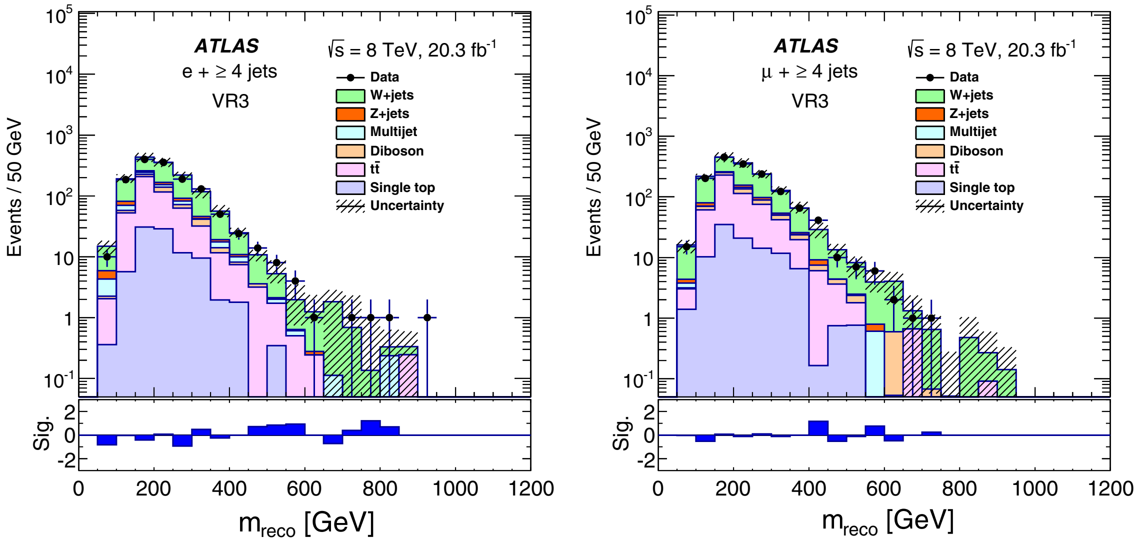

FIG. 8 (color online). Comparison between data and simulation for the $m_{\rm reco}$ distribution in validation region VR3 for the (left) electron and (right) muon channels. The shaded band shows the total uncertainty on the background prediction. The lower panel shows the significance of the difference between data and expectation in units of normal standard deviations.

The validation regions are orthogonal to the signal region but are nevertheless useful for checking with a larger number of events that the background normalization and kinematics are well modeled. The expected signal contribution in each validation region is approximately the size of the background uncertainty for signal masses around the previous limit (350 GeV) and decreases very rapidly for higher masses. VR2 and VR3 are used to validate the modeling of the final discriminant, m_{reco}, as shown in Figs. 7 and 8. VR1 is used to verify the modeling of variables other than m_{reco}, such as the H_{T} distribution and the p_{T} spectra for the individual objects.

VI. SYSTEMATIC UNCERTAINTIES

The uncertainties considered in this analysis can affect the normalization of signal and background and the shape of the final discriminant, m_{reco}. Each source of systematic uncertainty is assumed to be 100% correlated across all samples, but the different sources are treated as uncorrelated with one another. Table III shows the impact of the dominant uncertainties on the normalization of the background processes and a signal sample with a mass of 700 GeV.

A. Normalization uncertainties

Uncertainties affecting only the normalization include those on the integrated luminosity (±2.8%) and the cross sections for various background processes. The uncertainty on the integrated luminosity is derived following the same methodology as that detailed in Ref. [71]. This uncertainty is applied to all simulated signal and background processes.

After the final selection, the non-$W+$jets background has a total normalization uncertainty of 15%. The predicted contribution from the multijet background is negligible compared to the uncertainty on the non-$W+$jets background, so it is neglected.

As described in Sec. VA, the normalization of the $W+$jets background is determined from a fit to data using both lepton channels. The uncertainty on the $W+$jets normalization is determined by comparing that result to the normalization one would obtain if only the electron or only the muon channel were used. This is motivated by the fact that it is not known whether the normalization from the electron channel or the muon channel (or something in between) is correct and this procedure leads to an uncertainty of $+2.7/-4.4\%$. The statistical uncertainty from the fit is negligible (0.03%) in comparison.

The rest of the systematic uncertainties can modify both the normalization and shape of the m_{reco} distribution.

B. Shape uncertainties

Uncertainties on the trigger, reconstruction, and isolation efficiencies for the selected lepton are estimated using $Z\to ee$ and $Z\to\mu\mu$ events [72,73]. In addition, high jet-multiplicity $Z\to\ell\ell$ events are studied, from which extra uncertainties on the isolation efficiency are assigned to account for the difference between Z boson and $t\bar{t}$ events. Uncertainties on the $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction and the energy scale and resolution of the leptons were also considered; however, these have a very small impact on the results.

The jet energy resolution is measured by studying dijet events in data and simulation. The simulation is found to agree with data to better than 10% [74]. The differences in resolutions between data and simulations are used to determine the relative systematic uncertainty. The uncertainty on the jet energy scale is evaluated by repeating the analysis with the jet energy scale shifted by $\pm 1\sigma$ [64,66]. The jet reconstruction efficiency is estimated using track-based jets and is well described in simulation. To account for differences in the efficiency for reconstructing jets in simulated events compared to collider data, the efficiencies are measured in both samples and the difference is taken as the uncertainty. The uncertainty due to the JVF requirement is evaluated by comparing the signal and background distributions with the JVF cut shifted up and down by 10%, a variation that spans the difference observed between data and simulation in this quantity. The b-tagging efficiency for b-jets, as well as c-jets and light jets, is derived in data and a simulated $t\bar{t}$ sample, parametrized as a function

TABLE III. Overall normalization changes (expressed in %) in signal and background yields for the dominant systematic uncertainties considered. The selection presented here is the combination of the $e+$jets and $\mu+$jets channels after the final selection.

	Signal ($m_Q = 700$ GeV)	Non-$W+$jets	$W+$jets
Luminosity	$+2.8/-2.8$	$+2.8/-2.8$	$+2.8/-2.8$
Normalization		± 15	$+2.7/-4.4$
Lepton identification	$+1.6/-1.6$	$+1.5/-1.5$	$+1.4/-1.4$
Jet energy resolution	$+0.6/-0.6$	$+12/-12$	$+8.7/-8.7$
Jet energy scale	$+6.1/-4.3$	$+33/-34$	$+14/-18$
b-tagging	$+0.2/-0.2$	$+5.1/-5.3$	$+0.3/-0.3$
c-tagging	$+1.5/-1.5$	$+1.5/-1.5$	$+1.2/-1.2$
Light-jet tagging	$+1.0/-1.0$	$+0.9/-0.9$	$+1.0/-1.0$
$p_{\mathrm{T}}^{\mathrm{truth}}(V)$ re-weighting			$+5.7/-4.2$

of p_T and η [67,75]. The corresponding (in)efficiencies in the simulated samples are corrected to match those in data and the uncertainties from the calibration are propagated through the analysis.

The $W+$jets sample is assigned a $p_\mathrm{T}^\mathrm{truth}(V)$-dependent shape uncertainty due to the correction described in Sec. V A. Four sources of uncertainty on the $p_\mathrm{T}^\mathrm{truth}(V)$ correction are considered: (1) the statistical uncertainty on the parameters of the reweighting function; (2) the difference between the nominal reweighting function and alternative corrections obtained by only considering the electron or muon channel; (3) the dependence of the fit on the choice of bin width when deriving the reweighting function; (4) the difference between alternative parametrizations of the reweighting function. A closure test is performed to verify that any residual differences between data and prediction are well within the assigned uncertainty.

VII. RESULTS

The final m_reco distribution for the combined electron and muon channels is shown in Fig. 9 for three signal scenarios: $m_Q = 600$ GeV, $m_Q = 700$ GeV, and $m_Q = 800$ GeV. The observed distribution shows a slight excess over the SM expectation, but the excess is broader than expected for signal and is consistent with the background-only prediction at the level of 2 standard deviations. Therefore, the analysis proceeds to setting limits on the signal hypothesis.

The m_reco distribution for the combined electron and muon channels after the final selection (Fig. 9) is used to derive 95% confidence level (C.L.) limits on the $Q\bar{Q}$ production cross section using the CL_s method [76,77].

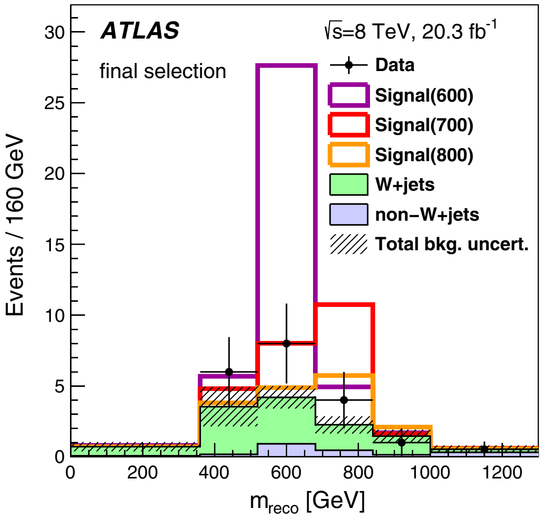

FIG. 9 (color online). Distribution of the final discriminant, the mass of the hadronically decaying heavy quark candidate, with the bin widths chosen as for the statistical analysis. The expected contribution from signal with $\mathrm{BR}(Q \to Wq) = 1$ is shown stacked on top of the total background prediction for three mass scenarios, $m_Q = 600$, 700, and 800 GeV. The backgrounds are stacked with the largest on top. The shaded band shows the total uncertainty on the background prediction.

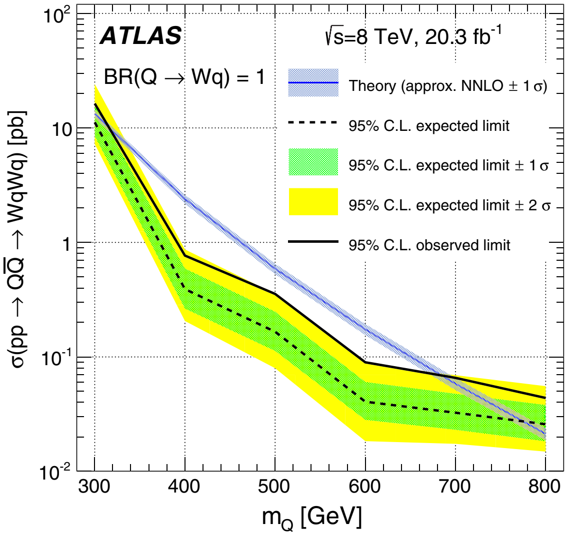

FIG. 10 (color online). The expected (black dashed line) and observed (black solid line) 95% C.L. upper limits on the cross section as a function of m_Q when setting $\mathrm{BR}(Q \to Wq) = 1$, which would be the case for a new chiral quark. The green and yellow shaded bands indicate the $\pm 1\sigma$ and $\pm 2\sigma$ intervals on the distribution of expected results for the chiral model if no signal exists. The blue line is the theoretical prediction for the total cross section [i.e., assuming $\mathrm{BR}(Q \to Wq) = 1$] with its uncertainties.

Limits on the pair production of new chiral quarks are evaluated by setting $\mathrm{BR}(Q \to Wq) = 1$. Figure 10 shows the observed and expected limits on a heavy chiral quark as a function of m_Q, compared to the theoretical prediction [33–38]. The total uncertainty on the theoretical cross section includes the contributions from the scale variations and PDF uncertainties. Using the central value of the theoretical cross section, the observed (expected) 95% C.L. limit on the mass of a new chiral quark is $m_Q >$ 690 GeV (780 GeV). This represents the most stringent limit to date on the mass of a new quark decaying exclusively into a W boson and a light quark (u, d, s). This limit is also applicable to the production of pairs of down-type vectorlike quarks with electric charge of $-4/3$ which each decay into a W boson and a light quark (d, s).

Next, the VLQ signal samples are used to set limits on the mass of a heavy quark that decays to a light quark (u, d, s) and either a W, Z, or H boson. The results are given as a function of the branching ratios $\mathrm{BR}(Q \to Wq)$ versus $\mathrm{BR}(Q \to Hq)$, with the branching ratio to Zq fixed by the requirement $\mathrm{BR}(Q \to Zq) = 1 - \mathrm{BR}(Q \to Wq) - \mathrm{BR}(Q \to Hq)$. The analysis loses sensitivity at low masses due to the tight selection requirements optimized for the decay $Q \to Wq$, so the results are presented as the upper and lower bounds on the mass range that is excluded at 95% C.L. The expected limits on m_Q as a function of the branching ratios are shown in Fig. 11 and the observed limits are shown in Fig. 12. For example, for the branching

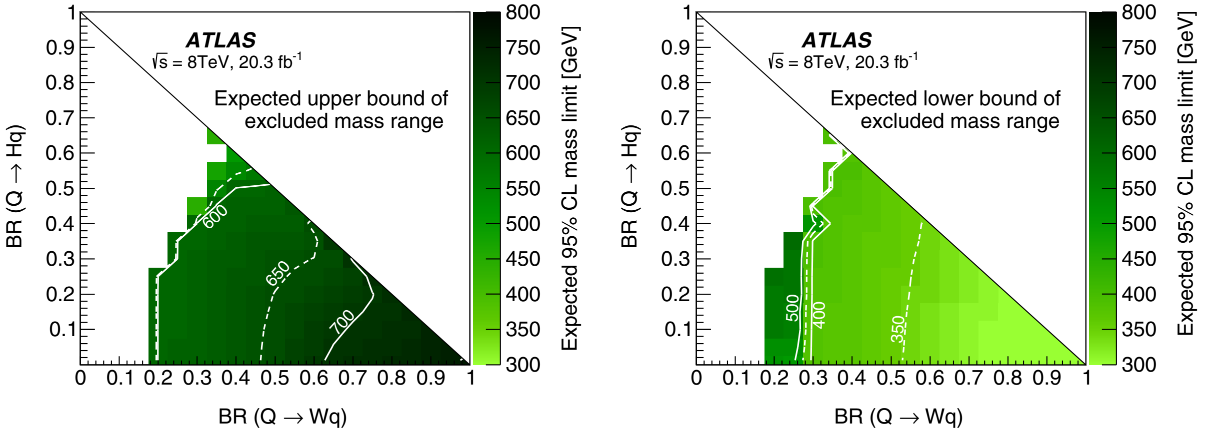

FIG. 11 (color online). The (left) upper and (right) lower bounds on the range of heavy quark masses expected to be excluded at 95% C.L., as a function of the branching ratio of the heavy quark to Wq versus Hq, with the branching ratio to Zq fixed by the requirement $\mathrm{BR}(Q \to Zq) = 1 - \mathrm{BR}(Q \to Wq) - \mathrm{BR}(Q \to Hq)$. The region above the diagonal is forbidden by unitarity.

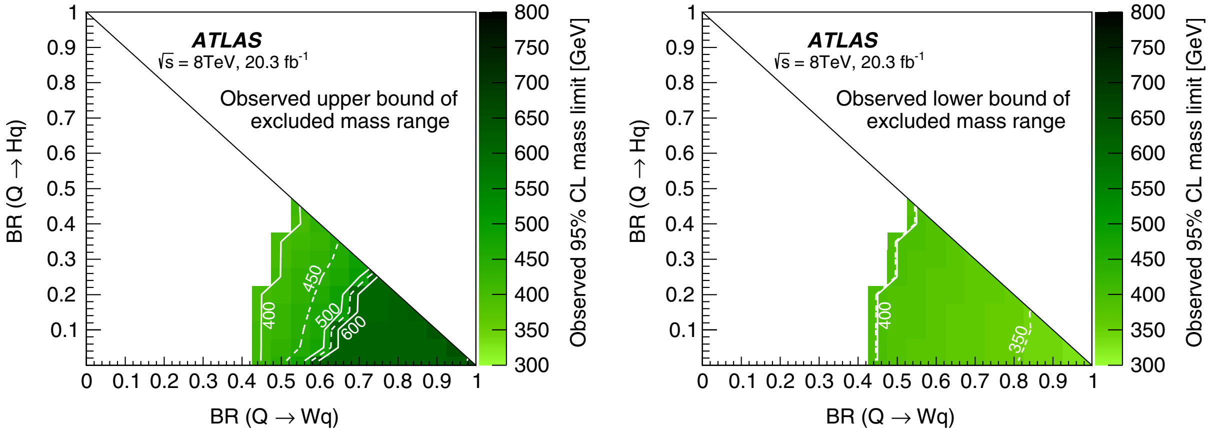

FIG. 12 (color online). The (left) upper and (right) lower bounds on the range of heavy quark masses observed to be excluded at 95% C.L., as a function of the branching ratio of the heavy quark to Wq versus Hq, with the branching ratio to Zq fixed by the requirement $\mathrm{BR}(Q \to Zq) = 1 - \mathrm{BR}(Q \to Wq) - \mathrm{BR}(Q \to Hq)$. The region above the diagonal is forbidden by unitarity.

ratios $\mathrm{BR}(Q \to Wq) = 0.6$, $\mathrm{BR}(Q \to Zq) = 0.4$, and $\mathrm{BR}(Q \to Hq) = 0$, the results exclude VLQs with a mass from 370 to 610 GeV. If no signal is present, the median expected exclusion range for that set of branching ratios is 340 to 690 GeV. For $\mathrm{BR}(Q \to Wq) = 0.6$, $\mathrm{BR}(Q \to Zq) = 0.3$, and $\mathrm{BR}(Q \to Hq) = 0.1$, the results exclude VLQs with a mass from 370 to 470 GeV, while the median expected exclusion range is 340 to 680 GeV. For $\mathrm{BR}(Q \to Wq) = 0.5$, $\mathrm{BR}(Q \to Zq) = 0.25$, and $\mathrm{BR}(Q \to Hq) = 0.25$, the results exclude VLQs with a mass from 390 to 410 GeV, while the median expected exclusion range is 360 to 650 GeV.

VIII. CONCLUSION

A search for new heavy quarks that decay to a W boson and a light quark (u, d, s) is performed with a data set corresponding to 20.3 fb^{-1} that was collected by the ATLAS detector at the LHC in pp collisions at $\sqrt{s} = 8$ TeV. No significant evidence of a heavy quark signal is observed when selecting events with one charged lepton, large $E_{\mathrm{T}}^{\mathrm{miss}}$, and four non-$b$-tagged jets. The results exclude new heavy chiral quarks with masses up to 690 GeV at 95% C.L. This search is also interpreted in the context of vectorlike quark models, for which the new heavy quark can decay to a light quark and either a W, Z, or H boson. New exclusions limits are presented in the two-dimensional plane of $\mathrm{BR}(Q \to Wq)$ versus $\mathrm{BR}(Q \to Hq)$.

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