Search for anomalous electroweak production of WW/WZ in association with a high-mass dijet system in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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A search is presented for anomalous quartic gauge boson couplings in vector-boson scattering. The data for the analysis correspond to 20.2 fb^{-1} of $\sqrt{s} = 8$ TeV pp collisions and were collected in 2012 by the ATLAS experiment at the Large Hadron Collider. The search looks for the production of WW or WZ boson pairs accompanied by a high-mass dijet system, with one W decaying leptonically and a W or Z decaying hadronically. The hadronically decaying W/Z is reconstructed as either two small-radius jets or one large-radius jet using jet substructure techniques. Constraints on the anomalous quartic gauge boson coupling parameters α_4 and α_5 are set by fitting the transverse mass of the diboson system, and the resulting 95% confidence intervals are $-0.024 < \alpha_4 < 0.030$ and $-0.028 < \alpha_5 < 0.033$.

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I. INTRODUCTION

One of the main goals of the LHC experiments is to elucidate the mechanism of electroweak symmetry breaking (EWSB). In the Standard Model (SM), EWSB is explained by the Brout–Englert–Higgs mechanism [1–3]. Although many measurements have been made of the properties of the Higgs boson, more information is needed for a complete picture of EWSB. Vector-boson scattering (VBS) is a key probe of EWSB, since it is sensitive to interactions between the longitudinal components of the gauge bosons.

ATLAS and CMS have recently presented results of VBS searches [4–6], and although the searches in the $W^{\pm}W^{\pm}$ channel are reaching sensitivity to the Standard Model (SM) VBS process, an observation has not yet been claimed. However, even without an observation of the SM process, these analyses have been able to constrain physics beyond the SM (BSM).

A common way of parametrizing BSM physics in VBS is through a low-energy effective theory [7]. Such an approach avoids having to choose a specific BSM theory and is particularly well suited if the energy scale of the BSM physics is too high for the new resonances of the theory to be observed directly. In this kind of framework, VBS can be modified by anomalous quartic gauge couplings (aQGCs). Searches for aQGCs have been performed by the LEP experiments [8–13], D0 [14], and the LHC experiments [4–6,15–20]. A typical prediction of aQGCs is an enhancement of the VBS cross section at high transverse momentum (p_{T}) of the vector bosons and at high invariant mass of the diboson system.

Experimentally, VBS is characterized by the presence of a pair of vector bosons (W, Z, or γ) and two forward jets with a large separation in rapidity and a large dijet invariant mass. Previous searches for aQGCs in VBS have focused on channels involving leptonic boson decays [$W(\ell\nu)$ and $Z(\ell^+\ell^-)$][1] and photons. The $V(qq')W(\ell\nu)$ channel ($V = W, Z$), however, offers some interesting advantages. The $V(qq')$ branching fractions are much larger than the leptonic branching fractions. Also, the kinematics of $V(qq')W(\ell\nu)$ are easier to reconstruct than $W(\ell\nu)W(\ell\nu)$ because there is one less neutrino in the final state, which enhances the sensitivity to aQGC-dependent kinematic effects. In addition, the use of jet substructure techniques allows good reconstruction efficiency in the high-p_{T} region, which is the most sensitive to aQGCs. The main challenge of the $V(qq')W(\ell\nu)$ channel is the presence of large backgrounds from $W +$ jets and $t\bar{t}$ events. These backgrounds make a SM VBS measurement in this channel very challenging because it is difficult to achieve a favorable signal-to-background ratio. On the other hand, an aQGC search is less sensitive to these backgrounds because it is possible to find regions of phase space where the aQGC signal is greatly enhanced over the SM processes, resulting in large signal-to-background ratios. This motivates a search for aQGCs in the $V(qq')W(\ell\nu)$ channel.

In this analysis, the approach used in Ref. [21] is adopted, which parametrizes aQGCs by adding two new operators to the SM,

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[1]Unless otherwise noted, $\ell = e, \mu$ in this paper.

$$\alpha_4\mathcal{L}_4 = \alpha_4 \mathrm{tr}[\mathbf{V}_\mu \mathbf{V}_\nu]\mathrm{tr}[\mathbf{V}^\mu \mathbf{V}^\nu],$$
$$\alpha_5\mathcal{L}_5 = \alpha_5 \mathrm{tr}[\mathbf{V}_\mu \mathbf{V}^\mu]\mathrm{tr}[\mathbf{V}_\nu \mathbf{V}^\nu], \quad (1)$$

where the $\mathbf{V}_\mu$ field is related to the gauge boson fields. The SM (including the Higgs boson) is recovered when $\alpha_4 = \alpha_5 = 0$. This model, with the simple addition of two aQGC parameters to the SM, is not an ultraviolet-complete theory, and it must be modified to prevent unitarity violation at high energies. In this analysis, the K-matrix unitarization method [21] is applied in order to ensure that the aQGCs do not lead to the violation of unitarity. This aQGC parametrization and unitarization method was also adopted in Refs. [4,6]. Both the α_4 and α_5 parameters lead to similar modifications of the VBS phenomenology: an increase in the cross section and changes in the kinematics, most notably an enhancement of VBS at high VV invariant mass.

This paper presents a study of the production of $V(qq')W(\ell\nu)$ accompanied by a high-mass dijet system, in a phase space optimized for sensitivity to aQGCs. The $V(qq')$ system is reconstructed in two different ways: as two small-radius jets, or as a single large-radius jet making use of jet substructure. A search for aQGC effects is performed using the transverse-mass distribution of the diboson system.

II. ATLAS DETECTOR

The ATLAS detector [22] has a cylindrical geometry,[2] and consists of several layers of subdetectors around the interaction point. The innermost layer, the inner detector (ID) provides charged-particle tracking for $|\eta| < 2.5$. The ID is surrounded by a superconducting solenoid providing a 2 T magnetic field, and the solenoid in turn is surrounded by a liquid-argon (LAr) electromagnetic (EM) calorimeter that provides coverage in the range $|\eta| < 3.2$. A scintillator-tile calorimeter provides hadronic measurements for $|\eta| < 1.7$ and LAr calorimeters in the forward region provide additional EM and hadronic measurements up to $|\eta| = 4.9$. A muon spectrometer (MS) surrounds the calorimeters and makes use of a toroidal magnetic field. The MS provides tracking capabilities for $|\eta| < 2.7$ and triggering for $|\eta| < 2.4$. Events are selected for off-line processing using a three-level trigger system.

[2]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (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 upward. 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 $\eta = -\ln\tan(\theta/2)$.

III. DATA AND MONTE CARLO SAMPLES

This analysis uses 20.2 ± 0.4 fb^{-1} [23] of 8 TeV pp collision data recorded by the ATLAS detector in 2012. Events used in this analysis are required to pass one of several single-lepton triggers. One set of triggers requires an isolated electron or muon with $p_\mathrm{T} > 24$ GeV. Another set of triggers requires an electron (muon) with $p_\mathrm{T} > 60(36)$ GeV, without the isolation requirement.

This analysis searches for anomalous contributions to electroweak (EWK) production of two vector bosons plus two jets, which is hereafter referred to as "EWK WV." The EWK WV process is modeled with Monte Carlo (MC) samples that include $V(qq')\ell\nu + 2\,$parton and $V(qq')\ell^+\ell^- + 2\,$parton production, and include all the purely electroweak [i.e., $\mathcal{O}(\alpha^6_\mathrm{EWK})$] tree-level diagrams that contribute to these final states. The EWK WV process definition includes both the VBS and non-VBS diagrams because the VBS-only process cannot be defined in a gauge-invariant way [24]. One example of the EWK WV diagrams is shown in Fig. 1. Production of $V(qq')\ell\nu + 2\,$parton and $V(qq')\ell^+\ell^- + 2\,$parton can also occur through diagrams that are $\mathcal{O}(\alpha^4_\mathrm{EWK}\alpha^2_\mathrm{S})$ at tree level, but such processes are not affected by quartic gauge couplings and are not considered as EWK WV, but rather are included in the diboson background described below. In the EWK WV MC sample definition, "ℓ" includes tau leptons, in order to account for contributions from $\tau \rightarrow (e/\mu) + X$ decays that could pass the event selection.

The EWK WV process is modeled with WHIZARD v2.1.1 [25,26], complemented by the PYTHIA 8 [27] parton shower, fragmentation, and hadronization modeling, and using the CT10 parton distribution function (PDF) set [28]. WHIZARD is used to generate both the SM samples and samples with nonzero aQGC values. The samples use dynamic factorization and renormalization scales equal to the diboson invariant mass. The SM and aQGC samples are normalized using the leading-order (LO) cross sections from WHIZARD.

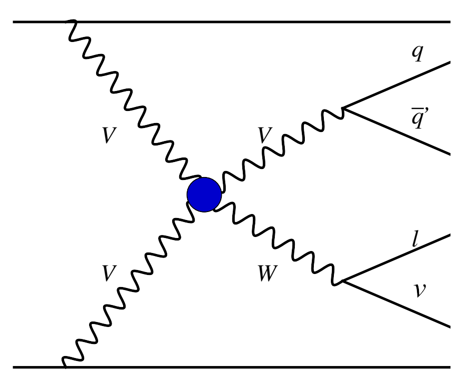

FIG. 1. A VBS diagram that contributes to EWK WV production. This analysis searches for modifications of the quartic gauge couplings.

The $W + \text{jets}$ and $Z + \text{jets}$ backgrounds are modeled using SHERPA v1.4.1 [29–32], with up to four partons in the matrix element. The CT10 PDF set is used. These samples are normalized using next-to-next-to leading-order (NNLO) inclusive cross sections obtained from FEWZ [33]. These samples do not contain electroweak production of $W + \text{jets}$ (for example, W-production through vector-boson fusion), which is modeled separately with SHERPA v1.4.3 and the CT10 PDF set.

Backgrounds from $t\bar{t}$ events and single-top-quark events in the Wt- and s-channels are generated with POWHEG BOX [34–38] using the CT10 PDF set. Parton showering is done with PYTHIA v6.426 [39] using the P2011C set of tuned parameters (P2011C tune) [40]. The t-channel single-top-quark process is modeled with AcerMC [41] plus PYTHIA v6.426 with the P2011C tune and the CTEQ6L1 PDF set [42]. The $t\bar{t}$ samples are normalized using the NNLO cross section including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms, calculated with top++2.0 [43–49]. The single-top-quark samples are normalized using NLO + NNLL calculations [50–52].

Backgrounds from diboson (WW, WZ, and ZZ) production are modeled with SHERPA v1.4.3 using the CT10 PDF set. These samples are normalized using NLO cross sections [53]. These background samples do not overlap with the EWK WV samples, since the former do not include purely electroweak production of dibosons in association with two jets.

The $W\gamma$ background is modeled with ALPGEN [54] interfaced with HERWIG v6.520.2 [55] and JIMMY [56], using the CTEQ6L1 PDF set and AUET2 tune [57]. The $Z\gamma$ background is modeled with SHERPA v1.4.1 and the CT10 PDF set.

The MC samples are passed through the ATLAS detector simulation [58], which is based on GEANT4 [59]. Some of the samples are passed through a fast simulation that uses a parametrization of the electromagnetic and hadronic calorimeters. The simulated hard-scattering processes are overlaid with minimum-bias events, in order to model additional pp interactions in the events (pileup). The simulated events are reweighted in order to better match the number of interactions per bunch crossing observed in data.

IV. OBJECT SELECTION

The analysis selects events with exactly one lepton (either an electron or muon), missing transverse momentum, and either four small-radius jets or two small-radius jets and one large-radius jet.

"Loose" electron candidates are reconstructed by matching energy deposits in the EM calorimeter to tracks in the ID. They must have transverse energy $E_{\mathrm{T}} > 15$ GeV and $|\eta| < 2.47$, excluding the transition region between the barrel and end cap calorimeters $1.37 < |\eta| < 1.52$. Their longitudinal impact parameter with respect to the primary vertex, z_0, must satisfy $|z_0 \sin\theta| < 0.5$ mm, and their transverse impact parameter d_0 must satisfy $|d_0|/\sigma_{d_0} < 5$, where σ_{d_0} is the uncertainty in d_0. This reduces electron candidates from heavy-flavor decays. Also, they must satisfy "medium" cut-based identification criteria from Ref. [60] that are based on the calorimeter shower shape and track variables, and which are designed to reduce fake electron candidates from backgrounds such as jets. The candidates are rejected if they are within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.1$ of a "good" muon, defined below.

"Loose" muon candidates are found by combining tracks from the ID with tracks from the MS. They must have a transverse momentum $p_{\mathrm{T}} > 15$ GeV, $|\eta| < 2.4$, and $|z_0 \sin\theta| < 0.5$ mm. They are also required to have a certain number of hits in each layer of the ID.

"Good" lepton candidates are a subset of loose lepton candidates that satisfy additional criteria. Good electrons must satisfy the "tight" cut-based identification criteria from Ref. [60]. Good muons must have $|d_0|/\sigma_{d_0} < 3$. Electrons and muons must both pass isolation requirements, in order to reduce contributions from jets misreconstructed as electrons, or from leptons originating from heavy-flavor hadronic decays. Electrons (muons) must have $R_{\mathrm{cal}}^{\mathrm{iso}} < 0.14(0.07)$ and $R_{\mathrm{ID}}^{\mathrm{iso}} < 0.07(0.07)$. Here $R_{\mathrm{cal}}^{\mathrm{iso}}$ is the scalar sum of the E_{T} of energy deposits in the calorimeter within a cone of size $\Delta R = 0.3$ around the lepton candidate (excluding the lepton candidate itself), divided by the electron E_{T} or muon p_{T}. The quantity $R_{\mathrm{ID}}^{\mathrm{iso}}$ is calculated as the scalar sum of the p_{T} of the tracks within $\Delta R = 0.3$ of the lepton candidate (but excluding the lepton candidate), divided by the electron E_{T} or muon p_{T}.

Small-radius jets (hereafter "small-R" jets) are reconstructed using the anti-k_t algorithm [61] with radius parameter 0.4. Small-R jets must have $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 4.5$, and must be separated from lepton candidates by at least $\Delta R = 0.3$. Small-R jets with $p_{\mathrm{T}} < 50$ GeV and $|\eta| < 2.4$ must also have a "jet vertex fraction" [62] with absolute value greater than 0.5, in order to reject jets from other simultaneous pp collisions.

Large-radius ("large-R") jets are reconstructed using the Cambridge–Aachen algorithm [63] with radius 1.2 and are "groomed" using a mass-drop filtering algorithm [64] with filtering criteria $\mu_{\mathrm{frac}} < 0.67$ and $y_f > 0.09$. This algorithm selects jets that contain substructure consistent with a two-body decay. Large-R jets must have $p_{\mathrm{T}} > 200$ GeV and $|\eta| < 1.2$, and be separated from lepton candidates by at least $\Delta R = 1.2$.

The missing transverse momentum $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ is calculated as the negative vector sum of the p_{T} of all the objects in the events. The p_{T} of electrons, muons, photons, and jets are taken from reconstructed objects, and a "soft term" accounting for the transverse energy of calorimeter clusters not associated with any reconstructed object is also included [65].

V. EVENT SELECTION

In order to ensure that selected events are due to proton–proton collisions, each event is required to have at least one reconstructed vertex with at least three tracks having $p_T > 400$ MeV. Events must have exactly one "good" electron or muon with $p_T(\ell) > 30$ GeV, and events containing any additional "loose" electrons or muons are vetoed. The E_T^{miss} in the event must be greater than 30 GeV. The leptonically decaying W candidate, W_{lep}, is formed by the four-momentum sum of the lepton and the missing momentum, where the z-component of the missing momentum is inferred by requiring the invariant mass of W_{lep} to be equal to the nominal W mass of 80.4 GeV [66].

For reconstructing the hadronic portion of the event, two different selection criteria are used. A "resolved" selection is developed that reconstructs the hadronically decaying W/Z candidate (V_{had}) as two small-R jets ($V \to \mathrm{jj}$), whereas a "merged" selection reconstructs the V_{had} as a single large-R jet ($V \to \mathrm{J}$).

For the resolved selection, the event must have at least four small-R jets. The V_{had} candidate is formed from the two jets that have m_{jj} closest to the nominal W mass, unless there are multiple jet pairs with m_{jj} within 15 GeV of the W mass, in which case V_{had} is chosen from among these jet pairs, using an algorithm that favors jet pairs with two high-p_T jets. From the remaining small-R jets, the two that have the highest m_{jj} are chosen as the "tagging" jets.

For the merged selection, the event must have at least one large-R jet, which represents the V_{had} candidate. In the case of multiple large-R jets, the one with mass closest to the nominal W mass is taken as the V_{had} candidate. The event must also have at least two small-R jets that each have $\Delta R(\mathrm{j}, V_{\mathrm{had}}) > 1.2$. Among these small-$R$ jets, the two with the highest m_{jj} are chosen as the tagging jets.

In both the resolved and merged selections, the V_{had} candidate must have $64 < m(V_{\mathrm{had}}) < 96$ GeV, and the invariant mass of the tagging jets must be $m_{\mathrm{jj,tag}} > 500$ GeV. The requirement on $m(V_{\mathrm{had}})$ favors the WW component of the EWK WV process over the WZ component; however, the latter is only expected to contribute 10%–15% of the total EWK WV events in the phase space of this analysis, both for the SM and for aQGC contributions.

In order to reduce the amount of background from $t\bar{t}$ and single-top-quark processes, a restriction is placed on the number of b-tagged jets in the event. Small-R jets are tagged as b-jets using the "MV1" algorithm [67,68] with a b-tag efficiency of 85%. In the resolved selection, the event is vetoed if (a) both of the jets associated with the V_{had} candidate are b-tagged, or (b) if any other jet in the event is b-tagged. The reason for not vetoing events that have only a single b-tagged V_{had}-jet is to prevent EWK WV events with a $W \to cs$ decay from being vetoed due to a mistagged c-jet. In the merged selection, the event is vetoed if any small-R jet with $\Delta R(\mathrm{j}, V_{\mathrm{had}}) > 0.4$ is b-tagged.

The aforementioned event selection is designed to give a phase space with characteristics typical of VBS events and is referred to as the "loose VBS" selection stage. On top of the loose VBS selection, additional selection criteria are applied that increase the sensitivity to aQGCs. The minimum $m_{\mathrm{jj,tag}}$ value is increased to 900 GeV in both the resolved and merged selections. In addition, events are required to have $\zeta_V > 0.9$, where ζ_V is the *boson centrality*, defined as

$$\zeta_V = \min\{\Delta\eta_-, \Delta\eta_+\}, \tag{2}$$

where $\Delta\eta_- = \min\{\eta(V_{\mathrm{had}}), \eta(W_{\mathrm{lep}})\} - \min\{\eta_{\mathrm{j_{tag1}}}, \eta_{\mathrm{j_{tag2}}}\}$ and $\Delta\eta_+ = \max\{\eta_{\mathrm{j_{tag1}}}, \eta_{\mathrm{j_{tag2}}}\} - \max\{\eta(V_{\mathrm{had}}), \eta(W_{\mathrm{lep}})\}$. In these equations, $\mathrm{j_{tag1}}$ and $\mathrm{j_{tag2}}$ refer to the two tagging jets. The variable ζ_V has large values when the tagging jets have large separation in η, and when the two boson candidates are between the tagging jets in η. The requirement $\zeta_V > 0.9$ implicitly forces $|\Delta\eta(\mathrm{j_{tag1}}, \mathrm{j_{tag2}})|$ to be greater than 1.8. Furthermore, the p_T of the W_{lep} candidate is required to be greater than 150 GeV.

For the merged selection, the p_T-balance A_{WV} must be less than 0.30, where

$$A_{WV} = \frac{|\vec{p}_T(V_{\mathrm{had}}) + \vec{p}_T(W_{\mathrm{lep}})|}{p_T(V_{\mathrm{had}}) + p_T(W_{\mathrm{lep}})}. \tag{3}$$

This requirement is based on the fact that the aQGC events are expected to have two bosons produced roughly back-to-back. For the resolved selection, it is required that $\cos(\theta_{\mathrm{j}}^*) < 0.50$, where θ_{j}^* is defined as the angle between the V_{had} direction and one of the jets from the V_{had} candidate. In this calculation, the V_{had}-jet direction is measured in the rest frame of the V_{had}, the V_{had} direction is measured in the WV rest frame, and the V_{had}-jet used in this calculation is chosen to be whichever jet gives $\cos(\theta_{\mathrm{j}}^*) > 0$. This $\cos(\theta_{\mathrm{j}}^*)$ requirement further improves aQGC sensitivity because aQGCs enhance the longitudinal polarization of the vector bosons at high p_T. The thresholds for $m_{\mathrm{jj,tag}}$, ζ_V, A_{WV}, and $\cos(\theta_{\mathrm{j}}^*)$ were optimized for the best expected sensitivity to aQGCs.

To remove overlap between the resolved and merged selections, events that pass both selections are put in the resolved category. The search for aQGCs is performed by using the transverse mass of the diboson system, defined as

$$m_T(WV) = \sqrt{(E_T(V_{\mathrm{had}}) + E_T(W_{\mathrm{lep}}))^2 - (p_x(V_{\mathrm{had}}) + p_x(W_{\mathrm{lep}}))^2 - (p_y(V_{\mathrm{had}}) + p_y(W_{\mathrm{lep}}))^2}, \tag{4}$$

where $E_{\mathrm{T}}(V_{\mathrm{had}}) = E(V_{\mathrm{had}}) \cdot \frac{p_{\mathrm{T}}(V_{\mathrm{had}})}{p(V_{\mathrm{had}})}$ and $E_{\mathrm{T}}(W_{\mathrm{lep}}) \equiv E_{\mathrm{T}}(\ell) + E_{\mathrm{T}}^{\mathrm{miss}}$. The merged category probes higher values of $m_{\mathrm{T}}(WV)$ than the resolved category. The signal efficiency of the resolved selection drops off rapidly over the range $600 < m_{\mathrm{T}}(WV) < 800$ GeV, and the merged selection efficiency surpasses the resolved selection efficiency for $m_{\mathrm{T}}(WV) \gtrsim 700$ GeV.

Events are split up into three categories: e^+ and μ^+ (resolved selection), e^- and μ^- (resolved selection), and the merged selection. The resolved category is split up by charge because the $W+$jets background and the aQGC signal are charge-asymmetric. The merged category is not split up by lepton charge, because of the small expected event yield in this category.

VI. BACKGROUND ESTIMATION

The main backgrounds in this analysis are due to $W+$jets and $t\bar{t}$ processes, with additional backgrounds from single-top-quark, nonelectroweak diboson, $Z+$jets, and multijet events. All background predictions are taken from MC simulation, except for the multijet background, which uses a data-driven prediction, and the $W+$jets background, which uses a MC prediction to which a data-driven scale factor is applied, as explained below.

About half of the background events in this analysis are from $W+$jets production. Its modeling is checked using a control region ("loose $W+$jets CR") defined using the "loose VBS" selection criteria, except that the $m(V_{\mathrm{had}})$

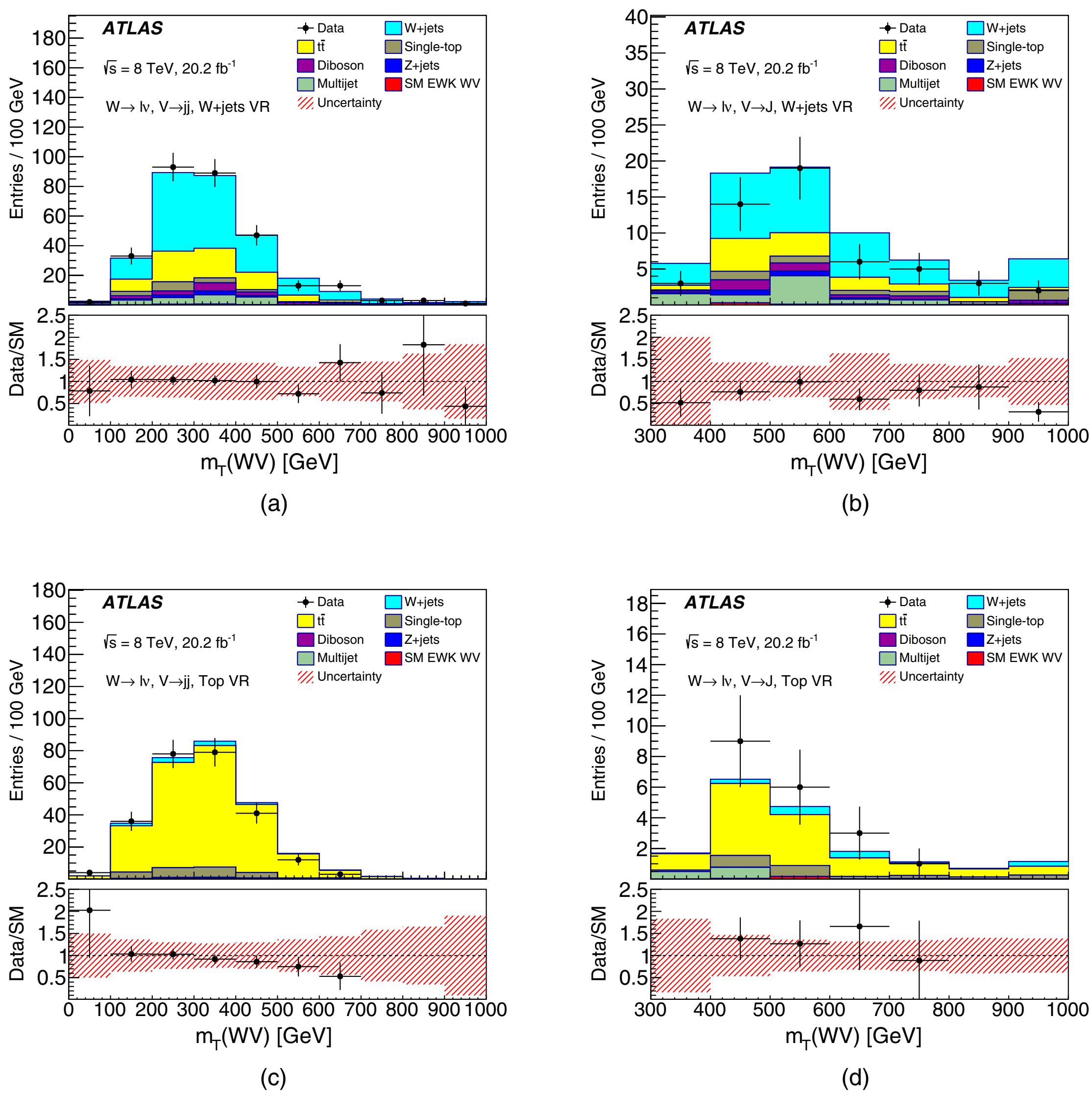

FIG. 2. The top row shows the observed $m_{\mathrm{T}}(WV)$ distribution in the $W+$jets validation region (VR), overlaid with the background prediction, for (a) the resolved ($V \to$ jj) region, e^+, e^-, μ^+, and μ^- combined; and (b) the merged ($V \to$ J) region, e^+, e^-, μ^+, and μ^- combined. The bottom row shows the observed $m_{\mathrm{T}}(WV)$ distribution in the top-production VR, again overlaid with the background prediction, for (c) the resolved region, e^+, e^-, μ^+, and μ^- combined; and (d) the merged region, e^+, e^-, μ^+, and μ^- combined. The last bin includes overflow.

selection is inverted: $36 < m(V_{\mathrm{had}}) < 64$ GeV or $m(V_{\mathrm{had}}) > 96$ GeV for the resolved selection, and $40 < m(V_{\mathrm{had}}) < 64$ GeV or $m(V_{\mathrm{had}}) > 96$ GeV for the merged selection. The background prediction is larger than the data in this region, which is attributed to an overestimate of the $W+\mathrm{jets}$ background by the MC simulation. An average scale factor of 0.82 is derived for $W+\mathrm{jets}$ from this region, after subtracting the predictions for non-$W+\mathrm{jets}$ events. This constant scale factor is applied to the $W+\mathrm{jets}$ prediction in all three event categories. The $W+\mathrm{jets}$ modeling is cross-checked in a validation region ("$W+\mathrm{jets}$ VR") defined using the same selection as the signal region, except inverting the $m(V_{\mathrm{had}})$ selection. The modeling of $m_{\mathrm{T}}(WV)$ in this validation region is shown in Figs. 2(a) and 2(b). The largest systematic uncertainties in the $W+\mathrm{jets}$ VR are jet uncertainties and uncertainties in the modeling of the $W+\mathrm{jets}$ process, which are described in Sec. VII.

Top-pair and single-top-quark production are the other major backgrounds in this analysis. Their modeling is checked in a validation region ("top VR") that uses the same selection as the signal region, except that the requirements on the number of b-tagged jets are inverted. The definition of a b-tagged jet is tightened for the top VR; the MV1 algorithm is used with a b-tag efficiency of 60%. The data–MC comparison in the top VR is shown in Figs. (2c) and 2(d). The largest systematic uncertainties in the top VR are jet uncertainties and uncertainties in the modeling of the $t\bar{t}$ process. In both the $W+\mathrm{jets}$ VR and top VR, the predicted event yields and $m_{\mathrm{T}}(WV)$ distribution shapes are consistent with those observed in data, within the systematic uncertainties.

Multijet processes are a fairly small background in this analysis. They can pass the event selection if a lepton from the decay of a heavy-flavor hadron passes the lepton selection. In the electron channel, multijet events can also contribute due to jets misreconstructed as electrons. They are modeled using a data-driven estimate as described below.

First, control regions are defined by event selections similar to those for the signal regions, but with modified lepton identification criteria, in order to enrich the control regions in multijet backgrounds. Leptons that satisfy the modified identification criteria are referred to as "bad" leptons. For the muon channel, the impact-parameter criterion is inverted: $|d_0|/\sigma_{d_0} > 3$. For the electron channel, the electron candidate must fail the "tight" cut-based identification but satisfy the "medium" cut-based identification criteria from Ref. [60]. In addition, for both the electron and muon channels, the isolation criteria are modified: $R_{\mathrm{cal}}^{\mathrm{iso}} > 0.04$ and $R_{\mathrm{ID}}^{\mathrm{iso}} < 0.5$. The shapes of the kinematic distributions [$m_{\mathrm{T}}(WV)$, $p_{\mathrm{T}}(W_{\mathrm{lep}})$, $E_{\mathrm{T}}^{\mathrm{miss}}$] of the multijet background are obtained from the data in these control regions, after subtracting the MC predictions for the nonmultijet backgrounds.

TABLE I. The expected number of events passing the final event selection, together with the number of events observed in data. The expected EWK WV contributions for a representative point in the aQGC parameter space ($\alpha_4 = 0.1$, $\alpha_5 = 0$) and for the SM ($\alpha_4 = \alpha_5 = 0$) are shown for comparison. The quoted errors include all systematic uncertainties in the expected yields. The error in the total background is computed including correlations between the various background components.

	Resolved channel		Merged channel
	e^+ and μ^+	e^- and μ^-	e and μ
$W+\mathrm{jets}$	92 ± 37	51 ± 29	19.4 ± 9.9
$t\bar{t}$	59 ± 18	63 ± 35	6.8 ± 2.8
Single-top	10.0 ± 5.6	5.5 ± 3.2	2.2 ± 1.2
Diboson	8.6 ± 5.7	10.8 ± 6.4	1.6 ± 1.2
$Z+\mathrm{jets}$	4.5 ± 1.5	3.4 ± 2.4	0.58 ± 0.64
Multijet	16 ± 16	12 ± 12	1.8 ± 1.9
Total background	190 ± 53	145 ± 54	32 ± 12
EWK WV (SM)	3.66 ± 0.82	2.34 ± 0.56	0.54 ± 0.22
EWK WV ($\alpha_4 = 0.1$, $\alpha_5 = 0$)	21.0 ± 4.2	9.2 ± 1.9	15.1 ± 4.4
Data	173	131	32

The multijet event yield is estimated by first performing a fit to the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution of the data that pass the final event selection, but with the $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV and $p_{\mathrm{T}}(W_{\mathrm{lep}}) > 150$ GeV criteria removed. The final multijet yield estimate is then obtained by scaling this fit result by the efficiency for multijet events to pass the $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV and $p_{\mathrm{T}}(W_{\mathrm{lep}}) > 150$ GeV requirements. That efficiency is also estimated from a bad-lepton control region. The multijet estimate was cross-checked with an alternative method that first applies the $p_{\mathrm{T}}(W_{\mathrm{lep}}) > 150$ GeV selection, and then obtains the multijet yield from a fit to the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution.

Remaining backgrounds originate from $Z+\mathrm{jets}$ and diboson processes, and are estimated with MC samples. The final estimates for all backgrounds are given in Table I, along with the expected signal.

The background modeling is further cross-checked in Fig. 3, which shows data–MC comparisons of the $p_{\mathrm{T}}(W_{\mathrm{lep}})$ and boson centrality distributions. In these plots, all of the signal-region selection criteria are applied, except for the selection criterion for the variable [$p_{\mathrm{T}}(W_{\mathrm{lep}})$ or boson centrality] being plotted. The data agree with the predictions within the systematic uncertainty bands.

VII. SYSTEMATIC UNCERTAINTIES

A variety of sources of systematic uncertainty are considered. The effect of systematic uncertainties in the background and signal rates, and in the shape of the $m_{\mathrm{T}}(WV)$ distribution of background and signal events, are accounted for.

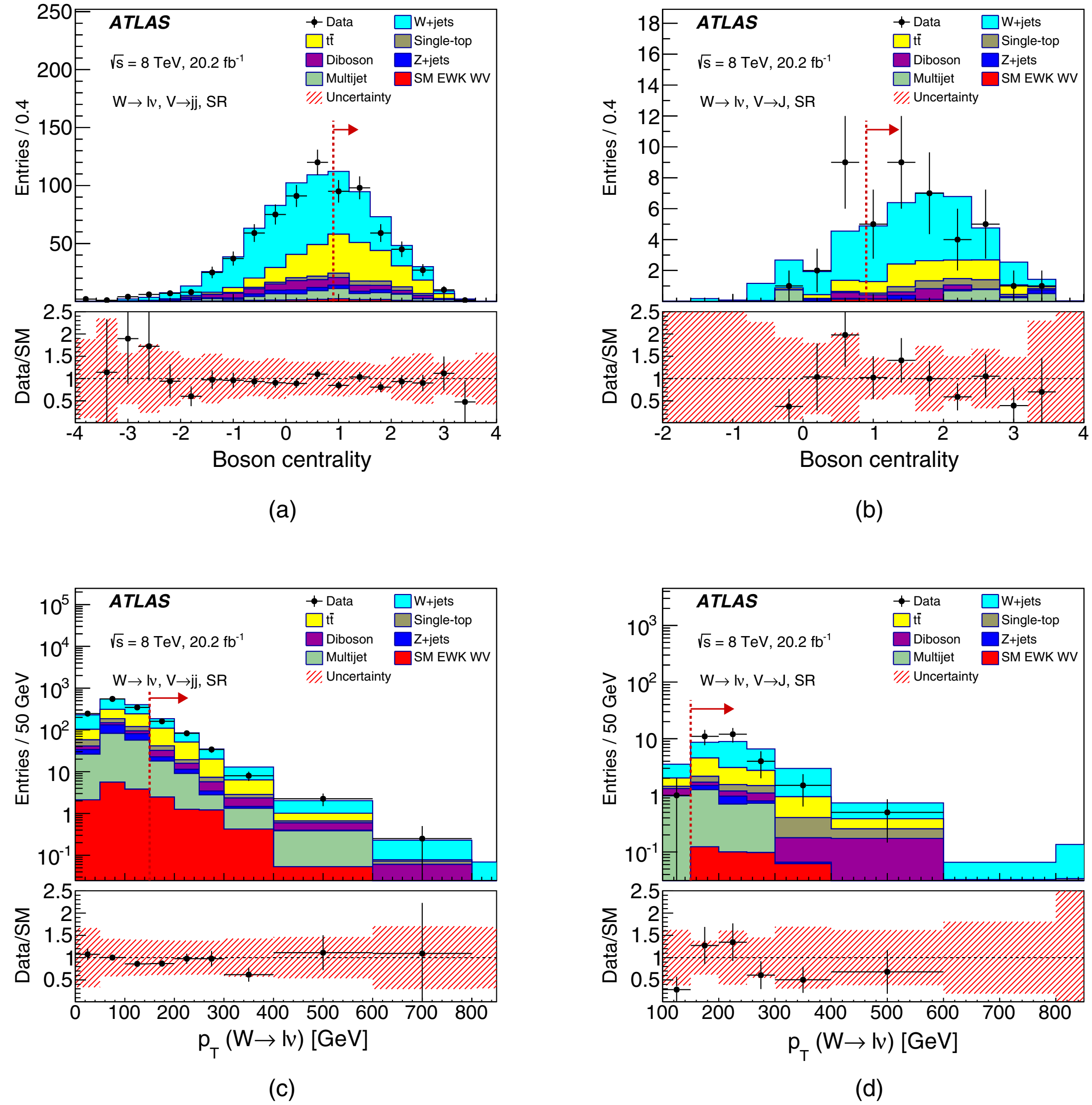

FIG. 3. The observed boson centrality (top) and $p_{\mathrm{T}}(W_{\mathrm{lep}})$ (bottom) distributions, compared to the SM prediction. Plots (a) and (c) show the resolved ($V \to \mathrm{jj}$) signal region (SR), and plots (b) and (d) show the merged ($V \to \mathrm{J}$) signal region, except that the $\zeta_V > 0.9$ requirement is not applied for the boson centrality plots, and the $p_{\mathrm{T}}(W_{\mathrm{lep}}) > 150$ GeV requirement is not applied for the $p_{\mathrm{T}}(W_{\mathrm{lep}})$ plots. The red vertical lines and arrows indicate the signal region selection. The last bin includes overflow.

Systematic uncertainties in the jet energy scale (JES) and jet energy resolution (JER) are calculated separately for small-R [69,70] and large-R jets. For the large-R jets, uncertainties in the jet mass scale and jet mass resolution are included and account for uncertainty in the modeling of the jet substructure. The large-R jet energy and mass scale uncertainties are derived from ratios of calorimeter-jets to track-jets and from $\gamma +$ jet balance studies. The large-R jet energy and mass resolution uncertainties are estimated by applying a smearing factor so that the resolutions increase by a factor of 20%; this uncertainty is based on previous studies of large-R jets [71,72]. The jet-related uncertainties are the most significant detector-related uncertainties in the analysis.

Uncertainties in lepton reconstruction and identification, soft terms entering the $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation, and b-tagging are accounted for and have a minor effect. The uncertainty in the integrated luminosity is also included [23].

Systematic uncertainties in the signal model are taken into account, including variations in the model of fragmentation, parton shower, and hadronization; factorization and renormalization scales; and the PDFs. Uncertainties in the $W/Z +$ jets background model are accounted for by varying the factorization and renormalization scales, and the scale for matching matrix elements to parton showers [30]. The full difference between the data-driven $W +$ jets scale factor and 1.00 is also included as an uncertainty: 0.82 ± 0.18; this scale factor is varied independently in each of the three event categories. Uncertainties in the $t\bar{t}$ modeling are estimated by varying the matrix-element generator, the fragmentation/parton-shower/hadronization

TABLE II. Summary of the fractional uncertainty in the total background yields in the signal region, broken down into different categories of systematic uncertainties.

	Fractional uncertainty	
Source	*Resolved*	*Merged*
$W/Z+$jets modeling	0.13	0.29
$t\bar{t}$ modeling	0.14	0.07
Multijet yield	0.06	0.05
Minor background yields	0.04	0.05
Jet reconstruction	0.21	0.17
Other detector/luminosity	0.04	0.03
Limited stats in MC or CR	0.02	0.06
Total	0.29	0.36

model, and the amount of initial-state and final-state radiation. A 100% uncertainty is applied to the multijet background prediction, and covers uncertainties in the data-driven estimation procedure. For the single-top-quark, diboson, and electroweak $W+$jets predictions, instead of computing separate modeling uncertainties from individual sources, an overall normalization uncertainty of 50% is applied, which is taken as an estimate of their modeling uncertainties based on studies of other background processes. The uncertainties in the multijet, single-top-quark, diboson, and electroweak $W+$jets backgrounds only increase the overall background uncertainty by about 2%–3%.

There is also a statistical uncertainty in the expected number of background and signal in each bin of $m_{\mathrm{T}}(WV)$,

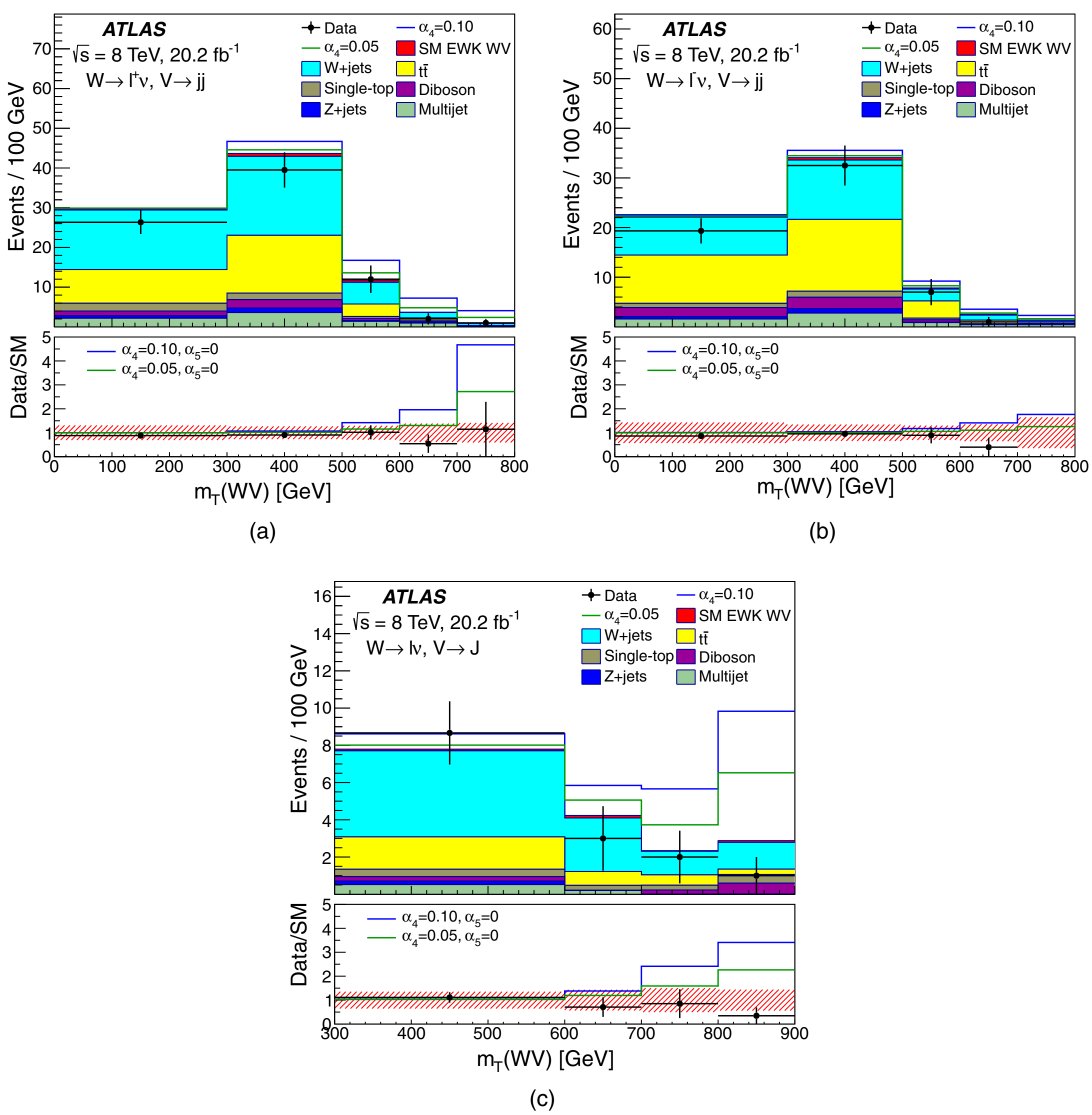

FIG. 4. The observed $m_{\mathrm{T}}(WV)$ distribution, overlaid with background and EWK WV prediction, after applying the full selection. The expected enhancements due to aQGC values of ($\alpha_4 = 0.1$, $\alpha_5 = 0$) and ($\alpha_4 = 0.05$, $\alpha_5 = 0$) are also shown. The plotted regions are (a) the resolved ($V \to$ jj) region, e^+ and μ^+ combined; (b) the resolved region, e^- and μ^- combined; and (c) the merged ($V \to$ J) region, e^+, e^-, μ^+, and μ^- combined. The last bin includes overflow.

TABLE III. The observed and expected lower and upper limits of the 95% confidence intervals for α_4 and α_5. The $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands on the expected lower and upper limits are also shown for comparison. The α_4 confidence intervals are computed while fixing α_5 to zero, and vice versa.

	Expected	Expected $\pm 1\sigma$	Expected $\pm 2\sigma$	Observed
lower limit, α_4	−0.060	[−0.11, −0.030]	[−0.26, −0.015]	−0.024
upper limit, α_4	0.062	[0.034, 0.091]	[0.018, 0.20]	0.030
lower limit, α_5	−0.084	[−0.15, −0.034]	[−0.24, −0.018]	−0.028
upper limit, α_5	0.080	[0.039, 0.13]	[0.024, 0.23]	0.033

due to the size of the MC samples and the numbers of events in the multijet control regions.

The uncertainties in the total background are dominated by jet uncertainties and $W/Z+\text{jets}$ modeling, and are summarized in Table II. The uncertainty in the signal yield is about 20% (30%) in the resolved (merged) categories and is dominated by the signal model variations and the jet uncertainties.

VIII. RESULTS

A search for aQGC contributions is performed by examining the $m_{\mathrm{T}}(WV)$ distribution of events that satisfy the full selection. The $m_{\mathrm{T}}(WV)$ distribution of events is shown in Fig. 4, split up into the three categories defined in Sec. V. The enhancements of EWK WV expected for different aQGC values are shown for comparison. No evidence of an aQGC is observed in the data, so the allowed 95% confidence intervals are computed for the aQGC parameters α_4 and α_5.

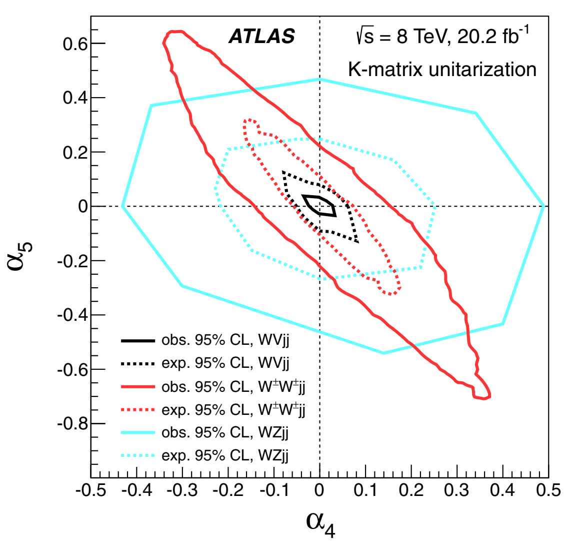

FIG. 5. The observed 2D confidence region (solid black contour) for α_4 and α_5, at 95% CL. The expected 2D confidence region (dotted black contour) is also shown, computed using the Asimov data set [73]. Results from this analysis (in black) are compared to observed and expected confidence regions from previous ATLAS analyses of $W^{\pm}W^{\pm}$ [17] (in red) and WZ [6] (in cyan) VBS production.

The confidence intervals on α_4 and α_5 are calculated by using a binned profile-likelihood [73] fit to the $m_{\mathrm{T}}(WV)$ distribution in the three event categories. Systematic uncertainties are incorporated into the fit using 28 nuisance parameters. The frequentist 95% confidence level (CL) intervals are computed using pseudoexperiments. For each aQGC point, the ratio of the likelihood to the likelihood of the best-fit aQGC point is calculated. An aQGC point is excluded at 95% CL if at least 95% of the random pseudoexperiments have a profile-likelihood ratio greater than the observed one. At 95% CL, the observed confidence intervals are $-0.024 < \alpha_4 < 0.030$ and $-0.028 < \alpha_5 < 0.033$, where the confidence interval on each parameter is calculated while fixing the other parameter to zero. The expected 95% confidence intervals are $-0.060 < \alpha_4 < 0.062$ and $-0.084 < \alpha_5 < 0.080$. The observed confidence intervals are stronger than expected; under the SM hypothesis, there is a 12%–15% probability of obtaining confidence intervals more stringent than the observed ones. The expected and observed confidence intervals are summarized in Table III. This table also shows the 1− and 2−sigma uncertainty bands on the expected confidence intervals. These uncertainty bands show that the measured confidence intervals can vary significantly from pseudoexperiment to pseudoexperiment; this behavior is expected since most of the sensitivity to the aQGC parameters comes from high-$m_{\mathrm{T}}(WV)$ bins with few events and large uncertainties. The two-dimensional (2D) confidence region for α_4 and α_5 is shown in Fig. 5. The observed α_4 and α_5 confidence intervals are more stringent than existing confidence intervals for these parameters, which are obtained from VBS $W^{\pm}W^{\pm} \to \ell\nu\ell\nu$ [17] and $WZ \to \ell\nu\ell\ell$ [6] measurements from ATLAS.

The use of the "merged" category of events significantly improves the aQGC sensitivity of the analysis because most of the aQGC sensitivity comes from the highest-$m_{\mathrm{T}}(WV)$ bins, where the merged category is powerful. The expected aQGC confidence intervals are about 40% more stringent when including this category than when only using the resolved events.

IX. CONCLUSIONS

A search is performed for anomalous quartic gauge couplings in WW and WZ production via vector-boson scattering. The analysis is performed with 20.2 fb^{-1} of ATLAS data from $\sqrt{s} = 8$ TeV pp collisions at the LHC.

The search is based on a signature of $W(\ell\nu)V(qq')$ plus two jets with a high dijet invariant mass. The $V(qq')$ system is reconstructed either as two separate jets or as a single, large-radius jet, making use of jet substructure techniques. A search phase space is used that is designed to be particularly sensitive to aQGCs and is based on event topology, the V decay angle, and high transverse momentum.

No excess is seen in the data, and so limits are placed on aQGC parameters by fitting the diboson transverse-mass distribution. At 95% CL, the observed limits are $-0.024 < \alpha_4 < 0.030$ and $-0.028 < \alpha_5 < 0.033$. These limits are more stringent than the previous constraints on these parameters, obtained in searches for vector-boson scattering in the $W^{\pm}W^{\pm} \to \ell\nu\ell\nu$ and $WZ \to \ell\nu\ell\ell$ channels. This result demonstrates that a semileptonic channel can have strong experimental sensitivity to new physics contributions to vector-boson scattering.

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