Search for Dark Matter Produced in Association with a Dark Higgs Boson Decaying into $W^{\pm}W^{\mp}$ or ZZ in Fully Hadronic Final States from $\sqrt{s} = 13$ TeV pp Collisions Recorded with the ATLAS Detector

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Several extensions of the Standard Model predict the production of dark matter particles at the LHC. An uncharted signature of dark matter particles produced in association with $VV = W^{\pm}W^{\mp}$ or ZZ pairs from a decay of a dark Higgs boson s is searched for using 139 fb^{-1} of pp collisions recorded by the ATLAS detector at a center-of-mass energy of 13 TeV. The $s \to V(q\bar{q})V(q\bar{q})$ decays are reconstructed with a novel technique aimed at resolving the dense topology from boosted VV pairs using jets in the calorimeter and tracking information. Dark Higgs scenarios with $m_s > 160$ GeV are excluded.

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Overwhelming astrophysical evidence [1–4] suggests the existence of dark matter (DM). DM cannot be accounted for within the Standard Model (SM) and its nature is one of the major questions in physics. Several extensions of the SM postulate stable, electrically neutral, weakly interacting massive particles (χ) [4] as DM candidates that can potentially be produced in high-energy collisions at the CERN LHC. Once produced, χ would escape detection, producing an imbalance in the measured transverse momentum [5], resulting in missing transverse momentum $\boldsymbol{p}_T^{\mathrm{miss}}$ (with magnitude $\boldsymbol{E}_T^{\mathrm{miss}}$). A wide class of models probed at the LHC postulate processes where one or more SM particles X are produced recoiling against χ, resulting in an "$X + \boldsymbol{E}_T^{\mathrm{miss}}$" signature. Searches at the LHC have considered X to be a hadronic jet [6,7], top or bottom quarks [8–11], a photon [12,13], a W or Z boson [14–16], or a Higgs boson [17–19].

This Letter presents a pioneering search for DM using the $X + \boldsymbol{E}_T^{\mathrm{miss}}$ signature where X is a hypothetical particle that decays into a vector-boson pair $VV = W^+W^-$ or ZZ. This signature was not explored for large $\boldsymbol{E}_T^{\mathrm{miss}}$ and resonant VV production with an invariant mass $m_{VV} > 160$ GeV. The signal region (SR) requires large $\boldsymbol{E}_T^{\mathrm{miss}}$ from DM particles and targets the $VV \to q\bar{q}q\bar{q}$ decay, which has the largest branching ratio $\mathcal{B}$. The background is dominated by vector-boson production in association with jets, referred to as $V + \mathrm{jets}$. The analysis employs control regions (CRs) requiring either a single muon (μ) or a pair of leptons $\ell^{\pm}\ell^{\mp}$ ($\ell = e, \mu$) in the final state to improve background modeling in the SR.

The discovery of a new boson with SM Higgs properties [20–22] confirmed the mechanism for electroweak symmetry breaking [23–28] and the generation of mass for SM particles. This success motivates a similar mechanism in the dark sector that contains the DM particle, where χ obtains mass via its Yukawa interactions with a dark Higgs boson s [29]. Furthermore, s alleviates the strict constraints from the observed DM relic density [30] by opening up a new annihilation channel into SM particles, when s, rather than χ, is the lightest state in the dark sector.

A two-mediator-based DM model [31] containing a new $U(1)'$ gauge symmetry, which yields an additional massive spin-1 vector Z' boson via the new scalar boson s, is used for the optimization and interpretation of the search presented in this Letter. The relevant model parameters are the Majorana DM particle mass m_χ, the Z' mass $m_{Z'}$, the dark Higgs mass m_s, and the Z' couplings g_q to quarks and g_χ to DM particles. The Born-level Feynman diagrams for the process are shown in Fig. 1. The $s + \chi\chi$ signal is produced through $q\bar{q} \to Z' \to s\chi\chi$, requiring an off-shell

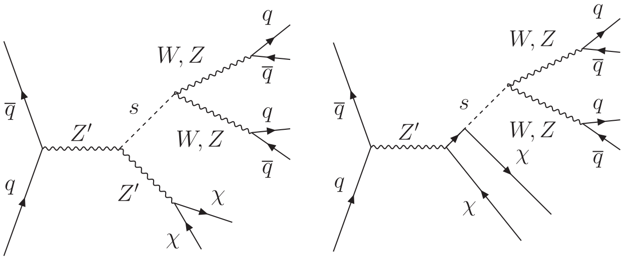

FIG. 1. Born-level Feynman diagrams for the $q\bar{q} \to Z' \to s\chi\chi$, $s \to V(q\bar{q})V(q\bar{q})$ process. The left diagram typically dominates.

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intermediate state such as a Z' or χ. The $s \to W^{\pm}W^{\mp}$ and $s \to ZZ$ processes become relevant for $m_s \gtrsim 160$ GeV and $m_s \gtrsim 180$ GeV, respectively [32]. The proposed framework shares similarities with previously explored spin-1 simplified DM models [33–37], with s being the only addition and χ being a Majorana rather than a Dirac fermion. Within this framework, searches for spin-1 mediators provide complementary sensitivity [38].

The search is performed using 139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector [39,40] in 2015–2018. Events in the SR and the single-muon CR were collected by triggering on $\boldsymbol{E}_T^{\text{miss}}$ reconstructed from calorimeter information [41] above a threshold that varied from 90 to 110 GeV. Events in the dilepton CR were recorded using single-lepton triggers with transverse momentum (p_T) thresholds of 24 GeV and higher, depending on the data-taking period, for electrons and muons.

SM background processes and the $s + \chi\chi$ signal were simulated using Monte Carlo (MC) event generators, except the multijet background, which is found to be negligible using a data-driven method. A detailed simulation of the ATLAS detector [42] based on GEANT4 [43] was used to simulate the detector response for all MC event samples. Contributions from additional pp interactions (pileup) were simulated with PYTHIA 8.186 [44] using the NNPDF23 LO (leading order) parton distribution function (PDF) set [45] and corrected to match data. Parton shower simulations with PYTHIA use the A14 set of tuned parameters [46] with the NNPDF23 LO PDF set.

Signal samples for the $pp \to Z' \to s\chi\chi \to VV\chi\chi \to q\bar{q}q\bar{q}\chi\chi$ process were generated at LO in QCD with up to one additional parton in the event, using MadGraph5_aMC@NLO 2.6.2 [47] interfaced to PYTHIA 8.230, both using the NNPDF23 LO PDF set. Samples were generated in the $(m_{Z'}, m_s)$ plane for $m_{Z'} = 0.5, 1, 1.7, 2.5$ TeV and in steps of 25 GeV for $160 < m_s/\text{GeV} < 360$, with $m_\chi = 200$ GeV to avoid $s \to \chi\chi$ decays. Other parameters were chosen as $g_\chi = 1.0$, $g_q = 0.25$ [36,37], and $\sin\theta = 0.01$, where θ is the mixing angle between SM and dark Higgs bosons [29], set to a small value [48].

The $V +$ jets processes were simulated with SHERPA 2.2.1 [49], including mass effects for b- and c-quarks and using NNPDF3.0 PDFs [50]. The perturbative calculations for $V +$ jets were performed at next-to-leading order (NLO) in QCD for up to two partons and at LO for up to four partons [51,52], and matched to the parton shower [53] using the ME + PS@NLO prescription [54]. The $V +$ jets samples are normalized using calculations at next-to-next-to-leading order (NNLO) in QCD [55]. Backgrounds from top quark pair ($t\bar{t}$) production and single top quark production were generated at NLO in QCD with POWHEG-BOX [56–59] v2 using the NNPDF3.0 NLO PDF set, interfaced to PYTHIA 8.230 for parton showering and hadronization. The $t\bar{t}$ samples are normalized using calculations at NNLO in QCD including next-to-next-to-leading logarithmic corrections for soft-gluon radiation [60–66]. The single-top-quark processes are normalized to cross sections at NLO in QCD from Hathor v2.1 [67,68]. Diboson (VV) samples were simulated with SHERPA 2.2.1 at NLO in QCD and normalized using calculations at NNLO in QCD using NNPDF3.0 NNLO PDFs. Backgrounds from associated VH production were generated at NLO in QCD with POWHEG-BOX interfaced to PYTHIA 8.186 using NNPDF3.0 NLO PDFs. The $qq \to VH$ and $gg \to VH$ processes were normalized using calculations at NNLO in QCD and at NLO in QCD combined with next-to-leading-logarithmic order corrections, respectively.

At least one pp collision vertex reconstructed from at least two inner detector (ID) tracks with $p_T^{\text{track}} > 0.5$ GeV is required in the event. The vertex with the highest $\sum(p_T^{\text{track}})^2$ in the event is designated the primary vertex (PV). The ID tracks must have at least seven hits and satisfy $p_T > 0.5$ GeV and $|\eta| < 2.5$ requirements [69,70]. Their transverse and longitudinal impact parameters relative to the PV must satisfy $|\text{d}_0| < 2$ mm and $|z_0 \sin(\theta)| < 3$ mm, respectively.

Muons are reconstructed by matching a track or track segment found in the muon spectrometer to an ID track. Muons must satisfy "medium" or "loose" requirements [71] such that medium (loose) muons must have $|\eta| < 2.5(2.7)$. Electrons are reconstructed by matching a cluster of energy in the calorimeter to an ID track. Electron candidates are identified using a likelihood-based method [72] and must satisfy the loose requirement and have $|\eta| < 2.47$. Electrons and muons must be isolated according to the track proximity criteria in Ref. [73]. Hadronic τ-lepton decays are identified by an algorithm based on a boosted decision tree [74].

Jets are formed from three-dimensional clusters of calorimeter cells with the anti-k_t algorithm [75,76]. Small-R jets use a radius parameter $R = 0.4$ and are referred to as "central" if they satisfy $|\eta| < 2.5$ and $p_T > 20$ GeV and "forward" if they fulfill $2.5 < |\eta| < 4.5$ and $p_T > 30$ GeV. Corrections for pileup [77] and the energy scale and resolution [78] are applied to small-R jets. In addition, central small-R jets with $20 < p_T/\text{GeV} < 60$ and $|\eta| < 2.4$ are identified as originating from the PV using associated tracks [79]. Small-R jets closer than $\Delta R = 0.2$ to an e, μ, or hadronic τ-decay candidate are rejected.

To better reconstruct the challenging multiprong $s \to V(q\bar{q})V(q\bar{q})$ decay, the novel track-assisted reclustering (TAR) algorithm [80] is used. This technique improves the resolution of jet substructure observables by considering both tracking and calorimeter information, combined with the flexibility of jet reclustering. The TAR jets are formed from small-R jets reclustered into larger jets with $R = 0.8$ using trimming parameters optimized for ATLAS [81]. The mass and other substructure observables of TAR jets are reconstructed using ID tracks. For this, ID tracks are first matched to the small-R jets that constitute the $R = 0.8$ jets.

Subsequently, the p_T of tracks matched to a given small-R jet are rescaled such that their sum equals the p_T of that jet, in order to compensate for the neutral jet components missed by the tracker [80]. The TAR algorithm is estimated to improve the sensitivity of the search by a factor of up to 2.5 in expected median discovery significance compared to the conventional large-R jet approach [82], neglecting systematic uncertainties.

In order to suppress contributions from background processes that involve top quarks, which decay almost exclusively to b-quarks, a multivariate algorithm is used to identify jets containing b-hadrons (b-tagging) with an efficiency of 77% [83]. The algorithm is applied to variable-radius track jets with $p_T > 10$ GeV and $|\eta| < 2.5$ formed from ID tracks using the anti-k_t algorithm [84] and a p_T-dependent radius parameter.

The $\boldsymbol{p}_T^{\mathrm{miss}}$ vector is computed as the negative vector sum of the transverse momenta of the e, μ, and small-R jet candidates in the event. The transverse momenta not associated with any e, μ, or jet candidates are accounted for using ID tracks [85]. In addition, an $\boldsymbol{E}_T^{\mathrm{miss}}$ significance $\mathcal{S}$ is computed from the expected resolutions for all the objects used in the $\boldsymbol{E}_T^{\mathrm{miss}}$ calculation [86] and is used to reject multijet background processes.

The signal is characterized by high $\boldsymbol{E}_T^{\mathrm{miss}}$ from DM particles, and substantial hadronic activity from $s \to V(q\bar{q})V(q\bar{q})$ decays that results in an invariant mass consistent with m_s. Thus, the SR requires $\boldsymbol{E}_T^{\mathrm{miss}} > 200$ GeV, no isolated e or μ, no τ lepton decays, and two or more small-R jets. Events in the SR are rejected if a loose electron or muon with $p_T > 7$ GeV is present. In addition, events in the SR and CRs are not considered if they contain hadronic τ-decay candidates with $p_T > 20$ GeV within $|\eta| < 2.5$. The smallest azimuthal angle between the $\boldsymbol{E}_T^{\mathrm{miss}}$ and any of the three highest-p_T (leading) small-R jets is required to be at least $\pi/9$ in order to reduce the multijet background arising from mismeasured jet momenta. This background is further suppressed by requiring $\mathcal{S} > 15$.

The $t\bar{t}$ and diboson processes contribute 1%–7% and 2%–8% of the background in the SR, respectively, while the dominant SM $Z(\nu\nu) + \mathrm{jets}$ and $W(\ell\nu) + \mathrm{jets}$ processes contribute 59%–73% and 15%–32%, respectively, depending on the topology. The modeling of $V + \mathrm{jets}$ is improved using two CRs: the single-muon CR (1μ-CR) enriched in $W + \mathrm{jets}$ and the two-lepton CR (2ℓ-CR) enriched in $Z + \mathrm{jets}$. The 1μ-CR follows the same selection as the SR, except that events must contain exactly one medium muon with $p_T > 27$ GeV and no loose electrons with $p_T > 7$ GeV. Events in the 2ℓ-CR are selected using the same requirements as the SR, except that events must contain exactly two loose electrons or two oppositely charged medium muons and satisfy $\mathcal{S} < 15$. The leading lepton must fulfill $p_T > 27(25)$ GeV for electrons (muons), while for the subleading one $p_T > 7$ GeV is required. The dilepton system is required to be consistent with an energetic Z boson, i.e., $p_T^{\ell\ell} > 200$ GeV and $83 < m_{\ell\ell}/\mathrm{GeV} < 99$.

In order to optimize the sensitivity over a broad VV-pair momentum range, two selection categories, merged and intermediate, are defined. For large s momenta, the dark Higgs boson's decay products become collimated and are reconstructed inside a single TAR jet. These topologies are targeted in the merged category, defined as containing at least one TAR jet with $p_T^{\mathrm{TAR}} > 300$ GeV, and mass m^{TAR} between 100 and 400 GeV. TAR jet substructure variables are employed to discriminate between the four-prong topology of $s \to V(q\bar{q})V(q\bar{q})$ decays and backgrounds with lower multiplicities. This is done using combinations of N-subjettiness [87] variables τ_N by requiring $0 < \tau_4/\tau_2 < 0.3$ and $0 < \tau_4/\tau_3 < 0.6$, which were also experimentally studied in Ref. [88]. The s-candidate mass is identified with m^{TAR}. The merged category dominates the sensitivity, and the product of acceptance and selection efficiency for $\sigma(pp \to s\chi\chi) \times \mathcal{B}(s \to VV)$ lies around 1%.

Moderate s-candidate momenta result in less-collimated decay products, which may not be captured by the nominal TAR jet. In such cases, events failing the merged-category requirements are considered in the intermediate category, where the s candidate is reconstructed from a TAR jet with $m^{\mathrm{TAR}} > 60$ GeV that is supplemented by up to two additional small-R jets within $\Delta R = 2.5$ of the TAR jet. If the mass of the TAR jet is compatible with m_W, i.e., $60 < m^{\mathrm{TAR}}/\mathrm{GeV} < 100$, the TAR jet is supplemented with the two small-R jets whose combined invariant mass is closest to m_W. If $m^{\mathrm{TAR}} > 100$ GeV, it is assumed that only one prong of the s decay was not reconstructed within the TAR jet, and thus it is supplemented with exactly one small-R jet. The s-candidate mass is required to lie between 100 and 400 GeV. The product of acceptance and selection efficiency for $\sigma(pp \to s\chi\chi) \times \mathcal{B}(s \to VV)$ ranges between 10% and 20%.

To account for changes in the background composition and benefit from increased signal sensitivity with higher $\boldsymbol{E}_T^{\mathrm{miss}}$, events in the merged category are further classified into ranges in $\boldsymbol{E}_T^{\mathrm{miss}}/\mathrm{GeV}$: [300, 500] and $[500, \infty)$. The range $[200, \infty)$ is used in the intermediate category. The same ranges are defined consistently in the 1μ-CR and the 2ℓ-CR. To ensure kinematic similarity to the $\boldsymbol{p}_T^{\mathrm{miss}}$ arising from the $V + \mathrm{jets}$ in the SR, $\boldsymbol{p}_T^{\mathrm{miss,no}\mu} = \boldsymbol{p}_T^{\mathrm{miss}} + \boldsymbol{p}_T^{\mu}$, which corresponds to the p_T carried by the W boson, is used in the 1μ-CR. Similarly, $\boldsymbol{p}_T^{\ell\ell}$ in the 2ℓ-CR corresponds to $\boldsymbol{p}_T^{\mathrm{miss}}$ in the SR.

The DM signal is extracted via a simultaneous maximum-likelihood fit [89,90] of signal and background simulations to the binned s-candidate mass distributions in the SR and to total yields in the CR categories. The normalizations of $W + \mathrm{jets}$ and $Z + \mathrm{jets}$ processes are free parameters in the fit and are constrained by the total event yields, summed over $\boldsymbol{E}_T^{\mathrm{miss}}$-bin and category, in the 1μ-CR and 2ℓ-CR. Experimental uncertainties related to the

TABLE I. Dominant sources of uncertainty for three dark Higgs scenarios after the fit to Asimov data generated from the expected values of the maximum-likelihood estimators including predicted signals with $m_{Z'} = 1$ TeV and m_s of (a) 160, (b) 235, and (c) 310 GeV. The uncertainty in the fitted signal yield relative to the theory prediction is presented. Total is the quadrature sum of statistical and total systematic uncertainties, which consider correlations.

	Uncertainty [%]		
Source of uncertainty	(a)	(b)	(c)
Signal modeling	11	10	10
$W+$jets modeling	9	21	14
$Z+$jets modeling	7	12	13
MC statistics	11	14	23
Jet energy scale	8	17	24
Jet energy resolution	11	18	15
Lepton reconstruction	8	9	5
Track reconstruction	6	7	5
Systematic uncertainty	30	42	55
Statistical uncertainty	16	25	50
Total uncertainty	34	49	74

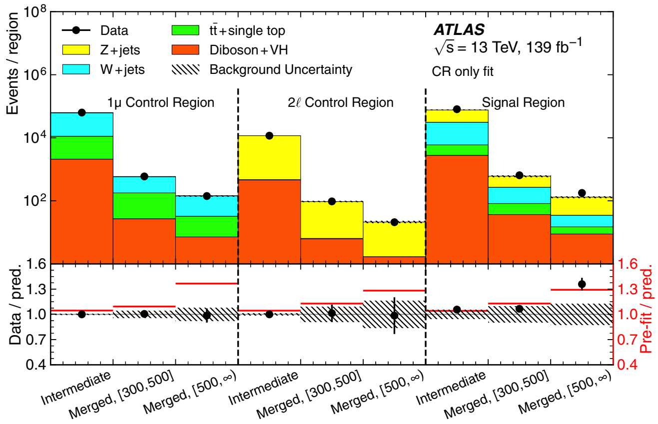
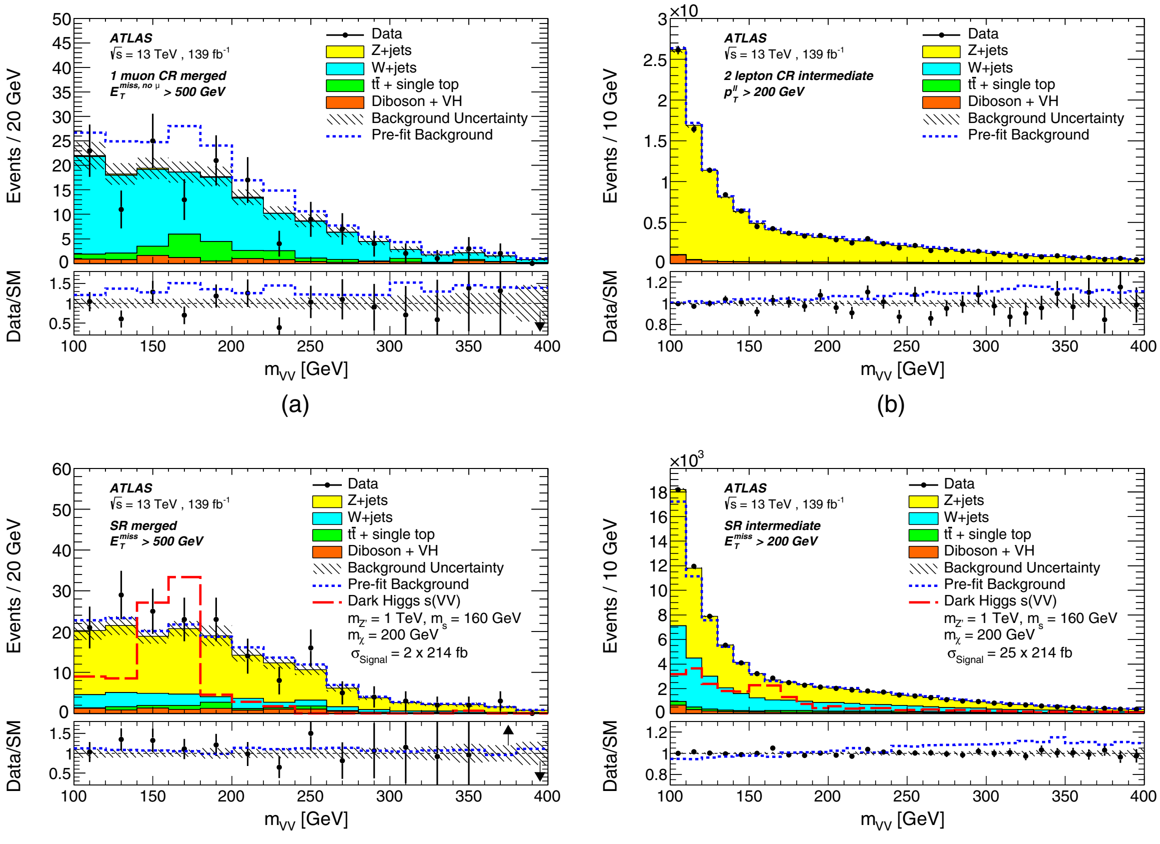


FIG. 2. Data overlaid on SM background postfit yields stacked in each SR and CR category and E_T^{miss} bin with the maximum-likelihood estimators set to the conditional values of the CR-only fit, and propagated to SR and CRs. The ratio of the data to SM expectations after the CR-only fit is shown in the lower panel, along with the red line representing the ratio of the prefit to the postfit background prediction. Prefit uncertainties cover differences between the data and prefit background prediction.

calibration of the scale and resolution of the jet energy [78] as well as to tracking efficiencies [70] affect the reconstruction of m_s using TAR jets. Other leading experimental systematic uncertainties arise from the finite number of MC events and the calibration of the lepton identification efficiencies [71,72]. Dominant theoretical systematic uncertainties originate from the modeling of the signal and the $W+$jets and $Z+$jets background processes. These encompass uncertainties from the choice of PDFs and factorization and normalization scales. In addition, to estimate the uncertainty from the choice of matrix element and parton shower generator for $W+$jets and $Z+$jets, alternative MC samples generated with MadGraph5_aMC@NLO 2.6.2 at LO in QCD with up to four parton emissions using the NNPDF23 LO PDF set and interfaced to PYTHIA 8.230 using a merging scale of $Q_{\mathrm{cut}} = 30$ GeV are considered. All other systematic uncertainties are estimated similarly to Ref. [17], except for the $t\bar{t}$ normalization, for which theoretical uncertainties [65] are considered. The systematic uncertainties, parametrized as nuisance parameters with Gaussian or log-normal prior probabilities, are profiled and used to constrain the template shapes and the normalizations varied in the fit [91]. Dominant uncertainties after the fit to Asimov data for three representative dark Higgs scenarios are quantified in Table I.

A first fit to the SM backgrounds is performed using only data from the CRs. The observed and fitted yields in the CR categories obtained after this fit are shown in Fig. 2. Also shown are the background yields predicted in the SR when using the observed parameter values from the CR-only fit. The fit reduces the MC-predicted $V+$jets contribution in the merged category. The overall yields in the CRs and the SR are found to be well described by SM simulations. The normalization and the p_T^V dependence of both $W+$jets and $Z+$jets are consistent within uncertainties with SM predictions in the SR and CRs. Figure 3 shows the mass distributions m_{VV} of the s candidate in two representative SR categories and the two corresponding categories in the 1μ-CR, obtained after a simultaneous fit to the SR and the CRs under the hypothesis that only SM predictions are present. The data distributions agree well with MC simulations in the CRs, indicating that $V+$jets background processes reconstructed with the novel TAR algorithm are well modeled. The observed results in the SR indicate that the data are in general well described by SM predictions. A mild excess around $m_{VV} = 160$ GeV is observed, yielding a 2.3σ local significance and 1.3σ global significance when considering nine independent m_s hypotheses. The excess in the intermediate region is narrower than the experimental resolution for m_s.

Upper limits are set on the product of the $pp \to s\chi\chi$ production cross section and $\mathcal{B}(s \to VV)$, using a modified frequentist approach (CL$_s$) [92] with a test statistic based on the profile likelihood in the asymptotic approximation [93]. Exclusion contours in the ($m_{Z'}$, m_s) plane for the dark Higgs model are presented in Fig. 4 and exclude $m_{Z'}$ up to 1.8 TeV for $m_s = 210$ GeV at 95% confidence level (C.L.). The observed exclusion range in $m_{Z'}$ becomes narrower than expected at low m_s owing to the small excess in data near $m_{VV} = 160$ GeV discussed above. The merged SR provides the maximal sensitivity attained at low m_s and high $m_{Z'}$, while the intermediate SR provides complementary sensitivity.



(a) (b)

(c) (d)

FIG. 3. Distributions of the invariant mass of the dark Higgs boson candidates in the 1μ-CR and 2ℓ-CR (upper row) and in the SR (lower row) in two representative categories, after the fit to data. The upper panels compare the data with the SM expectation before and after the background-only fit. The lower panels display the ratio of data to SM expectations after the fit, with its systematic uncertainty. Also shown is the ratio of SM expectations before and after the fit. The expected signal, with a cross section of 214 fb, from a representative dark Higgs model with $g_q = 0.25$, $g_\chi = 1.0$, and $\sin\theta = 0.01$, is scaled for presentation purposes. No m_{VV} shape information in the CRs is considered in the fit. Prefit uncertainties cover differences between the data and prefit background prediction.

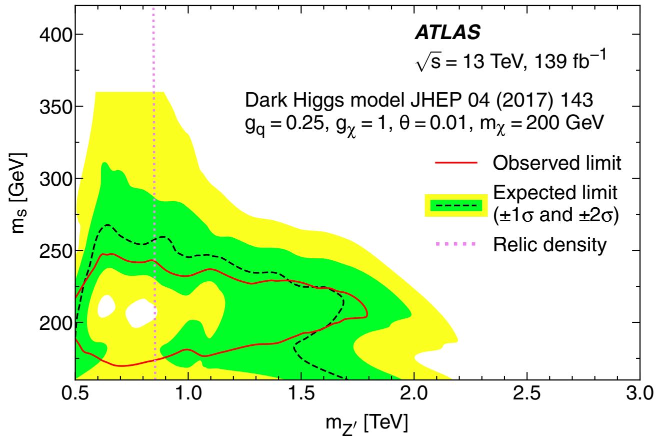


FIG. 4. Observed (expected) exclusion regions at 95% C.L. for the dark Higgs model in the $(m_{Z'}, m_s)$ plane, encircled by the solid (dashed) line. The expected $\pm1\sigma$ ($\pm2\sigma$) uncertainty is shown as the filled green (yellow) band. The observed relic density [30] is obtained for $m_{Z'} = 850$ GeV (dotted line).

In conclusion, this Letter presents a novel search for DM in previously uncovered final states with large E_T^{miss} and hadronic decays of resonant $VV = W^\pm W^\mp$ or ZZ pairs, with $m_{VV} > 160$ GeV, using the ATLAS detector at the LHC. No significant excess over the predicted background is found in 139 fb^{-1} of 13 TeV pp collision data. This search excludes previously uncharted parameter space of the dark Higgs model for $m_s > 160$ GeV and provides sensitivity complementary to other DM searches using $X + E_T^{\text{miss}}$ signatures.

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