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Search for dark matter in events with a Z boson and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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A search is presented for production of dark-matter particles recoiling against a leptonically decaying Z boson in 20.3 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector at the Large Hadron Collider. Events with large missing transverse momentum and two oppositely charged electrons or muons consistent with the decay of a Z boson are analyzed. No excess above the Standard Model prediction is observed. Limits are set on the mass scale of the contact interaction as a function of the dark-matter particle mass using an effective field theory description of the interaction of dark matter with quarks or with Z bosons. Limits are also set on the coupling and mediator mass of a model in which the interaction is mediated by a scalar particle.

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Astrophysical measurements indicate the existence of nonbaryonic dark matter [1,2]. However, collider-based searches, nuclear scattering experiments, and searches for particles produced from dark-matter annihilation have not yet revealed its particle nature nor discovered its non-gravitational interactions, if they exist [3]. Collider-based searches for weakly interacting massive particles (WIMPs, denoted as χ), specifically $pp \rightarrow \chi\bar{\chi} + X$ at the Large Hadron Collider (LHC) via some unknown intermediate state, are an important facet of the experimental program and provide sensitivity over a broad range of values of the WIMP mass m_χ , including for low masses where direct detection experiments are less sensitive. The presence of dark-matter particles, not directly observable in a collider detector, can be inferred from their recoil against Standard Model (SM) particles. The LHC collaborations have reported limits on the cross section for the process that includes initial state radiation (ISR), $pp \rightarrow \chi\bar{\chi} + X$, where the ISR component X is a hadronic jet [4,5], a photon [6,7], or a W or Z boson decaying hadronically [8]. Limits on dark matter produced in the decay of the Higgs boson have also been reported [9]. In this analysis, limits are set using the final state of a Z boson decaying to two oppositely charged electrons or muons, plus missing transverse momentum E_T^{miss} .

Since the nature of the intermediate state mediating the parton-WIMP interaction is not known, a useful approach is to construct an effective field theory (EFT) [10–12]. EFTs have often been used to describe interactions between dark-matter particles and quarks or gluons, but they have

recently been extended to describe direct interactions with electroweak bosons [13–15]. In the context of the EFT framework, the WIMP is considered to be the only new particle accessible at LHC energies, in addition to the SM fields. The mediator of the interaction is assumed to be heavy compared to the typical parton interaction energies involved, and the dark-matter particles are also assumed to be produced in pairs.

The EFTs considered in this analysis, depicted in Fig. 1, are expressed in terms of two parameters: m_χ and a mass scale M_\star , described in Ref. [10]. M_\star parameterizes the coupling between the WIMP and SM particles, where the coupling strength is normalized, or in inverse proportion, to the heavy-mediator mass scale. The coefficients of the Lagrangian's interaction terms appear as powers of M_\star , e.g. for the $D1$ operator as $1/M_\star^3$ and for the $D5$ and $D9$ operators as $1/M_\star^2$. The definition of the $D1$, $D5$, and $D9$ operators and the region of validity of the EFT limits are discussed in Refs. [10,16].

Following the approach of Ref. [13], the coupling of dark matter to electroweak bosons is considered for dimension-5 and dimension-7 operators. The dimension-7 operator

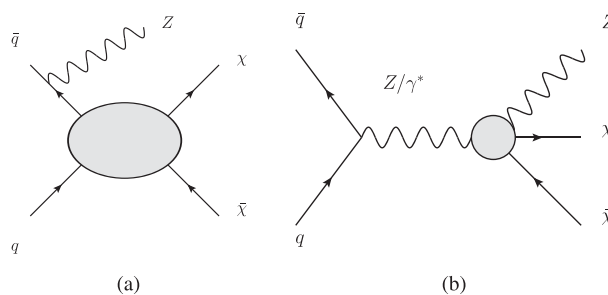


FIG. 1. The diagrams showing different types of $pp \rightarrow \chi\bar{\chi} + Z$ production modes considered in this analysis [13]. (a) shows a diagram that includes an ISR operator, and (b) shows a diagram that includes a $ZZ\chi\chi$ operator.

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couples dark matter to $Z\gamma^*$ as well as ZZ . Since a Z boson is in the final state for each operator, intermediate states with a Z or γ^* each contribute to the matrix element. The relative contribution of the Z and γ^* diagrams is a parameter of the theory.

This analysis considers models of dark-matter production where a Z boson is radiated as ISR or interacts directly with WIMPs. The latter case of an interaction between a Z boson and a WIMP is a process not previously investigated in the analysis of LHC experiments.

To complement the EFT analysis, this paper also examines the results in terms of a model in which the intermediate state is specified [17]. In this model a scalar-mediator η , with mass m_η , and a scalar-WIMP coupling strength f are responsible for the production of the dark-matter particles. The mediator η transforms as a color triplet and an electroweak doublet and has a hypercharge of $1/3$. The production cross section is proportional to f^4 . The same final state signature predicted by the EFT, $Z\chi\bar{\chi}$, is produced. This process is similar to supersymmetry processes in which the χ is a neutralino and the η is a squark doublet, but without a direct gluino analogue. This corresponds to a scenario where the gluino would be too heavy to be produced at the LHC and is therefore irrelevant.

In this analysis, a search for the production of a Z boson with subsequent decay to e^+e^- or $\mu^+\mu^-$ in association with large E_T^{miss} from the escaping $\chi\bar{\chi}$ particles is reported, based on 20.3 fb^{-1} of pp collision data collected by the ATLAS detector at a center-of-mass energy of $\sqrt{s} = 8 \text{ TeV}$. Only data collected with stable beams and all detector subsystems fully operational are used. Several signal regions with different requirements on the E_T^{miss} are defined to best probe the variety of models tested.

The ATLAS detector [18] consists of an inner detector (ID) surrounded by a solenoid that produces a 2 T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS) employing toroidal magnets. The ID measures charged-particle tracks over the full azimuthal angle and in a pseudorapidity [19] range of $|\eta| < 2.5$ using silicon pixel, silicon microstrip, and transition-radiation straw-tube detectors, the last of which also distinguishes electrons from heavier charged particles in the range $|\eta| < 2.0$. Liquid-argon (LAr) electromagnetic sampling calorimeters cover the range $|\eta| < 3.2$ with a typical granularity in $\Delta\eta \times \Delta\phi$ of 0.025×0.025 . A scintillator-tile calorimeter provides hadronic calorimetry for $|\eta| < 1.7$. In the end caps ($|\eta| > 1.5$), LAr is also used for the hadronic calorimeters matching the outer $|\eta|$ limit of the end cap electromagnetic calorimeters. The LAr forward calorimeters extend the coverage to $|\eta| < 4.9$ and provide both the electromagnetic and hadronic energy measurements. The MS covers $|\eta| < 2.7$ and provides triggering and precision tracking for muons. A three-level trigger system is used to select interesting events to be recorded for subsequent off-line analysis.

Electrons are required to have transverse energy E_T larger than 20 GeV and $|\eta| < 2.47$. The E_T is measured from the energy deposited in the electromagnetic calorimeter, and the electron's direction from the ID track. Electrons must satisfy the *medium* object quality requirements from Ref. [20] updated for 2012 run conditions, which are based on calorimeter shower shape, ID track quality, and the spatial match between the shower and the track. Electrons must be isolated, satisfying $\sum^{\Delta R < 0.2} p_T^{\text{track}}/E_T < 0.1$, where the sum is over the transverse momenta p_T^{track} of all other ID tracks with $p_T^{\text{track}} > 1 \text{ GeV}$ within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around the electron direction.

Muons are required to have $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$. A combined fit of the ID and MS tracks is used to reconstruct the muon p_T . High-quality tracks are ensured by requirements on the number of hits in the ID. Longitudinal and transverse impact parameters, z_0 and d_0 , respectively, must satisfy $|z_0| < 10 \text{ mm}$ and $|d_0| < 1 \text{ mm}$, with respect to the primary vertex, defined as the vertex with the highest $\sum (p_T^{\text{track}})^2$. The muon must be isolated, satisfying $\sum^{\Delta R < 0.2} p_T^{\text{track}}/p_T < 0.1$; here again, the muon track itself is excluded from the sum.

The anti- k_r jet algorithm [21] with radius parameter of 0.4 is used to reconstruct jets from topological clusters [22], which are three-dimensional clusters of neighboring energy deposits in the calorimeter cells. A calibration procedure is used in which the raw energy measurement from the calorimeter cluster is corrected to the jet energy scale. Jets are required to have $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$. Jets from secondary proton-proton collisions are removed by requiring that most of the tracks associated with the jet, weighted by p_T , originate at the primary vertex.

Since muons may generate delta-ray electrons or radiate photons that produce electron-positron pairs, electrons closer than $\Delta R = 0.2$ to a muon that passes the analysis selection are rejected. In addition, electrons and muons closer than $\Delta R = 0.4$ to a jet are also rejected.

The measurement of the missing transverse momentum, a vector in the transverse plane, \vec{E}_T^{miss} , with magnitude E_T^{miss} , is based on the measurement of the energy collected by the calorimeters and the momenta of muons. Muons and electrons with $p_T > 10 \text{ GeV}$, jets with $p_T > 20 \text{ GeV}$, low- p_T tracks which do not seed a topological cluster, and topological clusters not associated with a jet are included in the \vec{E}_T^{miss} calculation [23].

The candidate signal events were accepted by at least one of the several triggers that require either two leptons with low p_T or a single lepton with higher p_T . An event must have at least one reconstructed vertex with at least three associated tracks with $p_T > 400 \text{ MeV}$ to remove non-collision background. In addition, events must have two oppositely charged electrons or muons with invariant mass $m_{\ell\ell} \in [76, 106] \text{ GeV}$ to form a Z boson candidate. In order

to suppress events where the E_T^{miss} originates from mis-measured jets, the azimuthal angle between the dilepton system and the \vec{E}_T^{miss} , $\Delta\phi(\vec{E}_T^{\text{miss}}, p_T^{\ell\ell})$, must be greater than 2.5, the absolute value of the pseudorapidity of the dilepton system, $|\eta^{\ell\ell}|$, must be less than 2.5, and the ratio $|p_T^{\ell\ell} - E_T^{\text{miss}}|/p_T^{\ell\ell}$ must be less than 0.5, where $p_T^{\ell\ell}$ is the transverse momentum of the dilepton system. Events are removed if they contain one or more jets with $p_T > 25$ GeV to suppress top-quark pair background. Similarly, events containing a third lepton with $p_T > 7$ GeV, satisfying looser identification requirements than invoked for the leptons produced in the decay of the Z boson, are removed to suppress diboson background.

The various dark-matter models considered here have different E_T^{miss} spectra, leading to a variety of optimal lower thresholds of E_T^{miss} . Four inclusive signal regions are defined with lower thresholds in E_T^{miss} of 150, 250, 350, and 450 GeV.

The dominant background process is $ZZ \rightarrow \ell^+ \ell^- \bar{\nu} \nu$ ($\ell = e, \mu$), an irreducible background. The other irreducible background is $WW \rightarrow \ell^+ \nu \ell^- \bar{\nu}$, which may only be reduced through the mass window requirement. Reducible backgrounds may have jets produced in association with two leptons, where the jets are misidentified or unreconstructed, such as $i\bar{i} \rightarrow \ell^+ \nu b \ell^- \bar{\nu} \bar{b}$, $ZZ \rightarrow \ell^+ \ell^- \bar{q} q$, $WZ \rightarrow \bar{q} q' \ell^+ \ell^-$, or Z + jets (including decays to τ leptons). Additional reducible sources may produce events with more than two leptons where the additional leptons are misidentified or not reconstructed, or less than two leptons where jets are misidentified as leptons, such as $WZ \rightarrow \ell \nu \ell^+ \ell^-$ and W + jets, respectively.

The WZ and ZZ backgrounds are estimated from Monte Carlo (MC) simulation. The next-to-leading-order MC generator POWHEG BOX 1.0 [24] is used, which models the production from a $q\bar{q}$ initial state. The ZZ background sample is normalized to include the $gg \rightarrow ZZ$ contribution using MCFM 6.2 [25]. Parton distribution functions (PDFs) for these samples are modeled using CT10 [26]. The underlying event, as well as parton showers and hadronization, are simulated with PYTHIA 8.165 [27], using the AU2 tune [28]. QED radiative corrections are calculated using PHOTOS++ 3.0 [29]. The detector response is simulated with GEANT 4 [30,31]. The simulated samples are generated with pileup conditions similar to those observed in data. Pileup refers to the multiple interactions occurring in the same, or adjacent, beam bunch crossings as the hard process. Simulated events are reweighted so that the number of pileup interactions has the same distribution as in data events.

The WW , $t \rightarrow t$, Wt , and $Z \rightarrow \tau\tau$ backgrounds are estimated from data using the absence of signal in the $e\mu$ channel and the relative production rate of 1:1:2 for the ee , $\mu\mu$, and $e\mu$ channels. An $e\mu$ control region similar to the signal region is defined, and the background estimate for the ee and $\mu\mu$ signal regions is obtained from the

number of $e\mu$ events in the control region after correcting for the slightly different electron and muon acceptances and efficiencies.

The Z + jets background is estimated using two data-driven techniques. The first method, commonly referred to as the $ABCD$ method [32], considers the distribution of signal and background events in a phase space defined by two uncorrelated variables, here E_T^{miss} and $\eta^{\ell\ell}$, for which the signal and background have different shapes. The phase space is partitioned into four regions labeled A , B , C , and D . Region A is the signal region where selection requirements on both variables are invoked, while regions B , C , and D are control regions in which one or both selections are reversed. Contamination by signal events in the control regions is found to be negligible. The number of events in one control region scaled by the ratio of background events in two other control regions estimates the background contribution in the signal region. In the second method, the contribution is measured by fitting the distributions of $\Delta\phi(\vec{E}_T^{\text{miss}}, p_T^{\ell\ell})$ and E_T^{miss} at small values [$E_T^{\text{miss}} < 80$ GeV and $\Delta\phi(\vec{E}_T^{\text{miss}}, p_T^{\ell\ell}) < 2.5$] and extrapolating them to the signal regions. The two methods invoke all the standard selection requirements and give consistent results. The $ABCD$ method is used to provide the background estimate, and the difference between the two is taken as a systematic uncertainty on the estimate.

The W + jets background is estimated by reversing the electron isolation condition and loosening identification requirements for one electron in order to obtain a data sample enriched in jets reconstructed as electrons. The resultant E_T^{miss} distribution is fitted with a function of the form $N = A \cdot (E_T^{\text{miss}})^b$ below 300 GeV and extrapolated to the highest 450 GeV signal region. The fitted function is integrated over E_T^{miss} to obtain an estimated background above a given E_T^{miss} threshold. A normalization factor is derived from data in the low- E_T^{miss} region with all the analysis selections applied. This factor is applied to the extrapolated result to obtain an estimate of this background.

Background estimates are validated in signal-depleted control regions that are determined by similar selection criteria used to define the signal region, but where a requirement may be inverted or modified. For the dominant $ZZ \rightarrow \ell^+ \ell^- \bar{\nu} \nu$ background, estimated with MC simulation, the control region probes four-lepton events and is defined by the presence of two pairs of same-flavor, oppositely charged leptons for which the invariant mass of the pairs is within the Z boson mass window. For the subdominant $WZ \rightarrow \ell \nu \ell^+ \ell^-$ background, the control region is characterized by three leptons: a pair of same-flavor, oppositely charged leptons for which the invariant mass is within the Z boson mass window, an additional electron or muon, and a reconstructed $E_T^{\text{miss}} > 80$ GeV. For the minor WW and top-quark background, derived from a data-driven technique, events containing an electron and a

muon ($e\mu$) with opposite charge are used. The expected signal region event yield is obtained from correction factors that account for the relative dilepton reconstruction efficiencies and the ratio of same-flavor lepton production to mixed flavor. The predicted yields from MC simulation are consistent with the data-driven estimates and in all cases are consistent with the control region yields observed in data.

Samples of $pp \rightarrow ZZ\bar{\chi}\chi$ signals are generated using MADGRAPH 5 1.5.2 [33] with parton showering and hadronization modeled by PYTHIA 8.170 using the MSTW 2008 leading-order PDFs [34] and the AU2 tune. EFT operators $D1$ (scalar, spin independent), $D5$ (vector, spin independent), and $D9$ (tensor, spin dependent), following the definitions of Ref. [10], are representative of the full set of operators in which the Z boson is emitted as ISR. Similar E_T^{miss} distributions result from all the operators within each of the three types: scalar, vector, and tensor.

Two examples of the dimension-7 $ZZ\chi\chi$ operator mixtures are considered: one in which the $Z\gamma^*$ contribution is negligible and one in which it is maximal. Therefore the dimension-7 operators are referred to as $ZZ\chi\chi$ -maximal- γ^* and $ZZ\chi\chi$ -no- γ^* while the dimension-5 operator is referred to simply as $ZZ\chi\chi$. Cross sections for a few representative operators and for the scalar-mediator theory with representative coupling constant, $f = 6$, and $m_\eta = 1$ TeV are given in Table I.

Samples of $pp \rightarrow Z\chi\bar{\chi}$ events are propagated through the ATLAS detector using the full simulation of the ID and muon trackers and the parameterized simulation of the calorimeter [30], tuned to full simulation and data. The shapes of the simulated E_T^{miss} distributions for the signal operators are shown in Fig. 2 compared to the dominant SM background process $ZZ \rightarrow \ell^+\ell^-\bar{\nu}\nu$.

Contributions to the systematic uncertainty of the expected SM backgrounds are due largely to experimental sources affecting the E_T^{miss} measurement and to the efficiencies for the reconstruction and identification of electrons and muons. For example, when $E_T^{\text{miss}} > 120$ GeV, the

TABLE I. The power dependence of $1/M_\star$ for the EFT and the cross sections of WIMP production in association with an on-shell Z boson for various EFT operators and the scalar-mediator theory are shown. For the calculation of the production cross section, M_\star is taken to be 1 TeV for the EFT operators. The coupling constant of the scalar-mediator theory, f , is taken to be 6 and the mass of the mediator, m_η , is 1 TeV.

| | $D5$ | $D9$ | $ZZ\chi\chi$ max. γ^* | Scalar mediator |
|----------------------|------|------|------------------------------|-----------------|
| m_χ [GeV] | | | Cross sections [fb] | |
| 1 | 7.2 | 130 | 3.1 | 830 |
| 10 | 7.1 | 120 | 3.1 | 810 |
| 200 | 5.6 | 89 | 2.0 | 300 |
| 400 | 3.1 | 47 | 0.83 | 70 |
| 1000 | 0.25 | 3.4 | 0.023 | ... |
| M_\star^{-1} power | 2 | 2 | 3 | ... |

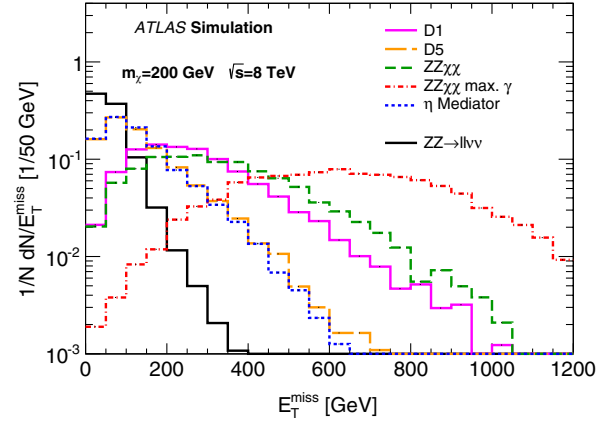


FIG. 2 (color online). Shape of the E_T^{miss} distribution in simulated samples of ZZ background, effective field theories of dark-matter interaction with a $q\bar{q}$ initial state ($D1$, $D5$, and $D9$ [10]) and interaction with a Z/γ^* intermediate state [13], and the scalar-mediator theory. The shapes of $ZZ\chi\chi$ -no- γ^* and $ZZ\chi\chi$ -maximal- γ^* are similar, as are the shapes of $D9$ and the dimension-5 $ZZ\chi\chi$ EFT, so only one of each is plotted. Each distribution is normalized to unit area. The mass of the scalar mediator m_η is 1 TeV, and the dark-matter particle mass is $m_\chi = 200$ GeV.

experimental systematic uncertainty for the ZZ background is dominated by the jet-energy scale (1.7% and 2.3% for electron and muon final states, respectively) and the electron and muon momentum scale (2.3% and 0.8%, respectively). Smaller systematic uncertainties are associated with the E_T^{miss} measurement and with the efficiencies for the reconstruction and identification of electrons and muons.

For the dominant background, $ZZ \rightarrow \ell^+\ell^-\bar{\nu}\nu$, determined from simulated samples, systematic theoretical uncertainties are derived from the generator differences, QCD factorization and renormalization scales, and PDF modeling. The largest theoretical uncertainty, the generator difference, is evaluated as the difference in yields calculated from samples simulated with SHERPA 1.4.1 [35] and POWHEG BOX. The systematic uncertainties associated with the ZZ background are summarized in Table II for each signal region. The luminosity uncertainty is 2.8% and

TABLE II. Summary of the systematic uncertainties for the largest background process: ($ZZ \rightarrow \ell^+\ell^-\bar{\nu}\nu$). Statistical uncertainties are from MC simulation sample size.

| Uncertainty source | E_T^{miss} threshold [GeV] | | | |
|--------------------|-------------------------------------|-----|-----|-----|
| | 150 | 250 | 350 | 450 |
| Statistical [%] | 2 | 6 | 13 | 24 |
| Experimental [%] | 3 | 6 | 9 | 8 |
| Theoretical [%] | 36 | 37 | 37 | 38 |
| Luminosity [%] | 3 | 3 | 3 | 3 |
| Total [%] | 36 | 38 | 40 | 46 |

TABLE III. Observed yields and expected SM backgrounds in each signal region. Statistical, systematic, and luminosity uncertainties are added in quadrature to give the total background estimate and uncertainties.

| Process | E_T^{miss} threshold [GeV] | | | |
|------------------------------|-------------------------------------|-------------------|-------------------|---------------------|
| | 150 | 250 | 350 | 450 |
| ZZ | 41 ± 15 | 6.4 ± 2.4 | 1.3 ± 0.5 | 0.3 ± 0.1 |
| WZ | 8.0 ± 3.1 | 0.8 ± 0.4 | 0.2 ± 0.1 | 0.1 ± 0.1 |
| WW, $t\bar{t}$, | 1.9 ± 1.4 | $0^{+0.7}_{-0.0}$ | $0^{+0.7}_{-0.0}$ | $0^{+0.7}_{-0.0}$ |
| $Z \rightarrow \tau^+\tau^-$ | | | | |
| Z + jets | 0.1 ± 0.1 | ... | ... | ... |
| W + jets | 0.5 ± 0.3 | ... | ... | ... |
| Total | 52 ± 18 | 7.2 ± 2.8 | 1.4 ± 0.9 | $0.4^{+0.7}_{-0.4}$ |
| Data | 45 | 3 | 0 | 0 |

is derived from beam-separation scans performed following the procedure described in Ref. [36].

The expected background and observed yields are reported in Table III. Figure 3 shows the E_T^{miss} distribution after applying all selection requirements other than the E_T^{miss} thresholds for the observed data, the expected SM backgrounds, and the hypothetical $pp \rightarrow Z\chi\bar{\chi}$ signals for various values of the mass scale.

No excess over the background is observed. Upper limits on the number of events from a new source are calculated employing a frequentist method with a profile likelihood ratio [37] using the unbinned yields and uncertainties from each E_T^{miss} region. The likelihood is a product of a Poisson distribution and Gaussian constraints for the total signal and background systematic uncertainties. The mean of the

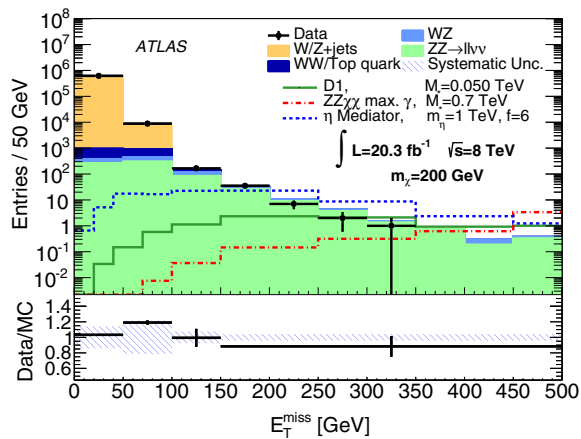


FIG. 3 (color online). E_T^{miss} distributions after all event selections other than the E_T^{miss} thresholds for the observed data; the expected SM backgrounds taken from simulation; the hypothetical $pp \rightarrow Z\chi\bar{\chi}$ signals for various values of the mass scale M_* . The dark-matter particle mass is $m_\chi = 200$ GeV. The last bin contains the events with $E_T^{\text{miss}} > 450$ GeV. The ratio of data to simulated backgrounds is also shown. The band shows the experimental systematic uncertainties on the ratio.

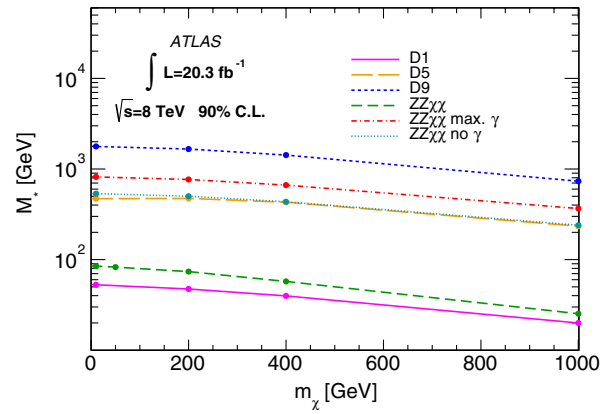


FIG. 4 (color online). Observed 90% C.L. lower limits on the mass scale M_* of considered effective field theories as a function of m_χ . For each operator, the values below the corresponding line are excluded.

Poisson distribution, for either signal and background or background alone, includes the effect of varying the nuisance parameters.

The E_T^{miss} region with the best expected limit is used to calculate the observed limit for each operator and mass point. Limits on the cross section for $pp \rightarrow Z\chi\bar{\chi}$ production are translated into limits on the mass scale of the effective operators mediating the interaction of the dark-matter particles with the initial state quarks or the Z/γ^* intermediate state. This is done using the relation $M_*^{\text{limit}} = M_*^{\text{generator}} \times (\sigma^{\text{generator}}/\sigma^{\text{limit}})^{1/2p}$, where the superscript indicates whether the parameter is a measured limit or calculated using MC simulation and p indicates the power of $(1/M_*)$ appearing in the EFT Lagrangian. These limits are shown in Fig. 4. They are also translated into limits on the χ -nucleon scattering cross section using the method in Ref. [10] for several effective operators mediating the interaction of the dark-matter particles with the $q\bar{q}$ initial state and are compared with other experimental results described in Refs. [38–46]. These limits, shown at 90% C.L. in Figs. 5 and 6, are less stringent than the lower limits for dark-matter candidates recoiling against a W or Z boson decaying to hadrons reported in Ref. [8]. The limits degrade by 13%–23% at 95% C.L., depending on the E_T^{miss} signal region under consideration.

A lower limit on the coupling, f , of the scalar-mediator model is also calculated based on the WIMP relic abundance in Ref. [47] and the expression for the freeze-out temperature from Ref. [48]. If the relic abundance lower limit calculated at some mass point (m_χ, m_η) is greater than the upper limit measured in this analysis, that mass point is excluded. Limits on the cross section times branching ratio in the scalar-mediator model are shown in Fig. 7, and limits on f as a function of mediator mass m_η and m_χ , as well as the exclusion region, are shown in Fig. 8.

Fiducial cross-section limits are calculated in each signal region to complement the limits on specific models. The

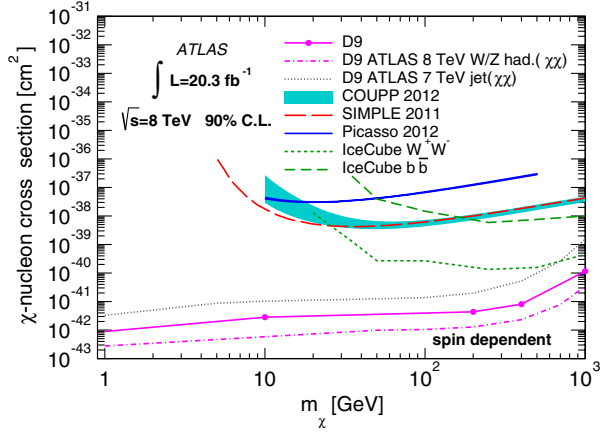


FIG. 5 (color online). Observed 90% C.L. upper limits on the χ -nucleon scattering cross section as a function of m_χ for the spin-dependent $D9$ effective operators mediating the interaction of the dark-matter particles with the $q\bar{q}$ initial state. The limits are compared with results from the published ATLAS hadronically decaying W/Z [8] and $j + \chi\chi$ [4] searches, COUPP [38], SIMPLE [39], PICASSO [40], and IceCube [41]. These limits are shown as they are given in the corresponding publications and are only shown for comparison with the results from this analysis, since they are obtained assuming the interactions are mediated by operators different from those used for the ATLAS limits.

reconstruction efficiency is defined as the ratio of reconstructed events satisfying all the selection criteria to the number of generated events within a fiducial region characterized by selection requirements at particle level

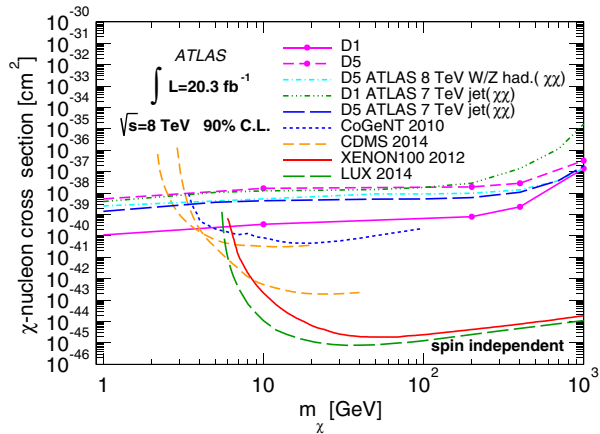


FIG. 6 (color online). Observed 90% C.L. upper limits on the χ -nucleon scattering cross section as a function of m_χ for spin-independent effective operators mediating the interaction of the dark-matter particles with the $q\bar{q}$ initial state. The limits are compared with results from the published ATLAS hadronically decaying W/Z [8] and $j + \chi\chi$ [4] searches, CoGeNT [42], XENON100 [43], CDMS [44,45], and LUX [46]. These limits are shown as they are given in the corresponding publications and are only shown for comparison with the results from this analysis, since they are obtained assuming the interactions are mediated by operators different from those used for the ATLAS limits.

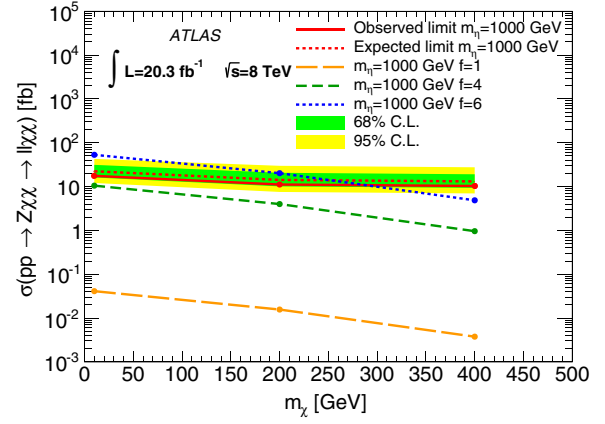


FIG. 7 (color online). Observed 95% C.L. upper limits on the cross section multiplied by the branching ratio of $Z \rightarrow \ell^+ \ell^-$ of the scalar-mediator theory as a function of m_χ . The observed cross-section limit for a scalar-mediator mass, m_η , of 1000 GeV is shown. Production cross sections predicted from theory are shown for $m_\eta = 1$ TeV and for different values of the coupling strength f .

identical to all the requirements on the reconstructed dilepton + E_T^{miss} system, where the E_T^{miss} is calculated summing over all neutrinos and dark-matter particles. The acceptance is the ratio of the number of generated events within the fiducial region to the total number of generated events. In addition, the generated leptons are required to be separated by at least $\Delta R = 0.2$ to match the isolation requirement. The reconstruction efficiency ranges from $(56.9 \pm 0.9)\%$ for $ZZ\chi\chi$ -max.- γ^* at $m_\chi = 1000$ GeV to $(77.9 \pm 3.1)\%$ for $D5$ at $m_\chi = 400$ GeV. The lowest

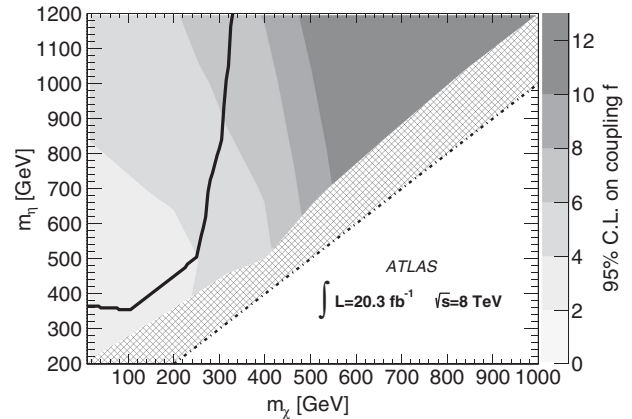


FIG. 8. Observed 95% C.L. upper limits on the coupling constant f of the scalar-mediator theory as a function of m_χ and the mediator mass m_η . The cross-hatching shows the theoretically accessible region outside the range covered by this analysis. The white region is phase space beyond the model's validity. In the excluded region in the upper left-hand corner, demarcated by the black line, the lower limit on f from the relic abundance calculations based on [47,48] is greater than the upper limit measured in this analysis.

TABLE IV. The observed and expected upper limits on the fiducial cross section at 95% C.L. for each signal region.

| | E_T^{miss} threshold [GeV] | | | |
|----------------------|-------------------------------------|------|------|------|
| | 150 | 250 | 350 | 450 |
| | Fiducial cross section [fb] | | | |
| Expected limits [fb] | 3.0 | 0.73 | 0.36 | 0.27 |
| Observed limits [fb] | 2.7 | 0.57 | 0.27 | 0.26 |

value of the reconstruction efficiency is used to calculate the fiducial cross-section limits in order to be conservative. The corresponding acceptances for the previous operators are $(30.3 \pm 0.5)\%$ and $(2.6 \pm 0.2)\%$, respectively, where the uncertainties are purely statistical and the variation in the acceptance arises primarily from the different E_T^{miss} spectra of the operators. The observed and expected upper limits on the fiducial cross section are given in Table IV.

In conclusion, a search for the production of dark-matter particles in association with a Z boson that decays leptonically in 20.3 fb^{-1} of pp collisions at $\sqrt{s} = 8 \text{ TeV}$ is presented for three EFT operators where the dark matter interacts directly with quarks: $D1$, $D5$, and $D9$. The new limits complement the limits reported in other LHC analyses. The results are also interpreted using EFT models where the dark matter interacts directly with pairs of electroweak bosons. Initial limits are set on the mass scale of the $ZZ\chi\chi$ EFT operators describing the interaction between dark matter and a Z or γ^* intermediate state. Upper limits are also set on the scattering cross section of dark-matter particles with nucleons for effective operators mediating the interaction of dark-matter particles with a $q\bar{q}$ initial state, and on a model in which the interaction between the dark matter and Z/γ^* is mediated by a scalar particle.

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