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Search for Dark Matter in Events with a Hadronically Decaying W or 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 dark matter pair production in association with a W or Z boson in pp collisions representing 20.3 fb^{-1} of integrated luminosity at $\sqrt{s} = 8$ TeV using data recorded with the ATLAS detector at the Large Hadron Collider. Events with a hadronic jet with the jet mass consistent with a W or Z boson, and with large missing transverse momentum are analyzed. The data are consistent with the standard model expectations. Limits are set on the mass scale in effective field theories that describe the interaction of dark matter and standard model particles, and on the cross section of Higgs production and decay to invisible particles. In addition, cross section limits on the anomalous production of W or Z bosons with large missing transverse momentum are set in two fiducial regions.

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Although the presence of dark matter in the Universe is well established, little is known of its particle nature or its nongravitational interactions. A suite of experiments is searching for a weakly interacting massive particle (WIMP), denoted by χ, and for interactions between χ and standard model (SM) particles [1].

One critical component of this program is the search for pair production of WIMPs at particle colliders, specifically $pp \to \chi\bar{\chi}$ at the Large Hadron Collider (LHC) via some unknown intermediate state. These searches have greatest sensitivity at low WIMP mass m_χ, where direct detection experiments are less powerful. At the LHC, the final-state WIMPs are invisible to the detectors, but the events can be detected if there is associated initial-state radiation of a SM particle [2]; an example is shown in Fig. 1.

The Tevatron and LHC collaborations have reported limits on the cross section of $pp \to \chi\bar{\chi} + X$ where X is a hadronic jet [2–4] or a photon [5,6]. Other LHC data have been reinterpreted to constrain models where X is a leptonically decaying W [7] or Z boson [8,9]. In each case, limits are reported in terms of the mass scale M_* of the unknown interaction expressed in an effective field theory as a four-point contact interaction [10–18]. In the models considered until now, the strongest limits come from monojet analyses, due to the large rate of gluon or quark initial-state radiation relative to photon, W or Z boson radiation. The operators studied in these monojet and monophoton searches assume equal couplings of the dark matter particles to up-type and down-type quarks $[C(u) = C(d)]$. For W boson radiation there is interference between the diagrams in which the W boson is radiated from the u quark or the d quark. In the case of equal coupling, the interference is destructive and gives a small W boson emission rate. If, however, the up-type and down-type couplings have opposite signs $[C(u) = -C(d)]$ to give constructive interference, the relative rates of gluon, photon, W or Z boson emission can change dramatically [7], such that mono-W-boson production is the dominant process.

In this Letter, a search is reported for the production of W or Z bosons decaying hadronically (to $q\bar{q}'$ or $q\bar{q}$, respectively) and reconstructed as a single massive jet in association with large missing transverse momentum from the undetected $\chi\bar{\chi}$ particles. This search, the first of its kind, is sensitive to WIMP pair production, as well as to other dark-matter-related models, such as invisible Higgs boson decays (WH or ZH production with $H \to \chi\bar{\chi}$).

The ATLAS detector [19] at the LHC covers the pseudorapidity [20] range $|\eta| < 4.9$ and the full azimuthal angle ϕ. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and an external muon spectrometer incorporating large superconducting toroidal magnets. A three-level trigger system is used to select interesting events for recording and subsequent offline analysis. Only data for which beams were stable and all subsystems described

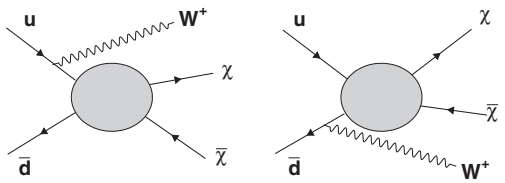

FIG. 1. Pair production of WIMPs ($\chi\bar{\chi}$) in proton–proton collisions at the LHC via an unknown intermediate state, with initial-state radiation of a W boson.

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above were operational are used. Applying these requirements to pp collision data, taken at a center-of-mass energy of $\sqrt{s} = 8$ TeV during the 2012 LHC run, results in a data sample with a time-integrated luminosity of 20.3 fb^{-1}. The systematic uncertainty on the luminosity is derived, following the same methodology as that detailed in Ref. [21], from a preliminary calibration of the luminosity scale obtained from beam-separation scans performed in November 2012.

Jet candidates are reconstructed using the Cambridge–Aachen algorithm [22] with a radius parameter of 1.2, and selected using a mass-drop filtering procedure [23,24], referred to as large-radius jets. These large-radius jets are supposed to capture the hadronic products of both quarks from W or Z boson decay. The internal structure of the large-radius jet is characterized in terms of the momentum balance of the two leading subjets, as $\sqrt{y} = \min(p_{T1}, p_{T2})\Delta R/m_{\text{jet}}$ where $\Delta R = \sqrt{(\Delta\phi_{1,2})^2 + (\Delta\eta_{1,2})^2}$ and m_{jet} is the calculated mass of the jet. Jet candidates are also reconstructed using the anti-k_t clustering algorithm [25] with a radius parameter of 0.4, referred to as narrow jets. The inputs to both algorithms are clusters of energy deposits in calorimeter cells seeded by those with energies significantly above the measured noise and calibrated at the hadronic energy scale [26]. Jet momenta are calculated by performing a four-vector sum over these clusters, treating each topological cluster [26] as an $(E, \vec{p})$ four vector with zero mass. The direction of $\vec{p}$ is given by the line joining the reconstructed interaction point with the energy cluster. Missing transverse momentum $E_{\text{T}}^{\text{miss}}$ is measured using all clusters of energy deposits in the calorimeter with $|\eta| < 4.5$. Electrons, muons, jets, and $E_{\text{T}}^{\text{miss}}$ are reconstructed as in Refs. [26–29], respectively. The reconstruction of hadronic W boson decays with large-radius jets is validated in a $t\bar{t}$-dominated control region with one muon, one large-radius jet ($p_{\text{T}} > 250$ GeV, $|\eta| < 1.2$), two additional narrow jets ($p_{\text{T}} > 40$ GeV, $|\eta| < 4.5$) separated from the leading large-radius jet, at least one b tag, and $E_{\text{T}}^{\text{miss}} > 250$ GeV (Fig. 2).

Candidate signal events are accepted by an inclusive $E_{\text{T}}^{\text{miss}}$ trigger that is more than 99% efficient for events with $E_{\text{T}}^{\text{miss}} > 150$ GeV. Events with significant detector noise and noncollision backgrounds are rejected as described in Ref. [3]. In addition, events are required to have at least one large-radius jet with $p_{\text{T}} > 250$ GeV, $|\eta| < 1.2$, m_{jet} between 50 GeV and 120 GeV, and $\sqrt{y} > 0.4$ to suppress background without hadronic W or Z boson decays. Two signal regions are defined by two thresholds in $E_{\text{T}}^{\text{miss}}$: 350 and 500 GeV. To suppress the $t\bar{t}$ background and multijet background, events are rejected if they contain more than one narrow jet with $p_{\text{T}} > 40$ GeV and $|\eta| < 4.5$ which is not completely overlapping with the leading large-radius jet by a separation of $\Delta R > 0.9$, or if any narrow jet has $\Delta\phi(E_{\text{T}}^{\text{miss}}, \text{jet}) < 0.4$. Finally, to suppress contributions

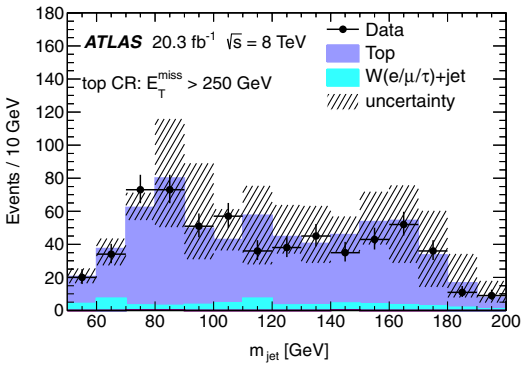

FIG. 2 (color online). Distribution of m_{jet} in the data and for the predicted background in the top control region (CR) with one muon, one large-radius jet, two narrow jets, and at least one b tag, and $E_{\text{T}}^{\text{miss}} > 250$ GeV, which includes a W peak and a tail due to the inclusion of (part of) the b jet from top decay. Uncertainties include statistical and systematic sources.

from $W \to \ell\nu$ production, events are rejected if they have any electron, photon, or muon candidates with $p_{\text{T}} > 10$ GeV and $|\eta| < 2.47$, 2.37, or 2.5, respectively.

The dominant source of background events is $Z \to \nu\bar{\nu}$ production in association with jets from initial-state radiation. A secondary contribution comes from production of jets in association with W or Z bosons with leptonic decays in which the charged leptons fail identification requirements or the τ leptons decay hadronically. These three backgrounds are estimated by extrapolation from a common data control region in which the selection is identical to that of the signal regions except that the muon veto is inverted and $W/Z +$ jets with muon decays are the dominant processes. In this muon control region dominated by $W/Z +$ jets with muon decays, the combined W and Z boson contribution is measured after subtracting other sources of background that are estimated using MC simulation [30] based on GEANT4 [31]. Two extrapolation factors from the contribution of $W/Z +$ jets in the muon control region to the contributions of $Z \to \nu\nu +$ jets and $W/Z +$ jets with leptonic decays in the muon-veto signal region, respectively, are derived as a function of m_{jet} from simulated samples of W and Z boson production in association with jets that are generated using SHERPA1.4.1 [32] and the CT10 [33] parton distribution function (PDF) set. A second control region is defined with two muons and $E_{\text{T}}^{\text{miss}} > 350$ GeV, which has limited statistics and is used only for the validation of the Z boson contribution. The W boson contribution is validated in a low-$E_{\text{T}}^{\text{miss}}$ control region with the same selection as the signal region but 250 GeV $< E_{\text{T}}^{\text{miss}} < 350$ GeV.

Other sources of background are diboson production, top quark pair production, and single-top production, which are estimated using simulated events. The MC@NLO4.03 generator [34] using the CT10 PDF with the AUET2 [35] tune, interfaced to HERWIG6.520 [36] and JIMMY4.31 [37] for the

TABLE I. Data and estimated background yields in the two signal regions. Uncertainties include statistical and systematic contributions.

Process	$E_{\mathrm{T}}^{\mathrm{miss}} > 350$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 500$ GeV
$Z \to \nu\bar{\nu}$	402^{+39}_{-34}	54^{+8}_{-10}
$W \to \ell^{\pm}\nu$, $Z \to \ell^{\pm}\ell^{\mp}$	210^{+20}_{-18}	22^{+4}_{-5}
WW, WZ, ZZ	57^{+11}_{-8}	$9.1^{+1.3}_{-1.1}$
$t\bar{t}$, single t	39^{+10}_{-4}	$3.7^{+1.7}_{-1.3}$
Total	707^{+48}_{-38}	89^{+9}_{-12}
Data	705	89

simulation of underlying events, is used for the productions of $t\bar{t}$ and single-top processes, both s-channel and Wt production. The single-top, t-channel process is generated with ACERMC3.8 [38] interfaced to PYTHIA8.1 [39], using the CTEQ6L1 [40] PDF with the AUET2B [35] tune. The diboson (ZZ, WZ, and WW) samples are produced using HERWIG6.520 and JIMMY4.31 with the CTEQ6L1 PDF and AUET2 tune.

Background contributions from multijet production in which large $E_{\mathrm{T}}^{\mathrm{miss}}$ is due to mismeasured jet energies are estimated by extrapolating from a sample of events with two jets and are found to be negligible [3].

Samples of simulated $pp \to W\chi\bar{\chi}$ and $pp \to Z\chi\bar{\chi}$ events are generated using MADGRAPH5 [41], with showering and hadronization modeled by PYTHIA8.1 using the AU2 [35] tune and CT10 PDF, including b quarks in the initial state. Four operators are used as a representative set based on the definitions in Ref. [14]: $C1$ scalar, $D1$ scalar, $D5$ vector (both the constructive and destructive interference cases), and $D9$ tensor. In each case, $m_{\chi} = 1, 50$, 100, 200, 400, 700, 1000, and 1300 GeV are used. The dominant sources of systematic uncertainty are due to the limited number of events in the control region, theoretical uncertainties in the simulated samples used for extrapolation, uncertainties in the large-radius jet energy calibration and momentum resolution [23], and uncertainties in the $E_{\mathrm{T}}^{\mathrm{miss}}$. Additional minor uncertainties are due to the levels of initial-state and final-state radiation, parton distribution functions, lepton reconstruction and identification efficiencies, and momentum resolution.

The data and predicted backgrounds in the two signal regions are shown in Table I for the total number of events and in Fig. 3 for the m_{jet} distribution. The data agree well with the background estimate for each $E_{\mathrm{T}}^{\mathrm{miss}}$ threshold. Exclusion limits are set on the dark matter signals using the predicted shape of the m_{jet} distribution and the CLs method [42], calculated with toy simulated experiments in which the systematic uncertainties have been marginalized. Figure 4 shows the exclusion regions at 90% confidence level (C.L.) in the M_* vs m_{χ} plane for various operators, where M_* need not be the same for the different operators.

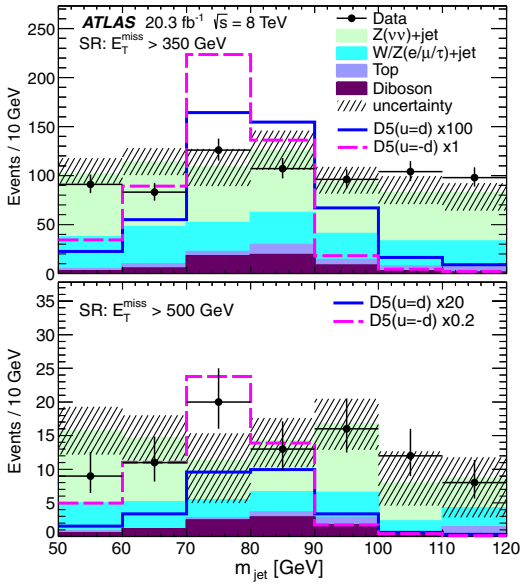

FIG. 3 (color online). Distribution of m_{jet} in the data and for the predicted background in the signal regions (SR) with $E_{\mathrm{T}}^{\mathrm{miss}} > 350$ GeV (top) and $E_{\mathrm{T}}^{\mathrm{miss}} > 500$ GeV (bottom). Also shown are the combined mono-W-boson and mono-Z-boson signal distributions with $m_{\chi} = 1$ GeV and $M_* = 1$ TeV for the $D5$ destructive and $D5$ constructive cases, scaled by factors defined in the legends. Uncertainties include statistical and systematic contributions.

Limits on the dark matter–nucleon scattering cross sections are reported using the method of Ref. [14] in Fig. 5 for both the spin-independent ($C1$, $D1$, $D5$) and the spin-dependent interaction model ($D9$). References [14,50] discuss the valid region of the effective field theory, which becomes a poor approximation if the mass of the intermediate state is below the momentum transferred in the interaction. The results are compared with measurements from direct detection experiments [43–49].

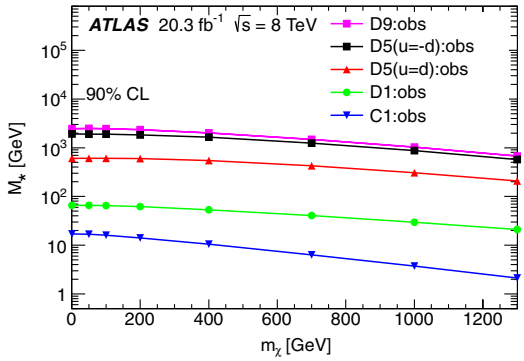

FIG. 4 (color online). Observed limits on the effective theory mass scale M_* as a function of m_{χ} at 90% C.L. from combined mono-W-boson and mono-Z-boson signals for various operators. For each operator, the values below the corresponding line are excluded.

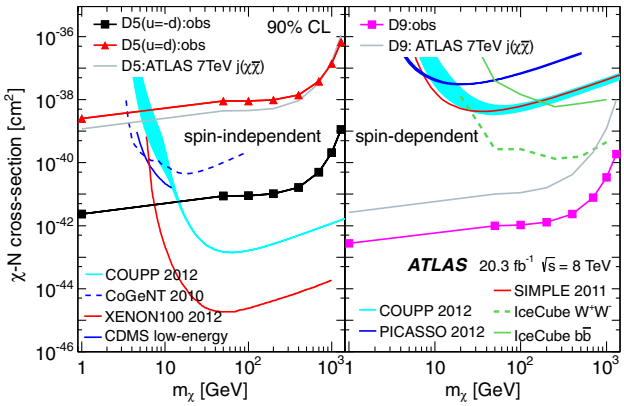

FIG. 5 (color online). Limits on χ–nucleon cross sections as a function of m_χ at 90% C.L. for spin-independent (left) and spin-dependent (right) operators in effective field theory, compared to previous limits [43–49].

This search for dark matter pair production in association with a W or Z boson extends the limits on the dark matter–nucleon scattering cross section in the low mass region $m_\chi < 10$ GeV where the direct detection experiments have less sensitivity. The new limits are also compared to the limits set by ATLAS in the 7 TeV monojet analysis [3]. For the spin-independent case with the opposite-sign up-type and down-type couplings, the limits are improved by about 3 orders of magnitude, as the constructive interference leads to a very large increase in the W-boson-associated production cross section. For other cases, the limits are similar.

To complement the effective field theory models, limits are calculated for a simple dark matter production theory with a light mediator, the Higgs boson. The upper limit on the cross section of Higgs boson production through WH and ZH modes and decay to invisible particles is 1.3 pb at 95% C.L. for $m_H = 125$ GeV. Figure 6 shows the upper limit of the total cross section of WH and ZH processes

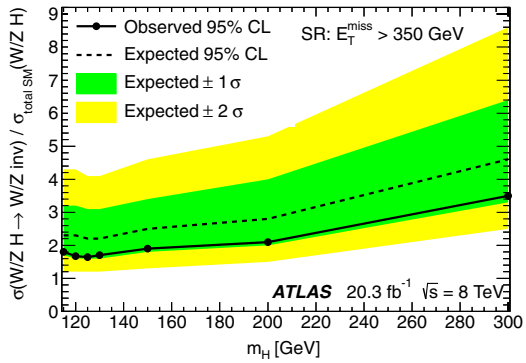

FIG. 6 (color online). Limit on the Higgs boson cross section for decay to invisible particles divided by the cross section for decays to standard model particles as a function of m_H at 95% C.L., derived from the signal region (SR) with $E_T^{miss} > 350$ GeV.

with $H \to \chi\bar{\chi}$, normalized to the SM next-to-leading order prediction for the WH and ZH production cross section (0.8 pb for $m_H = 125$ GeV) [51], which is 1.6 at 95% C.L. for $m_H = 125$ GeV.

In addition, limits are calculated on dark matter $W\chi\bar{\chi}$ or $Z\chi\bar{\chi}$ production within two fiducial regions defined at parton level: $p_T^{WorZ} > 250$ GeV, $|\eta^{WorZ}| < 1.2$; two quarks from W or Z boson decay with $\sqrt{y} > 0.4$; at most one additional narrow jet [$p_T > 40$ GeV, $|\eta| < 4.5$, ΔR (narrow jet, W or Z) > 0.9]; no electron, photon, or muon with $p_T > 10$ GeV and $|\eta| < 2.47$, 2.37, or 2.5, respectively; $p_T^{\chi\bar{\chi}} > 350$ or 500 GeV. The fiducial efficiencies are similar for various dark matter signals, and the smallest value is $(63 \pm 1)\%$ in both fiducial regions. The observed upper limit on the fiducial cross section is 4.4 fb (2.2 fb) at 95% C.L. for $p_T^{\chi\bar{\chi}} > 350$ GeV (500 GeV) and the expected limit is 5.1 fb (1.6 fb) with negligible dependence on the dark matter production model.

In conclusion, this Letter reports the first LHC limits on dark matter production in events with a hadronically decaying W or Z boson and large missing transverse momentum. In the case of constructive interference between up-type and down-type contributions, the results set the strongest limits on the mass scale of M_* of the unknown mediating interaction, surpassing those from the monojet signature.

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