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A B S T R A C T

A search is presented for dark matter produced in association with a hadronically decaying $W$ or $Z$ boson using 3.2 $fb^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the Large Hadron Collider. Events with a hadronic jet compatible with a $W$ or $Z$ boson and with large missing transverse momentum are analysed. The data are consistent with the Standard Model predictions and are interpreted in terms of both an effective field theory and a simplified model containing dark matter. © 2016 The Author. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP³.

Dark matter is the dominant component of matter in the universe, but its particle nature remains a mystery. Searches for a weakly interacting massive particle (WIMP), denoted by $\chi$, and for interactions between $\chi$ and Standard Model (SM) particles are a central component of the current set of dark-matter experiments.

At particle colliders, dark-matter particles may be produced in pairs via some unknown intermediate state. While in many models direct detection experiments have the greatest sensitivity for dark-matter masses $m_\chi$ between 10 and 100 GeV, searches for dark matter at particle colliders are most powerful for lower masses [1–3]. The final-state WIMPs are not directly detectable, but their presence can be inferred from the recoil against a visible particle [1]. Two example processes are shown in Fig. 1.

The Tevatron and LHC collaborations have reported limits on the cross section of $pp \rightarrow \chi \bar{\chi} + X$ and $pp \rightarrow \chi \bar{\chi} + X$, respectively, where $X$ is a hadronic jet [1–3], a photon ($\gamma$) [4,5], a $W/Z$ boson [6,7], or a Higgs boson [8,9]. In many cases, results are reported in terms of limits on the parameters of an effective field theory (EFT) formulated as a four-point contact interaction [10–18] between quarks and WIMPs. For such models, the strongest limits come from data in which the recoiling object is a jet. In other models, however, the interaction is between dark matter and vector bosons [19], such that the primary discovery mode would be in final states such as those analysed here, where the recoiling object is a $W$ or $Z$ boson.

In this Letter, a search is reported for the production of a $W$ or $Z$ boson 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 in data collected by the ATLAS detector from $pp$ collisions with centre-of-mass energy $\sqrt{s} = 13$ TeV. This search is sensitive to WIMP pair production, as well as to other dark-matter-related models which predict invisible Higgs boson decays ($WH$ or $ZH$ production with $H \rightarrow \chi \bar{\chi}$).

The ATLAS detector [20] at the LHC covers the pseudorapidity range $|\eta| < 4.9$ and the full azimuthal angle $\phi$. It consists of an inner tracking detector surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and an external muon spectrometer incorporating large superconducting toroidal magnets. A two-level trigger system is used to select interesting events to be recorded for subsequent offline analysis. Only data for which beams were stable and all subsystems described above were operational are used. Applying these requirements to $pp$ collision data, recorded during the 2015 LHC run, results in a data sample with a time-integrated luminosity of 3.2 $fb^{-1}$. The systematic uncertainty

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* E-mail address: atlas.publications@cern.ch.

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of 2.1% in the luminosity is derived following the same methodology as that detailed in Ref. [21].

Three non-exclusive categories of jet candidates are built, each using the anti-\(k_T\) clustering algorithm [22]. Two categories use clusters of energy deposits in calorimeter cells seeded by those with energies significantly above the measured noise and calibrated at the hadronic energy scale [25]. They are distinguished by their radius parameters; jets with radius parameter of 1.0 (0.4) are referred to as large-\(R\) jets (narrow jets). Large and narrow jets can share a fraction of their energy deposits. A third type of jet candidate is reconstructed from inner-detector tracks using the anti-\(k_T\) algorithm with \(R = 0.2\), referred to as track jets. Large-\(R\) jets are trimmed [26] to remove energy deposited by pile-up jets, the underlying event, and soft radiation. In this process, the constituents of large-\(R\) jets are reclustered using the \(k_T\) algorithm [23,24] with a distance parameter of 0.2, and subjects with transverse-momentum \(p_T\) less than 5% of the large-\(R\) jet \(p_T\) are removed. Large-\(R\) jets are required to satisfy \(p_T > 200\) GeV and \(|\eta| < 2.0\). These large-\(R\) jets are intended to capture the hadronic products of both quarks from the decay of a \(W\) or \(Z\) boson, while the narrow jets and track jets are helpful in background suppression. The internal structure of the large-\(R\) jet is characterized in terms of two quantities: \(D_2\) [27,28], which identifies jets with two distinct concentrations of energy [29,30], and \(m_{\text{jet}}\), which is the calculated invariant mass of the jet. Narrow jets are required to satisfy \(p_T > 20\) GeV for \(|\eta| < 2.5\) or \(p_T > 30\) GeV for \(2.5 < |\eta| < 4.5\). Track jets are required to satisfy \(p_T > 10\) GeV and \(|\eta| < 2.5\). For both the large-\(R\) and narrow jets, jet momenta are calculated by performing a four-vector sum over these component clusters, treating each topological cluster [25] as an \((E, \vec{p})\) four-vector with zero mass, and are calibrated to the hadronic scale. For narrow jets, the direction of \(\vec{p}\) is given by the line joining the reconstructed vertex with the barycentre of the energy cluster. The missing transverse momentum \(E_{\text{T}}^{\text{miss}}\) is calculated as the negative of the vector sum of the transverse momenta of reconstructed jets, leptons, and those tracks which are associated with the reconstructed vertex but not with any jet or lepton. A closely related quantity, \(E_{\text{T},\text{miss}}^{\text{EM}}\), is calculated in the same way but excluding reconstructed muons. A third variant, \(p_{\text{T}}^{\text{miss}}\), is the missing transverse momentum measured using inner detector tracks. The magnitudes of the three missing-transverse-momentum variants are denoted by \(E_{\text{T}}^{\text{miss}}, E_{\text{T},\text{miss}}^{\text{EM}},\) and \(p_{\text{T}}^{\text{miss}}\) respectively. Electrons, muons, jets, and \(E_{\text{T}}^{\text{miss}}\) are reconstructed as described in Refs. [25,31–33], respectively.

Candidate signal events are selected by an inclusive \(E_{\text{T}}^{\text{miss}}\) trigger that is more than 99% efficient for events with \(E_{\text{T}}^{\text{miss}} > 200\) GeV. Events triggered by detector noise and non-collision backgrounds are rejected as described in Ref. [34]. In addition, events are required to satisfy the requirements of \(E_{\text{T}}^{\text{miss}} > 250\) GeV, no reconstructed electrons or muons, and at least one large-\(R\) jet with \(p_T > 200\) GeV, \(|\eta| < 2.0\), \(m_{\text{jet}}\), and \(D_2\) consistent with a \(W\) or \(Z\) boson decay as in Ref. [35]. To further suppress background from multijet and \(\ell\ell\) production, events are required to satisfy \(p_{\text{T}}^{\text{miss}} > 30\) GeV, a minimum azimuthal angular distance, \(\Delta\phi\), of 0.6 between the \(E_{\text{T}}^{\text{miss}}\) and the nearest narrow jet, and \(\Delta\phi(E_{\text{T}}^{\text{miss}}, p_{\text{T}}^{\text{miss}}) < \pi/2\). Within a fiducial volume defined at parton level by similar selection requirements (except those on \(D_2\) and \(p_{\text{T}}^{\text{miss}}\)), the reconstruction efficiency for the signal models described above varies from 38% to 49%.

The dominant source of background events is \(Z \to \nu\bar{\nu}\) production in association with jets. A secondary contribution comes from the production of jets in association with a leptonically decaying \(W\) or \(Z\) boson in which the charged leptons are not identified or the \(\tau\) leptons decay hadronically. The third major background contribution comes from top-quark pair production. The kinematic distributions of these three largest backgrounds are estimated using simulated event samples but the normalization is determined using control regions where the dark-matter signal is expected to be negligible. Each control region requires \(E_{\text{T}}^{\text{miss}} > 200\) GeV and \(p_{\text{T}}^{\text{miss}} > 30\) GeV as well as one large-\(R\) jet satisfying the substructure requirement on \(D_2\) as applied in the signal region. The \(Z\) boson control region requires exactly two muons with dimuon invariant mass \(66 < m_{\mu\mu} < 116\) GeV. The \(W\) boson (top quark) control region requires exactly one muon, and zero (at least one) b-tagged track jet not associated with the large-\(R\) jet. Validation of the reconstruction of hadronic \(W\) boson decays with large-\(R\) jets is performed in the top-quark control region, as shown in Fig. 2, which also presents the distribution of the \(D_2\) substructure variable. Other sources of background are diboson production and single-top-quark production. The contribution to the signal region from multijet production is negligible.

Samples of simulated \(W + \) jets and \(Z + \) jets events are generated using \textsc{Sherpa} 2.1.1 [36]. Matrix elements are calculated for up to two partons at next-to-leading order (NLO) and four partons at leading order (LO) using the \textsc{Comix} [37] and \textsc{Open-Loops} [38] matrix element generators and merged with the \textsc{Sherpa} parton shower [39] using the ME+PS@NLO prescription [40]. The CT10 [41] PDF set is used in conjunction with dedicated parton shower tuning developed by the \textsc{Sherpa} authors. The \(W/Z\) production rates are normalized to a next-to-next-to-leading order (NNLO) calculation [42]. The production of \(\ell\ell\) and single-top processes, including s-channel, t-channel and Wt production is modelled with the \textsc{Powheg-Box} v2 generator [43–45] interfaced to \textsc{Pythia}6.428 [46]. In these generators the CT10 and CTEQ6L1 [47] PDF sets are used, respectively. Top-quark pair production is normalized to NNLO with next-to-next-to-leading-logarithm corrections [48] in QCD while single-top processes are normalized at NLO [49,50] in QCD. The diboson (\(WW, WZ, ZZ\)) processes are simulated using \textsc{Sherpa} 2.1.1 with the CT10 PDF and normalized at NLO [51,52] in QCD. The multijet process is described using samples simulated with \textsc{Pythia}8.186 [53] and the NNPDF2.3LO [54] PDF at leading order in QCD; these multijet samples were used to develop the background estimation strategy but not for the final background prediction.
Fig. 2. Pane (a) Distribution of $m_t$ in the data and for the predicted background in the top-quark control region. Pane (b) Distribution of jet substructure variable $D_2$ in the data and for the predicted background in events satisfying all signal region requirements other than those on $D_2$. Also shown is the distribution for the simplified model with a vector-boson mediator, scaled by a factor of $10^4$ for given values of $m_A$ and $m_{\text{med}}$: the mediator mass. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. The $E_{T,\text{miss}}$ distribution of the events in the control regions after the profile-likelihood fit to the data under the background-only hypothesis. Pane (a) shows the $t\bar{t}$ control region, pane (b) shows the $Z +\text{jets}$ control region, and pane (c) shows the $W +\text{jets}$ control region. The total background prediction before the fit is shown as a dashed line. The inset at the bottom of each plot shows the ratio of the data to the total post-fit background. The hatched bands represent the total uncertainty in the background. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Samples of simulated $VV\chi\bar{\chi}$ and $Z\chi\bar{\chi}$ events are generated using MadGraph5_AMC@NLO [55], and the underlying event and parton showering are simulated with Pythia8.186 [53]. Two theoretical models are used as benchmarks: a seven-dimensional $VV\chi\chi$ EFT [19] model ($V$ meaning $W$ or $Z$) and a vector-mediated simplified model [56]. The strength of the EFT interaction is controlled by a mass scale, $M_v$, and the strength of the simplified model interaction is controlled by the product of the couplings of the mediator to the SM and the dark matter (DM) particles, $g_{3\text{amDM}}$. The EFT model samples were generated with $M_v = 3000 \text{ GeV}$, and the simplified model samples were generated with couplings $g_{3\text{SM}} = 0.25$ and $g_{3\text{DM}} = 1$. The samples were generated as a function of dark-matter particle mass $m_{\chi}$ for the EFT model and in a grid of mediator mass $m_{\text{med}}$ and $m_{\chi}$ for the simplified model.

Major sources of systematic uncertainty are uncertainties in the modelling of large-$R$ jet observables, which have a $5\%$–$13\%$ impact on the expected background and signal yields, and the energy scale of the narrow jets, which contribute a $1\%$–$5\%$ uncertainty to the expected yields. Other sources of uncertainty include theoretical uncertainties in the simulated event samples used to model the background processes ($1\%$–$10\%$), parton distribution functions ($10\%$–$15\%$), and lepton reconstruction and identification efficiencies (up to $2\%$).

A profile-likelihood fit [57] to the $E_T^{\text{miss}}$ ($E_T^{\text{miss}} + m_{\text{med}}$) distribution in the signal region (control regions) is used to constrain the $W$ boson, $Z$ boson, and $t\bar{t}$ backgrounds and extract the signal strength, $\mu$, for each model as an overall normalization factor for the signal prediction. Besides the signal strength, three overall normalization factors for the $W$ boson, $Z$ boson, and $t\bar{t}$ backgrounds are parameters in the fit. The diboson and single-top backgrounds are estimated from simulation, and the multijet background is negligible. The likelihood function is defined as the product of Poisson distributions over all bins in $E_T^{\text{miss}}$ and $E_T^{\text{miss}} + m_{\text{med}}$ and the likelihood is simultaneously maximized over the signal and control regions.

Variations of the expected signal and background to allow for their systematic uncertainties are described with nuisance parameters constrained by Gaussian probability distribution functions, and correlations across signal and background processes and regions are taken into account.

A background-only ($\mu = 0$) fit, shows no deviation from SM predictions, and Figs. 3 and 4 show kinematic distributions after the profile-likelihood fit. The floating background-normalization parameters are consistent with unity within one standard deviation. Tables 1 and 2 show the expected event yields after applying the signal selection and the background normalization scale factors, respectively. The values in these tables are estimated for the background-only hypothesis.

Upper limits at 95% confidence level (C.L.) on $\mu$ are calculated using the $C_L$ method [58]. For the $VV\chi\chi$ EFT model, these limits are translated into constraints on the mass scale, $M_v$. Fig. 5(a) shows the limit on the mass scale, $M_v$, in the EFT model, as a function of $m_{\chi}$. Fig. 5(b) shows the limits on the signal strength, $\mu$, for a vector-mediated simplified model generated with couplings $g_{3\text{SM}} = 0.25$ and $g_{3\text{DM}} = 1$ in the plane of $m_{\chi}$ and $m_{\text{med}}$.

In conclusion, this Letter reports ATLAS limits on dark-matter production in events with a hadronically decaying $W$ or $Z$ boson and large missing transverse momentum. These limits from $3.2 \text{ fb}^{-1}$ of $13 \text{ TeV}$ pp collisions at the LHC improve on earlier ATLAS results. No statistically significant excess is observed over the Standard Model prediction.

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References


1 Department of Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany, NY, United States
3 Department of Physics, University of Alberta, Edmonton, AB, Canada
4 (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydina University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
7 Department of Physics, University of Arizona, Tucson, AZ, United States
8 Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Department of Physics, The University of Texas at Austin, Austin, TX, United States
12 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
13 Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
14 Institute of Physics, University of Belgrade, Belgrade, Serbia
15 Department for Physics and Technology, University of Bergen, Bergen, Norway
16 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
17 Department of Physics, Humboldt University, Berlin, Germany
18 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
19 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
20 (a) Department of Physics, Bogazici University, Istanbul, (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; (d) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
21 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
22 (a) INFN Sezione di Bologna, (b) Department of Fisica e Astronomia, Università di Bologna, Bologna, Italy
23 Physikalisches Institut, University of Bonn, Bonn, Germany
24 Department of Physics, Boston University, Boston, MA, United States
25 Department of Physics, Brandeis University, Waltham, MA, United States
26 (a) Universidade Federal de Rio de Janeiro COPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
27 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
28 (a) Transilvania University of Brasov, Brasov, Romania; (b) National Institute of Physics and Nuclear Engineering, Bucharest; (c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (d) University Politehnica Bucharest, Bucharest; (e) West University in Timisoara, Timisoara, Romania
29 Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina
30 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
31 Department of Physics, Carleton University, Ottawa, ON, Canada
32 CERN, Geneva, Switzerland
33 Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
34 (a) Departamento de Fisica, Pontificia Universidad Catolica de Chile, Santiago; (b) Departamento de Fisica, Universidad Técnica Federico Santa Maria, Valparaiso, Chile
35 (a) Instituto de High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Physics, Nanjing University, Jiangsu; (c) Physics Department, Tsinghua University, Beijing, China
36 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
37 Nevis Laboratory, Columbia University, Irvington, NY, United States
38 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
39 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
40 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
41 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
42 Physics Department, Southern Methodist University, Dallas, TX, United States
43 Physics Department, University of Texas at Dallas, Richardson, TX, United States
44 DESY, Hamburg and Zeuthen, Germany
45 Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
46 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
47 Department of Physics, Duke University, Durham, NC, United States
48 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
49 INFN Laboratori Nazionali di Frascati, Frascati, Italy
50 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
51 Section de Physique, Université de Genève, Geneva, Switzerland
52 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
53 (a) II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
54 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
55 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
56 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
58 Department of Modern Physics, University of Science and Technology of China, Anhui, China
59 (a) Kirchoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für Technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
61 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
Also at School of Physics, Shandong University, Shandong, China.

Also at Department of Physics, California State University, Sacramento, CA, United States.

Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at Eotvos Lorand University, Budapest, Hungary.

Also at Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, United States.

Also at International School for Advanced Studies (SISSA), Trieste, Italy.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.

Also at Institut de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.

Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at National Research Nuclear University MEPhI, Moscow, Russia.

Also at Department of Physics, Stanford University, Stanford, CA, United States.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at Flensburg University of Applied Sciences, Flensburg, Germany.

Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

Also affiliated with PKU-CHEP.

* Deceased.