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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

G. Aad et al.*

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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 \( \chi \), and for interactions between \( \chi \) and standard model (SM) particles [1].

One critical component of this program is the search for pair production of WIMPs at particle colliders, specifically \( pp \rightarrow \chi \bar{\chi} \) at the Large Hadron Collider (LHC) via some unknown intermediate state. These searches have greatest sensitivity at low WIMP mass \( m_{\chi} \), 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 \( pp \rightarrow \chi \bar{\chi} + X \) where \( X \) is a hadronic jet [2–4] or a photon [5,6]. Other LHC data have been interpreted 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 \( M_{\chi} \) 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 \( H \rightarrow \chi \bar{\chi} \)).

The ATLAS detector [19] at the LHC covers the pseudorapidity [20] range \( |\eta| < 4.9 \) and the full azimuthal angle \( \phi \). 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...
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 $\sqrt{\Delta} = \min(p_{T1}, p_{T2}) \Delta R / m_{\text{jet}}$ where $\Delta R = \sqrt{(\Delta \phi_{1,2})^2 + (\Delta \eta_{1,2})^2}$ and $m_{\text{jet}}$ 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 $E_T^{\text{miss}}$ is measured using all clusters of energy deposits in the calorimeter with $|\eta| < 4.5$. Electrons, muons, jets, and $E_T^{\text{miss}}$ 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 ($p_T > 250$ GeV, $|\eta| < 1.2$), two additional narrow jets ($p_T > 40$ GeV, $|\eta| < 4.5$) separated from the leading large-radius jet, at least one $b$ tag, and $E_T^{\text{miss}} > 250$ GeV (Fig. 2).

Candidate signal events are accepted by an inclusive $E_T^{\text{miss}}$ trigger that is more than 99% efficient for events with $E_T^{\text{miss}} > 150$ 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 $p_T > 250$ GeV, $|\eta| < 1.2$, $m_{\text{jet}}$ between 50 GeV and 120 GeV, and $\sqrt{\Delta}$ > 0.4 to suppress background without hadronic $W$ or $Z$ boson decays. Two signal regions are defined by two thresholds in $E_T^{\text{miss}}$: 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 $p_T > 40$ 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 $\Delta \phi(E_T^{\text{miss}} \text{ jet}) < 0.4$. Finally, to suppress contributions from $W \rightarrow \ell \nu$ production, events are rejected if they have any electron, photon, or muon candidates with $p_T > 10$ GeV and $|\eta| < 2.47, 2.37, \text{or } 2.5$, respectively.

The dominant source of background events is $Z \rightarrow \nu \bar{\nu}$ 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 $\tau$ 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 $W/Z + \text{jets}$ with muon decays are the dominant processes. In this muon control region dominated by $W/Z + \text{jets}$ with muon decays, the combined $W$ and $Z$ boson contribution is measured after subtracting other sources of background that are estimated using Monte Carlo simulation [30] based on GEANT4 [31]. Two extrapolation factors from the contribution of $W/Z + \text{jets}$ in the muon control region to the contributions of $Z \rightarrow \nu \bar{\nu}$ + jets and $W/Z + \text{jets}$ with leptonic decays in the muon-veto signal region, respectively, are derived as a function of $m_{\text{jet}}$ 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 $E_T^{\text{miss}} > 350$ 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-$E_T^{\text{miss}}$ control region with the same selection as the signal region but 250 GeV < $E_T^{\text{miss}}$ < 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 AUE02 [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.

<table>
<thead>
<tr>
<th>Process</th>
<th>$E_{T}^{miss} &gt; 350$ GeV</th>
<th>$E_{T}^{miss} &gt; 500$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \nu \bar{\nu}$</td>
<td>402$^{+39}_{-34}$</td>
<td>74$^{+39}_{-34}$</td>
</tr>
<tr>
<td>$W \rightarrow \ell^{\pm} \nu$, $Z \rightarrow \ell^{\pm} \ell^{\mp}$</td>
<td>210$^{+20}_{-18}$</td>
<td>22$^{+20}_{-18}$</td>
</tr>
<tr>
<td>WW, WZ, ZZ</td>
<td>57$^{+11}_{-11}$</td>
<td>9.1$^{+11}_{-11}$</td>
</tr>
<tr>
<td>$t\bar{t}$, single $t$</td>
<td>39$^{+10}_{-10}$</td>
<td>3.7$^{+10}_{-10}$</td>
</tr>
<tr>
<td>Total</td>
<td>707$^{+48}_{-38}$</td>
<td>89$^{+48}_{-38}$</td>
</tr>
<tr>
<td>Data</td>
<td>705</td>
<td>89</td>
</tr>
</tbody>
</table>

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 $E_{T}^{miss}$ 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 $pp \rightarrow WZ \chi\bar{\chi}$ and $pp \rightarrow ZZ \chi\bar{\chi}$ 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 $E_{T}^{miss}$. 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 $E_{T}^{miss}$ 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 $M_{s}$ vs $m_{\chi}$ plane for various operators, where $M_{s}$ need not be the same for the different operators.

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

FIG. 4 (color online). Observed limits on the effective theory mass scale $M_{s}$ as a function of $m_{\chi}$ 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.
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 \( m_t < 10 \text{ GeV} \) 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 \( WH \) with a light mediator is \( 1.3 \text{ pb} \) at 95% C.L. for \( m_H = 125 \text{ GeV} \). Figure 6 shows the upper limit of the total cross section of \( WH \) and \( ZH \) processes with \( H \rightarrow \chi \chi \), normalized to the SM next-to-leading order prediction for the \( WH \) and \( ZH \) production cross section (0.8 pb for \( m_H = 125 \text{ GeV} \)) \[51\], which is 1.6 at 95% C.L. for \( m_H = 125 \text{ GeV} \).

In addition, limits are calculated on dark matter \( W\chi \) or \( Z\chi \) production within two fiducial regions defined at parton level: \( p_T^{W/Z} > 250 \text{ GeV} \), \( |\eta^{W/Z}| < 1.2 \); two quarks from \( W \) or \( Z \) boson decay with \( \sqrt{s} > 0.4 \); at most one additional narrow jet \( \{p_T > 40 \text{ GeV} \}, |\eta| < 4.5, \Delta R \} \) (narrow jet, \( W \) or \( Z \)) \( > 0.9 \); no electron, photon, or muon with \( p_T > 10 \text{ GeV} \) and \( |\eta| < 2.47, 2.57, \) or 2.5, respectively; \( p_T^{\ell} > 350 \) 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 \( p_T^{\ell} > 350 \text{ GeV} \) (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 \( M_\chi \) of the unknown mediating interaction, surpassing those from the monojet signature.

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((ATLAS Collaboration))

1School of Chemistry and Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton, Alberta Canada
4Department of Physics, Ankara University, Ankara, Turkey
5Department of Physics, Gazi University, Ankara, Turkey
6Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
7Turkish Atomic Energy Authority, Ankara, Turkey
8High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
9Department of Physics, University of Arizona, Tucson, Arizona, USA
10Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
11Institute of Physics, University of Belgrade, Belgrade, Serbia
12Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13Institutes of Physics, University of Belgrade, Belgrade, Serbia
14Department of Physics and Technology, University of Bergen, Bergen, Norway
15Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
16Department of Physics, Humboldt University, Berlin, Germany
17Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19Department of Physics, Bogazici University, Istanbul, Turkey
20Department of Physics, Dogus University, Istanbul, Turkey
21Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
22Department of Physics, Boston University, Boston, Massachusetts, USA
23Department of Physics, Brandeis University, Waltham, Massachusetts, USA
24Universidade Federal do Rio de Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
25Department of Physics, Carleton University, Ottawa, Ontario, Canada
26Department of Physics, Brookhaven National Laboratory, Upton, New York, USA
27Department of Physics, Capital Normal University, Beijing, China
28Department of Physics, Nanjing University, Jiangsu, China
29School of Physics, Shandong University, Shandong, China
30Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
31Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China
32Department of Physics, Pontificia Universidad Católica de Chile, Santiago, Chile
33Department of Physics, Universidad Técnica Federico Santa María, Valparaíso, Chile
34National Institute for Research and Development of Isotopic and Molecular Technologies, Cluj Napoca, Romania
35National Institute for Research and Development of Isotopic and Molecular Technologies, Bucharest, Romania
36University Politehnica Bucharest, Bucharest, Romania
37West University in Timisoara, Timisoara, Romania
38Department of Física, Universidad de Buenos Aires, Buenos Aires, Argentina
39Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
40Department of Physics, Carleton University, Ottawa, Ontario, Canada
41CERN, Geneva, Switzerland
42Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
INFN Sezione di Milano, Italy
Dipartimento di Fisica, Università di Milano, Milano, Italy
B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada
P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
INFN Sezione di Napoli, Italy
Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York, USA
Ohio State University, Columbus, Ohio, USA
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
INFN Sezione di Pavia, Italy
Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
Petersburg Nuclear Physics Institute, Gatchina, Russia
INFN Sezione di Pisa, Italy
Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
Laboratorio de Instrumentacion e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Physics Department, University of Regina, Regina, Saskatchewan, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan
INFN Sezione di Roma I, Italy
Dipartimento di Fisica, Università La Sapienza, Roma, Italy
INFN Sezione di Roma Tor Vergata, Italy
Dipartimento di Fisica, Università Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre, Italy
Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco
Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco
Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.

Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

Also at TRIUMF, Vancouver BC, Canada.

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

Also at Novosibirsk State University, Novosibirsk, Russia.

Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

Also at Università di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPP), Canada.

Also at Department of Physics, Middle East Technical University, Ankara, Turkey.

Also at Louisiana Tech University, Ruston LA, United States of America.

Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.

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

Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America.

Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

Also at Department of Physics, University of Cape Town, Cape Town, South Africa.

Also at CERN, Geneva, Switzerland.

Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

Also at Manhattan College, New York NY, United States of America.

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

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

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

Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.

Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.

Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.

Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France.

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

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

Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.

Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America.

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

Also at DESY, Hamburg and Zeuthen, Germany.

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 of America.

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

Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America.

Also at Physics Department, Brookhaven National Laboratory, Upton NY, United States of America.

Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.

Also at Department of Physics, Oxford University, Oxford, United Kingdom.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America.

Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.