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The ATLAS Collaboration

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Search for dark matter produced in association with a hadronically decaying vector boson in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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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.

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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-\( k_L \) 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-\( k_L \) 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 \( k_L \) 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 \( p_T > 200 \text{ GeV} \) 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 calculated using invariant mass of the jet. Narrow jets are required to satisfy \( p_T > 20 \text{ GeV} \) for \( |\eta| < 2.5 \) or \( p_T > 30 \text{ GeV} \) for \( 2.5 < |\eta| < 4.5 \). Track jets are required to satisfy \( p_T > 10 \text{ GeV} \) 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 \( E_{T}^{\text{miss}} \) 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, \( E_{T}^{\text{miss},\text{jet}} \), is calculated in the same way but excluding reconstructed muons. A third variant, \( p_{T}^{\text{miss}} \), is the missing transverse momentum measured using inner detector tracks. The magnitudes of the three missing-transverse-momentum variants are denoted by \( E_{T}^{\text{miss}}, E_{T}^{\text{miss},\text{jet}}, \) and \( p_{T}^{\text{miss}} \) respectively. Electrons, muons, jets, and \( E_{T}^{\text{miss}} \) are reconstructed as described in Refs. [25, 31–33], respectively.

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

The dominant source of background events is \( Z \rightarrow \nu\bar{\nu} \) 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 \( E_{T}^{\text{miss}} > 200 \text{ GeV} \) and \( p_{T}^{\text{miss}} > 30 \text{ GeV} \) 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 \( 66 < m_{\mu\mu} < 116 \text{ GeV} \). 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 \( W + \text{jets} \) and \( Z + \text{jets} \) events are generated using 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 Comix [37] and OpenLoops [38] matrix element generators and merged with the 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 SHERPA authors. The \( W/Z \) production rates are normalized to a next-to-next-to-leading order (NNLO) calculation [42]. The production of \( t\bar{t} \) and single-top processes, including s-channel, t-channel and Wt production is modelled with the POWHEG-Box v2 generator [43–45] interfaced to PyTHIA6.428 [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 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 PyTHIA8.186 [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 $m_{\text{jet}}$ 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 $m_\chi$ 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 $E_{\text{T}}^{\text{miss}}$ 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 $Z$ + jets control region, and pane (c) shows the $W$ + 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.)
Fig. 4. The $E_{\text{miss}}^\text{miss}$ distribution of the events in the signal region after the profile-likelihood fit to the data under the background-only hypothesis. The inset shows the ratio of the data to the total background. Also shown is the $E_{\text{miss}}^\text{miss}$ distribution for the simplified model with a vector-boson mediator, scaled by a factor of $10^3$ for $m_{\chi} = 10 \text{ GeV}$ and $m_{\text{med}} = 10 \text{ TeV}$. The total background after the fit is shown as a dashed line. 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 $W\chi\bar{\chi}$ 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, $M_{\chi}$, 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, $g_{3M}g_{DM}$. The EFT model samples were generated with $M_{\chi} = 3000 \text{ GeV}$, and the simplified model samples were generated with couplings $g_{3M} = 0.25$ and $g_{DM} = 1$. 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 $E_{\text{miss}}$ ($E_{T,\text{miss}}$) 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 $E_{\text{miss}}$ and $E_{T,\text{miss}}$, 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 CL$_s$ method [58]. For the $VV\chi\chi$ EFT model, these limits are translated into constraints on the mass scale, $M_{\chi}$. Fig. 5(a) shows the limit on the mass scale, $M_{\chi}$, 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 $g_{3M} = 0.25$ and $g_{DM} = 1$ 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.

### Table 1

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z + \text{jets}$</td>
<td>$544 \pm 33$</td>
</tr>
<tr>
<td>$W + \text{jets}$</td>
<td>$275 \pm 24$</td>
</tr>
<tr>
<td>$t\bar{t}$ and single-top</td>
<td>$211 \pm 19$</td>
</tr>
<tr>
<td>Diboson</td>
<td>$89 \pm 12$</td>
</tr>
<tr>
<td>Total background</td>
<td>$1120 \pm 47$</td>
</tr>
<tr>
<td>Data</td>
<td>$1121$</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Process</th>
<th>Normalization factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z + \text{jets}$</td>
<td>$1.01 \pm 0.16$</td>
</tr>
<tr>
<td>$W + \text{jets}$</td>
<td>$0.90 \pm 0.16$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$0.91 \pm 0.18$</td>
</tr>
</tbody>
</table>

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References


The ATLAS Collaboration

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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 (ao) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin 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, Turkey; (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 (ao) INFN Sezione di Bologna, (b) Dipartimento di 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 do Rio de Janeiro COPE/EE/IE, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of São João del Rei (UFSJ), São João del Rei; (d) Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
27 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
28 (a) Transilvania University of Brașov, Brașov, 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 Física, 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 Física, Pontificia Universidad Catolica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaiso, Chile
35 (a) Instituto de Alta Energia Física (IHCF/IQSC), Instituto de Ciências Basicas da Unesp, Sao Paulo, Brazil; (b) Departamento de Física, Federal University of Rio de Janeiro (UFRJ), Rio de Janeiro; (c) Physics Department, University of São Paulo, São Paulo, Brazil
36 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
37 (ao) INFN Sezione in Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
38 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
39 Niels Bohr Institute, University of Copenhagen, København, Denmark
40 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
41 (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
42 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
43 Physics Department, Southern Methodist University, Dallas, TX, United States
44 Physics Department, University of Texas at Dallas, Richardson, TX, United States
45 DESY, Hamburg and Zeuthen, Germany
46 Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
47 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
48 Department of Physics, Duke University, Durham, NC, United States
49 SLAC – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
50 INFN Laboratori Nazionali di Frascati, Frascati, Italy
51 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
52 Section de Physique, Université de Genève, Geneva, Switzerland
53 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
54 (a) E. Andreonianashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
55 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
56 SLUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
57 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
58 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
59 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
60 Department of Modern Physics, University of Science and Technology of China, Anhui, China
61 (a) Kirchhoff-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
62 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
63 (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
63 Department of Physics, Indiana University, Bloomington, IN, United States
64 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
65 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
66 Joint Institute for Nuclear Research, Dubna, Russia
67 KER, High Energy Accelerator Research Organization, Tsukuba, Japan
68 Graduate School of Science, Kobe University, Kobe, Japan
69 Faculty of Science, Kyoto University, Kyoto, Japan
70 University of Education, Kyoto, Japan
71 Department of Physics, Kyushu University, Fukuoka, Japan
72 Instituto de Fisica La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
73 Physics Department, Lancaster University, Lancaster, United Kingdom
74 (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
75 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
76 Department of Physics, Jozef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
77 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
78 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
79 Department of Physics and Astronomy, University College London, London, United Kingdom
80 Louisiana Tech University, Ruston, LA, United States
81 Laboratoire de Physique Nuclcaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
82 Physiok institutionen, Lund universitet, Lund, Sweden
83 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
84 Institut für Physik, Universität Mainz, Mainz, Germany
85 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
86 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
87 Department of Physics, University of Massachusetts, Amherst, MA, United States
88 Department of Physics, McGill University, Montreal, QC, Canada
89 School of Physics, University of Melbourne, Victoria, Australia
90 Department of Physics, The University of Michigan, Ann Arbor, MI, United States
91 Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
92 INFN Sezione di Milano, (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
93 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
94 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
95 Group of Particle Physics, University of Montreal, Montreal, QC, Canada
96 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
97 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
98 National Research Nuclear University MEPhI, Moscow, Russia
99 D.V.Skobeltsyn Institute of Nuclear Physics, N.V. Lomonosov Moscow State University, Moscow, Russia
100 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
101 Nagasaki Institute of Applied Science, Nagasaki, Japan
102 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
103 INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
104 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
105 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
106 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
107 Department of Physics, Northern Illinois University, DeKalb, IL, United States
108 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
109 Department of Physics, New York University, New York, NY, United States
110 Ohio State University, Columbus, OH, United States
111 Faculty of Science, Okayama University, Okayama, Japan
112 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
113 Department of Physics, Oklahoma State University, Stillwater, OK, United States
114 Palacky University, Brno, Czech Republic
115 Center for High Energy Physics, University of Oregon, Eugene, OR, United States
116 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
117 Graduate School of Science, Osaka University, Osaka, Japan
118 Department of Physics, University of Oslo, Oslo, Norway
119 Department of Physics, Oxford University, Oxford, United Kingdom
120 INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
121 Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
122 National Research Center "Kurchatov Institute" B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
123 INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
124 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
125 Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
126 Department of Physics, University of Coimbra, Coimbra; (b) Centro de Fisica Nuclear da Universidade de Lisboa, Lisboa, Portugal
127 INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
128 INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
129 INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
130 Faculdade de Ciências de Lisboa, Universidade de Lisboa, Lisboa, Portugal
131 (a) Departamento de Física de Partículas, Instituto de Física de Partículas e Astrofísica, Universidade de Lisboa, Lisboa, Portugal
132 Department of Physics, University College London, London, United Kingdom
133 INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
134 INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
135 INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
136 Faculdade de Ciências de Lisboa, Universidade de Lisboa, Lisboa, Portugal
137 DMS/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 Department of Physics, King’s College London, London, United Kingdom.

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at Novosibirsk State University, Novosibirsk, Russia.

Also at TRIUMF, Vancouver, BC, Canada.

Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States.

Also at Physics Department, Al-Najah National University, Nablus, Palestine.

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

Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

Also at Department de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.

Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.

Also at Tomsk State University, Tomsk, Russia.

Also at Universita di Napoli Parthenope, Napoli, Italy.

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

Also at National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

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

Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

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

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

Also at Graduate School of Science, Osaka University, Osaka, Japan.

Also at Department of Physics, National Tsing Hua University, Taiwan.

Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

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

Also at CERN, Geneva, Switzerland.

Also at Georgian Technical University (GTU), Tbilisi, Georgia.

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

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

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
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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, 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 affiliated with PKU-CHEP.

∗ Deceased.