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


Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.112.041802

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: http://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariaal, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (http://dare.uva.nl)
Download date: 03 Mar 2019
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.*

(Received 16 September 2013; published 29 January 2014)

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 WIMPs with large missing transverse momentum are set in two fiducial regions.

DOI: 10.1103/PhysRevLett.112.041802

PACS numbers: 13.85.Rm, 14.70.Fm, 14.80.Bn, 95.35.+d

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 $pp \to \chi \chi$ 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 $pp \to \chi \chi + X$ 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 $\chi \chi$ 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 $H \to \chi \chi$).

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

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

* Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published articles title, journal citation, and DOI.
above were operational are used. Applying these requirements to pp collision data, taken at a center-of-mass energy of √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 √s = min(pT1, pT2) ΔR/mjet where ΔR = \sqrt{(Δϕ_{1,2})^2 + (Δη_{1,2})^2} and mjet is the calculated mass of the jet. Jet candidates are also reconstructed using the anti-kt 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 \(|η| < 4.5\). 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 \( tt \)-dominated control region with one muon, one large-radius jet (\( p_T > 250 \) GeV, \(|η| < 1.2\)), two additional narrow jets (\( p_T > 40 \) GeV, \(|η| < 4.5\)) 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, \(|η| < 1.2\), \( m_{\text{jet}} \) between 50 GeV and 120 GeV, and \( \sqrt{s} > 0.4 \) 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 \(|η| < 4.5\) which is not completely overlapping with the leading large-radius jet by a separation of \( ΔR > 0.9 \), or if any narrow jet has \( Δϕ(E_T^{\text{miss}} \text{jet}) < 0.4 \). Finally, to suppress contributions from \( W \to ℓν \) production, events are rejected if they have any electron, photon, or muon candidates with \( p_T > 10 \) GeV and \(|η| < 2.47, 2.37, \text{ or } 2.5\), respectively.

The dominant source of background events is \( Z \to ν \bar{ν} \) 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 \( Z \to ν \bar{ν} \) jets and \( W/Z+jets \) 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 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.

<table>
<thead>
<tr>
<th>Process</th>
<th>$E_{T}^{\text{miss}} &gt; 350$ GeV</th>
<th>$E_{T}^{\text{miss}} &gt; 500$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \nu\bar{\nu}$</td>
<td>402$^{+39}_{-34}$</td>
<td>54$^{+8}_{-10}$</td>
</tr>
<tr>
<td>$W \rightarrow \ell^{\pm}\nu$, $Z \rightarrow \ell^{\pm}\ell^{\mp}$</td>
<td>210$^{+20}_{-18}$</td>
<td>22$^{+5}_{-4}$</td>
</tr>
<tr>
<td>WW, WZ, ZZ</td>
<td>57$^{+11}_{-11}$</td>
<td>9.1$^{+1.3}_{-1.1}$</td>
</tr>
<tr>
<td>$t\bar{t}$, single $t$</td>
<td>39$^{+10}_{-4}$</td>
<td>3.7$^{+1.7}_{-1.3}$</td>
</tr>
<tr>
<td>Total</td>
<td>707$^{+48}_{-38}$</td>
<td>89$^{+9}_{-12}$</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 ACERM C3.8 [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 $E_{T}^{\text{miss}}$ 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 $pp \rightarrow W/Z\chi$ and $pp \rightarrow Z\chi$ 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, $m_{\chi} = 1, 50, 100, 200, 400, 700, 1000, \text{and } 1300$ 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 $E_{T}^{\text{miss}}$. 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 $m_{\text{jet}}$ distribution. The data agree well with the background estimate for each $E_{T}^{\text{miss}}$ threshold. Exclusion limits are set on the dark matter signals using the predicted shape of the $m_{\text{jet}}$ 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 $m_{\chi}$ vs $m_{\text{jet}}$ plane for various operators, where $M_{\chi}$ need not be the same for the different operators.
with $H \to \chi \chi'$, normalized to the SM next-to-leading order prediction for the $WH$ and $ZH$ production cross section (0.8 pb for $m_H = 125$ GeV) [51], which is 1.6 at 95% C.L. for $m_H = 125$ GeV.

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

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST, and NSFC, China; COLCIENCIAS, Colombia; MSM, CR, MPO, CR, and VSC CR, Czech Republic; DNR, DNSRC, and Lundbeck Foundation, Denmark; EPLANET, ERC, and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG, and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRS, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF, and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society, and Leverhulme Trust, United Kingdom; U.S. DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark,
The pseudorapidity is defined in terms of the polar angle \( \theta \), which is measured from the positive \( z \) axis points upward. Polar coordinates \((x, y, \theta)\) plane, \( \phi \) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle \( \eta = -\ln \tan(\theta/2) \).

[20] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the \( z \) axis along the beam pipe. The \( x \) axis points from the IP to the center of the LHC ring, and the \( y \) axis points upward. Polar coordinates \((r, \phi)\) are used in the transverse \((x, y)\) plane, \( \phi \) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle \( \eta = -\ln \tan(\theta/2) \).

---

D. Zieminska, 60 N. I. Zimin, 64 C. Zimmermann, 82 R. Zimmermann, 21 S. Zimmermann, 48 Z. Zinonos, 123a, 123b M. Ziolkowski, 142 R. Zitoun, 5 L. Živković, 35 G. Zobernig, 174 A. Zoccoli, 20a, 20b M. zur Nedden, 16 G. Zurzolo, 103a, 103b V. Zutshi, 107 and L. Zwalinski 30a

((ATLAS Collaboration))

1 School of Chemistry and Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany, New York, USA
3 Department of Physics, University of Alberta, Edmonton, Alberta Canada
4 Department of Physics, Ankara University, Ankara, Turkey
5 Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
6 Department of Physics, University of Arizona, Tucson, Arizona, USA
7 Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
8 Department of Physics, University of Athens, Athens, Greece
9 Physics Department, National Technical University of Athens, Zografou, Greece
10 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
11 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
12 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
13a Institute of Physics, University of Belgrade, Belgrade, Serbia
13b Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19a Department of Physics, Bogazici University, Istanbul, Turkey
19b Department of Physics, Dogus University, Istanbul, Turkey
19c Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20a INFN Sezione di Bologna, Italy
20b Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston, Massachusetts, USA
23 Department of Physics, Brandeis University, Waltham, Massachusetts, USA
24 Universidad Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
24a Federal University of Itaj de Fora (UFJF), Itaj de Fora, Brazil
24b Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
24c Instituto de Fisica, Universidade de SaoPaulo, Sao Paulo, Brazil
25 Department of Physics, Brookhaven National Laboratory, Upton, New York, USA
26a National Institute of Physics and Nuclear Engineering, Bucharest, Romania
26b National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
26c University Politehnica Bucharest, Bucharest, Romania
26d West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa, Ontario, Canada
30a CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
32a Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
32b Departamento de Física, Universidad Técnica Federico Santa Maria, Valparaíso, Chile
33a Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
33b Department of Modern Physics, University of Science and Technology of China, Anhui, China
33c Department of Physics, Nanjing University, Jiangsu, China
33d School of Physics, Shandong University, Shandong, China
34 Laboratoire de Physique Corpusculaire, Clermont Université et Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 School of Physics, Shanghai Jiao Tong University, Shanghai, China
36 Laboratory of Physics, Clermont Université and University 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, Universitàdi 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-MaskawaInstitute, Nagoya University, Nagoya, Japan
INFN Sezione di Napoli, Italy
Dipartimento di Scienze Fisiche, Universitàdi 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, Universitàdi Pisa, Pisa, Italy
Department of Physics and Astronomy, Universityof Pittsburgh, Pittsburgh, Pennsylvania, USA
Laboratorio de Instrumentacao 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, Universitàdi 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 Institucio 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 Academy Sinica, Taipei, Taiwan.
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, 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.