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Search for Dark Matter Candidates and Large Extra Dimensions in Events with a Photon and Missing Transverse Momentum in $pp$ Collision Data at $\sqrt{s} = 7$ TeV with the ATLAS Detector

G. Aad et al.*
(ATLAS Collaboration)
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Results of a search for new phenomena in events with an energetic photon and large missing transverse momentum in proton-proton collisions at $\sqrt{s} = 7$ TeV are reported. Data collected by the ATLAS experiment at the LHC corresponding to an integrated luminosity of 4.6 fb$^{-1}$ are used. Good agreement is observed between the data and the standard model predictions. The results are translated into exclusion limits on models with large extra spatial dimensions and on pair production of weakly interacting dark matter candidates.

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Events with an energetic photon and large missing momentum in the final state constitute a clean and distinctive signature in searches for new physics at colliders. In particular, monophoton, and monojet final states have been studied [1–8] in the context of searches for supersymmetry and large extra spatial dimensions (LED), aiming to provide a solution to the mass hierarchy problem, and the search for weakly interacting massive particles (WIMPs) as candidates for dark matter (DM).

The Arkani-Hamed, Dimopoulos, and Dvali (ADD) model for LED [9] explains the large difference between the electroweak unification scale $O(10^2)$ GeV and the Planck scale $M_{Pl} \sim O(10^{19})$ GeV by postulating the presence of $n$ extra spatial dimensions of size $R$, and defining a fundamental Planck scale in $4+n$ dimensions, $M_D$, given by $M_D^2 \sim M_{Pl}^2/R^n$. The extra spatial dimensions are compactified, resulting in a Kaluza-Klein tower of massive graviton modes. At hadron colliders, these graviton modes may escape detection and can be produced in association with an energetic photon or a jet, leading to a monophoton or monojet signature.

The presence of a nonbaryonic DM component in the Universe is inferred from the observation of its gravitational interactions [10], although its nature is otherwise unknown. A WIMP $\chi$ with mass $m_\chi$ in the range between 1 GeV and a few TeV is a plausible candidate for DM. It could be detected via its scattering with heavy nuclei [11], the detection of cosmic rays (energetic photons, electrons, positrons, protons, antiprotons, or neutrinos) from $\chi \bar{\chi}$ annihilation in astrophysical sources [10], or via $\chi \bar{\chi}$ pair production at colliders where the WIMPs do not interact with the detector and the event is identified by the presence of an energetic photon or jet from initial-state radiation. The interaction of WIMPs with standard model (SM) particles is assumed to be driven by a mediator with mass at the TeV scale and described using a nonrenormalizable effective theory [12] with several operators. The vertex coupling is suppressed by an effective cutoff mass scale $M_* \sim M/\sqrt{\Lambda_{112}}$, where $M$ denotes the mass of the mediator and $g_1$ and $g_2$ are the couplings of the mediator to the WIMP and SM particles.

This Letter reports results of the search for new phenomena in the monophoton final state, based on $\sqrt{s} = 7$ TeV proton-proton collision data corresponding to an integrated luminosity of 4.6 fb$^{-1}$ collected with the ATLAS detector at the LHC during 2011. The ATLAS detector is described in detail elsewhere [13]. The data are collected using a three-level trigger system that selects events with missing transverse momentum greater than 70 GeV. In the analysis, events are required to have a reconstructed primary vertex and $E_T^{miss} > 150$ GeV, where $E_T^{miss}$ is computed as the magnitude of the vector sum of the transverse momentum of all noise-suppressed calorimeter topological clusters with $|\eta| < 4.9$ [14,15]. A photon is also required with transverse momentum $p_T > 150$ GeV and $|\eta| < 2.37$, excluding the calorimeter barrel or endcap transition regions at 1.37 < $|\eta|$ < 1.52 [13]. With these criteria, the trigger selection is more than 98% efficient, as determined using events selected with a muon trigger. The cluster energies are corrected for the different response of the calorimeters to hadronic jets, $\tau$ leptons, electrons or photons, as well as dead material and out-of-cluster energy losses. The photon candidate must pass tight identification criteria [16] and is required to be isolated: the energy not associated with the photon cluster in a cone of radius $R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.4$ around the candidate is required to be less than 5 GeV. Jets are defined using the anti-$k_T$ jet algorithm [17] with the distance parameter set to $R = 0.4$. The measured jet $p_T$ is corrected for detector

*Full author list given at the end of the article.
effects and for contributions from multiple proton-proton interactions per beam bunch crossing (pileup) \cite{18}.

Events with more than one jet with $p_T > 30$ GeV and $|\eta| < 4.5$ are rejected. Events with one jet are retained to increase the signal acceptance and reduce systematic uncertainties related to the modeling of initial-state radiation. The reconstructed photon, $E_{T}^{\text{miss}}$ vector, and jets (if found) are required to be well separated in the transverse plane with $\Delta \phi(\gamma, E_{T}^{\text{miss}}) > 0.4$, $\Delta R(\gamma, \text{jet}) > 0.4$, and $\Delta \phi(\text{jet}, E_{T}^{\text{miss}}) > 0.4$. Additional quality criteria \cite{19} are applied to ensure that jets and photons are not produced by noisy calorimeter cells, and to avoid problematic detector regions. Events with identified electrons or muons are vetoed to reject mainly W/Z+jets and W/Z+γ background processes with charged leptons in the final state. Electron (muon) candidates are required to have $p_T > 20$ GeV and $|\eta| < 2.47$ ($p_T > 10$ GeV and $|\eta| < 2.4$), and to pass the medium (combined) criteria \cite{20}. The final data sample contains 116 events, where 88 and 28 events have zero and one jet, respectively.

The SM background to the monophoton signal is dominated by the irreducible $Z(\rightarrow \nu \bar{\nu}) + \gamma$ process, and receives contributions from W/Z+γ events with unidentified electrons, muons or hadronic τ decays, and W/Z+jets events with an electron or jet misreconstructed as a photon. In addition, the monophoton sample receives small contributions from top-quark, $\gamma \gamma$, diboson (WW, ZZ, WZ), γ+jets, and multijet processes.

Background samples of simulated W/Z+γ events are generated using ALPGEN 2.13 \cite{21}, interfaced to HERWIG 6.510 \cite{22} with JIMMY 4.31 \cite{23}, and SHERPA 1.2.3 \cite{24}, using CTEQ6L1 \cite{25} parton distribution functions (PDFs) and requiring a minimum photon $p_T$ of 40 GeV. Background samples of W/Z+jets and γ+jets processes are generated using ALPGEN plus HERWIG/JIMMY, with CTEQ6L1 PDFs. Top-quark production samples are generated using MC@NLO 4.01 \cite{26} and CT10 \cite{27} PDFs, while diboson processes are generated using HERWIG/JIMMY normalized to next-to-leading-order (NLO) predictions with MRST2007 \cite{28} PDFs. Multijet and γγ processes are generated using PYTHIA 6.426 \cite{29} with MRST2007 PDFs.

Signal Monte Carlo (MC) samples are generated according to the ADD model using the PYTHIA 8.150 leading-order (LO) perturbative QCD (pQCD) implementation with default settings, requiring a minimum photon $p_T$ of 80 GeV, and an ATLAS tune for the underlying event (UE) contribution \cite{30} including the CTEQ6L1 PDFs. The number of extra dimensions $n$ is varied from 2 to 6 and values of $M_{D}$ in the 1–2 TeV range are considered. For consistency with a previous monojet analysis performed in ATLAS \cite{7,8}, the yields corresponding to CTEQ6.6 \cite{31} PDFs are used, as obtained by reweighting these samples. The samples are normalized to NLO total cross sections \cite{32}. The LO-to-NLO factors decrease from 1.5 to 1.1 as $n$ increases.

Simulated events corresponding to the $\chi \bar{\chi} + \gamma$ process with a minimum photon $p_T$ of 80 GeV are generated using LO matrix elements from MADGRAPH \cite{33} interfaced to PYTHIA 6.426 using CTEQ6L1 PDFs. Values for $m_{\chi}$ between 1 GeV and 1.3 TeV are considered. In this analysis, WIMPs are assumed to be Dirac fermions and the vertex operator is taken to have the structure of a scalar, vector, axial-vector or tensor, corresponding, respectively, to the operators D1, D5, D8, and D9 in Refs. \cite{12,34}. These operators correspond to spin-independent (D1 and D5) and spin-dependent (D8 and D9) interactions. The MC samples are passed through a full simulation \cite{35} of the ATLAS detector and trigger system, based on GEANT4 \cite{36}. The simulated events are reconstructed and analyzed as the data.

The normalization of the MC predictions for the dominant W/Z+γ background processes are set using scale factors determined in a data control sample, resulting in a significant reduction of the background uncertainties. A $\gamma + \mu + E_{T}^{\text{miss}}$ control sample with an identified muon is defined by inverting the muon veto in the nominal event selection criteria discussed above. According to the simulation, the sample contains a 71% (19%) contribution from W+γ (Z+γ) processes. This control sample is used to normalize separately the W+γ and Z+γ MC predictions determined by ALPGEN and SHERPA, respectively. In each case, the scale factor is defined as the ratio of the data to the given MC prediction, after the contributions from the rest of the background processes are subtracted. The scale factors, extracted simultaneously to take into account correlations, are $k(W+\gamma) = 1.0 \pm 0.2$ and $k(Z+\gamma) = 1.1 \pm 0.2$, where statistical and systematic uncertainties are included (see below).

Dedicated studies are performed to determine the probability for electrons or jets to be identified as photons, resulting in data-driven estimates of W/Z+jet background contributions. (1) A data sample of Z boson candidates is employed to compute the fraction of electrons from the Z boson decay that are reconstructed as photons. This fraction decreases from 2% to 1% as $p_T$ increases from 150 to 300 GeV, and increases from 1% to 3% as $|\eta|$ increases. These rates are employed to determine the W(→$e\nu$)+jets background in the signal region, for which a control data sample selected with the nominal selection criteria and an electron instead of a photon is used. This results in a total W(→$e\nu$)+jet background estimation of $14 \pm 6$ events, where the uncertainty is dominated by the limited size of the control data sample. (2) Control samples enhanced in jets identified as photons are defined using nominal selection criteria with nonisolated photon candidates and/or photon candidates passing a loose selection \cite{16} but not the nominal identification requirements. The ratio of isolated to nonisolated photons in the loose-photon selected sample together with the number of nonisolated photons passing the nominal
identification requirements are used to determine the rate of jets identified as photons in the signal region, after the contribution from W/Z + γ processes has been subtracted. This gives an estimate of 4.3 ± 1.9 W/Z + jet background events.

The γ + jet and multijet background contributions to the signature of a photon and large $E_T^{\text{miss}}$ originate from the misreconstruction of the energy of a jet in the calorimeter. The direction of the $E_T^{\text{miss}}$ vector therefore tends to be aligned with the jet. These background contributions are determined from data using a control sample with the nominal selection criteria and at least one jet with $p_T > 30 \text{ GeV}$ and $\Delta \phi (\text{jet}, E_T^{\text{miss}}) < 0.4$. After the subtraction of electroweak boson and top-quark production processes, a linear extrapolation of the measured $p_T$ spectrum to $p_T < 30 \text{ GeV}$ leads to an estimate of $1.0 ± 0.5$ background events in the signal region, where the uncertainty is due to the ambiguity in the functional form used in the extrapolation. Background contributions from top-quark, γγ, and diboson production processes, determined using MC samples, are small. Finally, noncollision backgrounds are negligible.

A detailed study of systematic uncertainties on the background predictions has been performed. An uncertainty of 0.3% to 1.5% on the absolute photon energy scale [16], depending on the photon $p_T$ and $\eta$, translates into a 0.9% uncertainty on the total background prediction. Uncertainties on the simulated photon energy resolution, photon isolation, and photon identification efficiency introduce a combined 1.1% uncertainty on the background yield. Uncertainties on the simulated lepton identification efficiencies introduce a 0.3% uncertainty on the background predictions. The uncertainty on the absolute jet energy scale [18] and jet energy resolution introduce 0.9% and 1.2% uncertainties on the background estimation, respectively. A 10% uncertainty on the absolute energy scale for low $p_T$ jets and unclustered energy in the calorimeter, and a 6.6% uncertainty on the subtraction of pileup contributions, are taken into account. They affect the $E_T^{\text{miss}}$ determination and translate into 0.8% and 0.3% uncertainties on the background yield, respectively. The dependence of the predicted W/Z + γ backgrounds on the parton shower and hadronization model used in the MC simulations is studied by comparing the predictions from SHERPA and ALPGEN. This results in a conservative 6.9% uncertainty on the total background yield. Uncertainties due to the choice of PDFs and the variation of the renormalization and factorization scales in the W/Z + γ MC samples introduce an additional 1.0% uncertainty on the total background yields. Other sources of systematic uncertainty related to the trigger selection, the lepton $p_T$ scale and resolution, the pileup description, background normalization of the top quark, γγ and diboson contributions, and a 1.8% uncertainty on the total luminosity [37] introduce a combined uncertainty of less than 0.5% on the total predicted yields. The different sources of uncertainty are added in quadrature, resulting in a total 15% uncertainty on the background prediction.

In Table I, the observed number of events and the SM predictions are presented. The data are in agreement with the SM background-only hypothesis with a $p$ value of 0.2.

![FIG. 1 (color online). The measured $E_T^{\text{miss}}$ distribution (black dots) compared to the SM (solid lines), SM + ADD (dashed lines), and SM + WIMP (dotted lines) predictions, for two particular ADD and WIMP scenarios.](011802-3)
uncertainties related to the photon, jet, and $E_{T}^{miss}$ scales and resolutions, the photon reconstruction, the trigger efficiency, the pileup description, and the luminosity introduce a 6.8% uncertainty on the signal yield. Uncertainties related to the modeling of the initial- and final-state gluon radiation translate into a 3.5% uncertainty on the ADD signal yield. Systematic uncertainties due to PDFs result in a 0.8% to 1.4% uncertainty on the signal $A \times \epsilon$ and a 4% to 11% uncertainty on the signal cross section, increasing as $n$ increases. Variations of the renormalization and factorization scales by factors of 2 and $\frac{1}{2}$ introduce a 0.6% uncertainty on the signal $A \times \epsilon$ and an uncertainty on the signal cross section that decreases from 9% to 5% as $n$ increases.

Figure 2 shows the expected and observed 95% C.L. lower limits on $M_D$ as a function of $n$, as determined using the CL$_s$ method and considering uncertainties on both signal and SM background predictions. Values of $M_D$ below 1.93 TeV ($n = 2$), 1.83 TeV ($n = 3$ or 4), and 1.86 TeV ($n = 5$), and 1.89 TeV ($n = 6$) are excluded at 95% C.L.. The observed limits decrease by 3% to 2% after considering the $-1\sigma$ uncertainty from PDFs, scale variations, and parton shower modeling in the ADD theoretical predictions (dashed lines in Fig. 2). These results improve upon previous limits on $M_D$ from LEP and Tevatron experiments [1–3]. In this analysis, no weights are applied for signal events in the phase space region with $s > M_D^2$, which is sensitive to the unknown ultraviolet behavior of the theory. For $M_D$ values close to the observed limits, the visible signal cross sections decrease by 15% to 75% as $n$ increases when truncated samples with $s < M_D^2$ are considered. This analysis probes a kinematic range for which the model predictions are defined but ambiguous.

Similarly, 90% C.L. upper limits on the pair-production cross section of dark matter WIMP candidates are determined. The $A \times \epsilon$ of the selection criteria are typically $11.0 \pm 0.2$ (stat) $\pm 1.6$ (syst)% for the D1 operator, $18.0 \pm 0.3$ (stat) $\pm 1.4$ (syst)% for the D5 and D8 operators, and $23.0 \pm 0.3$ (stat) $\pm 2.1$ (syst)% for the D9 operator, with a moderate dependence on $m_{\chi}$. Experimental uncertainties, as discussed above, translate into a 6.6% uncertainty on the signal yields. Theoretical uncertainties on initial- and final-state gluon radiation introduce a 3.5% to 10% uncertainty on the signal yields. The uncertainties related to PDFs result in 1.0% to 8.0% and 5.0% to 30% uncertainties on the signal $A \times \epsilon$ and cross section, respectively. Variations of the renormalization and factorization scales lead to a change of 1.0% to 2.0% and 8.0% in the signal $A \times \epsilon$ and cross section, respectively. In the case of the D1 (D5) spin-independent operator, values of $M_\chi$ below 31 and 5 GeV (585 and 156 GeV) are excluded at 90% C.L. for $m_{\chi}$ equal to 1 GeV and 1.3 TeV, respectively. These results can be translated into upper limits on the nucleon-WIMP interaction cross section using the prescription in Refs. [12,39]. Figure 3 shows 90% C.L. upper limits on the nucleon-WIMP cross section as a function of $m_{\chi}$. In the case of the D1 (D5) spin-independent interaction, nucleon-WIMP cross sections above $2.7 \times 10^{-39}$ cm$^2$ and $5.8 \times 10^{-34}$ cm$^2$ (2.2 $\times 10^{-39}$ cm$^2$ and 1.7 $\times 10^{-36}$ cm$^2$) are excluded at 90% C.L. for $m_{\chi}$ = 1 GeV and $m_{\chi}$ = 1.3 TeV, respectively. Spin-dependent interactions cross sections in the range $7.6 \times 10^{-41}$ cm$^2$ to $3.4 \times 10^{-37}$ cm$^2$ (2.2 $\times 10^{-41}$ cm$^2$ to 2.7 $\times 10^{-38}$ cm$^2$) are excluded at 90% C.L. for the D8 (D9) operator and $m_{\chi}$ varying between 1 GeV and 1.3 TeV. The quoted observed limits on $M_\chi$ typically decrease by 2% to 10% if the $-1\sigma$ theoretical uncertainty is considered. This translates into a 10% to 50% increase of the quoted nucleon-WIMP cross section limits. The exclusion in the region 1 GeV < $m_{\chi}$ < 3.5 GeV (1 GeV < $m_{\chi}$ < 1 TeV) for spin-independent (spin-dependent)
nucleon-WIMP interactions is driven by the results from collider experiments, with the assumption of the validity of the effective theory, and is still dominated by the monojet results. The cross section upper limits improve upon CDF results [4] and are similar to those obtained by the CMS experiment [5,6].

In summary, we report results on the search for new phenomena in events with an energetic photon and large missing transverse momentum in proton-proton collisions at $\sqrt{s} = 7$ TeV at the LHC, based on ATLAS data corresponding to an integrated luminosity of 4.6 fb$^{-1}$. The measurements are in agreement with the SM predictions for the background. The results are translated into model-independent 90% and 95% confidence level upper limits on $\sigma \times A \times e$ of 5.6 and 6.8 fb, respectively. The results are presented in terms of improved limits on $M_D$ versus the number of extra spatial dimensions in the ADD model and upper limits on the spin-independent and spin-dependent contributions to the nucleon-WIMP elastic cross section as a function of the WIMP mass.

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[15] ATLAS uses a cylindrical coordinate system about the beam axis with polar angle $\theta$ and azimuthal angle $\phi$. Anticlockwise beam direction defines the positive $z$ axis, while the positive $x$ axis is defined as pointing from the collision point to the center of the LHC ring and the positive $y$ axis points upwards. We define transverse energy $E_T = E \sin \theta$, transverse momentum $p_T = p \sin \theta$, and pseudorapidity $\eta = -\ln(\tan(\theta/2))$.
The strange and charm quark masses (relevant for the D1 operator) are set to 0.1 and 1.42 GeV, respectively.
Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
Departamento de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
Physics Department, Brookhaven National Laboratory, Upton, New York, USA
National Institute of Physics and Nuclear Engineering, Bucharest, Romania
University Politehnica Bucharest, Bucharest, Romania
West University in Timisoara, Timisoara, Romania
Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, Carleton University, Ottawa, Ontario, Canada
CERN, Geneva, Switzerland

Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
Departamento de Fisica, Pontificia Universidad Catolica de Chile, Santiago, Chile
Departamento de Fisica, Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
Department of Modern Physics, University of Science and Technology of China, Anhui, China
Department of Physics, Nanjing University, Jiangsu, China
School of Physics, Shandong University, Shandong, China
Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
Nevis Laboratory, Columbia University, Irvington, New York, USA
Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
INFN Gruppo Collegato di Cosenza, Cosenza, Italy
Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
Physics Department, Southern Methodist University, Dallas, Texas, USA
Physics Department, University of Texas at Dallas, Richardson, Texas, USA
DESY, Hamburg and Zeuthen, Germany
Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
Department of Physics, Duke University, Durham, North Carolina, USA
SOPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
INFN Laboratori Nazionali di Frascati, Frascati, Italy
Dipartimento di Fisica, Università di Genova, Genova, Italy
INFN Sezione di Genova, Genova, Italy
E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
Department of Physics, Hampton University, Hampton, Virginia, USA
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, Indiana University, Bloomington, Indiana, USA
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City, Iowa, USA
Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
INFN Sezione di Lecce, Lecce, Italy
Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lund university, Lund, Sweden
Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
Department of Physics, McGill University, Montreal, Quebec, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics, The University of Michigan, Ann Arbor, Michigan
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
INFN Sezione di Milano, 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
Skobeltsyn Institute of Nuclear Physics, 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, 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, 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, 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, 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, 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 Instrumentacao e Fisica Experimental de Particulas—LIP, Lisboa, Portugal
Departamento de Física Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain

Instituto de Física, Academy of Sciences of the Czech Republic, Praha, Czech Republic

Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic

Czech Technical 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, Roma, Italy

Dipartimento di Fisica, Università La Sapienza, Roma, Italy

INFN Sezione di Roma Tor Vergata, Roma, Italy

Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy

INFN Sezione di Roma Tre, Roma, Italy

Dipartimento di 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

Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco

Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco

Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco

DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA

Department of Physics, University of Washington, Seattle, Washington, USA

Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

Department of Physics, Shinshu University, Nagano, Japan

Fachbereich Physik, Universität Siegen, Siegen, Germany

Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada

SLAC National Accelerator Laboratory, Stanford, California, USA

Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic

Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

Department of Physics, University of Johannesburg, Johannesburg, South Africa

School of Physics, University of the Witwatersrand, Johannesburg, South Africa

Department of Physics, Stockholm University, Stockholm, Sweden

The Oskar Klein Centre, Stockholm, Sweden

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA

Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

Department of Physics, University of Toronto, Toronto, Ontario, Canada

TRIUMF, Vancouver, British Columbia, Canada

Department of Physics and Astronomy, York University, Toronto, Ontario, Canada

Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA

Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA

INFN Gruppo Collegato di Udine, Udine, Italy

ICTP, Trieste, Italy

Dipartimento di Chimica, Fisica e Ambienti, Università di Udine, Udine, Italy

Department of Physics, University of Illinois, Urbana, Illinois, USA

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
aDeceased.
bAlso at Laboratorio de Instrumentacao e Fisica Experimental de Particulas–LIP, Lisboa, Portugal.
cAlso at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.
dAlso at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
eAlso at TRIUMF, Vancouver, British Columbia, Canada.
fAlso at Department of Physics, California State University, Fresno, CA, USA.
gAlso at Novosibirsk State University, Novosibirsk, Russia.
hAlso at Department of Physics, University of Coimbra, Coimbra, Portugal.
iAlso at Department of Physics, UASLP, San Luis Potosi, Mexico.
jAlso at Università di Napoli Parthenope, Napoli, Italy.
kAlso at Institute of Particle Physics (IPP), Canada.
lAlso at Department of Physics, Middle East Technical University, Ankara, Turkey.
mAlso at Louisiana Tech University, Ruston, LA, USA.
nAlso at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
oAlso at Department of Physics and Astronomy, University College London, London, United Kingdom.
pAlso at Group of Particle Physics, University of Wisconsin, Madison, Wisconsin, USA.
qAlso at Taiyuan Normal University, Taiyuan, China.
rAlso at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.
sAlso at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France.
aaAlso at Department of Physics, University of Arizona, Tucson, Arizona, USA.
abAlso at Dipartimento di Fisica, Università di Bari Aldo Moro, Bari, Italy.
cAlso at Department of Physics, St. Petersburg State University, St. Petersburg, Russia.
dAlso at University of Minnesota, Minneapolis, Minnesota, USA.
e Also at TRIUMF, Vancouver, British Columbia, Canada.
fAlso at Weizmann Institute of Science, Rehovot, Israel.
gAlso at University of California, Santa Barbara, California, USA.
hAlso at Georg-August-Universität Göttingen, Göttingen, Germany.
iAlso at Department of Physics, University of Ottawa, Ottawa, Ontario, Canada.
jkAlso at Dipartimento di Fisica, Università di Roma “La Sapienza”, Roma, Italy.
klAlso at IPN Orsay, Orsay, France.
llAlso at Institute of Physics, Polish Academy of Sciences, Warsaw, Poland.
mAlso at University of New Hampshire, Durham, New Hampshire, USA.
nAlso at Pusan National University, Pusan, Republic of Korea.
oAlso at Dipartimento di Fisica “E. Pancini”, Università di Napoli “Federico II”, Napoli, Italy.
pAlso at IN2P3, Lyon, France.
qAlso at Department of Physics, National Central University, Jhongli, Taiwan.
rAlso at Laboratoire de Physique des Hadrons, Université de Lyon, Villeurbanne, France.
sAlso at Physics Department, Rice University, Houston, Texas, USA.
tAlso at Dipartimento di Fisica, Università di Roma “La Sapienza”, Roma, Italy.
uAlso at Dipartimento di Fisica dell’Universita’ di Milano “Bicocca”, Milano, Italy.
vAlso at Centre deCalcul des Ens. Phys. Nucl. et Phys. des Particules (CEA-CNRS), Gif-sur-Yvette, France.
wAlso at Dipartimento di Fisica, Università di Pisa, Pisa, Italy.
xAlso at Departement de Physique Theorique, Université Libre de Bruxelles, Brussels, Belgium.
yAlso at Dipartimento di Fisica, Università di Pavia, Pavia, Italy.
zAlso at Department of Physics, University of California, Santa Cruz, California, USA.