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


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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 $M_{Pl}^n \sim M_D^{4+n} R^n$. 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 monophotonic 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 $M_* \sim M/\sqrt{81 g_2}$, 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 $1.37 < |\eta| < 1.52$ [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 $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.4$ 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.

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effects and for contributions from multiple proton-proton interactions per beam bunch crossing (pileup) [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 [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 \( W/Z + \gamma \) 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 [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 \( Z(\to \nu \bar{\nu}) + \gamma \) process, and receives contributions from \( W/Z + \gamma \) events with unidentified electrons, muons or hadronic \( \tau \) 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 \((WW, ZZ, WZ, \gamma + \text{jets, and multijet processes.})\)

Background samples of simulated \( W/Z + \gamma \) events are generated using ALPGEN 2.13 [21], interfaced to HERWIG 6.510 [22] with JIMMY 4.31 [23], and SHERPA 1.2.3 [24], using CTEQ6L1 [25] parton distribution functions (PDFs) and requiring a minimum photon \( p_T \) of 40 GeV. Background samples of \( W/Z + \) jets and \( \gamma + \) jets processes are generated using ALPGEN plus HERWIG/JIMMY, with CTEQ6L1 PDFs. Top-quark production samples are generated using MC@NLO 4.01 [26] and CT10 [27] PDFs, while diboson processes are generated using HERWIG/JIMMY normalized to next-to-leading-order (NLO) predictions with MRST2007 [28] PDFs. Multijet and \( \gamma \gamma \) processes are generated using PYTHIA 6.426 [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 [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 [7,8], the yields corresponding to CTEQ6.6 [31] PDFs are used, as obtained by reweighting these samples. The samples are normalized to NLO total cross sections [32]. The LO-to-NLO factors decrease from 1.5 to 1.1 as \( n \) increases.

Simulated events corresponding to the \( \chi \tilde{\chi} + \gamma \) process with a minimum photon \( p_T \) of 80 GeV are generated using LO matrix elements from MADGRAPH [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. [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 [35] of the ATLAS detector and trigger system, based on GENIE [36]. The simulated events are reconstructed and analyzed as the data.

The normalization of the MC predictions for the dominant \( W/Z + \gamma \) 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 \( W + \gamma \) (\( Z + \gamma \)) processes. This control sample is used to normalize separately the \( W + \gamma \) and \( Z + \gamma \) 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 \( W(\to e\nu) + \) 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 \( W(\to e\nu) + \) 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 [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 $W/Z + \gamma$ processes has been subtracted. This gives an estimate of $4.3 \pm 1.9$ $W/Z + \text{jet}$ background events.

The $\gamma + \text{jet}$ and multijet background contributions to the signature of a photon and large $E_T^{\text{miss}}$, originating 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 $p_T > 30$ 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 $p_T < 30$ GeV leads to an estimate of $1.0 \pm 0.5$ 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, $\gamma\gamma$, 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 $W/Z + \gamma$ 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 $W/Z + \gamma$ 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, $\gamma\gamma$ 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. Figure 1 shows the measured $E_T^{\text{miss}}$ distribution compared to the background predictions. The results are expressed in terms of model-independent 90% and 95% confidence level (C.L.) upper limits on the visible cross section, defined as the production cross section times acceptance times efficiency ($\sigma \times A \times e$), using the CL$_{s}$ modified frequentist approach [38] and considering the systematic uncertainties on the SM backgrounds and on the integrated luminosity. Values of $\sigma \times A \times e$ above 5.6 fb and 6.8 fb are excluded at 90% C.L. and 95% C.L., respectively. Typical event selection efficiencies of $e \sim 75\%$ are found in simulated ADD and WIMP signal samples.

The results are translated into 95% C.L. limits on the parameters of the ADD model. The typical $A \times e$ of the selection criteria is $20.0 \pm 0.4$(stat) $\pm 1.6$(syst)%, approximately independent of $n$ and $M_D$. Experimental

![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 $E_T^{\text{miss}}$ 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), 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 $\hat{s} > M_D^2$, 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 $\hat{s} < M_D^2$ 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. Values of $M_\chi$ below 585 and 100 GeV (794 and 188 GeV) are excluded for the D8 (D9) spin-dependent operator 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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[34] The strange and charm quark masses (relevant for the D1 operator) are set to 0.1 and 1.42 GeV, respectively.

In consultation with the authors of Ref. [12], a factor 4.7 × 10^{-39} cm^2 is used in the cross section formula for D8 and D9 operators instead of the quoted 9.18 × 10^{-40} cm^2.
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(AHLAS Collaboration)

1School of Chemistry and Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4Department of Physics, Ankara University, Ankara, Turkey
5Department of Physics, Dumlupinar University, Kutahya, Turkey
6Department of Physics, Gazi University, Ankara, Turkey
7Physics Division, TOBB University of Economics and Technology, Ankara, Turkey
8Turkish Atomic Energy Authority, Ankara, Turkey
9LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
10High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
11Physics Division, University of Arizona, Tucson, Arizona, USA
12Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
13Physics Department, University of Athens, Athens, Greece
14Physics Department, National Technical University of Athens, Zografou, Greece
15Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
16Department for Physics and Technology, University of Bergen, Bergen, Norway
17School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18Department of Physics, Bogazici University, Istanbul, Turkey
19aDepartment of Physics, Bogazici University, Istanbul, Turkey
19bDivision of Physics, Dogus University, Istanbul, Turkey
20Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20bDepartment of Physics, Istanbul Technical University, Istanbul, Turkey
20cINFN Sezione di Bologna, Bologna, Italy
21Department of Physics, University of Bonn, Bonn, Germany
22Department of Physics, Boston University, Boston, Massachusetts, USA
23Department of Physics, Brandeis University, Waltham, Massachusetts, USA
24a Universidade Federal do Rio de Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
24b Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
24c Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
24d Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton, New York, USA
26a National Institute of Physics and Nuclear Engineering, Bucharest, Romania
26b University Politehnica Bucharest, Bucharest, Romania
26c West University in Timisoara, Timisoara, Romania
27 Departamento de Fisica, 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
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
32a Departamento de Fisica, Pontificia Universidad Catolica de Chile, Santiago, Chile
32b Departamento de Fisica, Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
33 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
33a Department of Modern Physics, University of Science and Technology of China, Anhui, China
33b Department of Physics, Nanjing University, Jiangsu, China
33c School of Physics, Shandong University, Shandong, China
34 Laboratoire de Physique Corpusculaire, Clermont Universite and Universite Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington, New York, USA
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37a INFN Gruppo Collegato di Cosenza, Cosenza, Italy
37b Dipartimento di Fisica, Universita della Calabria, Arcavata di Rende, Italy
38 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
39 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas, Texas, USA
41 Physics Department, University of Texas at Dallas, Richardson, Texas, USA
42 DESY, Hamburg and Zeuthen, Germany
43 Institut fur Experimentelle Physik IV, Technische Universitat Dortmund, Dortmund, Germany
44 Institut fur Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham, North Carolina, USA
46 SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultat fur Mathematik und Physik, Albert-Ludwigs-Universitat, Freiburg, Germany
49 Section de Physique, Universite de Genève, Geneva, Switzerland
50a INFN Sezione di Genova, Genova, Italy
50b Dipartimento di Fisica, Universita di Genova, Genova, Italy
51 E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
51a High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 Il Physikalisches Institut, Justus-Liebig-Universitat Giessen, Giessen, Germany
53 SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universitat, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Universite Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton, Virginia, USA
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
58 Kirchhoff-Institut fur Physik, Ruprecht-Karls-Universitat Heidelberg, Heidelberg, Germany
58a Physikalisches Institut, Ruprecht-Karls-Universitat Heidelberg, Heidelberg, Germany
59 ZITI Institut fur technische Informatik, Ruprecht-Karls-Universitat Heidelberg, Mannheim, Germany
59a Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 Department of Physics, Indiana University, Bloomington, Indiana, USA
61 Institut fur Astro- und Teilchenphysik, Leopold-Franzens-Universitat, Innsbruck, Austria
62 University of Iowa, Iowa City, Iowa, USA
63 Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
64 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
65 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
66 Graduate School of Science, Kobe University, Kobe, Japan
67 Faculty of Science, Kyoto University, Kyoto, Japan
68 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

Physikalisches Institut, Universität zu Köln, Köln, Germany

Department of Physics, 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, 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, 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
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

*Deceased.

Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas–LIP, Lisboa, Portugal.

Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.

Also atParticle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

Also atTRIUMF, Vancouver, British Columbia, Canada.

Also atDepartment of Physics, California State University, Fresno, CA, USA.

Also atNovosibirsk State University, Novosibirsk, Russia.

Also atDepartment of Physics, University of Coimbra, Coimbra, Portugal.

Also atDepartment of Physics, UASLP, San Luis Potosi, Mexico.

Also atUniversità di Napoli Parthenope, Napoli, Italy.

Also atInstitut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also atManhattan College, New York, NY, USA.

Also atSchool of Physics, Shandong University, Shandong, China.

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

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

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

Also atDipartimento di Fisica, Università La Sapienza, Roma, Italy.

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

Also atSection de Physique, Université de Genève, Geneva, Switzerland.

Also atDepartamento de Fisica, Universidade de Minho, Braga, Portugal.

Also atDepartment of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.

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

Also atCalifornia Institute of Technology, Pasadena, CA, USA.

Also atInstitute of Physics, Jagiellonian University, Krakow, Poland.

Also atLAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.

Also atNevis Laboratory, Columbia University, Irvington, NY, USA.

Also atDepartment of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

Also atDepartment of Physics, Oxford University, Oxford, United Kingdom.

Also atInstitute of Physics, Academia Sinica, Taipei, Taiwan.

Also atDepartment of Physics, The University of Michigan, Ann Arbor, MI, USA.

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