EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2012-209

Submitted to: Physical Review Letters

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

The ATLAS Collaboration

Abstract

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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PACS numbers: 14.70.Kv, 13.85.Rm, 13.85.Qk, 14.80.Rt, 14.70.Bh

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 ${M_{Pl}}^2 \sim {M_D}^{2+n} R^n$. 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 monophoton or monojet signature.

The presence of a non-baryonic DM component in the universe is inferred from the observation of its gravitational interactions [10], although its nature is otherwise unknown. A WIMP χ with mass m_χ 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 non-renormalizable effective theory [12] with several operators. The vertex coupling is suppressed by an effective cut-off mass scale $M_* \sim M/\sqrt{g_1 g_2}$, 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 monophoton final states, 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 $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV, where $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 $p_{\mathrm{T}} > 150$ GeV and $|\eta| < 2.37$, excluding the calorimeter barrel/end-cap 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, τ 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 effects and for contributions from multiple proton-proton interactions per beam bunch crossing (pileup) [18].

Events with more than one jet with $p_{\mathrm{T}} > 30$ 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, $E_{\mathrm{T}}^{\mathrm{miss}}$ vector and jets (if found) are required to be well separated in the transverse plane with $\Delta\phi(\gamma, E_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$, $\Delta R(\gamma, \mathrm{jet}) > 0.4$, and $\Delta\phi(\mathrm{jet}, E_{\mathrm{T}}^{\mathrm{miss}}) > 0.4$. 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 $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.47$ ($p_{\mathrm{T}} > 10$ 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 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 multi-jet processes.

Background samples of simulated $W/Z+\gamma$ events are generated using ALPGEN [21], interfaced to HERWIG [22] with JIMMY [23], and SHERPA [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 γ+jets processes are generated using ALPGEN plus HERWIG/JIMMY, with CTEQ6L1 PDFs. Top-quark production samples are generated using MC@NLO [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. Multi-jet and $\gamma\gamma$ processes are generated using PYTHIA 6 [29] with MRST2007 PDFs.

Signal Monte Carlo (MC) samples are generated according to the ADD model using the PYTHIA 8 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 predictions [32]. The LO-to-NLO normalization 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 [33] interfaced to PYTHIA 6 using CTEQ6L1 PDFs. Values for m_χ 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 GEANT4 [36]. The simulated events are reconstructed and analyzed with the same analysis chain 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 $\gamma+\mu+E_{\mathrm{T}}^{\mathrm{miss}}$ 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 $k(W+\gamma) = 1.0\pm0.2$ and $k(Z+\gamma) = 1.1\pm0.2$, where statistical and systematic uncertainties are included.

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. 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 GeV 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 ± 6 events, where the uncertainty is dominated by the limited size of the control data sample. Control samples enhanced in jets identified as photons are defined using nominal selection criteria with non-isolated photon candidates and/or photon candidates passing a *loose* selection [16] but not the nominal identification requirements. The ratio of isolated to non-isolated photons in the loose-photon selected sample together with the number of non-isolated 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 ± 1.9 W/Z+jet background events.

The γ+jet and multi-jet background contributions to the signature of a photon and large $E_{\mathrm{T}}^{\mathrm{miss}}$ originate from the misreconstruction of the energy of a jet in the calorimeter. The direction of $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 $p_{\mathrm{T}} > 30$ GeV and $\Delta\phi(\mathrm{jet}, E_{\mathrm{T}}^{\mathrm{miss}}) < 0.4$. After the subtraction of electroweak boson and top-quark production processes, a linear extrapolation of the measured

p_{T} spectrum to $p_{\mathrm{T}} < 30$ 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, $\gamma\gamma$, and diboson production processes, determined using MC samples, are small. Finally, non-collision 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 η, 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution compared to the background predictions. The results are expressed in terms of model-independent 90% and 95% confidence level (CL) upper limits on the visible cross section, defined as the production cross section times acceptance times efficiency ($\sigma \times A \times \epsilon$), using the CL_s modified frequentist approach [38] and considering the systematic uncertainties on the SM backgrounds and on the integrated luminosity. Values of $\sigma \times A \times \epsilon$ above 5.6 fb and 6.8 fb are excluded at 90% CL and 95% CL, respectively. Typical event selection efficiencies of $\epsilon \sim 75\%$ are found in simulated ADD and WIMP signal samples.

Background source	Prediction	$\pm$ (stat.)	$\pm$ (syst.)
$Z(\to \nu\bar{\nu}) + \gamma$	93	$\pm$ 16	$\pm$ 8
$Z/\gamma^*(\to \ell^+\ell^-) + \gamma$	0.4	$\pm$ 0.2	$\pm$ 0.1
$W(\to \ell\nu) + \gamma$	24	$\pm$ 5	$\pm$ 2
W/Z + jets	18	–	$\pm$ 6
Top	0.07	$\pm$ 0.07	$\pm$ 0.01
$WW, WZ, ZZ, \gamma\gamma$	0.3	$\pm$ 0.1	$\pm$ 0.1
γ+jets and multi-jet	1.0	–	$\pm$ 0.5
Total background	137	$\pm$ 18	$\pm$ 9
Events in data (4.6 fb^{-1})	116		

TABLE I: The number of events in data compared to the SM predictions, including statistical and systematic uncertainties. In the case of W/Z + jets, γ+jets and multi-jet processes a global uncertainty is quoted.

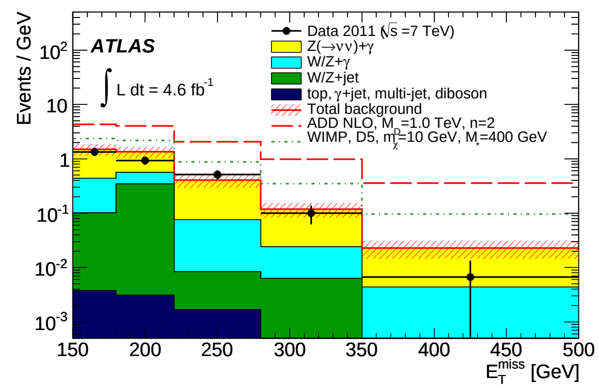

FIG. 1: The measured $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution (black dots) compared to the SM (solid lines), SM+ADD (dashed lines), and SM+WIMP (dotted lines) predictions, for two particular ADD and WIMP scenarios.

The results are translated into 95% CL limits on the parameters of the ADD model. The typical $A \times \epsilon$ of the selection criteria is $20.0 \pm 0.4(\text{stat.}) \pm 1.6(\text{syst.})\%$, approximately independent of n and M_D. Experimental uncertainties related to the photon, jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 two and one-half 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% CL 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% CL. The observed limits decrease by 3% to 2% after considering the -1σ uncertainty from PDFs, scale variations, and parton shower modeling in the ADD theoretical predictions (dashed lines in Figure 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.

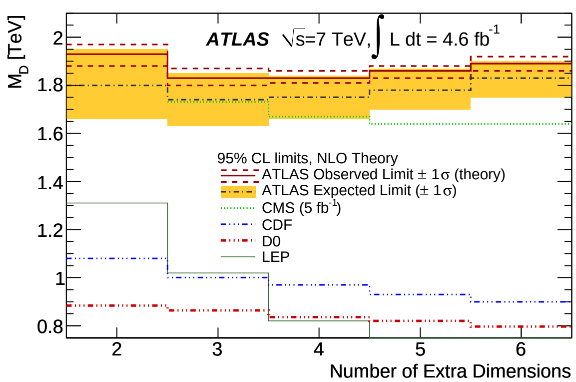

FIG. 2: Observed (solid lines) and expected (dashed-dotted lines) 95% CL limits on M_D as a function of the number of extra spatial dimensions n in the ADD model. The results are compared with previous results [1–3, 6] (other lines).

Similarly, 90% CL 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 $11.0 \pm 0.2(\text{stat.}) \pm 1.6(\text{syst.})\%$ for the D1 operator, $18.0 \pm 0.3(\text{stat.}) \pm 1.4(\text{syst.})\%$ for the D5 and D8 operators, and $23.0 \pm 0.3(\text{stat.}) \pm 2.1(\text{syst.})\%$ for the D9 operator, with a moderate dependence on m_χ. 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_* below 31 GeV and 5 GeV (585 GeV and 156 GeV) are excluded at 90% CL for m_χ equal to 1 GeV and 1.3 TeV, respectively. Values of M_* below 585 GeV and 100 GeV (794 GeV and 188 GeV) are excluded for the D8 (D9) spin-dependent operator for m_χ 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% CL upper limits on the nucleon-WIMP cross section as a function of m_χ. In the case of the D1 (D5) spin-independent interaction, nucleon-WIMP cross sections above 2.7×10^{-39} cm^2 and 5.8×10^{-34} cm^2 (2.2×10^{-39} cm^2 and 1.7×10^{-36} cm^2) are excluded at 90% CL for $m_\chi = 1$ GeV and $m_\chi = 1.3$ TeV, respectively. Spin-dependent interactions cross sections in the range 7.6×10^{-41} cm^2 to 3.4×10^{-37} cm^2 (2.2×10^{-41} cm^2 to 2.7×10^{-38} cm^2) are excluded at 90% CL for the D8 (D9) operator and m_χ varying between 1 GeV and 1.3 TeV. The quoted observed limits on M_* typically decrease by 2% to 10% if the -1σ 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. The cross section upper limits improve upon CDF results [4] and are similar to those obtained by the CMS experiment [6] which uses axial-vector operators to describe spin-dependent interactions.

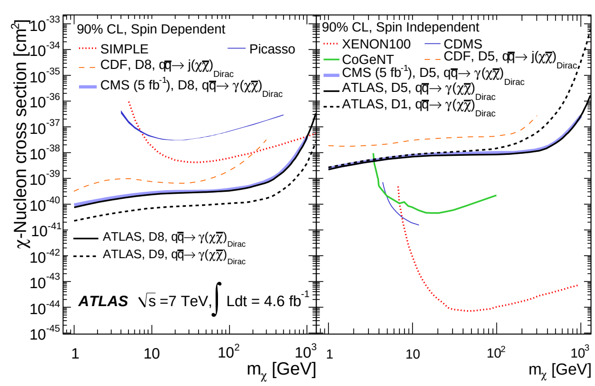

FIG. 3: 90% CL upper limits on the nucleon-WIMP cross section as a function of m_χ for spin-dependent (left) and spin-independent (right) interactions [12, 39]. The results are compared with previous results [4, 6, 11].

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 $\sigma \times A \times \epsilon$ of 5.6 fb 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.

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; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, 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; 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, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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