Search for Higgs and Z boson decays to Jψγ and Y(nS)γ with the ATLAS detector


DOI
10.1103/PhysRevLett.114.121801

Publication date
2015

Document Version
Final published version

Published in
Physical Review Letters

Citation for published version (APA):

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

UvA-DARE is a service provided by the library of the University of Amsterdam (https://dare.uva.nl)
Search for Higgs and Z Boson Decays to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ with the ATLAS Detector

G. Aad et al.

(ATLAS Collaboration)

(Received 15 January 2015; published 26 March 2015)

A search for the decays of the Higgs and Z bosons to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ ($n = 1, 2, 3$) is performed with $pp$ collision data samples corresponding to integrated luminosities of up to $20.3 \text{ fb}^{-1}$ collected at $\sqrt{s} = 8 \text{ TeV}$ with the ATLAS detector at the CERN Large Hadron Collider. No significant excess of events is observed above expected backgrounds and 95\% C.L. upper limits are placed on the branching fractions. In the $J/\psi\gamma$ final state the limits are $1.5 \times 10^{-3}$ and $2.6 \times 10^{-6}$ for the Higgs and Z boson decays, respectively, while in the $\Upsilon(1S, 2S, 3S)\gamma$ final states the limits are $(1.3, 1.9, 1.3) \times 10^{-3}$ and $(3.4, 6.5, 5.4) \times 10^{-6}$, respectively.

DOI: 10.1103/PhysRevLett.114.121801

PACS numbers: 14.80.Bn, 13.38.Dg, 14.70.Hp, 14.80.Ec

Rare decays of the recently discovered Higgs boson [1,2] to a quarkonium state and a photon may offer unique sensitivity to both the magnitude and sign of the Yukawa couplings of the Higgs boson to quarks [3–6]. These couplings are challenging to access in hadron colliders through the direct $H \to q\bar{q}$ decays, owing to the overwhelming QCD background [7].

Among the channels proposed as probes of the light quark Yukawa couplings [4,6], those with the heavy quarkonia $J/\psi$ or $\Upsilon(nS)$ ($n = 1, 2, 3$), collectively denoted as $Q$, in the final state are the most readily accessible, without requirements for dedicated triggers and reconstruction methods beyond those used for identifying the $J/\psi$ or $\Upsilon$. In particular, the decay $H \to J/\psi\gamma$ may represent a viable probe of the $Hc\bar{c}$ coupling [4], which is sensitive to physics beyond the Standard Model (SM) [8,9], at the Large Hadron Collider (LHC). The expected SM branching fractions for these decays have been calculated to be $B(H \to J/\psi\gamma) = (2.8 \pm 0.2) \times 10^{-6}$, $B(H \to \Upsilon(nS)\gamma) = (6.1^{+17.4}_{-6.1}, 2.0^{+6.0}_{-1.9}, 2.4^{+1.8}_{-1.3}) \times 10^{-10}$ [5]. No experimental information on these branching fractions exists. These decays are a source of background and potential control sample for the nonresonant decays $H \to \mu^+\mu^-\gamma$. These nonresonant decays are sensitive to new physics [10].

Rare decay modes of the Z boson have attracted attention focused on establishing their sensitivity to new physics [11]. Several estimates of the SM branching fraction for the decay $Z \to J/\psi\gamma$ are available [12–14] with the most recent being $(9.96 \pm 1.86) \times 10^{-8}$ [14]. Measuring these $Z \to Q\gamma$ branching fractions, benefitting from the larger production cross section relative to the Higgs case, would provide an important benchmark for the search and eventual observation of $H \to Q\gamma$ decays. Additionally, experimental access to resonant $Q\gamma$ decay modes would also provide an invaluable tool for the more challenging measurement of inclusive associated $Q\gamma$ production, which has been suggested as a promising probe of the nature of quarkonium production in hadronic collisions [15,16].

The decays $Z \to Q\gamma$ have not yet been observed, with the only experimental information arising from inclusive measurements, such as $B(Z \to J/\psi X) = (3.51^{+0.23}_{-0.25}) \times 10^{-3}$ and the 95\% confidence level (C.L.) upper limits $B[Z \to \Upsilon(nS)X] < (4.4, 13.9, 9.4) \times 10^{-5}$, from LEP experiments [17–21].

This Letter presents a search for decays of the recently observed Higgs boson and the Z boson to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ final states. The decays $J/\psi \to \mu^+\mu^-$ and $\Upsilon(nS) \to \mu^+\mu^-$ are used to reconstruct the quarkonium states. The search is performed with a sample of $pp$ collision data corresponding to an integrated luminosity of $19.2 \text{ fb}^{-1}$ (20.3 fb$^{-1}$) for the $J/\psi\gamma$ [($\Upsilon(nS)\gamma$)] analysis, respectively, recorded at a center-of-mass energy $\sqrt{s} = 8 \text{ TeV}$ with the ATLAS detector [22], described in detail in Ref. [23].

Higgs boson production is modeled using the POWHEG-BOX Monte Carlo (MC) event generator [24–28], separately for the gluon fusion (ggF) and vector-boson fusion (VBF) processes calculated in quantum chromodynamics (QCD) up to next-to-leading order in $\alpha_s$. The Higgs boson transverse momentum ($p_T$) distribution predicted for the ggF process is reweighted to match the calculations of Refs. [29,30], which include QCD corrections up to next-to-next-to-leading order and QCD soft-gluon resum-mations up to next-to-next-to-leading logarithms. Quark mass effects in ggF production [31] are also accounted for.

Physics beyond the SM that modifies the charm coupling can also change production dynamics and branching fractions. In this analysis we assume the production rates and dynamics for a SM Higgs boson with $m_H = 125 \text{ GeV}$, obtained from Ref. [32], with an uncertainty on the

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

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published articles title, journal citation, and DOI.
The transverse momentum of each reconstructed inner-detector track and calorimeter energy deposits within $\Delta R = \sqrt{\Delta \phi^2 + (\Delta \eta)^2}$ is required to be less than 0.2 of the leading muon’s $p_T$. The transverse momentum of the inner-detector track associated with the leading muon is subtracted from the sum and the subleading muon is also subtracted if it falls within the isolation cone. To reject backgrounds from $b$-hadron decays, the measured transverse decay length $L_{xy}$ between the dimuon vertex and the primary $pp$ vertex is required to be less than three times its uncertainty $\sigma_{L_{xy}}$. In this case, the primary $pp$ vertex is defined as the reconstructed vertex with the highest $\sum_i p_T^2$ of all associated tracks used to form the vertex.

Photon reconstruction is seeded by clusters of energy in the electromagnetic calorimeter. Clusters without matching tracks are classified as unconverted photon candidates. Clusters matched to tracks consistent with the hypothesis of a photon conversion into an $e^+e^-$ pair are classified as converted photon candidates. Reconstructed photon candidates are required to have transverse momentum $p_T > 36$ GeV, pseudorapidity $|\eta| < 2.37$, excluding the barrel/endcap calorimeter transition region $1.37 < |\eta| < 1.52$, and to satisfy the “tight” photon identification criteria. To further suppress the contamination from jets, an isolation requirement is imposed. The sum of the transverse momentum of all tracks and calorimeter energy deposits within $\Delta R = 0.2$ of the photon direction, excluding those associated with the reconstructed photon, is required to be less than 8% of the photon’s transverse momentum.

The total signal efficiency (kinematic acceptance, trigger, and reconstruction efficiencies) in the $J/\psi\gamma$ final state is 22% and 12% for the Higgs and $Z$ boson decays, respectively. The corresponding efficiencies for the $Y(nS)\gamma$ final state are 28% and 15%. The $m_{\mu\mu}$ resolution is similar for both the Higgs and $Z$ boson decays and varies between 1.2% and 1.8%. The $m_{\mu\mu}$ resolution is 1.4% and 2.4% for the barrel and endcap categories, respectively.

The main source of background, referred to as inclusive QCD background, is dominated by inclusive quarkonium production where a jet in the event is reconstructed as a photon. For the $Y(nS)\gamma$ final state, events containing $Z \rightarrow \mu^+\mu^-$ decays with final-state photon radiation (FSR) constitute a second source of background, a contribution which is found to be negligible in the $J/\psi\gamma$ final state. The normalization of both of these background sources is extracted directly from a fit to data. The modeling of the

dominant ggF production mode of 12%. The VBF signal model is appropriately scaled to account for the production of a Higgs boson in association with a $W$ or $Z$ boson or in association with a $t\bar{t}$ pair, correcting for the relative production rates and experimental acceptances for these channels. Contributions from nonresonant $H \rightarrow (Z^0/\gamma^*)t\rightarrow \mu^+\mu^-\gamma$ decays are expected to be negligible with respect to the present sensitivity.

The POWHEG-BOX MC event generator is also used to model $Z$ boson production. The total cross section is extracted from Ref. with an uncertainty of 4%.

The Higgs and $Z$ boson decays are simulated as a cascade of two-body decays. Effects of the helicity of the quarkonium states in the dimuon kinematics are accounted for in both cases. For Higgs and $Z$ boson events generated using POWHEG-BOX, PYTHIA8.1 is used to simulate showering and hadronization while PHOTOS is used to provide QED radiative corrections to the final state. The simulated events are passed through the full GEANT4 simulation of the ATLAS detector and processed with the same software used to reconstruct data events.

The data used to perform the search in the $J/\psi\gamma$ channel were collected using a trigger that required at least one muon with $p_T > 18$ GeV. The events used in the $Y(nS)\gamma$ channel were collected with a trigger requiring an isolated muon with $p_T > 24$ GeV and a dimuon trigger with $p_T$ thresholds of 18 and 8 GeV for each of the muons, respectively. Events are retained for analysis if they were collected under stable LHC beam conditions and the detector components were operating normally.

Muons are reconstructed from inner-detector tracks combined with independent muon spectrometer tracks or track segments and are required to have $p_T > 3$ GeV and pseudorapidity $|\eta| < 2.5$. Candidate $Q \rightarrow \mu^+\mu^-$ decays are reconstructed from pairs of oppositely charged muons consistent with originating from a common vertex. The highest-$p_T$ muon in a pair, called the leading muon in the following, is required to have $p_T^\mu > 20$ GeV. Dimuons with a mass, $m_{\mu\mu}$, within 0.2 GeV of the $J/\psi$ mass are identified as $J/\psi \rightarrow \mu^+\mu^-$ candidates. In case both muons in the pair are within $|\eta| < 1.05$, the said requirement is tightened to 0.15 GeV. Dimuons with $8.0 < m_{\mu\mu} < 12.0$ GeV are considered as $Y(nS) \rightarrow \mu^+\mu^-$ candidates. The transverse momentum of each $Q \rightarrow \mu^+\mu^-$ candidate, $p_T^{\mu\mu}$, is required to exceed 36 GeV.

Selected $Q \rightarrow \mu^+\mu^-$ candidates are subjected to isolation and vertex quality requirements. The sum of the $p_T$ of the reconstructed inner-detector tracks and calorimeter energy deposits within $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$ is 0.2 of the leading muon is required to be less than 10% of the muon’s $p_T$. The transverse momentum of the inner-detector track associated with the leading muon is subtracted from the sum and the subleading muon is also subtracted if it falls within the isolation cone. To reject backgrounds from
TABLE I. The number of observed events in each analysis category. For comparison, the expected background yield is given in parentheses for the two $m_{\mu\mu}$ ranges of interest. The Higgs and $Z$ boson contributions expected for branching fraction values of $10^{-3}$ and $10^{-6}$, respectively, are also shown. For $\Upsilon(nS)\gamma$, the 1S, 2S, and 3S contributions are summed.

<table>
<thead>
<tr>
<th>Category</th>
<th>Observed (expected background)</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass range [GeV]</td>
<td>$J/\psi\gamma$</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>80–100</td>
</tr>
<tr>
<td>BU</td>
<td>30</td>
<td>9</td>
</tr>
<tr>
<td>BC</td>
<td>29</td>
<td>8</td>
</tr>
<tr>
<td>EU</td>
<td>35</td>
<td>8</td>
</tr>
<tr>
<td>EC</td>
<td>23</td>
<td>6</td>
</tr>
<tr>
<td>BU</td>
<td>93</td>
<td>42</td>
</tr>
<tr>
<td>BC</td>
<td>71</td>
<td>32</td>
</tr>
<tr>
<td>EU</td>
<td>125</td>
<td>49</td>
</tr>
<tr>
<td>EC</td>
<td>85</td>
<td>31</td>
</tr>
</tbody>
</table>

The background from inclusive QCD processes is modeled with a nonparametric data-driven approach using templates to describe the kinematic distributions. The approach exploits a sample of loosely selected $\mu^+\mu^-\gamma$ events, around 2400 in the $J/\psi\gamma$ channel and around 3200 in the $\Upsilon(nS)\gamma$ channel. These control samples are formed from events satisfying the nominal $Q_{\gamma}$ selection, but with relaxed dimuon and photon transverse momenta ($p_T^\gamma > 25$ GeV and $p_T^{\mu\mu} > 25$ GeV) and isolation requirements (separate fractional calorimeter energy and track momentum isolation for the photon and dimuon system of less than 60%). Contamination of this sample from signal events is expected to be negligible. Probability density functions (pdfs) used to model the $p_T^{\mu\mu}$, $p_T^\gamma$, $\Delta\eta(\mu^+\mu^-\gamma)$ and $\Delta\phi(\mu^+\mu^-\gamma)$ distributions of this control sample, independently for each category, are constructed using Gaussian kernel density estimation [46]. To account for kinematic correlations, the distributions of $p_T^\gamma$, $\Delta\eta(\mu^+\mu^-\gamma)$ and $\Delta\phi(\mu^+\mu^-\gamma)$ are estimated in eight exclusive regions of $p_T^{\mu\mu}$. In the case of the dimuon and photon isolation variables, correlations are accounted for by using two-dimensional histograms derived in five exclusive regions of $p_T^{\mu\mu}$. The $m_{\mu\mu}$ distributions are modeled using Gaussian pdfs, with parameters derived from a fit to the control sample. In the $\Upsilon(nS)\gamma$ channel, the data control sample is corrected for contamination from $Z \rightarrow \mu^+\mu^-\gamma$ decays. The pdfs of these kinematic and isolation variables are sampled to generate an ensemble of pseudocandidates, each with a complete $Q_{\gamma}$ four-vector and an associated pair of correlated dimuon and photon isolation values. The nominal selection requirements are imposed on the ensemble and the surviving pseudocandidates are used to construct templates for the kinematic distributions, notably the inclusive QCD background $m_{\mu\mu}$ and $p_T^{\mu\mu}$ distributions.

The background from $Z \rightarrow \mu^+\mu^-\gamma$ decays is modeled with templates derived from a sample of simulated $Z$ boson events with $m_{\mu\mu}$ in the $\Upsilon(nS)$ mass region. To validate this background model with data, the sidebands of the $m_{\mu\mu}$ distribution in several validation regions, defined by relaxed kinematic or isolation requirements, are used to compare the prediction of the background model with the data. Good agreement within the statistical uncertainties is observed.

The composition of the inclusive QCD background and the $Z \rightarrow \mu^+\mu^-\gamma$ decay contribution is investigated with data. The details of the composition do not enter directly the background estimation for this search, but the composition itself is a crucial input in feasibility studies for future searches or measurements, where projections of these backgrounds to different center-of-mass energies or luminosity conditions are needed. To facilitate this study, the selection requirements on $m_{\mu\mu}$ and $|L_{xy}/\sigma_{L_{xy}}|$ are relaxed to include the sideband regions. In the $J/\psi\gamma$ final state, a simultaneous unbinned maximum likelihood fit to the $m_{\mu\mu}$ and $|L_{xy}/\sigma_{L_{xy}}|$ distributions is performed. Once the simultaneous fit is performed, the composition of the subset of events satisfying the nominal $m_{\mu\mu}$ and $|L_{xy}/\sigma_{L_{xy}}|$ requirements is estimated. After the complete event selection, around 56% of the events originate from prompt $J/\psi$ production, 3% from nonprompt $J/\psi$ production (from $b$-hadron decays) and 41% are combinatoric backgrounds from nonresonant dimuon events.

A separate simultaneous fit to the $m_{\mu\mu}$ and $m_{\mu\mu}$ distributions of the same sample of candidate $J/\psi$ events finds no significant contribution from $Z \rightarrow \mu^+\mu^-\gamma$ decays, a
The conclusion that is also supported by a study based on simulated $Z \rightarrow \mu^+\mu^-$ events.

For the $\Upsilon(nS)$ final state a simultaneous fit is performed to the $m_{\mu\mu}$ and $p_T^{\mu\mu}$ distributions. The full event selection, inclusive $\Upsilon(nS)$ production accounts for 7% of events, 27% of the events are produced in $Z \rightarrow \mu^+\mu^-\gamma$ decays, and 66% of the events are associated with combinatoric backgrounds from nonresonant dimuon events. The contribution from $Z \rightarrow \mu^+\mu^-\gamma$ decays is in agreement with the MC expectation.

Trigger efficiencies and efficiencies for muon and photon identification are determined from samples of $Z \rightarrow \ell\ell$, $Z \rightarrow \ell\ell\gamma$ ($\ell = e, \mu$), and $J/\psi \rightarrow \mu^+\mu^-$ decays in data [43,47]. The systematic uncertainty on the expected signal yield associated with the trigger efficiency is estimated to be 1.7%. The photon (both converted and unconverted) and muon reconstruction and identification efficiency uncertainties are estimated to be 0.5% (0.7%) and 0.4% (0.4%) for the Higgs boson ($Z$ boson) signal, respectively. An uncertainty on the integrated luminosity of 2.8% is derived using the method described in Ref. [48]. The photon energy scale uncertainty, determined from $Z \rightarrow e^+e^-$ and validated using $Z \rightarrow \ell\ell\gamma$ decays [49], is propagated through the simulated signal samples as a function of $\eta^2$ and $p_T^\gamma$. The uncertainty associated with the description of the photon energy scale in the simulation is found to be less than 0.2% of the three-body invariant mass while the uncertainty associated with the photon energy resolution is found to be negligible relative to the overall three-body invariant mass resolution. Similarly, the systematic uncertainty associated with the muon momentum measurement is determined using data samples of $J/\psi \rightarrow \mu^+\mu^-$ and $Z \rightarrow \mu^+\mu^-$ decays and validated using $\Upsilon(nS) \rightarrow \mu^+\mu^-$ decays [43]. For the $p_T^\gamma$ range relevant to this analysis, the systematic uncertainties associated with the muon momentum scale are negligible.

The uncertainty in the shape of the inclusive QCD background is estimated through the study of variations in the background modeling procedure. The shape of the pdf is allowed to vary around the nominal shape within an envelope associated with shifts in the $p_T^{\mu\mu}$ and $p_T^\gamma$ distributions. Furthermore, a separate background model, generated without removing the contamination from $Z \rightarrow \mu^+\mu^-\gamma$ decays, provides an upper bound on potential mismodeling associated with this process.

Results are extracted by means of a simultaneous unbinned maximum likelihood fit, performed to the selected events with $30 \text{ GeV} < m_{\mu\mu} < 230 \text{ GeV}$ separately in each of the analysis categories. In the $J/\psi\gamma$ final state, the fit is performed on the $m_{\mu\mu}$ and $p_T^{\mu\mu}$ distributions, while for the $\Upsilon(nS)\gamma$ candidates a similar fit is performed using the $m_{\mu\mu}$, $p_T^{\mu\mu}$, and $m_{\mu\mu}$ distributions. The latter distribution provides discrimination between the three $\Upsilon(nS)$ states and constrains the $Z \rightarrow \mu^+\mu^-\gamma$ background normalization. No significant $Z \rightarrow Q\bar{Q}$ or $H \rightarrow Q\bar{Q}$ signals are observed, as shown in Figs. 1 and 2.

Upper limits on the branching fractions for the Higgs and $Z$ boson decays to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ are set using the CL$_s$ modified frequentist formalism [50] with the profile likelihood ratio test statistic [51]. The expected SM production cross sections are assumed for the Higgs and $Z$ bosons. The results are summarized in Table II.

The 95% C.L. upper limit on the branching fraction for $H \rightarrow J/\psi\gamma$ decays corresponds to about 540 times the expected SM branching fraction. The upper limits on the $Z \rightarrow J/\psi\gamma$ and $Z \rightarrow \Upsilon(nS)\gamma$ branching fractions significantly constrain the allowed range of values obtained from theoretical calculations [12–14]. Upper limits are also set on the combined branching fractions $B[H \rightarrow \Upsilon(nS)\gamma] < 2.0 \times 10^{-3}$ and $B[Z \rightarrow \Upsilon(nS)\gamma] < 7.9 \times 10^{-6}$, where the relative contribution of each final state to the potential

FIG. 1 (color online). The $m_{\mu\mu}$ and $p_T^{\mu\mu}$ distributions of the selected $J/\psi\gamma$ candidates, along with the results of the unbinned maximum likelihood fit to the signal and background model ($S + B$ fit). The error bars on the data points correspond to the statistical uncertainties. The Higgs and $Z$ boson contributions as expected for branching fraction values of $10^{-3}$ and $10^{-6}$, respectively, are also shown.
signal is profiled (allowed to float to the values that maximize the likelihood) during the fit.

In conclusion, the first search for the decays of the SM Higgs and Z bosons to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ ($n = 1, 2, 3$) has been performed with $\sqrt{s} = 8$ TeV pp collision data samples corresponding to integrated luminosities of up to 20.3 fb$^{-1}$ collected with the ATLAS detector at the LHC. No significant excess of events is observed above the background. In the $J/\psi\gamma$ final state, the 95% C.L. upper limits on the relevant branching fractions for the SM Higgs and Z bosons are $1.5 \times 10^{-3}$ and $2.6 \times 10^{-6}$, respectively. The corresponding upper limits in the $\Upsilon(1S, 2S, 3S)\gamma$ channels are $(1.3, 1.9, 1.3) \times 10^{-3}$ and $(3.4, 6.5, 5.4) \times 10^{-6}$, for the SM Higgs and Z bosons, respectively. These are the first experimental bounds on exclusive Higgs and Z boson decays to final states involving quarkonia.

### TABLE II. Expected and observed branching fraction limits at 95% C.L. for $\sqrt{s} = 8$ TeV. The $\pm 1\sigma$ fluctuations of the expected limits are also given. For the Higgs decay search, limits are also set on the cross section times branching fraction $\sigma(pp \to H) \times B(H \to Q\gamma)$.

<table>
<thead>
<tr>
<th>Decay</th>
<th>$J/\psi$</th>
<th>$\Upsilon(1S)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\Upsilon(3S)$</th>
<th>$\sum_{n}\Upsilon(nS)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(Z \to Q\gamma)$</td>
<td>$10^{-6}$</td>
<td>$2.0 \pm 1.0 \pm 0.6$</td>
<td>$4.9 \pm 2.5$</td>
<td>$6.2 \pm 2.6 \pm 0.9$</td>
<td>$5.4 \pm 3.7$</td>
</tr>
<tr>
<td>$B(H \to Q\gamma)$</td>
<td>$10^{-3}$</td>
<td>$2.6$</td>
<td>$3.4$</td>
<td>$6.5$</td>
<td>$5.4$</td>
</tr>
<tr>
<td>$\sigma(pp \to H) \times B(H \to Q\gamma)$</td>
<td>$[b]$</td>
<td>$1.5 \pm 0.3$</td>
<td>$1.8 \pm 0.9$</td>
<td>$2.1 \pm 1.1 \pm 0.6$</td>
<td>$1.8 \pm 0.9 \pm 0.5$</td>
</tr>
<tr>
<td>$B(S+B)$</td>
<td>$[b]$</td>
<td>$1.3$</td>
<td>$1.9$</td>
<td>$1.9$</td>
<td>$1.3$</td>
</tr>
</tbody>
</table>

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, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; 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.


(ATLAS Collaboration)

1Department of Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany NY, United States of America
3Department of Physics, University of Alberta, Edmonton AB, Canada
4Department of Physics, University of Alberta, Anchorage AK, United States of America
5LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
6High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States of America
7Department of Physics, Arizona State University, Tempe, AZ, United States of America
8Department of Physics, University of Arizona, Tucson, AZ, United States of America
9Department of Physics, University of Athens, Athens, Greece
10Department of Physics, National Technical University of Athens, Zografou, Greece
11Institut de Physique, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13Institute of Physics, University of Belgrade, Belgrade, Serbia
14Department for Physics and Technology, University of Bergen, Bergen, Norway
15Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States of America
16Department of Physics, Humboldt University, Berlin, Germany
17Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19Department of Physics, Bogazici University, Istanbul, Turkey
20Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
21Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
22INFN Sezione di Bologna, Bologna, Italy
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, ON, Canada

TRIUMF, Vancouver, BC, Canada

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

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

Department of Physics and Astronomy, Tufts University, Medford, MA, United States of America

Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

Department of Physics and Astronomy, University of California Irvine, Irvine, CA, United States of America

INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy

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

Department of Physics, University of Illinois, Urbana, IL, United States of America

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 y de Ingeniería Electrónica de Barcelona (IMB-CNMTM), University of Valencia and CSIC, Valencia, Spain

Department of Physics, University of British Columbia, Vancouver, BC, Canada

Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada

Department of Physics, University of Warwick, Coventry, United Kingdom

Waseda University, Tokyo, Japan

Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, WI, United States of America

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, CT, United States of America

Yerevan Physics Institute, Yerevan, Armenia

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

Deceased.

Also at Department of Physics, King’s College London, London, United Kingdom.

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

Also at Novosibirsk State University, Novosibirsk, Russia.

Also at TRIUMF, Vancouver, BC, Canada.

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

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

Also at Tomsk State University, Tomsk, Russia.

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

Also at Università di Napoli Parthenope, Napoli, Italy.

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

Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

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

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

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

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

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

Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

Also at CERN, Geneva, Switzerland.

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

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

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

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

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

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

Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.

Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at Section de Physique, Université de Genève, Geneva, Switzerland.
Also at International School for Advanced Studies (SISSA), Trieste, Italy.
Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America.
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
Also at National Research Nuclear University MEPhI, Moscow, Russia.
Also at Department of Physics, Stanford University, Stanford CA, United States of America.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at Department of Physics, Oxford University, Oxford, United Kingdom.
Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America.
Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.
Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.