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Citation: G. Aad et al. "Search for Down-Type Fourth Generation Quarks with the ATLAS Detector in Events with One Lepton and Hadronically Decaying W Bosons." Physical Review Letters 109 (2012).

As Published: <http://dx.doi.org/10.1103/PhysRevLett.109.032001>

Publisher: American Physical Society

Persistent URL: <http://hdl.handle.net/1721.1/74646>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

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Search for Down-Type Fourth Generation Quarks with the ATLAS Detector in Events with One Lepton and Hadronically Decaying W Bosons

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(Received 29 February 2012; published 20 July 2012)

This Letter presents a search for pair production of heavy down-type quarks decaying via $b' \rightarrow Wt$ in the lepton + jets channel, as $b'\bar{b}' \rightarrow W^-tW^+\bar{t} \rightarrow b\bar{b}W^+W^-W^+W^- \rightarrow l^\pm \nu b\bar{b}q\bar{q}q\bar{q}q\bar{q}$. In addition to requiring exactly one lepton, large missing transverse momentum, and at least six jets, the invariant mass of nearby jet pairs is used to identify high transverse momentum W bosons. In data corresponding to an integrated luminosity of 1.04 fb^{-1} from pp collisions at $\sqrt{s} = 7 \text{ TeV}$ recorded with the ATLAS detector, a heavy down-type quark with mass less than 480 GeV can be excluded at the 95% confidence level.

DOI: [10.1103/PhysRevLett.109.032001](https://doi.org/10.1103/PhysRevLett.109.032001)

PACS numbers: 13.85.Rm, 12.60.-i, 14.65.Jk

A fourth generation of chiral quarks is a natural extension to the standard Model (SM). It can explain some discrepancies observed in meson-mixing data and can provide an additional source of CP violation in B_s decays. A review of theoretical and experimental motivations for a fourth generation of quarks can be found in Refs. [1,2].

This Letter presents a search for a fourth generation down-type quark, b' . If b' is chiral and its mass is larger than $m_t + m_W$, then it decays predominantly as $b' \rightarrow Wt \rightarrow WWb$. Pair production of b' quarks leads therefore to four W bosons and two b quarks in the final state. This analysis applies more broadly to any heavy quarks that decay into a W boson and a t quark, though the fourth generation b' model is chosen as the benchmark. The previous limit in the single lepton channel is $m_{b'} > 372 \text{ GeV}$ from CDF, based on 4.8 fb^{-1} of data [3]. Searches using two or more high p_T leptons in the final state have also been done at the Tevatron [4] and at the Large Hadron Collider (LHC) [5–7] with comparable sensitivity.

In the decay mode studied here, one of the four W bosons decays leptonically and the others decay hadronically. This lepton + jets channel has more SM background than the mode with two W bosons decaying leptonically, but significantly larger acceptance. If the mass difference between the b' quark and the top quark is large, the momentum of the W boson from the $b' \rightarrow Wt$ decay is also large, and the W boson decay products become collimated. At the mass scales relevant to this search, the two quarks from the hadronic W decay give rise to two jets close to each other but still resolvable in the detector as separate jets. The angle between the decay products is related to the transverse momentum (p_T) of the W boson

by $\Delta R \approx 2m_W/p_T^W$ [8]. To distinguish the b' signature from the SM backgrounds, the number of jet pairs with small opening angle and invariant mass close to the W boson mass is therefore used.

The major challenge for the lepton + jets mode is the estimation of the SM background. The dominant source is $t\bar{t}$ production with additional jets, while W + jets is the next most important contribution. The significant theoretical uncertainty in the level of gluon radiation affects the prediction of these backgrounds. As the signal is distinguished from the background largely by the kinematic properties of the jets, there are also significant experimental uncertainties due to the energy scale and resolution of the jet energy measurements. Most of these uncertainties can be reduced by examining signal-depleted samples which are sensitive to them. Other backgrounds include single top, Z + jets where a lepton is not detected, and multijet production in which a jet is misidentified as a lepton.

The data for this search were recorded with the ATLAS detector [9]. The momenta of charged particles with pseudorapidity $|\eta| < 2.5$ are measured with the inner detector (ID), which includes a silicon pixel detector, a silicon microstrip detector, and a straw-tube detector, all operating in a uniform 2 T axial magnetic field. Electromagnetic (EM) calorimetry is provided by a high-granularity, three-layer-depth sampling liquid argon detector in the region $|\eta| < 3.2$. Jet reconstruction also uses hadronic calorimetry provided by a scintillating tile detector with iron absorbers in the region $|\eta| < 1.7$, and liquid argon detectors over $1.5 < |\eta| < 4.9$. The muon spectrometer (MS) includes tracking chambers for precision measurement in the bending plane up to $|\eta| = 2.7$ and fast trigger chambers up to $|\eta| = 2.4$. The trigger chambers measure also the coordinate in the nonbending plane. The muon detectors operate in a magnetic field generated by three superconducting air-core toroids.

The events used in this analysis were selected using inclusive single electron and muon triggers [10]. Electron

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candidates are identified by localized energy deposits in the EM calorimeter with transverse energy $E_T > 20$ GeV and $|\eta| < 2.47$. The energy cluster must satisfy shower-shape requirements [11] and should be matched with a track reconstructed in the ID. Muon candidates must have transverse momentum $p_T > 18$ GeV, $|\eta| < 2.4$, and a consistent trajectory reconstructed by combining segments in the ID and MS.

The data used in this search were collected in the first half of 2011, and correspond to a total integrated luminosity of $1.04 \pm 0.04 \text{ fb}^{-1}$. During this period, the average number of collisions per bunch crossing was six. The event reconstruction is affected by collisions during the same bunch crossing as the selected event (in-time pileup) and, to a lesser extent, collisions during adjacent bunch crossings, within the time the detectors are sensitive for each trigger (out-of-time pileup). The simulation takes both kinds of pileup into account.

The signal and SM backgrounds are modeled using a variety of generators. Pair-production of b' quarks decaying to Wt with subsequent showering and hadronization is generated with PYTHIA [12] using the MRST2007 LO* parton distribution function (PDF) set [13]. Seven samples with $m_{b'}$ masses ranging from 300 to 600 GeV are used. The cross section for each b' mass is calculated at approximate next-to-next-to-leading order (NNLO) using HATHOR [14]. For a b' quark with a mass of 350 GeV, the cross section is $3.20^{+0.10+0.12}_{-0.19-0.12} \text{ pb}$, where the first uncertainty comes from varying the renormalization and factorization scales by a factor of 2, and the second one from the PDFs. For a 500 GeV b' quark, the cross section is $0.33^{+0.01+0.01}_{-0.02-0.01} \text{ pb}$.

Top quark pair production is modeled using ALPGEN [15] where hard emission of up to three partons is described using QCD matrix elements, HERWIG [16] is used to model the parton shower, and JIMMY [17] describes multiple parton interactions. The rate of top quark production predicted by the simulation is validated with data using an event sample with three, four, or five jets, where little or no b' signal is expected.

Production of a W or Z boson in association with many jets is described in ALPGEN with hard parton emission of up to five partons and HERWIG for the parton shower. The W + jets background is normalized using a data-driven method which fits templates from simulated events to a data sample dominated by W decays [18]. The Z + jets background is normalized to a NNLO calculation [19].

Other processes considered are the production of dibosons (WW , WZ , ZZ), modeled with ALPGEN and HERWIG and normalized to next-to-leading-order (NLO) calculations [20]; single top, modeled with MC@NLO [21] and HERWIG; and $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}WW$, $t\bar{t}Wj$, $t\bar{t}Zj$, and $WWjj$, all modeled with MADGRAPH [22] and PYTHIA.

The multijet background is strongly suppressed by the requirements described below. The residual contribution is

estimated using a data-driven technique called the matrix method, described in detail in Ref. [23]. Validation of this background estimate is done by reversing these requirements to enhance the multijet contribution.

Electrons, jets, muons, and missing transverse momentum are used to select events for this search. Electrons are required to have $E_T > 25$ GeV and be within the pseudorapidity range $|\eta| < 2.47$, excluding the barrel-end-cap transition region $1.37 < |\eta| < 1.52$. Electrons must pass tight identification requirements [11] and also satisfy calorimeter isolation: the energy not associated with the electron cluster inside a cone of size $\Delta R = 0.2$ around the electron direction must be smaller than 3.5 GeV after the correction for the contributions from interactions additional to the hard process.

Jets are reconstructed from topological calorimeter clusters using the anti- k_t algorithm [24] with radius parameter 0.4. These jets are then calibrated to the hadronic energy scale using p_{T-} and η -dependent correction factors obtained from simulation and validated with collision data [25]. For this analysis, jets are required to satisfy $p_T > 25$ GeV and $|\eta| < 2.5$. The closest jet within an η - ϕ cone of 0.2 around an electron candidate is removed.

Muon candidates must satisfy $p_T > 20$ GeV and $|\eta| < 2.5$ and pass tight identification requirements [23]. Muons must also satisfy calorimeter isolation, which requires that the energy, excluding the estimated energy deposited by the muon, is smaller than 4 GeV in a cone of size $\Delta R = 0.3$ around the muon direction, and track isolation, which requires that the summed momentum of all tracks excluding the muon track is smaller than 4 GeV in a cone of size $\Delta R = 0.3$. Finally, all muons within a cone of size $\Delta R = 0.4$ around any jet with $p_T > 20$ GeV are removed.

The missing transverse momentum (E_T^{miss}) is constructed from the vector sum of topological calorimeter energy deposits and muon momenta, projected onto the transverse plane [26].

If each b' quark decays to a top quark and a W boson, the resulting final state is $t\bar{t}W^+W^-$. In the lepton + jets decay channel, the final state contains one lepton, E_T^{miss} from the undetected neutrino, and many jets from the eight quarks. Exactly one lepton (e or μ) must pass the selection described above. Since not all jets are expected to satisfy the momentum and rapidity requirements, at least six jets are required.

To reduce the multijet background, additional requirements are placed on the E_T^{miss} and the transverse mass of the leptonically decaying W boson, $m_T^W = \sqrt{2E_T^{\text{miss}}p_T^\ell\{1 - \cos[\Delta\phi(E_T^{\text{miss}}, p_T^\ell)]\}}$. In the electron channel, $E_T^{\text{miss}} > 35$ GeV and $m_T^W > 25$ GeV are required, and in the muon channel, $E_T^{\text{miss}} > 20$ GeV and $E_T^{\text{miss}} + m_T^W > 60$ GeV are required. Only events with six or more jets are considered. For a b' quark with a mass of 350 GeV, $11.2 \pm 1.7\%$ of signal events are accepted with this selection. For a

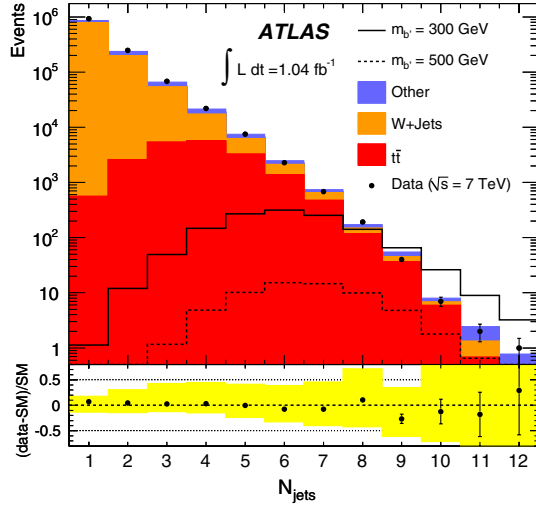


FIG. 1 (color online). Jet multiplicity distribution for signal and backgrounds for events with at least one jet. The shaded SM backgrounds are stacked on one another, while the b' signal histograms are not. In this figure and those following, the bottom plot shows the relative difference between the SM prediction and the data together with the uncertainty (shaded band) due to statistics, jet energy scale, and $W + \text{jets}$ normalization.

b' quark with a mass of 500 GeV, $13.5 \pm 2.0\%$ of signal events are retained.

At this stage of the selection, pair production of b' quarks is distinguished mostly by the large number of energetic jets, as shown in Fig. 1. Events with b' decays contain jets from three hadronic W decays, while $t\bar{t}$ background events contain only one hadronic W decay.

To identify these hadronic W decays, pairs of jets separated by $\Delta R < 1.0$ are examined. This choice of ΔR selects W bosons with high p_T and reduces the combinatorial background in events with large jet multiplicity. The number of reconstructed W bosons (N_W) is defined as the number of such jet pairs with an invariant mass in the range 70–100 GeV. This range is not symmetric around the W boson mass as additional energy is often included in the cone. Each jet may contribute to only one identified hadronic W decay. In Fig. 2, the invariant masses of dijet pairs in a control sample of events with only three to five jets are shown. Good agreement is observed between the data and simulation across the entire spectrum including the region close to the W boson mass, where a bump can be seen in the $t\bar{t}$ simulation.

The efficiency of finding a simulated W decay with both quarks matched to separate reconstructed jets depends on the W boson p_T . For simulated $t\bar{t}$ and b' events passing the selection described above and containing a W boson with a p_T of about 250 GeV the two jets from the W boson are found approximately 80% of the time. Once both jets are found, the efficiency that the jets have $\Delta R < 1.0$ and a dijet mass within the specified invariant mass range is approximately 70%, as can be seen in Fig. 3.

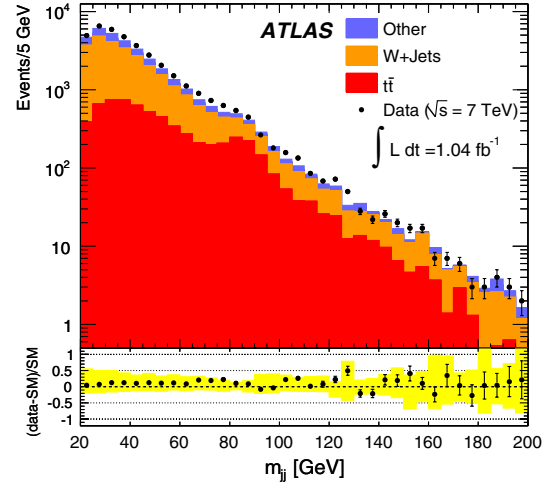


FIG. 2 (color online). The invariant mass distribution of jet pairs with $\Delta R < 1.0$ for data and simulation in a control sample of events with exactly three to five jets.

To further distinguish the potential b' signal from the backgrounds, nine exclusive bins are examined, defined as a function of the multiplicity of hadronic W decays ($N_W = 0, 1, \geq 2$) and jet multiplicity ($N_{\text{jet}} = 6, 7, \geq 8$).

The agreement between data and simulation for the description of the number of jets is validated in events with a scalar sum (H_T) of transverse energies of jets and leptons less than 400 GeV and no reconstructed hadronic W decays, to suppress potential b' contributions.

Table I shows the major sources of systematic uncertainty. The main contributions to uncertainty in the modeling of the backgrounds and b' signal come from the jet energy scale and the level of initial and final state radiation (ISR and FSR) in the top quark pair background. The jet

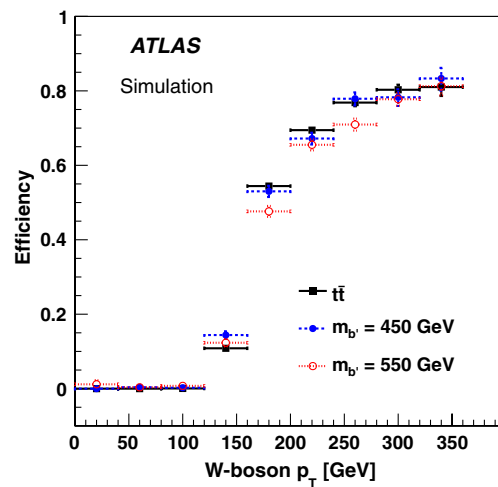


FIG. 3 (color online). The efficiency for jet pairs from a simulated W boson decay to have $\Delta R < 1.0$ and a dijet mass within 70–100 GeV, for simulated $t\bar{t}$ and signal events. Events are required to have exactly six jets.

TABLE I. Systematic uncertainties in the predicted total background in the signal region. Some of the uncertainties have been constrained in background-dominated regions, profiled as described in the text. Smaller systematic uncertainties, such as those related to lepton identification and theory, and small uncertainties on the rate, are not profiled and are not included here. For the profiled systematics, the uncertainty before profiling is given in parentheses.

| Uncertainty on background | |
|---------------------------------|---------------------------|
| Profiled uncertainties | |
| $W + \text{jets}$ normalization | $\pm 5\%$ ($\pm 16\%$) |
| ISR/FSR | $\pm 12\%$ ($\pm 17\%$) |
| Jet energy resolution | $\pm 3\%$ ($\pm 6\%$) |
| Jet reconstruction efficiency | $\pm 2\%$ ($\pm 3\%$) |
| Not-profiled uncertainties | |
| Jet energy scale | $\pm 31\%$ |
| $t\bar{t}$ simulation generator | $\pm 6\%$ |
| $t\bar{t}$ showering model | $\pm 3\%$ |

energy scale uncertainty is extracted from dijet events and validated with $\gamma + \text{jet}$ events as discussed in Ref. [25], with an additional uncertainty due to in-time pileup. The amounts of simulated ISR and FSR are varied according to their uncertainties for both background and signal events. Jet reconstruction efficiency and jet energy resolution lead to smaller uncertainties in the predicted background.

For the largest background source, $t\bar{t}$ with additional jets, uncertainties in the description of the parton shower and fragmentation model are estimated by comparing predictions of POWHEG [27] with PYTHIA to POWHEG with HERWIG. Uncertainties in the modeling of the production and decay of the top quark are estimated by comparing the predictions from POWHEG with HERWIG and ALPGEN.

The $W + \text{jets}$ normalization uncertainty is 4%, plus 24% per jet added in quadrature [18]. The uncertainties in lepton reconstruction efficiency and energy scale are derived in dilepton samples dominated by $Z \rightarrow \ell\ell$ decays and applied to the simulated background and signal samples.

The systematic uncertainties are treated as correlated between signal and background, and between electron and muon channels, except where they are specific to the background model (e.g. $W + \text{jets}$ normalization) or to a channel (e.g. electron or muon efficiencies).

To extract the most likely value of the $b'\bar{b}'$ cross section in the nine bins of (N_W, N_{jet}) multiplicity, a binned maximum likelihood fit using a profile likelihood ratio is performed, varying each background rate within its uncertainty, and allowing shape and rate variation due to the systematic uncertainties described above. The signal and background rates are fitted simultaneously.

Events in the final selection which have low hadronic W boson or jet multiplicity ($N_W < 2$ and $N_{\text{jet}} < 8$) are dominated by background processes and serve to constrain some of the systematic uncertainties. The likelihood is

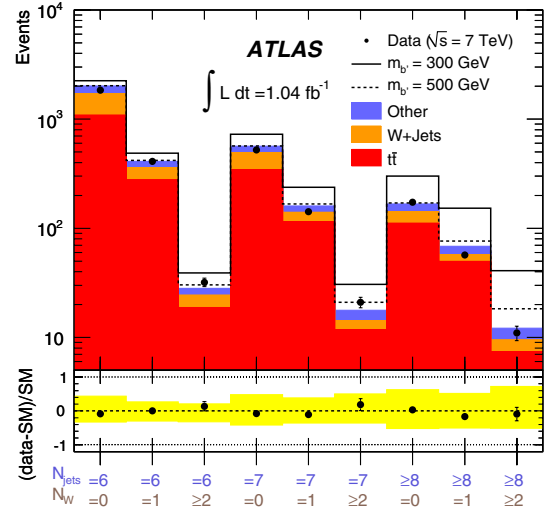


FIG. 4 (color online). Distribution of the numbers of events observed in the data and expected from SM processes for jet multiplicity $N_{\text{jet}} = 6, 7, \geq 8$ with hadronic W multiplicity $N_W = 0, 1, \geq 2$. The expected b' signals for two masses are also shown, stacked on top of the backgrounds.

maximized with respect to the variation due to the systematic uncertainties. This procedure serves to reduce some of the systematic uncertainties, those listed as profiled in Table I.

The expected background and signal contributions, as well as the observed numbers of events in the data, are shown in Fig. 4 and given in Table II for the nine bins of jet and hadronic W -boson multiplicity. No evidence for the production of b' quarks is observed. The CLs method [28] is used to set 95% confidence level (C.L.) cross section

TABLE II. Expected and observed number of events in each bin of jet and hadronic W decay multiplicity. Estimates for two signal samples with different b' masses are also shown. The contributions from different background sources are shown in Fig. 4.

| N_{jet} | N_W | Expected background | Observed events | b' 350 GeV b' 500 GeV | |
|------------------|----------|----------------------|-----------------|-----------------------|---|
| | | | | | |
| 6 | 0 | 2060^{+850}_{-750} | 1839 | 80 | 5 |
| 6 | 1 | 410^{+104}_{-150} | 410 | 47 | 8 |
| 6 | ≥ 2 | 28^{+10}_{-16} | 32 | 7 | 2 |
| 7 | 0 | 570^{+320}_{-230} | 521 | 60 | 4 |
| 7 | 1 | 166^{+49}_{-68} | 142 | 46 | 7 |
| 7 | ≥ 2 | $17.9^{+6.6}_{-6.8}$ | 21 | 11 | 3 |
| ≥ 8 | 0 | 170^{+180}_{-70} | 173 | 56 | 3 |
| ≥ 8 | 1 | 69^{+33}_{-27} | 57 | 50 | 8 |
| ≥ 8 | ≥ 2 | $12.1^{+8.6}_{-5.2}$ | 11 | 22 | 6 |

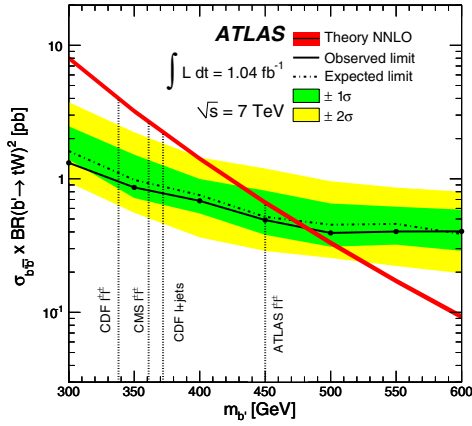


FIG. 5 (color online). Expected and observed cross section exclusion upper limits at 95% C.L. for a fourth generation b' quark. Systematic uncertainties on the expected limit are shown with shaded bands. Previously published limits from CDF [3,4], CMS [5], and ATLAS [7] are also shown.

upper limits for the pair production of fourth generation quarks, b' . The median expected upper limit is extracted in the background-only hypothesis. The results are shown in Fig. 5 as a function of the b' mass. Systematic uncertainties are taken into account and it is assumed that the branching ratio (BR) for $b' \rightarrow Wt$ is 100%. These cross section limits are interpreted as limits on the b' mass by finding the intersection of the limit curves with the theoretical cross section curve. Uncertainty in the theoretical cross section includes renormalization and factorization scale and PDF uncertainties calculated with HATHOR [14].

Masses below 480 GeV are excluded at the 95% confidence level, while the expected limit is $m_{b'} > 470$ GeV. For a particle with a mass of 480 GeV, the expected exclusion limit on the pair production cross section is $\sigma < 0.54^{+0.45}_{-0.22}$ pb, while the observed exclusion is $\sigma < 0.47$ pb.

In conclusion, a search for pair production of heavy down-type quarks decaying via $b' \rightarrow Wt$ in the lepton + jets channel has been performed using 1.04 fb^{-1} of $\sqrt{s} = 7$ TeV pp collision data recorded with the ATLAS detector, selecting events based on the number of jets and hadronic W decays. A heavy down-type quark with mass less than 480 GeV is excluded at the 95% confidence level, improving significantly on previous limits.

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, 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; GNAS,

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; MSTB, 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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