PDF hosted at the Radboud Repository of the Radboud University Nijmegen

The following full text is a preprint version which may differ from the publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/157984

Please be advised that this information was generated on 2018-11-25 and may be subject to change.
Observation of long-range elliptic anisotropies in $\sqrt{s} = 13$ and $2.76$ TeV $pp$ collisions with the ATLAS detector

The ATLAS Collaboration

Abstract

ATLAS has measured two-particle correlations as a function of relative azimuthal-angle, $\Delta\phi$, and pseudorapidity, $\Delta\eta$, in $\sqrt{s} = 13$ and $2.76$ TeV $pp$ collisions at the LHC using charged particles measured in the pseudorapidity interval $|\eta| < 2.5$. The correlation functions evaluated in different intervals of measured charged-particle multiplicity show a multiplicity-dependent enhancement at $\Delta\phi \sim 0$ that extends over a wide range of $\Delta\eta$, which has been referred to as the “ridge”. Per-trigger-particle yields, $Y(\Delta\phi)$, are measured over $2 < |\Delta\eta| < 5$. For both collision energies, the $Y(\Delta\phi)$ distribution in all multiplicity intervals is found to be consistent with a linear combination of the per-trigger-particle yields measured in collisions with less than 20 reconstructed tracks, and a constant combinatoric contribution modulated by $\cos (2\Delta\phi)$. The fitted Fourier coefficient, $v_2$, exhibits factorization, suggesting that the ridge results from per-event $\cos (2\phi)$ modulation of the single-particle distribution with Fourier coefficients $v_2$. The $v_2$ values are presented as a function of multiplicity and transverse momentum. They are found to be approximately constant as a function of multiplicity and to have a $p_T$ dependence similar to that measured in $p+Pb$ and $Pb+Pb$ collisions. The $v_2$ values in the 13 and 2.76 TeV data are consistent within uncertainties. These results suggest that the ridge in $pp$ collisions arises from the same or similar underlying physics as observed in $p+Pb$ collisions, and that the dynamics responsible for the ridge has no strong $\sqrt{s}$ dependence.

© 2015 CERN for the benefit of the ATLAS Collaboration.
Reproduction of this article or parts of it is allowed as specified in the CC-BY-3.0 license.
Measurements of two-particle angular correlations in high-multiplicity proton-proton (pp) collisions at a center-of-mass energy √s = 7 TeV at the LHC showed an enhancement in the production of pairs at small azimuthal-angle separation, Δφ, that extends over a wide range of pseudorapidity differences, Δη, and which is often referred to as the “ridge” [1]. The ridge has also been observed in proton-lead (p+Pb) collisions [2–7], where it is found to result from a global sinusoidal modulation of the per-event single-particle azimuthal angle distributions [3–6]. While many theoretical interpretations of the ridge, including those based on hydrodynamics [8–12], saturation [13–22], or other mechanisms [23–27], have been, or could be applied to both pp and p+Pb collisions, it has not yet been demonstrated that the ridge in pp collisions results from single-particle azimuthal anisotropies. Testing whether the ridges in pp and p+Pb collisions arise from the same underlying features of the single-particle distributions may provide insight into the physics responsible for the phenomena. Separately, a study of the √s dependence of the ridge in pp collisions may help distinguish between competing explanations.

This letter uses 14 nb⁻¹ of √s = 13 TeV data and 4.0 pb⁻¹ of √s = 2.76 TeV data recorded during LHC Run 2 and Run 1, respectively, to address these issues. The maximum number of inelastic interactions per crossing was 0.04 and 0.5 for the 13 and 2.76 TeV data, respectively. Two-particle angular correlations are measured as a function of Δη and Δφ in different intervals of the measured charged-particle multiplicity and different p_T intervals spanning 0.3 < p_T < 5.0 GeV; p_T-integrated results use 0.5 < p_T < 5.0 GeV. Per-trigger-particle yields are obtained from the long-range (Δη>2) component of the correlation. A new template-fitting method is applied to these yields to test for sinusoidal modulation similar to that observed in p+Pb collisions.

The measurements were performed using the ATLAS inner detector (ID), minimum-bias trigger scintillators (MBTS), forward calorimeter (FCal), and the trigger and data acquisition systems [28]. The ID detects charged particles within |η|<2.5\(^1\) using a combination of silicon pixel detectors, silicon micro-strip detectors (SCT), and a straw-tube transition radiation tracker (TRT), all immersed in a 2 T axial magnetic field [29]. The MBTS system detects charged particles using two hodoscopes of counters positioned at z = ±3.6 m. The FCal covers 3.1<|η|<4.9 and uses tungsten and copper absorbers with liquid argon as the active medium. Between Run 1 and Run 2, an additional, innermost pixel layer was added to the ID and the MBTS was replaced.

The ATLAS trigger system [30] consists of a Level-1 (L1) trigger implemented using a combination of dedicated electronics and programmable logic, and a software-based high-level trigger (HLT). Charged-particle tracks were reconstructed in the HLT using methods similar to those applied in the offline analysis, allowing triggers that select on the number of tracks with p_T>0.4 GeV associated with a single vertex. For the 13 TeV measurements, a minimum-bias L1 trigger required one or more signals in the MBTS while the high-multiplicity trigger (HMT) required at least 900 SCT hits and at least 60 HLT-reconstructed tracks. For the 2.76 TeV data the minimum-bias trigger selected random crossings at L1 and applied a threshold to the number of SCT and pixel hits in the HLT, while several HMT triggers were formed by applying thresholds on the total FCal transverse energy at L1 and different thresholds on the number of HLT-reconstructed tracks. HMT triggers are only used where their multiplicity selection is more than 90% efficient.

Charged-particle tracks and collision vertices are reconstructed in the ID using algorithms that were re-optimized between LHC Runs 1 and 2 [31]. Tracks used in the analysis are required to have p_T>0.3 GeV.

\(^1\) ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, θ) are used in the transverse plane, φ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as η = −ln tan(θ/2).
$|\eta|<2.5$ and to satisfy additional selection criteria that differ slightly between the 2.76 [4] and 13 TeV [32] data.

Events used in the analysis are required to have at least one reconstructed vertex. For events containing multiple vertices (pileup), only tracks associated with the vertex having the largest $\sum p_T^2$, where the sum is over all tracks associated with the vertex, are used. The measured charged-particle multiplicity, $N_{\text{rec}}$, is defined as the number of tracks having $p_T>0.4$ GeV associated with this vertex. The distributions of $N_{\text{ch}}$ are shown in Fig. 1. The structures in the distributions result from the different HMT trigger thresholds.

The efficiency, $\epsilon(p_T, \eta)$, of the track reconstruction and track selection requirements is evaluated using simulated non-diffractive $pp$ events obtained from the PYTHIA 8 [33] event generator (A2 tune [34], MSTW2008LO PDFs [35]) that are passed through a GEANT4 [36] simulation of the ATLAS detector response and reconstructed using the algorithms applied to the data [37]. The efficiencies for the two data sets are similar, but differ due to changes in the detector and reconstruction algorithms between Runs 1 and 2. In the simulated events, the efficiency reduces the measured multiplicity relative to the PYTHIA 8 $p_T > 0.4$ GeV charged-particle multiplicity by approximately multiplicity-independent factors of $1.18 \pm 0.05$ and $1.22 \pm 0.05$ for 13 and 2.76 TeV data, respectively. The uncertainties in these factors result from systematic uncertainties in the tracking efficiencies, which are described in detail in Ref. [32]. Those systematic uncertainties vary with pseudorapidity between 1.1% (central) and 6.5% (forward) and result from uncertainties on the material description.

The present analysis follows methods used in previous ATLAS two-particle correlation measurements in Pb+Pb and $p+Pb$ collisions [4, 6, 38–40]. Two-particle correlations for charged particle pairs with transverse momenta $p_T^a$ and $p_T^b$, are measured as a function of $\Delta \phi \equiv \phi^a - \phi^b$ and $\Delta \eta \equiv \eta^a - \eta^b$, with $|\Delta \eta| \leq 5$, determined by the acceptance of the ID. The particles $a$ and $b$ are conventionally referred to as the “trigger” and “associated” particles, respectively. The correlation function is defined as:

$$C(\Delta \eta, \Delta \phi) = \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)} ,$$

where $S(\Delta \eta, \Delta \phi)$ is the number of events with $|\Delta \eta| \leq 5$ and $|\Delta \phi| \leq 5$ and $B(\Delta \eta, \Delta \phi)$ is the number of events with $|\Delta \eta| \leq 5$ and $|\Delta \phi| \leq 5$ for the baseline distribution, respectively.
where $S$ and $B$ represent the same event and “mixed event” pair distributions respectively [41]. When constructing $S$ and $B$, pairs are weighted by the inverse product of their reconstruction efficiencies $1/(\epsilon(p_T^a, \eta^a)\epsilon(p_T^b, \eta^b))$. Detector acceptance effects largely cancel in the $S/B$ ratio.

Examples of correlation functions in the 13 TeV data are shown in Fig. 2 for N_{rec} intervals 10–30 (left) and \geq 120 (right), respectively, for $0.5 < p_T < 5.0$ GeV. The $C(\Delta \eta, \Delta \phi)$ distributions have been truncated at different maximum values to suppress a strong peak at $\Delta \eta = \Delta \phi = 0$ that arises primarily from jets. The correlation functions also show a $\Delta \eta$-dependent enhancement centered at $\Delta \phi = \pi$, which is understood to result primarily from dijets. In the higher $N_{rec}$ interval, a ridge is observed as the enhancement near $\Delta \phi = 0$ that extends over the full $\Delta \eta$ range of the measurement.

One-dimensional correlation functions, $C(\Delta \phi)$, are obtained by integrating the numerator and denominator of Eq. 1 over the long-range part of the correlation function, $2<|\Delta \eta|<5$. These are converted into “per-trigger-particle yields,” $Y(\Delta \phi)$, according to [4, 6, 41]:

$$Y(\Delta \phi) = \left( \frac{\int B(\Delta \phi)d\Delta \phi}{N^a} \right) C(\Delta \phi), \quad (2)$$

where $N^a$ denotes the efficiency-corrected total number of trigger particles. Results are shown in Fig. 3 for selected $N_{rec}^{ch}$ intervals in the 13 and 2.76 TeV data, for the $p_T^{a,b}$ ranges $0.5 < p_T^{a,b} < 5.0$ GeV. Panel (a) in the figure shows $Y(\Delta \phi)$ for $0 \leq N_{rec}^{ch} < 20$ for both collision energies; these exhibit a minimum at $\Delta \phi = 0$. Panels (b), (d) and (f) show results from 13 TeV data for the 40–50, 60–70, and $\geq 90$ $N_{rec}^{ch}$ intervals, respectively. Panels (c) and (e) show the results from 2.76 TeV data for 50–60 and 70–80 $N_{rec}^{ch}$ intervals, respectively. With increasing $N_{rec}^{ch}$, the minimum at $\Delta \phi = 0$ fills in, and a peak appears and increases in amplitude.

To study further the ridge in $pp$ collisions, a template fitting procedure is applied to the $Y(\Delta \phi)$ distributions. The measured $Y(\Delta \phi)$ distributions are assumed to result from a superposition of a “peripheral”
Figure 3: Per-trigger-particle yields, $Y(\Delta \phi)$, for $0.5 < p_T^{a,b} < 5.0$ GeV in different $N_{ch}^{\text{rec}}$ intervals in 2.76 and 13 TeV data. Panel (a): $0 \leq N_{ch}^{\text{rec}} < 20$ for both data sets. Panels (c) and (e): 50–60 and 70–80 $N_{ch}^{\text{rec}}$ intervals for 2.76 TeV data. Panels (b), (d) and (f): 40–50, 60–70, and $\geq 90$ $N_{ch}^{\text{rec}}$ intervals for 13 TeV data. In panels (b)–(f), the open points and curves show different components of the template (see legend) that are shifted, where necessary, for presentation.

The $Y(\Delta \phi)$ distribution, scaled up by a multiplicative factor and a constant modulated by $\cos(2\Delta \phi)$. The resulting template fit function,

$$Y^{\text{templ}}(\Delta \phi) = F \ Y^{\text{periph}}(\Delta \phi) + Y^{\text{ridge}}(\Delta \phi),$$

where

$$Y^{\text{ridge}}(\Delta \phi) = G \ (1 + 2v_{2,2} \cos(2\Delta \phi)),$$

has two free parameters, $F$ and $v_{2,2}$. The coefficient, $G$, which represents the magnitude of the combinatoric component of $Y^{\text{ridge}}(\Delta \phi)$, is fixed by requiring that $\int_0^{\pi} d\Delta \phi \ Y^{\text{templ}} = \int_0^{\pi} d\Delta \phi \ Y$. The peripheral
distribution is obtained from the $0 \leq N_{ch}^{\text{rec}} < 20$ interval. In the fitting procedure, the $\chi^2$ is calculated accounting for statistical uncertainties in both $Y(\Delta\phi)$ and $Y_{\text{periph}}(\Delta\phi)$ distributions.

The results of the template fitting procedure are shown in panels (b)–(f) of Fig. 3. The scaled $Y_{\text{periph}}(\Delta\phi)$ distributions shifted up by $G$ are shown with open points; the $Y_{\text{ridge}}(\Delta\phi)$ functions shifted up by $F Y_{\text{periph}}(0)$ are shown with the dashed lines; and the full fit function is shown by the solid curves. The function in Eq. 3 successfully describes the measured $Y(\Delta\phi)$ distributions in all $N_{ch}^{\text{rec}}$ intervals. In particular, it simultaneously describes the ridge, which arises from an interplay of the concave $Y_{\text{periph}}(\Delta\phi)$ and the cosine function, the height of the peak in the $Y(\Delta\phi)$ at $\Delta\phi \sim \pi$, and the narrowing of that peak which results from a negative contribution of the $2v_{2,2} \cos (2\Delta\phi)$ term in the region near $\Delta\phi = \pi/2$.

If the $\cos (2\Delta\phi)$ dependence of $Y(\Delta\phi)$ arises from modulation of the single-particle $\phi$ distributions, then $v_{2,2}$ should factorize such that $v_{2,2}(p_T^1, p_T^2) = v_2(p_T^1)v_2(p_T^2)$ [38–40], where $v_2$ is the $\cos(2\phi)$ Fourier coefficient of the single-particle anisotropy. To test this, the analysis was performed using three $p_T^b$ intervals: 0.5–5.0, 0.5–1.0, and 2.0–3.0 GeV with $0.5 < p_T^b < 5.0$ GeV; results from 2.76 TeV data for the 2.0–3.0 GeV interval were obtained using wider $N_{ch}^{\text{rec}}$ intervals to improve statistics. Results are shown in the top panels of Fig. 4; the left and right panels show 2.76 and 13 TeV data, respectively. A significant $p_T^b$ dependence is seen. Separately, the same analysis was applied requiring both $p_T^1$ and $p_T^b$ to fall within the above intervals. If factorization holds, the $v_2$ values calculated using:

$$v_2(p_T^1) = v_2(p_{T1}, p_{T2}) / \sqrt{v_2,2(p_{T2}, p_{T2})},$$  

(5)

where $p_{T1}$ and $p_{T2}$ indicate which of the three intervals, 0.5–5.0, 0.5–1.0, and 2.0–3.0 GeV, $p_T^1$ and $p_T^b$ are required to lie within, should be independent of $p_{T2}$. The $v_2$ values obtained using Eq. 5 are shown in the middle panels of Fig. 4. For both collision energies, the three sets of $v_2$ values agree within uncertainties, indicating that $v_{2,2}$ factorizes.

This analysis is sensitive to potential $N_{ch}^{\text{rec}}$-dependent changes in the width of the dijet peak in $Y(\Delta\phi)$. The PYTHIA 8 sample shows a modest $N_{ch}^{\text{rec}}$-dependent broadening of $Y(\Delta\phi)$ for small $N_{ch}^{\text{rec}}$. To test the sensitivity of the results presented here to such a shape change, the analysis was repeated using 0–5, 0–10, and 10–20 $N_{ch}^{\text{rec}}$ intervals to form $Y_{\text{periph}}(\Delta\phi)$. The largest resulting change in $v_{2,2}$ was taken as a systematic uncertainty, which varies between 6% at $N_{ch}^{\text{rec}} = 30$ to 2% for $N_{ch}^{\text{rec}} \geq 60$ in the 13 TeV data, and is less than <6% for all $N_{ch}^{\text{rec}}$ for the 2.76 TeV data. When using the 0–5 $N_{ch}^{\text{rec}}$ interval for $Y_{\text{periph}}(\Delta\phi)$, $v_{2,2}$ values consistent with those shown in Fig. 4 are measured in $N_{ch}^{\text{rec}}$ intervals 5–10, 10–15 and 15–20.

Previous applications of the peripheral subtraction method in $p+Pb$ analyses assumed zero hard scattering yield at the minimum (ZYAM) [4, 6] and, so, subtracted $Y(0)$ from $Y_{\text{periph}}(\Delta\phi)$. Such a subtraction will necessarily change the $v_{2,2}$ values, and, when applied to the 13 TeV data, reduces the measured $v_{2,2}$ by a multiplicative factor that varies from 0.4 to 0.8 over $30 \leq N_{ch}^{\text{rec}} < 130$. However, if, as suggested by the data, $Y_{\text{periph}}(\Delta\phi)$ contains a modulated soft component,

$$Y_{\text{periph}}(\Delta\phi) = Y_{\text{hard}}(\Delta\phi) + G_0 \left(1 + 2v_{2,2}^0 \cos (2\Delta\phi) \right),$$  

(6)

the peripheral ZYM method will subtract $2FG_0 v_{2,2}^0 \cos (2\Delta\phi)$ as part of the template fit, thereby reducing the extracted $v_{2,2}$. In contrast, the procedure used in this analysis subtracts $FG_0 \left(1 + 2v_{2,2}^0 \cos (2\Delta\phi) \right)$, which reduces $G$ in Eq. 4 but has less impact on $v_{2,2}$. In particular, if $v_{2,2}^0$ is equal to the real $v_{2,2}$ in a given $N_{ch}^{\text{rec}}$ interval, there will be no bias. Since the measured $v_{2,2}$ is approximately $N_{ch}^{\text{rec}}$-independent, the bias resulting from the presence of $v_{2,2}$ in the peripheral sample is expected to be small. Any systematic effect due to the variation of $v_{2,2}$ with $N_{ch}^{\text{rec}}$ is covered by the systematic uncertainty on the peripheral interval, described above.
Figure 4: Measured $v_{2,2}$ (top) and $v_2$ (middle) values versus $N_{\text{ch}}^{\text{rec}}$ for different $p_T^{\pi}$ intervals for 2.76 (left) and 13 TeV (right) data. Results are averaged over $N_{\text{ch}}^{\text{rec}}$ bins of width 10 spanning the range $20 < N_{\text{ch}}^{\text{rec}} < 100$ and $20 < N_{\text{ch}}^{\text{rec}} < 130$ for 2.76 and 13 TeV data, respectively, except for the $2.0 < p_T^{\pi} < 3.0$ GeV results for the 2.76 TeV data which are averaged over bins of width 20. Measured $v_2$ values versus $p_T^{\pi}$ (bottom) for 13 and 2.76 TeV data for the $50 \leq N_{\text{ch}}^{\text{rec}} < 60$ interval (left) and for three $N_{\text{ch}}^{\text{rec}}$ intervals in the 13 TeV data (right). Results are averaged over the $p_T^{\pi}$ intervals indicated by horizontal error bars. On all points, the vertical error bars indicate statistical uncertainties. The shaded bands indicate systematic uncertainties. For clarity, they are only shown for the $0.5 < p_T^{\pi} < 5.0$ GeV case in the middle, for 2.76 TeV data in the lower left, and for the $40 \leq N_{\text{ch}}^{\text{rec}} < 50$ case in the lower right panels.

Potential systematic uncertainties on $v_{2,2}$ due to a residual $\Delta \phi$ dependence of the two-particle acceptance.
that does not cancel in the $S/B$ ratio are evaluated following Ref. [42] and are found to be less than 1%. The effect of the uncertainty on the tracking efficiency on $v_{2.2}$ is determined to be less than 1%. A separate systematic on $v_{2.2}$ due to the $p_{T}$ resolution of the charged-particle measurement is estimated to be 2% (6%) for $p_{T} > 0.5$ GeV ($p_{T} < 0.5$ GeV). Events with unresolved multiple vertices decrease the measured $v_{2.2}$ by increasing the combinatoric pedestal in $Y(\Delta \phi)$ without increasing the modulation. The resulting systematic on $v_{2.2}$ increases with $N_{\text{ch}}^{\text{rec}}$ and is estimated to be less than 0.25% and 5% for the 13 and 2.76 TeV data, respectively. The combined systematic uncertainties on $v_{2.2}$ and on $v_2$ are shown by the shaded boxes in Fig. 4. The total $v_{2.2}$ systematic uncertainty for $0.5<p_{T}^{a,b}<5.0$ GeV varies between $\sim 5\%$ at low $N_{\text{ch}}^{\text{rec}}$ to $\sim 3\%$ at high $N_{\text{ch}}^{\text{rec}}$ in the 13 TeV data, while in the 2.76 TeV data the uncertainty is 8% for all $N_{\text{ch}}^{\text{rec}}$. The systematic uncertainty on $v_2$ is approximately half that for $v_{2.2}$.

As shown in Fig. 4, the measured $v_2$ are independent of $N_{\text{ch}}^{\text{rec}}$ and are consistent between the two collision energies within uncertainties. The $p_{T}$ dependence of $v_2$ for the 50–60 $N_{\text{ch}}^{\text{rec}}$ interval, shown in the bottom left panel of Fig. 4, is similar for both collision energies to that previously measured in $p$+Pb and Pb+Pb collisions. It increases with $p_{T}$ at low $p_{T}$, reaches a maximum between 2 and 3 GeV, and then decreases at higher $p_{T}$. The bottom right panel of Fig. 4 shows the $p_{T}$ dependence of $v_2$ for different $N_{\text{ch}}^{\text{rec}}$ intervals; no significant dependence is observed.

In summary, ATLAS has measured the multiplicity and $p_{T}$ dependence of two-charged-particle correlations in $\sqrt{s}$=13 and 2.76 TeV $pp$ collisions at the LHC. The correlation functions at both energies show a ridge whose strength increases with multiplicity. A new template fitting procedure shows that the per-trigger-particle yields for $|\Delta \eta|>2$ are described well by a superposition of the yields measured in a low-multiplicity interval and a constant modulated by $\cos(2\Delta \phi)$. The extracted Fourier coefficients, $v_{2.2}$, exhibit factorization, which is characteristic of a global modulation of the per-event single-particle distributions. The amplitudes, $v_2$, of the single-particle modulation, are $N_{\text{ch}}^{\text{rec}}$-independent and agree between 2.76 and 13 TeV within uncertainties. They increase with $p_{T}$ for $p_{T} < 3$ GeV and then decrease for $3<p_{T}<5.0$ GeV, following a trend similar to that observed in $p$+Pb and Pb+Pb collisions. These results suggest that the ridges in $pp$ and $p$+Pb collisions arise from a similar physical mechanism which does not have a strong $\sqrt{s}$ dependence.

**Acknowledgements**

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; BMWFW and FWF, Austria; ANAS, Azerbaijan; STFC, 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; DNF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMWF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; RGC, Hong Kong SAR, China; 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 MIZŠ, 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.

References


5 LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
7 Department of Physics, University of Arizona, Tucson AZ, United States of America
8 Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13 Institute of Physics, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Department of Physics, Dogus University, Istanbul, Turkey
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
26 (a) Transilvania University of Brasov, Brasov, Romania; (b) National Institute of Physics and Nuclear Engineering, Bucharest; (c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (d) University Politehnica Bucharest, Bucharest; (e) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington NY, United States of America
36 Niels Bohr Institute, University of Copenhagen, København, Denmark
37 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
39 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas TX, United States of America
41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham NC, United States of America
46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
61 Department of Physics, Indiana University, Bloomington IN, United States of America
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
63 University of Iowa, Iowa City IA, United States of America
64 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University of Education, Kyoto, Japan
70 Department of Physics, Kyushu University, Fukuoka, Japan
71 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
72 Physics Department, Lancaster University, Lancaster, United Kingdom
73 (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce,
Italy
74 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
75 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
76 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
77 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
78 Department of Physics and Astronomy, University College London, London, United Kingdom
79 Louisiana Tech University, Ruston LA, United States of America
80 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
81 Fysiska institutionen, Lunds universitet, Lund, Sweden
82 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
83 Institut für Physik, Universität Mainz, Mainz, Germany
84 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
85 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
86 Department of Physics, University of Massachusetts, Amherst MA, United States of America
87 Department of Physics, McGill University, Montreal QC, Canada
88 School of Physics, University of Melbourne, Victoria, Australia
89 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
90 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
91 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
92 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
93 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
94 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
95 Group of Particle Physics, University of Montreal, Montreal QC, Canada
96 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
97 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
98 National Research Nuclear University MEPhI, Moscow, Russia
99 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
100 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
101 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
102 Nagasaki Institute of Applied Science, Nagasaki, Japan
103 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
104 (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
105 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
106 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
107 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
108 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
109 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
110 Department of Physics, New York University, New York NY, United States of America
Ohio State University, Columbus OH, United States of America
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
Department of Physics, Oklahoma State University, Stillwater OK, United States of America
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
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
(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
(a) Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Física, Universidade do Minho, Braga; (f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); (g) Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics (Protvino), NRC KI,Russia, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
(a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
(a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
(a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
Department of Physics, University of Washington, Seattle WA, United States of America
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Department of Physics, Shinshu University, Nagano, Japan
Fachbereich Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby BC, Canada
SLAC National Accelerator Laboratory, Stanford CA, United States of America
(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
(a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
(a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
Physics Department, Royal Institute of Technology, Stockholm, Sweden
Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Institute of Physics, Academia Sinica, Taipei, Taiwan
Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto ON, Canada
(a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, 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
(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) 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 and Instituto de Microelectrónica de Barcelona (IMB-CNM), 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

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 & Astronomy, University of Louisville, Louisville, KY, United States of America

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 Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal
Also at Tomsk State University, Tomsk, Russia
Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

Also at Universita 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 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

Also at Louisiana Tech University, Ruston LA, United States of America
Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain

Also at Graduate School of Science, Osaka University, Osaka, Japan
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 Manhattan College, New York NY, United States of America
Also at Hellenic Open University, Patras, Greece

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 School of Physics, Shandong University, Shandong, China
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 University of Malaya, Department of Physics, Kuala Lumpur, Malaysia

* Deceased