Observation of long-range elliptic anisotropies in \( \sqrt{s} = 13 \) and \( 2.76 \text{ TeV} \) \( pp \) 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 \( 2.76 \text{ TeV} \) \( pp \) 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 \( p+\text{Pb} \) and \( \text{Pb}+\text{Pb} \) 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 \( p+\text{Pb} \) 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 $\sqrt{s} = 7$ TeV at the LHC showed an enhancement in the production of pairs at small azimuthal-angle separation, $\Delta \phi$, that extends over a wide range of pseudorapidity differences, $\Delta \eta$, 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 $\sqrt{s}$ dependence of the ridge in pp collisions may help distinguish between competing explanations.

This letter uses 14 nb$^{-1}$ of $\sqrt{s} = 13$ TeV data and 4.0 pb$^{-1}$ of $\sqrt{s} = 2.76$ 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 $\Delta \eta$ and $\Delta \phi$ 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 ($|\Delta \eta| > 2$) 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 $|\eta| < 2.5^1$ 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 $z = \pm 3.6$ m. The FCal covers $3.1 < |\eta| < 4.9$ 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 tracks. 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 $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. 

|η|<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 $N^{\text{rec}}$ 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 \textsc{pythia} 8 [33] event generator (A2 tune [34], MSTW2008LO PDFs [35]) that are passed through a \textsc{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 \textsc{pythia} 8 $p_T>0.4$ GeV charged-particle multiplicity by approximately multiplicity-independent factors of $1.18\pm0.05$ and $1.22\pm0.05$ 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 $|\Delta \eta|\leq5$, 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:

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

Figure 1: Distributions of the multiplicity, $N^{\text{rec}}$, of reconstructed charged particles having $p_T>0.4$ GeV for the 2.76 (left) and 13 TeV (right) data used in this analysis.
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 $N_{\text{rec}}$ 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 $N_{\text{rec}}$ 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]:

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

where $N^a$ denotes the efficiency-corrected total number of trigger particles. Results are shown in Fig. 3 for selected $N_{\text{rec}}$ 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 $0 \leq N_{\text{rec}} < 20$ 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 $\geq 90$ $N_{\text{rec}}$ intervals, respectively. Panels (c) and (e) show the results from 2.76 TeV data for 50–60 and 70–80 $N_{\text{rec}}$ intervals, respectively. With increasing $N_{\text{rec}}$, the minimum at $\Delta\phi = 0$ fills in, and a peak appears and increases in amplitude.

To study further the ridge in $p p$ 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 \( 0.5 < p_T^{a,b} < 5.0 \text{ GeV} \) in different \( N^{\text{rec}} \) intervals in 2.76 and 13 TeV data. Panel (a): \( 0 \leq N^{\text{rec}} < 20 \) for both data sets. Panels (c) and (e): 50–60 and 70–80 \( N^{\text{rec}} \) intervals for 2.76 TeV data. Panels (b), (d) and (f): 40–50, 60–70, and \( \geq 90 \) \( N^{\text{rec}} \) 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.

\( Y(\Delta \phi) \) 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

\[ Y^{\text{ridge}}(\Delta \phi) = G \ (1 + 2\nu_{2,2} \cos(2\Delta \phi)), \]

has two free parameters, \( F \) and \( \nu_{2,2} \). 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 $v_{2,2}(p_T^1, p_T^b) = v_2(p_T^2) v_2(p_T^b)$ [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 $0.5 < p_T^1 < 5.0$ 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:

$$v_2(p_T^1) = v_2(p_T^1, p_T^b)/\sqrt{v_2^2(p_T^2, p_T^b)},$$

where $p_T^1$ and $p_T^2$ 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 $p_T^2$. 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,

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

the peripheral ZYAM 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 $p_T^b$ 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 $2.0 < p_T^b < 3.0$ GeV results for the 2.76 TeV data which are averaged over bins of width 20. Measured $v_2$ values versus $p_T^a$ (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 $p_T^a$ 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 $0.5 < p_T^b < 5.0$ 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 $\phi$ and $p_T$ 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 systematic uncertainty for $v_{2,2}$ and $v_2$ are shown by the shaded boxes in Fig. 4. The total systematic uncertainty for $0.5<p_T^{a,b}<5.0$ GeV varies between ~5% at low $N_{\text{ch}}^{\text{rec}}$ to ~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 $|\Delta \eta|\geq 2$ 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 $p_T$ at low $p_T$, reaches a maximum between 2 and 3 GeV, and then decreases 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; 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; 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


The ATLAS Collaboration

L. Adamczyk138a, D.L. Adams25, J. Adelman108, S. Adomeit100, T. Adye131, A.A. Affolder74,
T. Agatonovic-Jovin15, J. Agnello154, J.A. Aguilar-Saavedra126a,126f, S.P. Ahlen22, F. Ahmadov65.b,
G. Aielli133a,133b, H. Akerstedt146a,146b, T.P.A. Åkesson81, A.V. Akimov96, G.L. Alberghi20a,20b,
J. Albert169, S. Albrand55, M.J. Alconada Verzini71, M. Aleksić30, I.N. Aleksandrov65, C. Alexia26b,
B.M.M. Allbrooke149, P.P. Allport8, A. Aloisio104a,104b, A. Alonso36, F. Alonso71, C. Alpigiani138,
A. Altheimer35, B. Alvarez Gonzalez30, D. Álvarez Piqueras167, M.G. Alviggi104a,104b, B.T. Amadio15,
K. Amako66, Y. Amano Cautinho24, C. Amelung23, D. Amidei89, S.P. Amor Dos Santos126a,126c,
A. Amorim126a,126d, S. Amoroso48, N. Amram153, G. Amundsen23, C. Anastopoulos139, L.S. Anci49,
A. Andreazza79a,19b, V. Andrei58a, S. Angelidakis9, I. Angelozzi107, P. Anger44, A. Angerami35,
F. Anghinolfi30, A.V. Anisenkov109,e, N. Anjos12, A. Anovni124a,124b, M. Antonelli47, A. Antonov98,
J. Antos144b, F. Anulli32a, M. Aoki66, L. Aperio Bella18, G. Arabidze90, Y. Arai66, J.P. Araque126a,
A.T.H. Arco45, F.A. Arduh71, J-F. Argevin95, S. Argyropoulos63, M. Arik192, A.J. Armbuster19,
N. Ashah42, A. Ashkenazi153, B. Åsman146a,146b, L. Asquith149, K. Assamagan28, R. Astalos144a,
M. Atkinson165, N.B. Atlay141, K. Augsten128, M. Aurousseau145b, G. Avolio30, B. Aven153,
M.K. Ayoub117, G. Azuelos95,d, M.A. Baak30, A.E. Baas58a, M.J. Baca18, C. Bacci134a,134b,
H. Bachacou136, K. Backes30, M. Backhaus30, P. Bagiacchi132a,132b, P. Bagnaia132a,132b,
Y. Bai33a, T. Bain5, J.T. Baines131, O.K. Baker176, E.M. Baldin109,c, P. Balek129, T. Balestrin148,
F. Balli84, W.K. Balunas122, E. Banas39, S. Banerjee175.e, A.A.E. Bannoura151, L. Barak92,
E.L. Barberio88, D. Barberis50a,50b, M. Barbero65, T. Barillari101, M. Barisonzi164a,164b, T. Barklow143,
N. Barlow28, S.L. Barnes84, B.M. Barnett131, R.M. Barnett15, Z. Barnovská8, A. Barconelli33a,
G. Barone23, A.J. Barr120, F. Barreiro82, J. Barreiro Guimarães da Costa33a, R. Bartoldus143,
A.E. Barton72, P. Bartos144a, A. Basalaev123, A. Bassalat117, A. Basye165, R.L. Bates53, S.J. Batista158,
J.R. Batley87, M. Battaglia137, M. Bauge132a,132b, F. Bauer136, H.S. Bawa143,f, J.B. Beacham111,
M.D. Beattie72, T. Beau90, P.H. Beauchemin61, R. Beccherle124a,124b, P. Bechtle21, H.P. Beck17,d,
K. Becker120, M. Becker83, M. Beckingham170, C. Becot117, A.J. Beddall19b, A. Beddall19b,
V.A. Bednyakov65c, C.P. Bee148, L.J. Beevers107, T.A. Beermann30, M. Beget25, J.K. Behr120,
C. Belanger-Champagne87, W.H. Bell49, G. Bella153, L. Bellagamba20a, A. Bellerive29, M. Bellomo86,
K. Belotskiy98, O. Beltramello30, O. Benary153, D. Benckendorff135a, M. Bender100, K. Bendlitz146a,146b,
N. Benekos10, Y. Benhammou153, E. Benhar Noccioli49, J.A. Benitez Garcia159b, D.P. Benjamin45,
J.R. Bensinger23, S. Bentvelsen120, M. Beretta87, D. Berger107,
E. Bergeaas Kuutmann166, N. Berger3, F. Berghaus169, J. Beringer15, C. Bernard22, N.R. Bernard86,
C. Bernardi110, F.U. Bernlochner21, T. Berry77, P. Berta129, C. Bertellà83, G. Bertoli146a,146b,
F. Bertolucci124a,124b, C. Bertels13, D. Bertsche113, M.I. Besana31a, G.J. Besjes36,
O. Bessidskaia Bylund146a,146b, M. Bessner42, N. Besson136, C. Betancourt48, S. Bethke101,
A.J. Bevan76, W. Bhimji15, R.M. Bianchi125, L. Bianchini23, M. Bianco30, O. Biebel100,
D. Biedermann16, N.V. Biesuz124a,124b, M. Biglietti134a, J. Bilbao De Mendizábal99, H. Bilokon47,
M. Bindi54, S. Binet117, A. Bingul19b, C. Bini132a,132b, S. Biondi20a,20b, D.M. Bjergaard45,
C.W. Black150, J.E. Black143, K.M. Black22, D. Blackburn138, R.E. Blair6, J.-B. Blanchard136,
J.E. Blanco77, T. Blazek144a, I. Bloch32, C. Blocker23, W. Blum183, U. Blumenschein54, S. Blunier32a,
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
(a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
37 (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
38 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
39 Physics Department, Southern Methodist University, Dallas TX, United States of America
40 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
41 DESY, Hamburg and Zeuthen, Germany
42 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
44 Department of Physics, Duke University, Durham NC, United States of America
45 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46 INFN Laboratori Nazionali di Frascati, Frascati, Italy
47 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
48 Section de Physique, Université de Genève, Geneva, Switzerland
49 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
50 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi, Georgia
51 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
52 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
53 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
54 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
55 Department of Physics, Hampton University, Hampton VA, United States of America
56 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
57 (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
58 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
59 (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
60 Department of Physics, Indiana University, Bloomington IN, United States of America
61 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
62 University of Iowa, Iowa City IA, United States of America
63 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
64 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
65 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
66 Graduate School of Science, Kobe University, Kobe, Japan
67 Faculty of Science, Kyoto University, Kyoto, Japan
68 Kyoto University of Education, Kyoto, Japan
69 Department of Physics, Kyushu University, Fukuoka, Japan
70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 (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 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
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 Department of Physics, Royal Holloway University of London, 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 Física 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
142 Department of Physics, Simon Fraser University, Burnaby BC, Canada
143 SLAC National Accelerator Laboratory, Stanford CA, United States of America
144 (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
145 (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
146 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
148 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
150 School of Physics, University of Sydney, Sydney, Australia
151 Institute of Physics, Academia Sinica, Taipei, Taiwan
152 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
158 Department of Physics, University of Toronto, Toronto ON, Canada
159 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada
160 Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
161 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
163 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
164 (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
165 Department of Physics, University of Illinois, Urbana IL, United States of America
166 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
167 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
168 Department of Physics, University of British Columbia, Vancouver BC, Canada
169 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
170 Department of Physics, University of Warwick, Coventry, United Kingdom
171 Waseda University, Tokyo, Japan
172 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
173 Department of Physics, University of Wisconsin, Madison WI, United States of America
174 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
175 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany