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.
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 $|\eta|<2.5$\textsuperscript{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.

\textsuperscript{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 $\eta = -\ln \tan(\theta/2)$. 
$|\eta|<2.5$ 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, $N_{\text{ch}}^\text{rec}$, is defined as the number of tracks having $p_T>0.4$ GeV associated with this vertex. The distributions of $N_{\text{ch}}^\text{rec}$ are shown in Fig. 1. The structures in the distributions result from the different HMT trigger thresholds.

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

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 $1.18\pm0.05$ 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:

$$C(\Delta\eta, \Delta\phi) = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}, \quad (1)$$

$S(\Delta\eta, \Delta\phi)$ and $B(\Delta\eta, \Delta\phi)$ are the correlated and uncorrelated distributions, 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 $N_{\text{ch}}$ 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 $\Delta \eta = \Delta \phi = 0$. 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 $N_{\text{ch}}$ 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]:

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

where $N^a$ denotes the efficiency-corrected total number of trigger particles. Results are shown in Fig. 3 for selected $N_{\text{ch}}$ 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 $0 \leq N_{\text{ch}} < 20$ 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 $\geq 90$ $N_{\text{ch}}$ intervals, respectively. Panels (c) and (e) show the results from 2.76 TeV data for 50–60 and 70–80 $N_{\text{ch}}$ intervals, respectively.

With increasing $N_{\text{ch}}$, 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 $0.5 < p_T < 5.0$ GeV in different $N_{\text{ch}}$ intervals in 2.76 and 13 TeV data. Panel (a): $0 \leq N_{\text{ch}} < 20$ for both data sets. Panels (c) and (e): 50–60 and 70–80 $N_{\text{ch}}$ intervals for 2.76 TeV data. Panels (b), (d) and (f): 40–50, 60–70, and $\geq 90$ $N_{\text{ch}}$ 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 $\int_0^{2\pi} d\Delta \phi \ Y^{\text{templ}} = \int_0^{2\pi} d\Delta \phi \ Y$. The peripheral
distribution is obtained from the $0 \leq N_{ch}^{rec} < 20$ interval. In the fitting procedure, the $\chi^2$ is calculated accounting for statistical uncertainties in both $Y(\Delta \phi)$ and $Y_{periph}^{\phi}(\Delta \phi)$ distributions.

The results of the template fitting procedure are shown in panels (b)–(f) of Fig. 3. The scaled $Y_{periph}^{\phi}(\Delta \phi)$ distributions shifted up by $G$ are shown with open points; the $Y_{ridge}^{\phi}(\Delta \phi)$ functions shifted up by $F Y_{periph}^{\phi}(0)$ 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 $N_{ch}^{rec}$ intervals. In particular, it simultaneously describes the ridge, which arises from an interplay of the concave 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 $v_{2,2}(p_T^a, p_T^b) = v_2(p_T^a)v_2(p_T^b)$ [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 $0.5 < p_T^a < 5.0 \text{ GeV}$; results from 2.76 TeV data for the 2.0–3.0 GeV interval were obtained using wider $N_{ch}^{rec}$ 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 $p_T^a$ and $p_T^b$ to fall within the above intervals. If factorization holds, the $v_2$ values calculated using:

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

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, $p_T^a$ and $p_T^b$ are required to lie within, should be independent of $p_T^b$. 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 $N_{ch}^{rec}$-dependent changes in the width of the dijet peak in $Y(\Delta \phi)$. The PYTHIA8 sample shows a modest $N_{ch}^{rec}$-dependent broadening of $Y(\Delta \phi)$ for small $N_{ch}^{rec}$. 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 $N_{ch}^{rec}$ intervals to form $Y_{periph}^{\phi}(\Delta \phi)$. The largest resulting change in $v_{2,2}$ was taken as a systematic uncertainty, which varies between 6% at $N_{ch}^{rec} = 30$ to 2% for $N_{ch}^{rec} \geq 60$ in the 13 TeV data, and is less than <6% for all $N_{ch}^{rec}$ for the 2.76 TeV data. When using the 0–5 $N_{ch}^{rec}$ interval for $Y_{periph}^{\phi}(\Delta \phi)$, $v_{2,2}$ values consistent with those shown in Fig. 4 are measured in $N_{ch}^{rec}$ 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 $Y_{periph}^{\phi}(\Delta \phi)$. 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$\leq N_{ch}^{rec} < 130$. However, if, as suggested by the data, $Y_{periph}^{\phi}(\Delta \phi)$ contains a modulated soft component,

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

the peripheral ZYAM method will subtract $2FG_0v_{2,2}^0 \cos (2 \Delta \phi)$ 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 $N_{ch}^{rec}$ interval, there will be no bias. Since the measured $v_{2,2}$ is approximately $N_{ch}^{rec}$-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 $N_{ch}^{rec}$ is covered by the systematic uncertainty on the peripheral interval, described above.

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Figure 4: Measured $v_{2,2}$ (top) and $v_2$ (middle) values versus $N_{\text{rec}}^\text{ch}$ for different $p_T^b$ intervals for 2.76 (left) and 13 TeV (right) data. Results are averaged over $N_{\text{rec}}^\text{ch}$ bins of width 10 spanning the range $20 < N_{\text{rec}}^\text{ch} < 100$ and $20 < N_{\text{rec}}^\text{ch} < 130$ 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 $50 \leq N_{\text{rec}}^\text{ch} < 60$ interval (left) and for three $N_{\text{rec}}^\text{ch}$ 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 $40 \leq N_{\text{rec}}^\text{ch} < 50$ 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 $v_{2,2}$ systematic uncertainty for $0.5<p_T<5.0$ 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 $p_T \lesssim 3$ 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.

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