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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, $v_{2,2}$, 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 $|\eta|<2.5$[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 $z = \pm3.6$ 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 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, ϕ) 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 $\eta = -\ln\tan(\theta/2)$.

$|\eta|<2.5$ 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 $\sum p_{\mathrm{T}}^2$, where the sum is over all tracks associated with the vertex, are used. The measured charged-particle multiplicity, $N_{\mathrm{ch}}^{\mathrm{rec}}$, is defined as the number of tracks having $p_{\mathrm{T}}>0.4$ GeV associated with this vertex. The distributions of $N_{\mathrm{ch}}^{\mathrm{rec}}$ are shown in Fig. 1. The structures in the distributions result from the different HMT trigger thresholds.

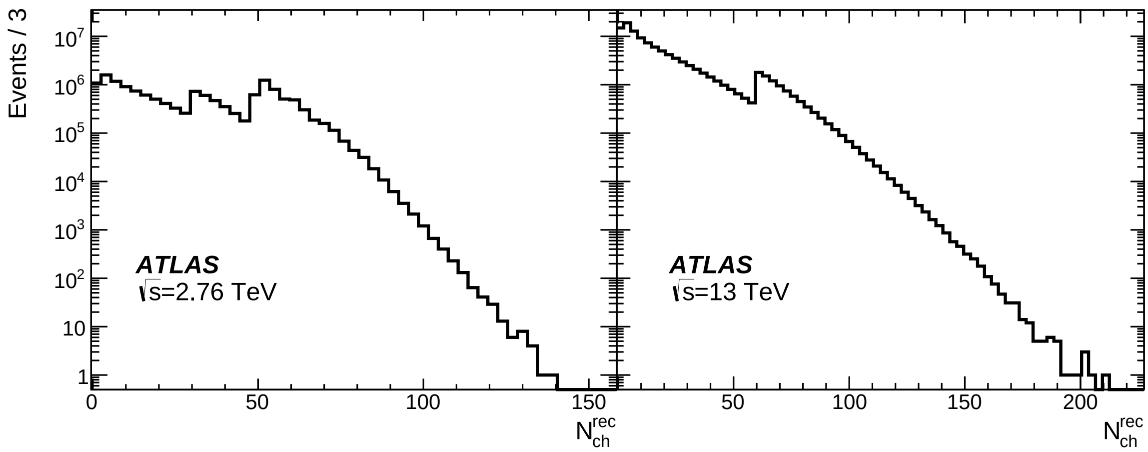

Figure 1: Distributions of the multiplicity, $N_{\mathrm{ch}}^{\mathrm{rec}}$, of reconstructed charged particles having $p_{\mathrm{T}}>0.4$ GeV for the 2.76 (left) and 13 TeV (right) data used in this analysis.

The efficiency, $\epsilon(p_{\mathrm{T}}, \eta)$, 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 $p_{\mathrm{T}} > 0.4$ GeV charged-particle multiplicity by approximately multiplicity-independent factors of 1.18 ± 0.05 and 1.22 ± 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 $p_{\mathrm{T}}^{\mathrm{a}}$ and $p_{\mathrm{T}}^{\mathrm{b}}$, 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:

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

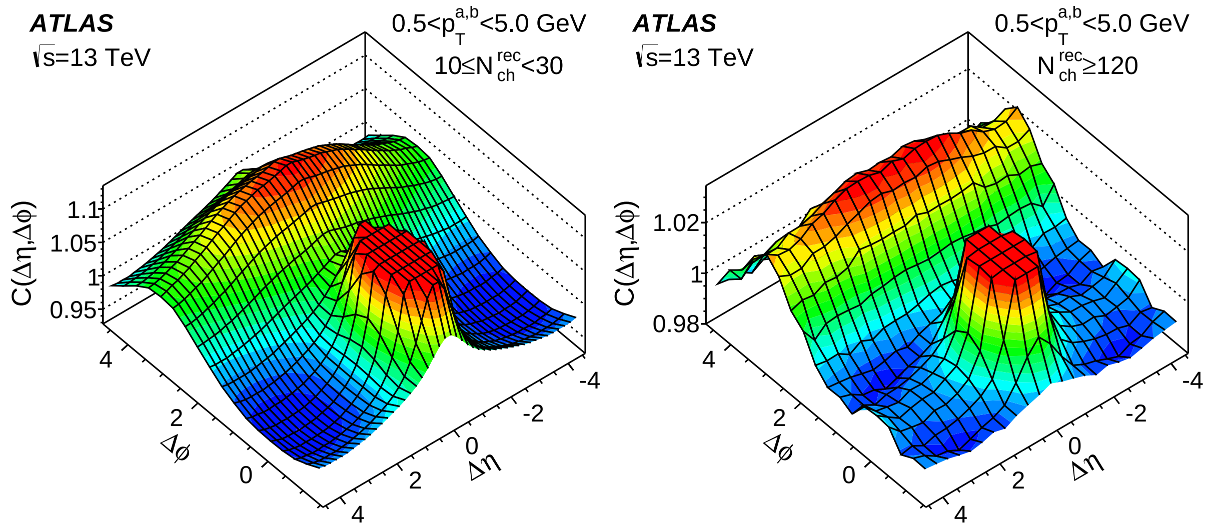

Figure 2: Two-particle correlation functions, $C(\Delta\eta, \Delta\phi)$, in 13 TeV pp collisions in $N_{\mathrm{ch}}^{\mathrm{rec}}$ intervals 10–30 (left) and $\geq$ 120 (right) for charged particles having $0.5<p_{\mathrm{T}}<5.0$ GeV. The distributions have been truncated to suppress the peak at $\Delta\eta$=$\Delta\phi$=0 and are plotted over $|\eta| < 4.6$ to avoid statistical fluctuations at larger $|\Delta\eta|$.

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 $1/(\epsilon(p_{\mathrm{T}}^{\mathrm{a}}, \eta^a)\epsilon(p_{\mathrm{T}}^{\mathrm{b}}, \eta^b))$. 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 $N_{\mathrm{ch}}^{\mathrm{rec}}$ intervals 10–30 (left) and ≥120 (right), respectively, for $0.5 < p_{\mathrm{T}}^{\mathrm{a,b}} < 5.0$ 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 $N_{\mathrm{ch}}^{\mathrm{rec}}$ 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]:

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

where N^a denotes the efficiency-corrected total number of trigger particles. Results are shown in Fig. 3 for selected $N_{\mathrm{ch}}^{\mathrm{rec}}$ intervals in the 13 and 2.76 TeV data, for the $p_{\mathrm{T}}^{\mathrm{a,b}}$ ranges $0.5<p_{\mathrm{T}}^{\mathrm{a,b}}<5.0$ GeV. Panel (a) in the figure shows $Y(\Delta\phi)$ for $0\leq N_{\mathrm{ch}}^{\mathrm{rec}}<20$ 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 $N_{\mathrm{ch}}^{\mathrm{rec}}$ intervals, respectively. Panels (c) and (e) show the results from 2.76 TeV data for 50–60 and 70–80 $N_{\mathrm{ch}}^{\mathrm{rec}}$ intervals, respectively. With increasing $N_{\mathrm{ch}}^{\mathrm{rec}}$, 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"

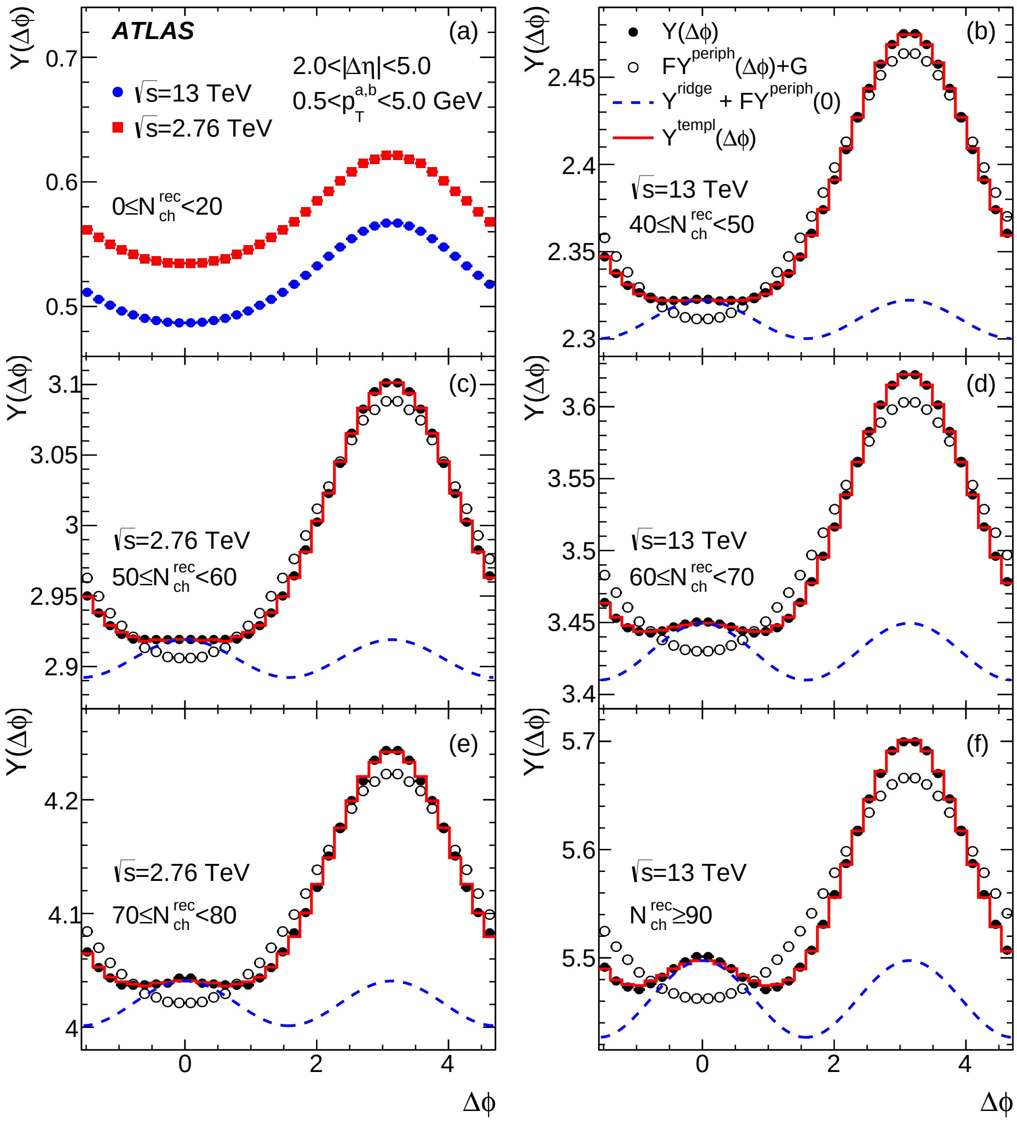

Figure 3: Per-trigger-particle yields, $Y(\Delta\phi)$, for $0.5<p_{\mathrm{T}}^{\mathrm{a,b}}<5.0$ GeV in different $N_{\mathrm{ch}}^{\mathrm{rec}}$ intervals in 2.76 and 13 TeV data. Panel (a): $0\leq N_{\mathrm{ch}}^{\mathrm{rec}}<20$ for both data sets. Panels (c) and (e): 50–60 and 70–80 $N_{\mathrm{ch}}^{\mathrm{rec}}$ intervals for 2.76 TeV data. Panels (b), (d) and (f): 40–50, 60–70, and ≥90 $N_{\mathrm{ch}}^{\mathrm{rec}}$ 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,

$$Y^{\mathrm{templ}}(\Delta\phi) = F\,Y^{\mathrm{periph}}(\Delta\phi) + Y^{\mathrm{ridge}}(\Delta\phi)\,, \tag{3}$$

where

$$Y^{\mathrm{ridge}}(\Delta\phi) = G\left(1 + 2v_{2,2}\cos\left(2\Delta\phi\right)\right)\,, \tag{4}$$

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

The results of the template fitting procedure are shown in panels (b)–(f) of Fig. 3. The scaled $Y^{periph}(\Delta\phi)$ distributions shifted up by G are shown with open points; the $Y^{ridge}(\Delta\phi)$ functions shifted up by $FY^{periph}(0)$ 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}^{rec} intervals. In particular, it simultaneously describes the ridge, which arises from an interplay of the concave $Y^{periph}(\Delta\phi)$ 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 ϕ 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 $0.5 < p_T^a < 5.0$ 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:

$$v_2(p_{T1}) = v_{2,2}(p_{T1}, p_{T2}) / \sqrt{v_{2,2}(p_{T2}, p_{T2})}, \quad (5)$$

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^a 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}^{rec}-dependent changes in the width of the dijet peak in $Y(\Delta\phi)$. The PYTHIA 8 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 $Y^{periph}(\Delta\phi)$. 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 $Y^{periph}(\Delta\phi)$, $v_{2,2}$ 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+Pbanalyses assumed zero hard scattering yield at the minimum (ZYAM) [4, 6] and, so, subtracted $Y(0)$ from $Y^{periph}(\Delta\phi)$. 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 $30 \leq N_{ch}^{rec} < 130$. However, if, as suggested by the data, $Y^{periph}(\Delta\phi)$ contains a modulated soft component,

$$Y^{periph}(\Delta\phi) = Y^{hard}(\Delta\phi) + G_0\left(1 + 2v_{2,2}^0\cos(2\Delta\phi)\right), \quad (6)$$

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.

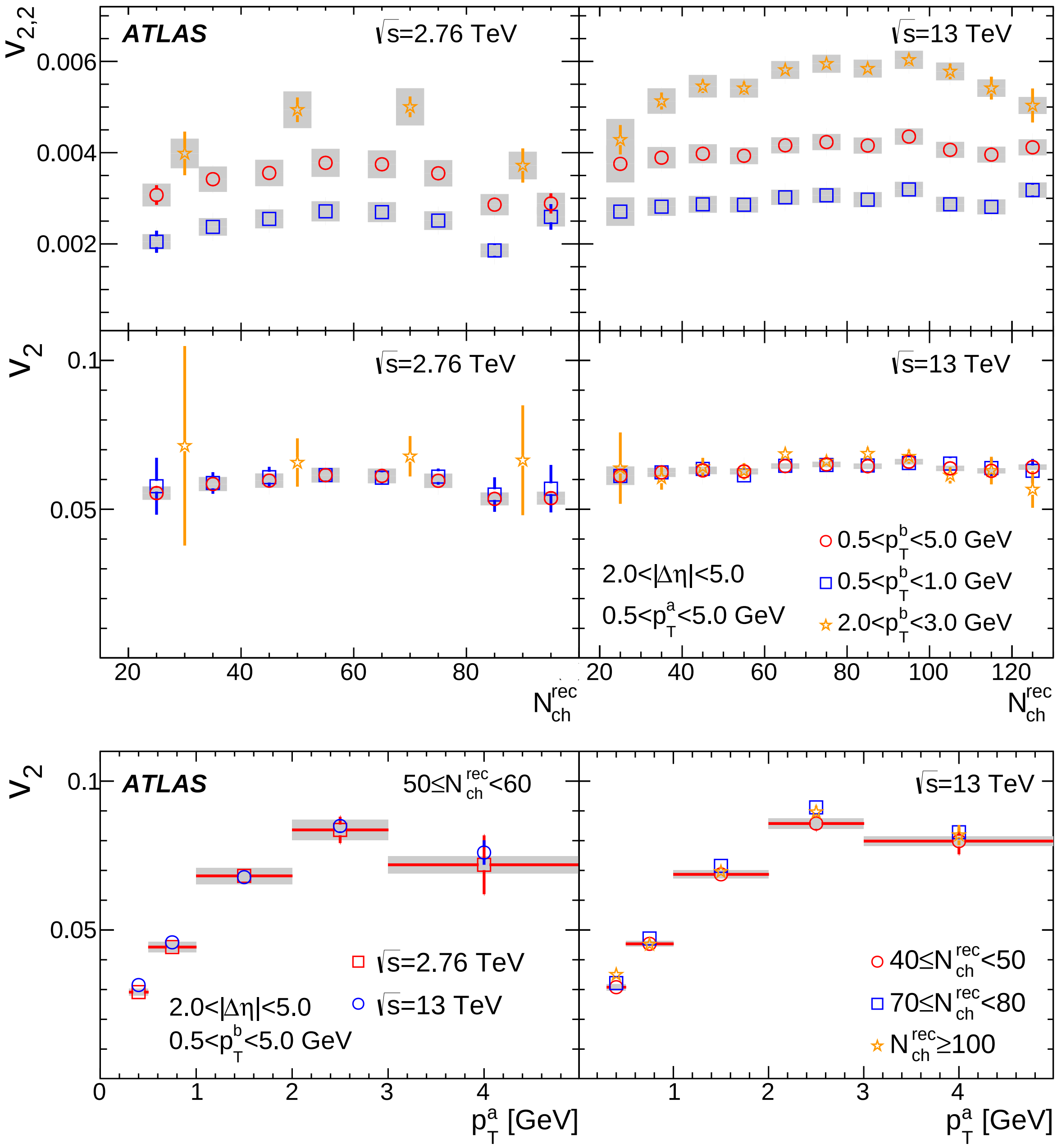

Figure 4: Measured $v_{2,2}$ (top) and v_2 (middle) values versus $N_{\mathrm{ch}}^{\mathrm{rec}}$ for different $p_{\mathrm{T}}^{\mathrm{a,b}}$ intervals for 2.76 (left) and 13 TeV (right) data. Results are averaged over $N_{\mathrm{ch}}^{\mathrm{rec}}$ bins of width 10 spanning the range $20 < N_{\mathrm{ch}}^{\mathrm{rec}} < 100$ and $20 < N_{\mathrm{ch}}^{\mathrm{rec}} < 130$ for 2.76 and 13 TeV data, respectively, except for the $2.0 < p_{\mathrm{T}}^{\mathrm{b}} < 3.0$ GeV results for the 2.76 TeV data which are averaged over bins of width 20. Measured v_2 values versus $p_{\mathrm{T}}^{\mathrm{a}}$ (bottom) for 13 and 2.76 TeV data for the $50{\leq}N_{\mathrm{ch}}^{\mathrm{rec}}{<}60$ interval (left) and for three $N_{\mathrm{ch}}^{\mathrm{rec}}$ intervals in the 13 TeV data (right). Results are averaged over the $p_{\mathrm{T}}^{\mathrm{a}}$ 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 $0.5{<}p_{\mathrm{T}}^{b}{<}5.0$ GeV case in the middle, for 2.76 TeV data in the lower left, and for the $40{\leq}N_{\mathrm{ch}}^{\mathrm{rec}}{<}50$ 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 ϕ 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_{ch}^{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 ~5% at low N_{ch}^{rec} to ~3% at high N_{ch}^{rec} in the 13 TeV data, while in the 2.76 TeV data the uncertainty is 8% for all N_{ch}^{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_{ch}^{rec} and are consistent between the two collision energies within uncertainties. The p_T dependence of v_2 for the 50–60 N_{ch}^{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_{ch}^{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_{ch}^{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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