Observation of Associated Near-Side and Away-Side Long-Range Correlations in $\sqrt{s_{NN}} = 5.02$ TeV Proton-Lead Collisions with the ATLAS Detector

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Two-particle correlations in relative azimuthal angle ($\Delta\phi$) and pseudorapidity ($\Delta\eta$) are measured in $\sqrt{s_{\rm NN}} = 5.02$ TeV $p+\mathrm{Pb}$ collisions using the ATLAS detector at the LHC. The measurements are performed using approximately 1 $\mu\mathrm{b}^{-1}$ of data as a function of transverse momentum ($p_{\rm T}$) and the transverse energy ($\Sigma E_{\rm T}^{\rm Pb}$) summed over $3.1 < \eta < 4.9$ in the direction of the Pb beam. The correlation function, constructed from charged particles, exhibits a long-range ($2 < |\Delta\eta| < 5$) "near-side" ($\Delta\phi \sim 0$) correlation that grows rapidly with increasing $\Sigma E_{\rm T}^{\rm Pb}$. A long-range "away-side" ($\Delta\phi \sim \pi$) correlation, obtained by subtracting the expected contributions from recoiling dijets and other sources estimated using events with small $\Sigma E_{\rm T}^{\rm Pb}$, is found to match the near-side correlation in magnitude, shape (in $\Delta\eta$ and $\Delta\phi$) and $\Sigma E_{\rm T}^{\rm Pb}$ dependence. The resultant $\Delta\phi$ correlation is approximately symmetric about $\pi/2$, and is consistent with a dominant $\cos 2\Delta\phi$ modulation for all $\Sigma E_{\rm T}^{\rm Pb}$ ranges and particle $p_{\rm T}$.

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Proton-nucleus ($p+A$) collisions at the Large Hadron Collider (LHC) provide both an interesting environment for the study of QCD at high parton density and important baseline measurements, especially for the interpretation of results from the LHC Pb + Pb program [1]. In particular, it has been suggested that $p+\mathrm{Pb}$ collisions at LHC energies are an important system for the study of a possible saturation of the growth of parton densities at low Bjorken-x.

High-multiplicity events provide a rich environment for studying observables associated with high parton densities in hadronic collisions. An important tool to probe the physics of these events is the two-particle correlation function measured in terms of the relative pseudorapidity ($\Delta\eta$) and azimuthal angle ($\Delta\phi$) of selected particle pairs, $C(\Delta\eta, \Delta\phi)$. The first studies of two-particle correlation functions in the highest-multiplicity $p+p$ collisions at the LHC [2] showed an enhanced production of pairs of particles at $\Delta\phi \sim 0$, with the correlation extending over a wide range in $\Delta\eta$, a feature frequently referred to as a "ridge." Many of the physics mechanisms proposed to explain the $p+p$ ridge, including multiparton interactions [3], parton saturation [4–6], and collective expansion of the final state [7], are also expected to be relevant in $p+\mathrm{Pb}$ collisions. A recent measurement by the CMS Collaboration [8] has demonstrated that a ridge is clearly visible over $|\Delta\eta| < 4$ in high-multiplicity $p+\mathrm{Pb}$ collisions at the LHC. During final preparation of this Letter, the ALICE Collaboration submitted a Letter addressing similar physics, within the range $|\Delta\eta| < 1.8$, with some differences in the analysis technique [9].

To provide further insight into the physical origin of these long-range correlations, this Letter presents ATLAS measurements of two-particle angular correlations over $|\Delta\eta| < 5$ in $p+\mathrm{Pb}$ collisions, based on an integrated luminosity of approximately 1 $\mu\mathrm{b}^{-1}$ recorded during a short run in September 2012. The LHC was configured with a 4 TeV proton beam and a 1.57 TeV per-nucleon Pb beam that together produced collisions with a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\rm NN}} = 5.02$ TeV and a rapidity shift of −0.47 relative to the ATLAS rest frame [10].

The measurements presented in this Letter are performed using the ATLAS inner detector (ID), forward calorimeters (FCal), minimum-bias trigger scintillators (MBTS), and the trigger and data acquisition systems [11]. The ID measures charged particles within $|\eta| < 2.5$ using a combination of silicon pixel detectors, silicon microstrip detectors, and a straw-tube transition radiation tracker, all immersed in a 2 T axial magnetic field [12]. The MBTS detect charged particles over $2.1 < |\eta| < 3.9$ using two hodoscopes of 16 counters positioned at $z = \pm 3.6$ m. The FCal consists of two sections that cover $3.1 < |\eta| < 4.9$. The FCal modules are composed of tungsten and copper absorbers with liquid argon as the active medium, which together provide 10 interaction lengths of material. Minimum-bias $p+\mathrm{Pb}$ collisions are selected by a trigger that requires a signal in at least two MBTS counters.

The $p+\mathrm{Pb}$ events used for this analysis are required to have a reconstructed vertex containing at least two associated tracks, with its z position satisfying $|z_{\rm vtx}| < 150$ mm. Noncollision backgrounds and photonuclear interactions are suppressed by requiring at least one hit in a MBTS counter on each side of the interaction point,

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and the difference between times measured on the two sides to be less than 10 ns. Events containing multiple $p+\mathrm{Pb}$ collisions (pileup) are suppressed by rejecting events with two reconstructed vertices that are separated in z by more than 15 mm. The residual pileup fraction is estimated to be $\lesssim 10^{-4}$. About 1.95×10^6 events pass these event selection criteria.

Charged particle tracks are reconstructed in the ID using an algorithm optimized for $p+p$ minimum-bias measurements [13]. In this analysis, the tracks are required to have $p_{\mathrm{T}} > 0.3$ GeV and $|\eta| < 2.5$, at least seven hits in the silicon detectors (out of a typical value of 11), and a hit in the first pixel layer when one is expected. In addition, the transverse (d_0) and longitudinal ($z_0\sin\theta$) impact parameters of the tracks measured with respect to the primary vertex are required to be less than 1.5 mm and to satisfy $|d_0/\sigma_{d_0}| < 3$ and $|z_0\sin\theta/\sigma_z| < 3$, respectively, where σ_{d_0} and σ_z are uncertainties on d_0 and $z_0\sin\theta$ obtained from the track-fit covariance matrix.

The efficiency, $\epsilon(p_{\mathrm{T}}, \eta)$, for track reconstruction and track selection cuts is evaluated using $p+\mathrm{Pb}$ Monte Carlo events produced with the HIJING event generator [14] with a center-of-mass boost matching the beam conditions. The response of the detector is simulated using GEANT4 [15,16] and the resulting events are reconstructed with the same algorithms as applied to the data. The efficiency increases with p_{T} by 6% between 0.3 and 0.5 GeV, and varies only weakly for $p_{\mathrm{T}} > 0.5$ GeV, where it ranges from 82% at $\eta = 0$ to 70% at $|\eta| = 2$ and 60% at $|\eta| > 2.4$. It is also found to vary by less than 2% over the range of $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ observed in the $p+\mathrm{Pb}$ data.

The two-particle correlation (2PC) analyses are performed in different intervals of $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$, the sum of transverse energy measured in the FCal with $3.1 < \eta < 4.9$ (in the z direction of the lead beam) with no correction for the difference in response to electrons and hadrons. The distribution of $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ for events passing all selection criteria is shown in Fig. 1. These events are divided into 12 $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ intervals (indicated by vertical lines in Fig. 1) to study the variation of 2PC with overall event activity. Two larger intervals, $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}} > 80$ GeV and $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}} < 20$ GeV, containing 2% and 52% of the events, respectively, hereafter referred to as "central" and "peripheral," are used for detailed studies of the 2PC at high and low overall event activity. The quantity $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ instead of charged particle multiplicity is used to characterize the event activity, since the latter is observed to have strong correlations with the 2PC measurements, particularly for events selected with low and high multiplicities. However, for reference, the average ($\langle N_{\mathrm{ch}}\rangle$) and the standard deviation ($\sigma_{N_{\mathrm{ch}}}$) of the efficiency-corrected multiplicity of charged particles with $p_{\mathrm{T}} > 0.4$ GeV and $|\eta| < 2.5$ have been calculated for each $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ range, yielding $\langle N_{\mathrm{ch}}\rangle = 150 \pm 7$, $\sigma_{N_{\mathrm{ch}}} = 35 \pm 2$ for central events and $\langle N_{\mathrm{ch}}\rangle = 25 \pm 1$, $\sigma_{N_{\mathrm{ch}}} = 18 \pm 1$ for peripheral events.

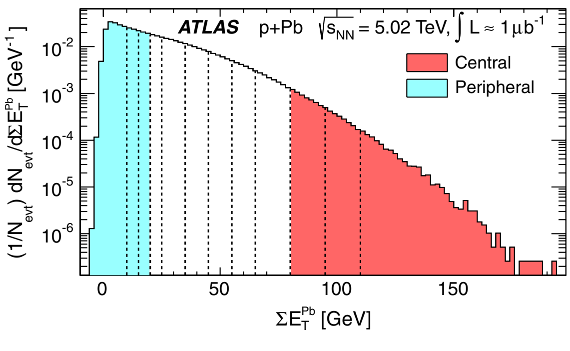

FIG. 1 (color online). Distribution of $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ for minimum-bias $p+\mathrm{Pb}$ events. Vertical lines indicate the boundaries of the event activity classes. Shaded bands indicate the larger peripheral and central intervals having $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}} < 20$ GeV and $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}} > 80$ GeV, respectively.

The correlation functions are given [17–19] by

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

where $\Delta\phi = \phi_a - \phi_b$ and $\Delta\eta = \eta_a - \eta_b$ and S and B represent pair distributions constructed from the same event and from "mixed events," [20] respectively. The labels a and b denote the two particles in the pair (conventionally referred to as "trigger" and "associated" particles, respectively [8]), which may be selected from different p_{T} intervals. The mixed-event distribution, $B(\Delta\phi, \Delta\eta)$, that measures uncorrelated pair yields was constructed by choosing pairs of particles from different events of similar z_{vtx} and track multiplicity, to match the effects of detector acceptance, occupancy, and material on $S(\Delta\phi, \Delta\eta)$, and of similar $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$. The 1D distributions $S(\Delta\phi)$ and $B(\Delta\phi)$ are obtained by integrating $S(\Delta\phi, \Delta\eta)$ and $B(\Delta\phi, \Delta\eta)$, respectively, over $2 < |\Delta\eta| < 5$. This $|\Delta\eta|$ range is chosen to focus on the long-range features of the correlation functions. The normalization of $C(\Delta\phi, \Delta\eta)$ is chosen such that the $\Delta\phi$-averaged value of $C(\Delta\phi)$ is unity. To correct $S(\Delta\phi, \Delta\eta)$ and $B(\Delta\phi, \Delta\eta)$ for the inefficiencies, each particle is weighted by the inverse of the tracking efficiency. Remaining detector distortions not accounted for in the efficiency largely cancel in the same-event to mixed-event ratio.

Examples of 2D correlation functions are shown in Figs. 2(a) and 2(b) for charged particles with $0.5 < p_{\mathrm{T}}^{a,b} < 4$ GeV in peripheral and central events. The correlation function for peripheral events shows a sharp peak centered at $(\Delta\phi, \Delta\eta) = (0, 0)$ due to pairs originating from the same jet, Bose-Einstein correlations, as well as high-p_{T} resonance decays, and a broad structure at $\Delta\phi \sim \pi$ from dijets, low-p_{T} resonances, and momentum conservation that is collectively referred to as "recoil" in the remainder of this Letter. In the central events, the correlation function reveals a ridgelike structure at $\Delta\phi \sim 0$ (the near-side) that extends over the full measured $\Delta\eta$ range, with an amplitude of a few percent. The distribution at $\Delta\phi \sim \pi$

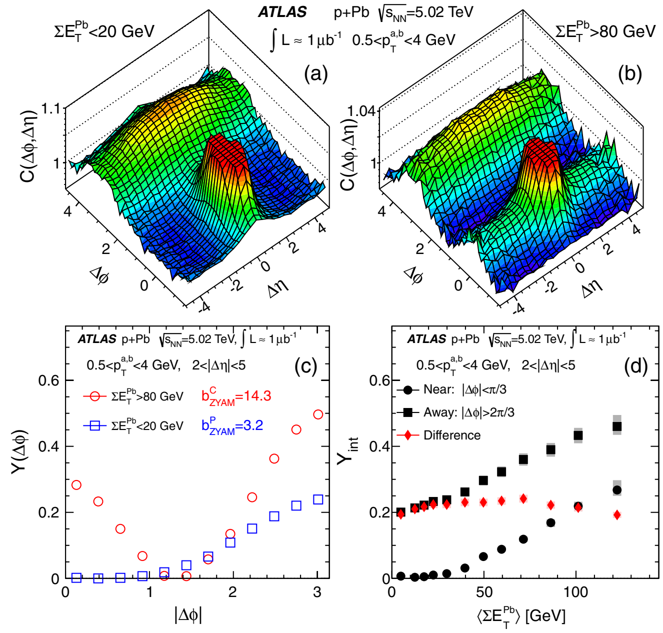

FIG. 2 (color online). Two-dimensional correlation functions for (a) peripheral events and (b) central events, both with a truncated maximum to suppress the large correlation at $(\Delta\eta, \Delta\phi) = (0, 0)$; (c) the per-trigger yield $\Delta\phi$ distribution together with pedestal levels for peripheral ($b^{\mathrm{P}}_{\mathrm{ZYAM}}$) and central ($b^{\mathrm{C}}_{\mathrm{ZYAM}}$) events, and (d) integrated per-trigger yield as function of $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ for pairs in $2 < |\Delta\eta| < 5$. The shaded boxes represent the systematic uncertainties, and the statistical uncertainties are smaller than the symbols.

(the away-side) is also broadened relative to peripheral events, consistent with the presence of a long-range component in addition to that seen in peripheral events.

The strength of the long-range component is quantified by the "per-trigger yield," $Y(\Delta\phi)$, which measures the average number of particles correlated with each trigger particle, folded into the 0-π range [2,17–19],

$$Y(\Delta\phi) = \left(\frac{\int B(\Delta\phi) d\Delta\phi}{\pi N_a}\right) C(\Delta\phi) - b_{\mathrm{ZYAM}}, \qquad (2)$$

where N_a denotes the number of efficiency-weighted trigger particles, and b_{ZYAM} represents the pedestal arising from uncorrelated pairs. The parameter b_{ZYAM} is determined via a zero-yield-at-minimum (ZYAM) method [17,21] in which a second-order polynomial fit to $C(\Delta\phi)$ is used to find the location of the minimum point, $\Delta\phi_{\mathrm{ZYAM}}$, and from this to determine b_{ZYAM}. The stability of the fit is studied by varying the $\Delta\phi$ fit range. The uncertainty in b_{ZYAM} depends on the local curvature around $\Delta\phi_{\mathrm{ZYAM}}$, and is estimated to be 0.03%–0.1% of the minimum value of $C(\Delta\phi)$. At high p_{T} where the number of measured counts is low, this uncertainty is of the same order as the statistical uncertainty.

The systematic uncertainties due to the tracking efficiency are found to be negligible for $C(\Delta\phi)$, since detector effects largely cancel in the correlation function ratio. However $Y(\Delta\phi)$ is sensitive to the uncertainty on the tracking efficiency correction for the associated particles. This uncertainty is estimated by varying the track quality cuts and the detector material in the simulation, reanalyzing the data using corresponding Monte Carlo efficiencies and evaluating the change in the extracted $Y(\Delta\phi)$. The resulting uncertainty on $Y(\Delta\phi)$ is estimated to be 2.5% due to the track selection and 2%–3% related to the limited knowledge of detector material. The analysis procedure is validated by measuring correlation functions in fully simulated HIJING events [15,16] and comparing it to the correlations measured using the generated particles. The agreement is better than 2% for $C(\Delta\phi)$ and better than 3% for $Y(\Delta\phi)$.

Figure 2(c) shows the $Y(\Delta\phi)$ distributions for $2 < |\Delta\eta| < 5$ in peripheral and central events separately. The yield for the peripheral events has an approximate $1 - \cos\Delta\phi$ shape with an away-side maximum, characteristic of a recoil contribution. In contrast, the yield in the central events has near-side and away-side peaks with the away-side peak having a larger magnitude. These features are consistent with the onset of a significant $\cos 2\Delta\phi$ component in the distribution. To quantify further the properties of these long-range components, the distributions are integrated over $|\Delta\phi| < \pi/3$ and $|\Delta\phi| > 2\pi/3$, and plotted as a function of $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ in Fig. 2(d). The near-side yield is close to 0 for $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}} < 20$ GeV and increases with $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$, consistent with the CMS result [8]. The away-side yield shows a similar variation as a function of $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$, except that it starts at a value significantly above zero, even for events with low $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$. The yield difference between these two regions is found to be approximately independent of $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$, indicating that the growth in the yield with increasing $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ is the same on the near-side and away-side.

To further investigate the connection between the near-side and away-side, the $Y(\Delta\phi)$ distributions for peripheral and central events are shown in Fig. 3 in various p_{T}^a ranges with $0.5 < p_{\mathrm{T}}^b < 4$ GeV. Distributions of the difference between central and peripheral yields, $\Delta Y(\Delta\phi)$, are also shown in this Figure. This difference is observed to be nearly symmetric around $\Delta\phi = \pi/2$. To illustrate this symmetry, the $\Delta Y(\Delta\phi)$ distributions in Fig. 3 are overlaid with functions $a_0 + 2a_2 \cos 2\Delta\phi$ and $a_0 + 2a_2 \cos 2\Delta\phi + 2a_3 \cos 3\Delta\phi$, with the coefficients calculated as $a_n = \langle \Delta Y(\Delta\phi) \cos n\Delta\phi \rangle$. Using only the a_0 and a_2 terms describes the ΔY distributions reasonably well, indicating that the long-range component of the two-particle correlations can be approximately described by a recoil contribution plus a $\Delta\phi$-symmetric component. The inclusion of the a_3 term improves slightly the agreement with the data.

The near-side and away-side yields integrated over $|\Delta\phi| < \pi/3$ and $|\Delta\phi| > 2\pi/3$, respectively (Y_{int}), and the differences between those integrated yields in central and peripheral events (ΔY_{int}) are shown in Fig. 4 as a function of p_{T}^a. The yields are shown separately for the two $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ ranges in panels (a) and (b) and the differences

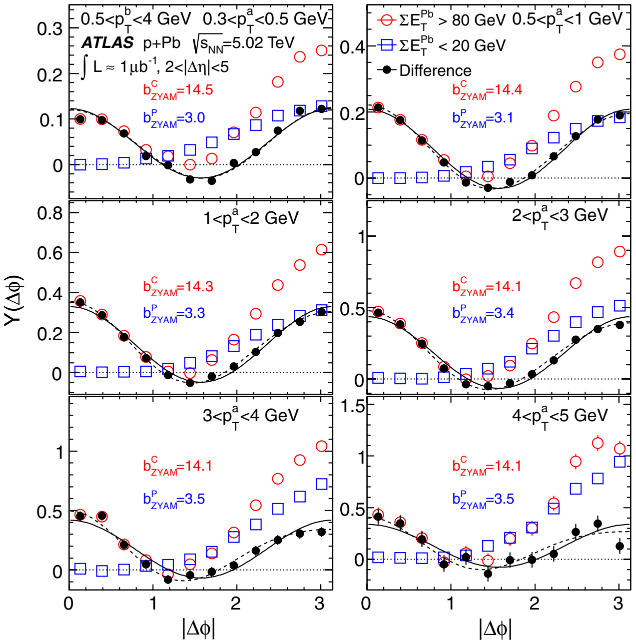

FIG. 3 (color online). Distributions of per-trigger yield in the peripheral and the central event activity classes and their differences (solid symbols), for different ranges of p_T^a and $0.5 < p_T^b < 4$GeV, together with functions $a_0 + 2a_2 \cos 2\Delta\phi$ (solid line) and $a_0 + 2a_2 \cos 2\Delta\phi + 2a_3 \cos 3\Delta\phi$ (dashed line) obtained via a Fourier decomposition (see text). The values for the ZYAM-determined pedestal levels are indicated on each panel for peripheral ($b^P_{\rm ZYAM}$) and central ($b^C_{\rm ZYAM}$) $\Sigma E_T^{\rm Pb}$ bins.

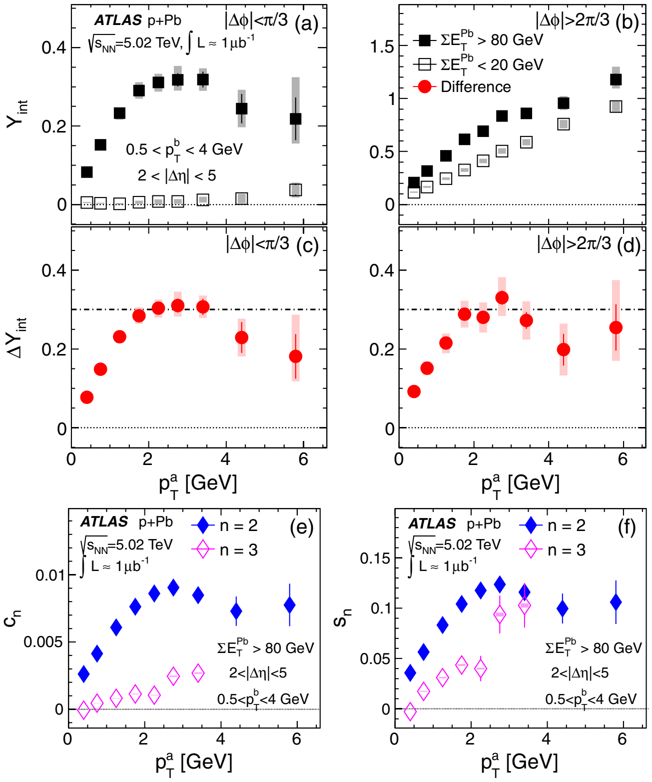

FIG. 4 (color online). Integrated per-trigger yields, $Y_{\rm int}$ (see text), vs p_T^a for $0.5 < p_T^b < 4$ GeV in peripheral and central events, on the (a) near-side and (b) away-side. The panels (c) and (d) show the difference, $\Delta Y_{\rm int}$. Panels (e) and (f) show the p_T dependence of c_n and s_n for $n = 2, 3$, respectively. The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively.

are shown in panels (c) and (d). Qualitatively, the differences have a similar p_T^a dependence and magnitude on the near-side and away-side; they rise with p_T^a and reach a maximum around 3–4 GeV. This pattern is visible for the near-side even before subtraction, as shown in panel (a), but is less evident in the unsubtracted away-side due to the dominant contribution of the recoil component. A similar dependence is observed for long-range correlations in Pb + Pb collisions at approximately the same p_T [22,23].

The relative amplitude of the $\cos n\Delta\phi$ modulation of $\Delta Y(\Delta\phi)$, c_n, for $n = 2, 3$ can be estimated using a_n, and the extracted value of $b_{\rm ZYAM}$ for central events,

$$c_n = a_n/(b^C_{\rm ZYAM} + a_0). \qquad (3)$$

Figure 4(e) shows c_2 and c_3 as a function of p_T^a for $0.5 < p_T^b < 4$ GeV. The value of c_2 is much larger than c_3 and exhibits a behavior similar to $\Delta Y(\Delta\phi)$ at the near-side and away-side. Using the techniques discussed in Ref. [23], c_n can be converted into an estimate of s_n, the average nth Fourier coefficient of the event-by-event single-particle ϕ distribution, by assuming the factorization relation $c_n(p_T^a, p_T^b) = s_n(p_T^a)s_n(p_T^b)$. From this, $s_n(p_T^a)$ is calculated as $s_n(p_T^a) = c_n(p_T^a, p_T^b)/\sqrt{c_n(p_T^b, p_T^b)}$, where $c_n(p_T^b, p_T^b)$ is obtained from Eq. (3) using the a_n extracted from the difference between the central and peripheral data shown in Fig. 2(c). The $s_2(p_T^a)$ values obtained this way exceed 0.1 at ∼2–4 GeV, as shown in Fig. 4(f). The $s_3(p_T^a)$ values are smaller than $s_2(p_T^a)$ over the measured p_T range. The factorization relation used to compute $s_2(p_T^a)$ is found to be valid within 10%–20% when selecting different subranges of p_T^b within 0.5–4 GeV, while the precision of $s_3(p_T^a)$ data does not allow a quantitative test of the factorization. The analysis is also repeated for correlation functions separately constructed from like-sign pairs and unlike-sign pairs, and the resulting c_n and s_n coefficients are found to be consistent within their statistical and systematic uncertainties.

In summary, ATLAS has measured two-particle correlation functions in $\sqrt{s_{NN}} = 5.02$ TeV p + Pb collisions in different intervals of $\Sigma E_T^{\rm Pb}$ over $2 < |\Delta\eta| < 5$. An away-side contribution is observed that grows rapidly with increasing $\Sigma E_T^{\rm Pb}$ and which matches many essential features of the near-side ridge observed here, as well as in previous high-multiplicity p + p, p + Pb and Pb + Pb data at the LHC. Thus, while the ridge in p + p and p + Pb collisions has been characterized as a near-side phenomenon, these results show that it has both near-side and away-side components that are symmetric around $\Delta\phi \sim \pi/2$, with a $\Delta\phi$ dependence that is approximately described by a $\cos 2\Delta\phi$

modulation. A Fourier decomposition of the correlation function, $C(\Delta\phi)$, yields a pair $\cos 2\Delta\phi$ amplitude of about 0.01 at $p_T \sim 3$ GeV, corresponding to a single-particle amplitude of about 0.1. Similar findings are obtained independently by the ALICE Collaboration [9], albeit over a more restricted phase space ($|\Delta\eta| < 1.8$ and $p_T <$ 2–4 GeV). The two results are found to be consistent within this common region.

Some of the features of the data, including the presence of an away-side component, are qualitatively predicted in the color glass condensate approach [6], which models saturation of the parton distribution in the Pb nucleus. The estimated amplitudes of the modulation on the single-particle level are also found to be comparable in magnitude and p_T dependence to similar modulations observed in heavy-ion collisions, commonly attributed to collective expansion of the hot, dense matter [23]. Thus, although the original motivation for this work was to study the possible effects of high parton density in the initial state of $p+\text{Pb}$ collisions, the results presented here are also consistent with contributions of final-state collective effects in high-multiplicity events [24,25].

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