Two-particle azimuthal correlations in γp interactions using pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

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1. Introduction

A wide variety of measurements suggest the existence of collectivity in the collisions of small systems such as the proton-proton (pp) [1–5] and proton-nucleus (pA) [6–17] collisions. Such collectivity could indicate the formation of a hot, strongly interacting “quark gluon plasma” (QGP), characterized by nearly ideal hydrodynamic behavior [18–20], or could alternatively arise from gluon saturation in the initial state [21,22]. Properties of the QGP have been previously studied in a wide range of high-energy nucleus-nucleus (AA) collisions at the CERN LHC and BNL RHIC [23–33]. In these studies, collectivity is observed via the azimuthal correlations of particles that are far apart in rapidity. This phenomenon is known as the “ridge” [21], and has been unexpectedly observed in high-multiplicity pp and pPb collisions since the start of the LHC operation [1–17]. The two-particle azimuthal correlations can be characterized by their Fourier components ($V_{n\Delta}$) where $n$ represents the order of the moment. If the two-particle correlations can be factorized into the product of the corresponding single particle azimuthal distributions, then the single-particle azimuthal anisotropy Fourier coefficients $v_n$ can be extracted as $v_n = \sqrt{V_{n\Delta}}$ [34]. The second ($v_2$) and third ($v_3$) coefficients are known as elliptic and triangular flow, respectively, and are directly related to the initial collision geometry and its fluctuations, which influence the medium evolution and provide information about its fundamental transport properties [35–38].

In high-multiplicity events, $v_2$ and $v_3$ depend upon the hadron species [15,39–43] and scale with the number of valence quarks in the hadron [15]. Such results suggest a common origin of the collectivity seen in PbPb, as well as in high-multiplicity pp and pPb events, where a hydrodynamic description can be used to reasonably reproduce the measurements in each case [44–47]. Probing systems with even smaller interaction regions is therefore important to understand the reach of such a hydrodynamic description. The search for collectivity has been recently extended to electron-positron (e$^+$e$^-$), electron-proton (ep), photon-proton (γp), and photon-nucleus interactions [48–52]. So far, no long-range near-side ridge has been detected in these systems. In e$^+$e$^-$ collisions [48,49], strong exclusion limits have been set on the ridge yield, while in ep collisions (deep inelastic scattering and photoproduction) [50,51], the extracted Fourier coefficients are finite but do not conclusively imply collective behavior. In photon-nucleus collisions [52], finite $v_2$ and $v_3$ are measured after applying a template fit procedure to remove noncollective correlations, assuming they scale with multiplicity.

High-energy pPb ultra-peripheral collisions at the LHC, where the impact parameter is larger than the nucleus radius provide a new system to extend the search of long-range correlations to photon-proton collisions. At TeV energies, the lead (Pb) nuclei generate a very large quasi-real photon flux [53]. In the equivalent photon approximation [54–56], this flux can be considered

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as γ beams of virtuality $Q^2 < 1/R^2$, where $R$ is the effective radius of the charge distribution. For Pb nuclei at 2.56TeV with radius $R \approx 7$fm, the quasi-real photon beams have virtualities $Q^2 < 10^{-3}$ GeV$^2$, but very large longitudinal energy, up to $E_γ = \hbar c/\alpha R \approx 73$ GeV, where $α$ is the reciprocal Lorentz relativistic factor.

This study complements recent results from small collision systems, such as $e^+e^-$ and $e\gamma$ [48,49,51]. The CMS detector has been used to collect a large sample of γp interactions that occur in ultra-peripheral PbPb collisions. The beam energies were 6.50TeV for the protons and 2.56TeV per nucleon for the Pb nuclei, resulting in a center-of-mass energy per nucleon pair (√sNN) of 8.16TeV. The resulting γp center-of-mass energy can fluctuate up to 1.4 TeV. The γp results are compared to both hadronic minimum bias (MB) PbPb collisions (previously studied in Ref. [57]) and predictions of the hijing v8.2 [58] model interfaced with the Delphes v3.4.2 fast simulation package [59]. The minimum bias data are compared to predictions from the HIJING v2.1 generator [60] coupled to a full GEANT4 simulation of the detector [61].

2. Experimental apparatus and data sample

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume is the silicon tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections that cover the range $|\eta| < 3.0$. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. It consists of 1440 silicon pixels and 15148 silicon strip detector modules, and provides an impact parameter resolution of about 15μm and a transverse momentum ($p_T$) resolution better than 1.5% at $p_T \approx 100$GeV/c. Event selection for this analysis makes use of detectors in the forward region: hadron forward (HF) calorimeters that use quartz fibers embedded in a steel absorber covering the region 3.0 < $|\eta| < 5.2$ and the two Zero Degree Calorimeters (ZDCs) which measure neutral particles with $|\eta| > 8.3$ [52]. Analysis in the midrapidity region is based upon objects produced by the CMS particle-flow (PF) algorithm [63], which reconstructs and identifies final-state particles with an optimized combination of information from the various elements of the CMS detector. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [64].

The analysis is performed using data recorded by CMS during the LHC pPb run in 2016 with an integrated luminosity of 68.8 nb$^{-1}$. The proton-going direction is towards the side of the detector with positive $\eta$. As a result of the energy difference between the colliding beams, the nucleon-nucleon (NN) center-of-mass for PbPb collisions is not at rest with respect to the laboratory frame. Massless particles emitted at $\eta_{cm} = 0$ in the NN center-of-mass frame will be detected at $\eta = +0.465$ in the laboratory frame. The event samples were collected by the CMS experiment with a two-level trigger system [57] consisting in the level-1 (L1), where events are selected by custom hardware processors and the high-level trigger (HLT), that uses fast versions of the offline software.

Samples of both γp-enhanced and MB events were collected requiring energy deposits in at least one of the HF calorimeters above a threshold of approximately 1 GeV at L1. The HLT system requires the presence of at least one charged particle (track) with $p_T > 0.4$GeV/c in the pixel tracker. Track reconstruction was performed online as part of the HLT trigger with a reconstruction algorithm that is identical to the one used offline [65]. More details of the MB trigger can be found in Ref. [66]. For each event, the reconstructed vertex with the highest number of associated tracks was selected as the primary vertex. A zero bias trigger requiring only the presence of proton and lead bunches in the CMS detector was used to independently study the trigger efficiency ($\epsilon_{trg}$). The beam bunches were detected by induction counters placed 175m from the interaction point on each side of the experiment. In addition, a sample of events with neither beam present was collected for noise studies.

3. Event selection

For both γp and MB samples, the reconstructed primary vertex was required to be within 15 cm of the nominal interaction point along the beam axis (z) and within 0.15 cm in the transverse plane. The strategy for track selection is described in Ref. [65]. The impact parameter significance of reconstructed tracks with respect to the primary vertex in the longitudinal and transverse directions was required to be $<3$ standard deviations. Finally, the relative uncertainty in the $p_T$ of the track was required to be $<10\%$. At least two reconstructed tracks with $|\eta| < 2.4$ and $p_T > 0.4$GeV/c were required to be associated with the primary vertex. Beam-related background was suppressed by rejecting events for which $<25\%$ of all reconstructed tracks pass the standard track selection criteria as in Ref. [57].

Typical pPb collisions produce particles at both positive and negative rapidity [40,57,67]. However, γp events are expected to be very asymmetric in the laboratory frame since the photon energy is generally much smaller than the proton beam energy.

For the γp-enhanced selection, a rapidity gap is defined as a continuous region in which there is low detector activity, as done in Ref. [68]. The detector acceptance $|\eta| < 5.0$ is divided into 20 bins. Threshold values are assigned to each $\eta$ bin, they delimit the energy from all PF candidates that can be considered significant and which contain at least 99.7% of detector activity caused by detector noise or by beam-gas events. These thresholds were obtained by studying the zero-bias events triggered on noncolliding bunches. For each event, a given $\eta$ bin was considered to be empty if the energy registered from the PF candidates was below its assigned threshold value. For the 10 bins in the regions $|\eta| < 2.5$ the energy threshold was 6 GeV and no high-purity tracks with $p_T > 200$MeV/c were allowed. For the four bins from $-5.0 < \eta < -3.0$ in the lead-going region the thresholds were 16.9, 15.3, 16.4, and 13.4 GeV, respectively. For the bin $-2.5 > \eta > -3.0$ only neutral hadrons were considered and the energy threshold was 13.4GeV. The forward rapidity gap ($\Delta^F$) variable was then defined as the difference from $\eta = -5.0$ to the lower edge of the first nonempty $\eta$ bin.

The MB selection requires the coincidence of at least one tower with energy above 3.0 GeV in both HF calorimeters and at least two tracks with $|\eta| < 2.5$. In contrast, a γp-enhanced selection is designed to capture events with an intact Pb nucleus, particle production in the positive $\eta$ region, and a large rapidity gap [69-71]. The first two requirements are met by requiring no neutrons in the ZDC on the Pb-going side and at least 10 GeV in the highest energy tower of the HF calorimeter on the p-going side. To ensure a large rapidity gap, we require $5.0 < \Delta^\eta < 7.5$. This corresponds to not having a particle within the negative-$\eta$ region. A total of $8.6 \times 10^4$ γp-enhanced and $1.0 \times 10^5$ MB candidate events were selected. In Ref. [68] the purity of the γp-enhanced sample with the ZDC selection is estimated to be about 95% and it is weakly dependent on particle multiplicity. The requirement of no neutron emission used in this analysis gives an additional suppression of pomerom-Pb events.

The reconstructed track multiplicity ($N^{lum}_{trk}$) is defined as the number of tracks from the primary vertex with $p_T > 0.4$GeV/c, and $|\eta| < 2.4$. Fig. 1 shows the $N^{lum}_{trk}$ spectra for the γp-enhanced and
MB data samples along with simulations from the pythia8 and hijing event generators. For the γp-simulated sample, the events are restricted to those with no tracks in the η < 0 region and normalized to the γp-enhanced yield. In contrast to the MB sample, the γp-enhanced spectrum drops very rapidly with multiplicity up to a limiting value of 34. The $N_{\text{off}}$ value corresponding to the $2 \leq N_{\text{off}} < 35$ range for the γp-enhanced sample is ≈2.9 and about 16.6 for the MB sample. The $N_{\text{off}}$ distribution from the zero bias data control sample has $N_{\text{off}} \approx 0.84$. The γp-simulated sample shows a shape and range that is consistent with the γp-enhanced data sample. Three $N_{\text{off}}$ bins are used to analyze the γp-enhanced events: $2 \leq N_{\text{off}} < 5$, $5 \leq N_{\text{off}} < 10$, $10 \leq N_{\text{off}} < 35$. The first two deliver a comparable number of particle pairs and the third one aims to probe the higher $N_{\text{off}}$ domain by averaging the last part of the distribution. Table 1 indicates the $N_{\text{off}}$ values for the data and simulated γp and MB samples. The mean $p_T$, $\langle p_T \rangle$, values of charged particles in the γp and MB data samples are 0.67 ± 0.01 and 0.74 ± 0.01 GeV/c respectively.

4. Analysis technique

To ensure a high tracking efficiency, only tracks with $0.3 < p_T < 3.0$ GeV/c are used in the analysis. The two-particle correlation analysis techniques described below are identical to those used in previous CMS measurements in pp, pPb, and PbPb collisions [3,6,26]. For each multiplicity class, the “trigger particles” are tracks whose $p_T$, labeled as $p_T^{\text{trg}}$, is within a particular given range. The number of trigger particles in the event is denoted by $N_{\text{trg}}$. Particle pairs are then formed by associating each trigger particle with the remaining tracks whose $p_T$ is denoted as $p_T^{\text{assoc}}$. In this analysis $p_T^{\text{trg}}$ and $p_T^{\text{assoc}}$ have a common range. Two different $p_T$ ranges are studied, i.e., $[0.3, 3.0]$ and $[1.0, 3.0]$ GeV/c. These are the same as those used in previous studies of the ridge [6] and observations of correlations between $v_n$ coefficients [57] in pPb collisions.

The two-dimensional correlation function is defined as

$$\frac{1}{N_{\text{trg}}} \frac{\Delta^2 N_{\text{pair}}}{\Delta \eta \Delta \phi} = B(0,0) S(\Delta \eta, \Delta \phi) \frac{B(\Delta \eta, \Delta \phi)}{B(0,0)},$$

(1)

where Δη and Δφ are the differences in η and φ of the pair and $N_{\text{pair}}$ is the number of pairs. The same-event pair distribution, $S(\Delta \eta, \Delta \phi)$, represents the yield of particle pairs from the same event in a given (Δη, Δφ) bin. Entries have been weighted by the product of inverse efficiencies evaluated for the kinematics of the two particles. The mixed-event pair distribution $B(\Delta \eta, \Delta \phi)$ is constructed by pairing the trigger particles in each event with the associated charged particles from 100 different randomly selected events in the same 0.5 cm wide vertex range and from the same track multiplicity class. It accounts for random combinatorial backgrounds and pair-acceptance effects. The same-event and mixed-event pair distributions are first calculated for each event, and then averaged over the events within the track multiplicity class. The mixed-event distribution is normalized by the sum of background events. The ratio $B(0,0)/B(\Delta \eta, \Delta \phi)$ is the pair-acceptance correction factor, where $B(0,0)$ represents the mixed-event associated yield for both particles of the pair going in the same direction and thus having maximum pair acceptance.

Fig. 2 (left) shows the two-particle correlation functions for γp-enhanced (upper row) and MB (lower row) events within the multiplicity range $2 \leq N_{\text{off}} < 35$ as functions of Δη and Δφ. This range integrates all the yields for all statistics for γp events, significantly suppressing fluctuations seen in smaller bins. For the γp distribution, the Δη range is limited to |Δη| < 2.5 by the Δη selection and the acceptance of the tracker. Both distributions show a large jet peak centered at Δφ = 0, as well as a broader distribution from the recoiling jet centered at Δφ = π. Neither distribution displays a “ridge”-like structure at |Δφ| ≥ 0 for |Δη| > 2. Fig. 2 (right) shows the projections of the two-dimensional correlation functions onto the Δφ axis. The distributions are fitted over the Δφ range [0, π] to a Fourier decomposition series $\propto 1 + \sum_n 2V_{n,0} \cos(n \Delta \phi)$, from where the measured $V_{n,0}$ are extracted. Only the first three terms are included in the fit, since additional terms have a negligible effect on its quality.

In order to reduce the contribution to $v_n$ coefficients from back-to-back jet correlations, one can correct $v_n$ by subtracting correlations from very low-multiplicity events ($v_n^{\text{null}}$), as done in Refs. [4,57,72]. In order to test whether a collective signal is present, the data are compared to pythia8 predictions, which do not include collective effects.

5. Systematic uncertainties

The systematic uncertainties of the experimental procedure are evaluated by varying the analysis conditions and extracting new $V_{n,0}$ coefficients. The following effects were considered:
Fig. 2. Two-dimensional (left) and one-dimensional (right) correlation plots for γp-enhanced (upper) and MB (lower) events for $0.3 < p_T < 3.0\text{ GeV/c}$ and $2 < N_{\text{offline}}^{\text{track}} < 35$. For the two-dimensional distributions, the jet peak centered at $\Delta\eta = \Delta\phi = 0$ is truncated to increase visibility. The rapidity gap requirement for the γp-enhanced sample limits the $|\Delta\eta|$ range to $|\Delta\eta| < 2.5$. The one-dimensional $\Delta\phi$ distributions are symmetrized by construction around $\Delta\phi = 0$ and $\pi$. The Fourier coefficients, $V_n$, in the right column are fit over the $[0, \pi]$ range. Points outside this range are shown as open circles and are obtained by symmetrization of those in $[0, \pi]$. Statistical error bars are shown for both one-dimensional distributions.

1. The systematic uncertainties associated with the choice of the $\Delta\eta$ range, which has a resolution of 0.5 units in $\eta$ and ensures low detector activity on one half of the detector, were estimated by repeating the analysis with $\Delta\eta \in (4.5, 5.0)$, just below the range of the nominal analysis. This alternative selection affects the track multiplicity and decreases the purity of the γp-enhanced sample up to 8% [68]. The estimated size of this uncertainty has maximum values of 7% for $V_{1\Lambda}$ and 27% for $V_{2\Lambda}$ within the $N_{\text{offline}}^{\text{track}}$ range considered in this analysis. For the MB data there is no rapidity gap requirement and so no systematic uncertainty is assigned for this effect.
2. The effect of tracking inefficiency and misreconstructed track rate was studied by varying the track quality requirements. The selection thresholds on the significance of the transverse and longitudinal track impact parameter were varied from 2 to 5 standard deviations. In addition, the relative $p_T$ uncertainty is varied from 0.05 to 0.10. This translates into a 3.5% uncertainty in $V_{1\Delta}$ for the $2 \leq N_{\text{trk}} \leq 5$ category.

3. The sensitivity of the results to the primary vertex position along the beam axis ($z_{\text{vert}}$) was quantified by comparing events with different $z_{\text{vert}}$ locations from $-15$ to $+15$ cm. The magnitude of this systematic effect goes up to 150% for $V_{1\Delta}$ with numerical estimations of $\pm 0.003$ for $5 \leq N_{\text{trk}} \leq 10$ and $10 \leq N_{\text{trk}} \leq 35$ respectively, in the $0.3 < p_T < 3.0 \text{ Ge}\text{e}c$ category, and up to $\pm 0.013$ for $1.0 < p_T < 3.0 \text{ Ge}\text{e}c$.

4. The trigger efficiency depends upon $N_{\text{trk}}^{\text{offline}}$. It decreases substantially for $N_{\text{trk}}^{\text{offline}} < 10$, reaching 70% for $N_{\text{trk}}^{\text{offline}} = 2$. To study this effect, a parallel data sample with weighted events as $(1/\varepsilon_{\text{trk}})$ was produced. The full difference of the $V_{1\Delta}$ with and without the correction was taken as the uncertainty. This uncertainty is 2.3% for $V_{1\Delta}$ and 17% for $V_{2\Delta}$ for the sample with $2 \leq N_{\text{trk}}^{\text{offline}} < 5$.

The systematic uncertainties were added in quadrature. For the $pT$-enhanced sample with $N_{\text{trk}}^{\text{offline}} < 35$ the final uncertainties in $V_{n\Delta}$ are 8.4 and 31% for $n = 1$ and 2, respectively. For the minimum bias sample the uncertainties for $V_{2\Delta}$ are 11% for $2 \leq N_{\text{trk}}^{\text{offline}} < 5$ and smaller than 2.6% for the rest of the $N_{\text{trk}}^{\text{offline}}$ range. Since $p_T^{\text{pPb}}$ and $p_T^{\text{DMP}}$ have the same range, the fractional uncertainties in $v_n$ are half those of $V_{n\Delta}$.

### 6. Results

Fig. 3 and Table 2 show the measured $V_{n\Delta}$ coefficients as a function of $N_{\text{trk}}^{\text{offline}}$ for the two different $p_T$ ranges for the $pT$ and MB pPb samples. For the MB sample, the results are consistent with those in [57] before the subtraction procedure. Both the $\gamma$- and $p_T$-enhanced distributions show a negative $V_{1\Delta}$, a positive $V_{2\Delta}$ of smaller magnitude than $V_{1\Delta}$, and a $V_{3\Delta}$ that is consistent with zero. For a given $N_{\text{trk}}^{\text{offline}}$ and $p_T$ range, both $V_{1\Delta}$ and $V_{2\Delta}$ are larger in the $\gamma$-$p_T$ sample than in the MB results. For both samples, the magnitude of $V_{1\Delta}$ tends to decrease with $N_{\text{trk}}^{\text{offline}}$, while $V_{2\Delta}$ has at most a weak $N_{\text{trk}}^{\text{offline}}$ dependence. Their magnitudes are both larger in the higher $p_T$ range.

Fig. 3 also shows predictions from the PYTHIA8 generator for $V_{n\Delta}$ from $\gamma$-$p_T$ collisions. The predictions of $V_{2\Delta}$ and $V_{3\Delta}$ from PYTHIA8 are reasonably consistent with the $\gamma$-$p_T$ data and have a similar dependence upon $p_T$ and $N_{\text{trk}}^{\text{offline}}$. The $V_{1\Delta}$ prediction is smaller in magnitude than the measured values for the low $p_T$ range.

Table 2

| $p_T$ range | $\leq N_{\text{trk}}^{\text{offline}}$ | $5 \leq N_{\text{trk}}^{\text{offline}} < 10$ | $10 \leq N_{\text{trk}}^{\text{offline}} < 35$ |
|-------------|----------------------------------|-------------------------------------|----------------------------------|
| $0.3 < p_T < 3.0 \text{ Ge}\text{e}c$ | $V_{1\Delta} = -0.086 \pm 0.006$ | $-0.075 \pm 0.005 -0.074 \pm 0.007$ |
| $V_{2\Delta} = 0.012 \pm 0.004$ | $0.015 \pm 0.004 0.026 \pm 0.006$ |
| $V_{3\Delta} = 0.002 \pm 0.001$ | $-0.002 \pm 0.004 -0.010 \pm 0.006$ |

Fig. 4 shows $v_2$ as a function of $N_{\text{trk}}^{\text{offline}}$ and $p_T$ for both $\gamma$-$p_T$ and MB data sets. For $0.3 < p_T < 3.0 \text{ Ge}\text{e}c$, the MB results are consistent with previously published CMS results [57]. Predictions from the PYTHIA8 and HIJING generators are also shown for $\gamma$-$p_T$ and MB pPb interactions respectively, none of the models include collective effects. For both data and simulations, $v_2$ varies slowly with track multiplicity for the $\gamma$-$p_T$ and pPb samples. At a given $N_{\text{trk}}^{\text{offline}}$, $v_2$ is larger in the higher $p_T$ range. This is similar to trends observed in e$p$ collisions [50,51]. The increase of $v_2$ with $p_T$ is also present in the simulations although both generators slightly overshoot the data at higher $p_T$. For pPb collisions it has been shown that fluctuations in the proton shape can increase $v_2$ [73]. It is noticeable that at a given $p_T$ and $N_{\text{trk}}^{\text{offline}}$, $v_2$ is higher for $\gamma$-$p_T$ than for pPb interactions. Tabulated results are provided in the HEPData record for this analysis [74].

### 7. Summary

For the first time, the study of long-range particle correlations has been extended to photon-proton $(\gamma$-$p_T)$ interactions. This study used proton-lead (pPb) collisions at $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$ recorded with the CMS detector. The two-particle $V_{n\Delta}$ coefficients and corresponding single-particle $v_n$ azimuthal anisotropies are reported as functions of the multiplicity of charged hadrons $(N_{\text{trk}}^{\text{offline}})$ for two transverse momenta $(p_T)$ ranges. For the $\gamma$-$p_T$ sample, the largest observed multiplicity was $N_{\text{trk}}^{\text{offline}} \sim 35$. The mean $p_T$ of charged particles is smaller in the $\gamma$-$p_T$ sample than for pPb collisions within the same multiplicity range. No evidence for a long-range near-side ridge-like structure was found for either the $\gamma$-$p_T$ or hadronic minimum bias pPb (MB) samples within this multiplicity range. In all $N_{\text{trk}}^{\text{offline}}$ and $p_T$ ranges, $V_{1\Delta}$ is negative, $V_{2\Delta}$ is positive with a smaller magnitude than $V_{1\Delta}$, and $V_{3\Delta}$ is consistent with zero. The magnitudes of both $V_{1\Delta}$ and $V_{2\Delta}$ increase with $p_T$. This increase has also been seen in electron-proton collisions. At a given $p_T$ and track multiplicity, $v_2$ is larger for $\gamma$-$p_T$-enhanced events than for pPb interactions. Predictions from the PYTHIA8 model describe well the $\gamma$-$p_T$ data within uncertainties. This suggests the data are dominated by noncollective effects. Within the present experimental sensitivity, no significant collectivity signal is observed.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

Complete statement will be provided in proof.

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References

[1] CMS Collaboration, Observation of long-range, near-side angular correlations in proton-proton collisions at the LHC, J. High Energy Phys. 09 (2010) 091, https://doi.org/10.1007/JHEP09(2010)091, arXiv:1008.4122.

[2] ATLAS Collaboration, Observation of long-range elliptic azimuthal anisotropies in $\sqrt{s}=13$ and 2.76 TeV pp collisions with the ATLAS detector, Phys. Rev. Lett. 116 (2016) 172301, https://doi.org/10.1103/PhysRevLett.116.172301, arXiv:1509.04776.

[3] CMS Collaboration, Measurement of long-range near-side two-particle angular correlations in pp collisions at $\sqrt{s}=13$ TeV, Phys. Rev. Lett. 116 (2016) 172302, https://doi.org/10.1103/PhysRevLett.116.172302, arXiv:1510.03068.

[4] CMS Collaboration, Evidence for collectivity in pp collisions at the LHC, Phys. Lett. B 765 (2017) 193, https://doi.org/10.1016/j.physletb.2016.12.009, arXiv:1606.06198.

[5] ATLAS Collaboration, Measurement of azimuthal anisotropy of muons from charmed and bottom hadrons in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector, Phys. Rev. Lett. 124 (2020) 082301, https://doi.org/10.1103/PhysRevLett.124.082301, arXiv:1908.01650.

[6] CMS Collaboration, Observation of long-range near-side angular correlations in p+Pb collisions at the LHC, Phys. Lett. B 718 (2013) 795, https://doi.org/10.1016/j.physletb.2012.11.025, arXiv:1210.5482.

[7] C. Addala et al., PHENIX, Measurement of long-range angular correlations and azimuthal anisotropies in high-multiplicity $p+Au$ collisions at $\sqrt{s}_{NN}=200$ GeV, Phys. Rev. C 95 (2017) 034910, https://doi.org/10.1103/PhysRevC.95.034910, arXiv:1609.02894.

[8] C. Addala et al., PHENIX, Creation of quark-gluon plasma droplets with three distinct geometries, Nat. Phys. 15 (2019) 214, https://doi.org/10.1038/s41567-018-0360-0, arXiv:1805.02973.
[9] ATLAS Collaboration, 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, Phys. Rev. Lett. 110 (2013) 182302, https://doi.org/10.1103/PhysRevLett.110.182302, arXiv:1212.5198.

[10] ATLAS Collaboration, Measurement with the ATLAS detector of multi-particle azimuthal correlations in p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Lett. B 725 (2013) 60, https://doi.org/10.1016/j.physletb.2013.06.057, arXiv:1303.2084.

[11] ALICE Collaboration, Long-range angular correlations on the near and away side in p-pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Rev. C 82 (2015) 2, https://doi.org/10.1103/PhysRevC.82.024904, arXiv:1503.03874.

[12] J. Adam et al., STAR, Beam-energy dependence of identified two-particle angular correlations in $\sqrt{s_{NN}} = 7.7 − 200$ GeV Au+Au collisions, Phys. Rev. C 101 (2020) 014916, https://doi.org/10.1103/PhysRevC.101.014916, arXiv:1906.09204.

[13] J. Adam et al., STAR, Correlation measurements between flow harmonics in Au+Au collisions at RHIC, Phys. Rev. B 783 (2019) 459, https://doi.org/10.1103/PhysRevC.100.044904, arXiv:1905.05775.

[14] S. Voloshin, Y. Zhang, Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions, Phys. Rev. C 70 (1999) 665, https://doi.org/10.1103/PhysRevC.70.024904, arXiv:hep-ph/9807282.

[15] B.H. Alver, C. Gombeaud, M. Luzum, J.-F. Ollitrault, Triangular flow in hydrodynamics and transport theory, Phys. Rev. C 82 (2010) 034911, https://doi.org/10.1103/PhysRevC.82.034911, arXiv:0907.5469.

[16] C.G.B. Schenke, S. Jeon, Elliptic and triangular flow in event-by-event D = 3 + 1 viscous hydrodynamics, Phys. Rev. Lett. 106 (2011) 042301, https://doi.org/10.1103/PhysRevLett.106.042301, arXiv:1009.2444.

[17] C.S.Z. Qu, U. Heinz, Hydrodynamic elliptic and triangular flow in Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV, Phys. Lett. B 707 (2012) 151, https://doi.org/10.1016/j.physletb.2011.12.041, arXiv:1110.3033.

[18] B. Alver, G. Roland, Collision geometry fluctuations and triangular flow in heavy-ion collisions, Phys. Rev. C 81 (2010) 054905, https://doi.org/10.1103/PhysRevC.82.034903, arXiv:1001.0318, Phys. Rev. C 82 (2010) 034903 (Erratum).

[19] CMS Collaboration, Elliptic flow of charm and strange hadrons in high-multiplicity p+p collisions at $\sqrt{s} = 5.02$ TeV, Phys. Rev. Lett. 121 (2018) 112301, https://doi.org/10.1103/PhysRevLett.121.112301, arXiv:1804.07677.

[20] CMS Collaboration, Centrality and pseudorapidity dependence of the transverse energy density in p+p collisions at $\sqrt{s} = 5.02$ TeV, Phys. Rev. C 100 (2019) 024902, https://doi.org/10.1103/PhysRevC.100.024902, arXiv:1810.05745.

[21] ALICE Collaboration, Multi-strange baryon production in p+p collisions at $\sqrt{s} = 5.02$ TeV, Phys. Lett. B 758 (2016) 389, https://doi.org/10.1016/j.physletb.2016.05.027, arXiv:1512.07227.

[22] S.S. Adler et al., PHENIX, Elliptic flow of identified hadrons in Au+Au collisions at $\sqrt{s} = 200$ GeV, Phys. Rev. Lett. 91 (2003) 182301, https://doi.org/10.1103/PhysRevLett.91.182301, arXiv:nucl-ex/0305013.

[23] J. Adams et al., STAR, Distributions of charged hadrons associated with high transverse momentum particles in pp and Au+Au collisions at $\sqrt{s} = 200$ GeV, Phys. Rev. Lett. 95 (2005) 152301, https://doi.org/10.1103/PhysRevLett.95.152301, arXiv:nucl-ex/0501016.

[24] R.D. Weller, P. Romatschke, One fluid to rule them all: viscous hydrodynamic description of event-by-event central pp and Pb-Pb collisions at $\sqrt{s} = 5.02$ TeV, Phys. Lett. B 774 (2017) 351, https://doi.org/10.1016/j.physletb.2017.09.077, arXiv:1701.07145.

[25] P. Bozek, Collective flow in p+p and d+Pb collisions at TeV energies, Phys. Rev. C 85 (2012) 014911, https://doi.org/10.1103/PhysRevC.85.014911, arXiv:1111.0885.

[26] P. Bozek, W. Broniowski, Correlations from hydrodynamic flow in p+p collisions, Phys. Lett. B 718 (2013) 1557, https://doi.org/10.1016/j.physletb.2013.12.051, arXiv:1211.0845.

[27] P. Bozek, W. Broniowski, Collective dynamics in high-energy proton-nucleus collisions, Phys. Rev. C 88 (2013) 014903, https://doi.org/10.1103/PhysRevC.88.014903, arXiv:1304.3044.

[28] A. Badea, A. Baty, P. Chang, G.M. Innocenti, M. Maggi, C. Meginn, M. Peters, T.-A. Sheng, J. Thaler, Y.-J. Lee, Measurements of two-particle correlations in $e^{-}$ collisions at 91 GeV with ALEPH archived data, Phys. Rev. Lett. 123 (2019) 212302, https://doi.org/10.1103/PhysRevLett.123.212302, arXiv:1905.00489.

[29] Y.C. Chen et al., Belle, Measurement of two-particle correlations of hadrons in $e^{-}$ collisions at Belle, Phys. Rev. Lett. 128 (2022) 142005, https://doi.org/10.1103/PhysRevLett.128.142005, arXiv:2201.01694.

[30] I. Abt et al., ZEUS, Two-particle azimuthal correlations as a probe of collective behaviour in deep inelastic ep scattering at HERA, J. High Energy Phys. 04 (2020) 070, https://doi.org/10.1007/JHEP04(2020)070, arXiv:1912.07431.

[31] I. Abt et al., ZEUS, Azimuthal correlations in photoproduction and deep inelastic ep scattering at HERA, J. High Energy Phys. 12 (2021) 102, https://doi.org/10.1007/JHEP12(2021)102, arXiv:2108.08102.

[32] ATLAS Collaboration, Two-particle azimuthal correlations in photoproduction, Phys. Rev. C 104 (2021) 014903, https://doi.org/10.1103/PhysRevC.104.014903, arXiv:2101.07771.

[33] A. Baltz, The physics of ultraperipheral collisions at the LHC, Phys. Rep. 458 (2008) 1, https://doi.org/10.1016/j.physrep.2007.12.001, arXiv:0706.3356.

[34] C.F. von Weizäcker, Radiation emitted in collisions of very fast electrons, Z. Phys. 88 (1934) 612, https://doi.org/10.1007/BF01331110.

[35] E.J. Williams, Nature of the high-energy particles of penetrating radiation and status of ionization and radiation formulæ, Phys. Rev. 45 (1934) 729, https://doi.org/10.1103/PhysRev.45.729.

[36] E. Fermi, On the theory of collisions between atoms and electrically charged particles, Nuovo Cimento 2 (1925) 143, https://doi.org/10.1007/BF02969194, arXiv:hep-th/0205086.

[37] CMS Collaboration, Observation of correlated azimuthal anisotropy Fourier harmonics in pp and p-Pb collisions at the LHC, Phys. Rev. Lett. 120 (2018) 092301, https://doi.org/10.1103/PhysRevLett.120.092301, arXiv:1709.01819.
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