Physics Letters B 844 (2023) 137905

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

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

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ARTICLE INFO

Article history:
Received 28 April 2022
Received in revised form 14 March 2023
Accepted 6 April 2023
Available online 20 July 2023
Editor: M. Doser

Keywords:
CMS
Photon-proton
Collectivity

ABSTRACT

The first measurements of the Fourier coefficients ($V_{n\Delta}$) of the azimuthal distributions of charged hadrons emitted from photon-proton (γp) interactions are presented. The data are extracted from 68.8 nb^{-1} of ultra-peripheral proton-lead (pPb) collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV using the CMS detector. The high energy lead ions produce a flux of photons that can interact with the oncoming proton. This γp system provides a set of unique initial conditions with multiplicity lower than in photon-lead collisions but comparable to recent electron-positron and electron-proton data. The $V_{n\Delta}$ coefficients are presented in ranges of event multiplicity and transverse momentum (p_{T}) and are compared to corresponding hadronic minimum bias pPb results. For a given multiplicity range, the mean p_{T} of charged particles is smaller in γp than in pPb collisions. For both the γp and pPb samples, $V_{1\Delta}$ is negative, $V_{2\Delta}$ is positive, and $V_{3\Delta}$ consistent with 0. For each multiplicity and p_{T} range, $V_{2\Delta}$ is larger for γp events. The γp data are consistent with model predictions that have no collective effects.

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 ($\mathrm{e}^+\mathrm{e}^-$), 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 $\mathrm{e}^+\mathrm{e}^-$ 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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https://doi.org/10.1016/j.physletb.2023.137905

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

This study complements recent results from small collision systems, such as e^+e^- and ep [48,49,51]. The CMS detector has been used to collect a large sample of γp interactions that occur in ultra-peripheral pPb collisions. The beam energies were 6.50 TeV for the protons and 2.56 TeV per nucleon for the Pb nuclei, resulting in a center-of-mass energy per nucleon pair ($\sqrt{s_{\text{NN}}}$) of 8.16 TeV. 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) pPb collisions (previously studied in Ref. [57]) and predictions of the PYTHIA 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 15 148 silicon strip detector modules, and provides an impact parameter resolution of about 15 μm and a transverse momentum (p_{T}) resolution better than 1.5% at $p_{\text{T}} \approx 100\,\text{GeV}/c$. 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 $|\eta| > 8.3$ [62]. 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 $68.8\ \text{nb}^{-1}$. The proton-going direction is towards the side of the detector with positive η. As a result of the energy difference between the colliding beams, the nucleon-nucleon (NN) center-of-mass for pPb collisions is not at rest with respect to the laboratory frame. Massless particles emitted at $\eta_{\text{cm}} = 0$ 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 $p_{\text{T}} > 0.4\,\text{GeV}/c$ 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 ($\varepsilon_{\text{trig}}$). The beam bunches were detected by induction counters placed 175 m 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 $p_{\text{T}} > 0.4\,\text{GeV}/c$ 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 η 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 η 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 $p_{\text{T}} > 200\,\text{MeV}/c$ 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 13.4 GeV. The forward rapidity gap ($\Delta\eta^F$) variable was then defined as the difference from $\eta = -5.0$ to the lower edge of the first nonempty η 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 η 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 $5.0 < \Delta\eta^F < 7.5$. This corresponds to not having a particle within the negative-η region. A total of 8.6×10^6 γp-enhanced and 1.0×10^9 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 pomeron-Pb events.

The reconstructed track multiplicity ($N_{\text{trk}}^{\text{offline}}$) is defined as the number of tracks from the primary vertex with $p_{\text{T}} > 0.4\,\text{GeV}/c$, and $|\eta| < 2.4$. Fig. 1 shows the $N_{\text{trk}}^{\text{offline}}$ spectra for the γp-enhanced and

Table 1
Mean $N_{\mathrm{trk}}^{\mathrm{offline}}$ for the γp-enhanced and the MB data sets for five classes of $N_{\mathrm{trk}}^{\mathrm{offline}}$ (abreviated as $N_{\mathrm{trk}}^{\mathrm{off}}$). Statistical uncertainties are negligible.

Sample	$2 \le N_{\mathrm{trk}}^{\mathrm{off}} < 5$	$5 \le N_{\mathrm{trk}}^{\mathrm{off}} < 10$	$10 \le N_{\mathrm{trk}}^{\mathrm{off}} < 35$	$5 \le N_{\mathrm{trk}}^{\mathrm{off}} < 35$	$2 \le N_{\mathrm{trk}}^{\mathrm{off}} < 35$
γp-enhanced	2.6	5.8	11.3	6.0	2.9
γp-simulated	2.6	5.9	11.4	6.2	2.9
MB	3.0	6.9	21.5	18.5	16.6
MB-simulated	3.1	6.9	20.7	17.2	15.7

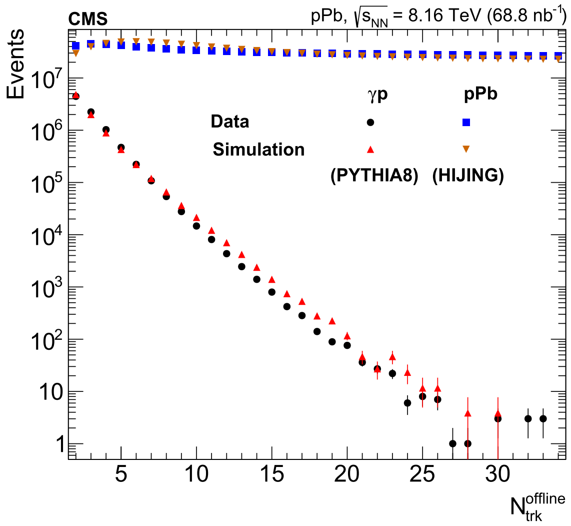

Fig. 1. The $N_{\mathrm{trk}}^{\mathrm{offline}}$ spectra for γp and MB samples. The simulated γp distribution has been normalized to the same event yield as the γp-enhanced data sample.

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 $\eta < 0$ 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 $\langle N_{\mathrm{trk}}^{\mathrm{offline}}\rangle$ value corresponding to the $2 \le N_{\mathrm{trk}}^{\mathrm{offline}} < 35$ range for the γp-enhanced sample is $\approx$2.9 and about 16.6 for the MB sample. The $N_{\mathrm{trk}}^{\mathrm{offline}}$ distribution from the zero bias data control sample has $\langle N_{\mathrm{trk}}^{\mathrm{offline}}\rangle \approx 0.84$. The γp-simulated sample shows a shape and range that is consistent with the γp-enhanced data sample. Three $N_{\mathrm{trk}}^{\mathrm{offline}}$ bins are used to analyze the γp-enhanced events: $2 \le N_{\mathrm{trk}}^{\mathrm{offline}} < 5$, $5 \le N_{\mathrm{trk}}^{\mathrm{offline}} < 10$, $10 \le N_{\mathrm{trk}}^{\mathrm{offline}} < 35$. The first two deliver a comparable number of particle pairs and the third one aims to probe the higher $N_{\mathrm{trk}}^{\mathrm{offline}}$ domain by averaging the last part of the distribution. Table 1 indicates the $\langle N_{\mathrm{trk}}^{\mathrm{offline}}\rangle$ values for the data and simulated γp and MB samples. The mean p_{T}, $\langle p_{\mathrm{T}}\rangle$, 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 $0.3 < p_{\mathrm{T}} < 3.0$ 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 $p_{\mathrm{T}}^{\mathrm{trig}}$, is within a particular given range. The number of trigger particles in the event is denoted by N_{trig}. Particle pairs are then formed by associating each trigger particle with the remaining tracks whose $p_{\mathrm{T}}$is denoted as $p_{\mathrm{T}}^{\mathrm{assoc}}$. In this analysis $p_{\mathrm{T}}^{\mathrm{trig}}$ and $p_{\mathrm{T}}^{\mathrm{assoc}}$ 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

$$\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2N^{\mathrm{pair}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\phi} = B(0,0)\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}, \tag{1}$$

where $\Delta\eta$ and $\Delta\phi$ are the differences in η and ϕ of the pair and N^{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 ($\Delta\eta$, $\Delta\phi$) bin. Entries have been weighted by the product of inverse efficiencies evaluated for the kinematics of the two particles. The mixed-event pair distribution $B(\Delta\phi,\Delta\eta)$ 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 $2 \le N_{\mathrm{trk}}^{\mathrm{offline}} < 35$ as functions of $\Delta\eta$ and $\Delta\phi$. This $N_{\mathrm{trk}}^{\mathrm{offline}}$ range integrates all the yields all statistics for γp events, significantly suppressing fluctuations seen in smaller bins. For the γp distribution, the $\Delta\eta$ range is limited to $|\Delta\eta| < 2.5$ by the $\Delta\eta^F$ selection and the acceptance of the tracker. Both distributions show a large jet peak centered at $\Delta\eta = \Delta\phi = 0$, as well as a broader distribution from the recoiling jet centered at $\Delta\eta = 0$ and $\Delta\phi = \pi$. Neither distribution displays a "ridge"-like structure at $|\Delta\phi| \approx 0$ for $|\Delta\eta| > 2$. Fig. 2 (right) shows the projections of the two-dimensional correlation functions onto the $\Delta\phi$ axis for $|\Delta\eta| > 2$, away from the jet fragmentation peak. These distributions are fitted over the $\Delta\phi$ range $[0,\pi]$ to a Fourier decomposition series $\propto 1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)$, from where the measured $V_{n\Delta}$ 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^{sub}), 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 $V_{n\Delta}$ coefficients. The following effects were considered:

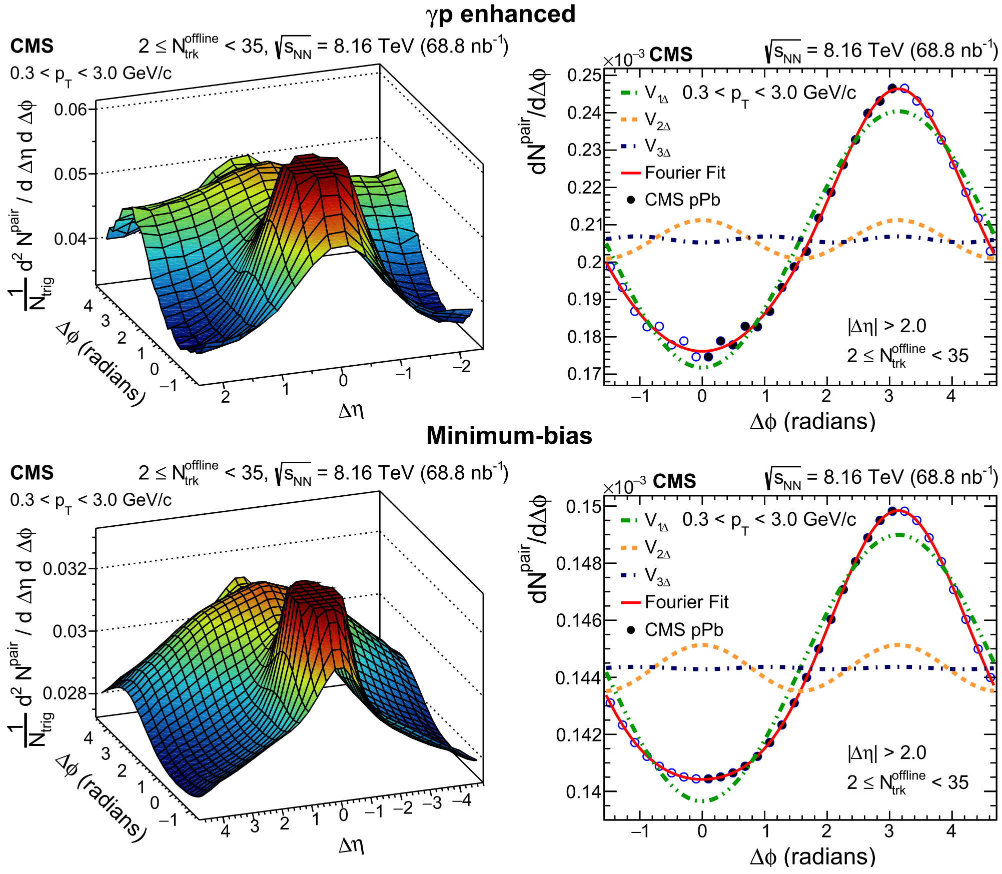

Fig. 2. Two-dimensional (left) and one-dimensional (right) correlation plots for γp-enhanced (upper) and MB (lower) events for $0.3 < p_T < 3.0$ GeV/c and $2 \leq N_{trk}^{offline} < 35$. For the two-dimensional distributions, the jet peak centered at $\Delta\eta = \Delta\phi = 0$ is truncated to increase 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 π. The Fourier coefficients, $V_{n\Delta}$ in the right column are fit over the $\Delta\phi$ range $[0, \pi]$. 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.

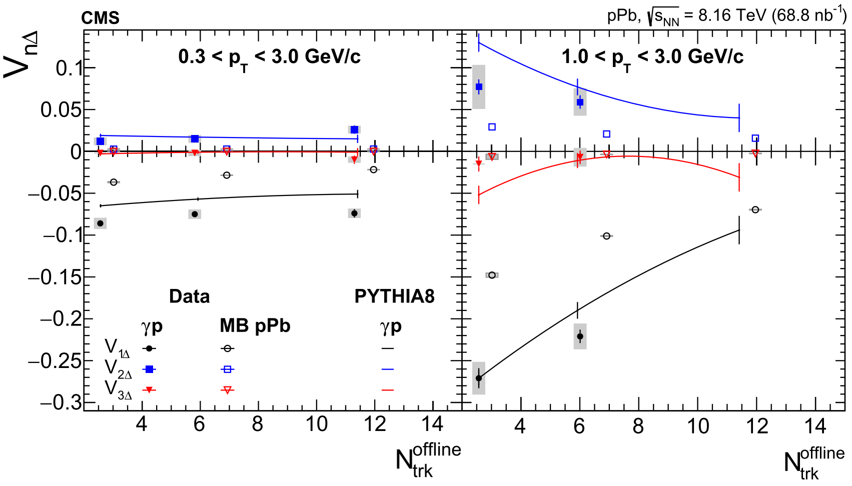

Fig. 3. Dependence of $V_{n\Delta}$ on $N_{trk}^{offline}$ for γp and MB events for two different $p_T$ranges. Systematic uncertainties are shown by the shaded bars in the two panels. The $2 \leq N_{trk}^{offline} < 5$, $5 \leq N_{trk}^{offline} < 10$, $10 \leq N_{trk}^{offline} < 35$ are used for the lower p_T range and $2 \leq N_{trk}^{offline} < 5$ and $5 \leq N_{trk}^{offline} < 35$ for the higher range. The points are placed at the mean value of the corresponding $N_{trk}^{offline}$ range. Lines indicate the prediction for γp events from PYTHIA8.

1. The systematic uncertainties associated with the choice of the $\Delta\eta^F$ range, which has a resolution of 0.5 units in η and ensures low detector activity on one half of the detector, were estimated by repeating the analysis with $\Delta\eta^F \in [4.5, 5.0)$, 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 $V_{1\Delta}$ and 27% for $V_{2\Delta}$ within the $N_{trk}^{offline}$ 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.

Table 2
The $V_{n\Delta}$ coefficients for γp-enhanced events, as functions of $p_\mathrm{T}$and $N_\mathrm{trk}^\mathrm{offline}$. Statistical and systematic uncertainties are added in quadrature.

$p_\mathrm{T}$range		$2 \le N_\mathrm{trk}^\mathrm{offline} < 5$	$5 \le N_\mathrm{trk}^\mathrm{offline} < 10$	$10 \le N_\mathrm{trk}^\mathrm{offline} < 35$
$0.3 < p_\mathrm{T} < 3.0\,\mathrm{GeV}/c$	$V_{1\Delta}$	-0.086 ± 0.006	-0.075 ± 0.005	-0.074 ± 0.007
	$V_{2\Delta}$	0.012 ± 0.004	0.015 ± 0.004	0.026 ± 0.006
	$V_{3\Delta}$	-0.002 ± 0.001	-0.002 ± 0.004	-0.010 ± 0.006
		$2 \le N_\mathrm{trk}^\mathrm{offline} < 5$	$5 \le N_\mathrm{trk}^\mathrm{offline} < 35$	
$1.0 < p_\mathrm{T} < 3.0\,\mathrm{GeV}/c$	$V_{1\Delta}$	-0.271 ± 0.021	-0.221 ± 0.017	
	$V_{2\Delta}$	0.077 ± 0.027	0.059 ± 0.017	
	$V_{3\Delta}$	-0.015 ± 0.009	-0.007 ± 0.013	

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 $p_\mathrm{T}$uncertainty is varied from 0.05 to 0.10. This translates into a 3.5% uncertainty in $V_{1\Delta}$ for the $2 \le N_\mathrm{trk}^\mathrm{offline} < 5$ category.
3. The sensitivity of the results to the primary vertex position along the beam axis (z_vtx) was quantified by comparing events with different z_vtx locations from -15 to $+15\,\mathrm{cm}$. The magnitude of this systematic effect goes up to 150% for $V_{3\Delta}$ with numerical estimations of ± 0.003 for $5 \le N_\mathrm{trk}^\mathrm{offline} < 10$ and $10 \le N_\mathrm{trk}^\mathrm{offline} < 35$ respectively, in the $0.3 < p_\mathrm{T} < 3.0\,\mathrm{GeV}/c$ category, and up to ± 0.013 for $1.0 < p_\mathrm{T} < 3.0\,\mathrm{GeV}/c$.
4. The trigger efficiency depends upon $N_\mathrm{trk}^\mathrm{offline}$. It decreases substantially for $N_\mathrm{trk}^\mathrm{offline} < 10$, reaching 70% for $N_\mathrm{trk}^\mathrm{offline} = 2$. To study this effect, a parallel data sample with weighted events as $(1/\varepsilon_\mathrm{trig})$ was produced. The full difference of the $V_{n\Delta}$ 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 $2 \le N_\mathrm{trk}^\mathrm{offline} < 5$.

The systematic uncertainties were added in quadrature. For the γp-enhanced sample with $N_\mathrm{trk}^\mathrm{offline} < 35$ 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 $2 \le N_\mathrm{trk}^\mathrm{offline} < 5$ and smaller than 2.6% for the rest of the $N_\mathrm{trk}^\mathrm{offline}$ range. Since $p_\mathrm{T}^\mathrm{trig}$ and $p_\mathrm{T}^\mathrm{assoc}$ 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 $N_\mathrm{trk}^\mathrm{offline}$ for the two different p_T ranges for the γp and MB pPb samples. For the MB sample, the results are consistent with those in [57] before the subtraction procedure. Both the γp and MB 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 $N_\mathrm{trk}^\mathrm{offline}$ and $p_\mathrm{T}$range, both $V_{1\Delta}$ and $V_{2\Delta}$ are larger in the γp samples than in the MB results. For both samples, the magnitude of $V_{1\Delta}$ tends to decrease with $N_\mathrm{trk}^\mathrm{offline}$, while $V_{2\Delta}$ has at most a weak $N_\mathrm{trk}^\mathrm{offline}$ dependence. Their magnitudes are both larger in the higher $p_\mathrm{T}$range.

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

Fig. 4 shows v_2 as a function of $N_\mathrm{trk}^\mathrm{offline}$ and $p_\mathrm{T}$for both γp and MB data sets. For $0.3 < p_\mathrm{T} < 3.0\,\mathrm{GeV}/c$, the MB results are consistent with previously published CMS results [57]. Predictions from the PYTHIA8 and HIJING generators are also shown for γp 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 γp and pPb samples. At a given $N_\mathrm{trk}^\mathrm{offline}$, v_2 is larger in the higher $p_\mathrm{T}$range. This is similar to trends observed in ep collisions [50,51]. The increase of v_2 with $p_\mathrm{T}$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 $p_\mathrm{T}$and $N_\mathrm{trk}^\mathrm{offline}$, v_2 is higher for γp 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 (γp) interactions. This study used proton-lead (pPb) collisions at $\sqrt{s_\mathrm{NN}} = 8.16\,\mathrm{TeV}$ recorded with the CMS detector. The two-particle $V_{n\Delta}$ Fourier coefficients and corresponding single-particle v_2 azimuthal anisotropies are reported as functions of the multiplicity of charged hadrons ($N_\mathrm{trk}^\mathrm{offline}$) for two transverse momenta (p_T) ranges. For the γp sample, the largest observed multiplicity was $N_\mathrm{trk}^\mathrm{offline} \sim 35$. The mean $p_\mathrm{T}$of charged particles is smaller in the γp 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 γp or hadronic minimum bias pPb (MB) samples within this multiplicity range. In all $N_\mathrm{trk}^\mathrm{offline}$ and $p_\mathrm{T}$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 $p_\mathrm{T}$and track multiplicity, v_2 is larger for γp-enhanced events than for MB pPb interactions. Predictions from the PYTHIA8 model describe well the γp 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.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the

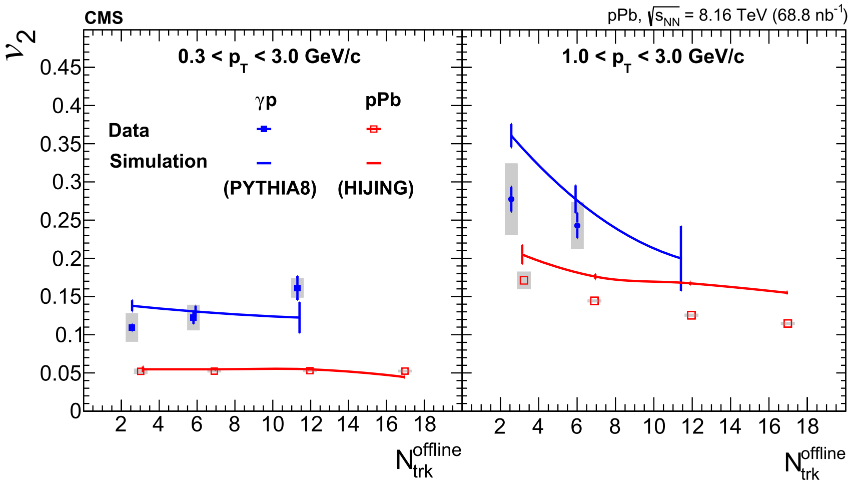

Fig. 4. Single-particle azimuthal anisotropy v_2 versus $N_{\text{trk}}^{\text{offline}}$ for γp-enhanced and pPb samples in two p_{T}regions. Systematic uncertainties are shown by the shaded bars in the two panels. Predictions from the PYTHIA8 and HIJING generators are shown for the γp and MB pPb samples respectively. For the γp events, same $N_{\text{trk}}^{\text{offline}}$ bin arrangement as in Fig. 3 is kept while for pPb the bins [2, 5), [5, 10), [10, 15) and [15, 20) are used.

technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MOST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MoSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; The Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B05F650021 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

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