Pseudorapidity dependence of long-range two-particle correlations in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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Two-particle correlations in pPb collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV are studied as a function of the pseudorapidity separation ($\Delta\eta$) of the particle pair at small relative azimuthal angle ($|\Delta\phi| < \pi/3$). The correlations are decomposed into a jet component that dominates the short-range correlations ($|\Delta\eta| < 1$), and a component that persists at large $\Delta\eta$ and may originate from collective behavior of the produced system. The events are classified in terms of the multiplicity of the produced particles. Finite azimuthal anisotropies are observed in high-multiplicity events. The second and third Fourier components of the particle-pair azimuthal correlations, V_2 and V_3, are extracted after subtraction of the jet component. The single-particle anisotropy parameters v_2 and v_3 are normalized by their laboratory frame midrapidity value and are studied as a function of $\eta_{\mathrm{c.m.}}$. The normalized v_2 distribution is found to be asymmetric about $\eta_{\mathrm{c.m.}} = 0$, with smaller values observed at forward pseudorapidity, corresponding to the direction of the proton beam, while no significant pseudorapidity dependence is observed for the normalized v_3 distribution within the statistical uncertainties.

I. INTRODUCTION

Studies of two-particle correlations play an important role in understanding the underlying mechanism of particle production in high-energy nuclear collisions [1–3]. Typically, these correlations are studied in a two-dimensional $\Delta\phi$-$\Delta\eta$ space, where $\Delta\phi$ and $\Delta\eta$ are the differences in the azimuthal angle ϕ and the pseudorapidity η of the two particles.

A notable feature in the two-particle correlations is the so-called "ridge," which is an extended correlation structure in relative pseudorapidity $\Delta\eta$ concentrated at small relative azimuthal angle $|\Delta\phi| \approx 0$. The ridge, first observed in nucleus-nucleus (AA) collisions [4–6], has been studied both at the BNL Relativistic Heavy Ion Collider (RHIC) and CERN Large Hadron Collider (LHC) over a wide range of collision energies and system sizes [4–15]. In AA collisions, such long-range two-particle correlations have been associated with the development of collective hydrodynamic flow, which transfers the azimuthal anisotropy in the initial energy density distribution to the final state momentum anisotropy through strong rescatterings in the medium produced in such collisions [16–20]. A recent study suggests that anisotropic escape probabilities may already produce large final-state anisotropies without the need for significant rescattering [21]. Another possible mechanism proposed to account for the initial-state correlations is the color glass condensate (CGC), where the two-gluon density is enhanced at small $\Delta\phi$ over a wide $\Delta\eta$ range [22,23]. However, to reproduce the magnitude of the ridge in AA collisions, the CGC-based models also require

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a late-stage collective flow boost to produce the observed stronger angular collimation effect [24,25]. As a purely initial-state effect, the CGC correlations are expected to be independent of the formation of a thermally equilibrated quark-gluon plasma, while the collective hydrodynamic flow requires a medium that is locally thermalized. The latter condition might not be achieved in small systems.

Measurements at the LHC led to the discovery of a long-range ridge structure in small systems. The ridge has been observed in high-multiplicity proton-proton (pp) [9,26,27] and proton-lead (pPb) collisions [10–12,28]. A similar long-range structure was also found in the most central deuteron-gold (dAu) and ^{3}He-gold collisions at RHIC [13–15]. To investigate whether collective flow is responsible for the ridge in pPb collisions, multiparticle correlations were studied at the LHC [29–31] in events with different multiplicities. The second harmonic anisotropy parameter, v_2, of the particle azimuthal distributions measured using four-, six-, eight-, or all-particle correlations were found to have the same value [31], as expected in a system with global collective flow [32]. In addition, the v_2 parameters of identified hadrons were measured as a function of transverse momentum (p_T) in pPb [33,34] and in dAu collisions [13]. The $v_2(p_T)$ distributions were found to be ordered by the particle mass, i.e., the distributions for the heavier particles are boosted to higher p_T, as expected from hydrodynamics, where the particles move with a common flow velocity. The similarities between the correlations observed in the small systems and in heavy ion collisions suggest a common hydrodynamic origin [29,35,36]. However it is still under investigation whether hydrodynamics can be applied reliably to pp or pA systems.

As predicted by hydrodynamics and CGC [37,38], as well as phenomenological models like EPOS [39], the average transverse momentum, $\langle p_T \rangle$, of the produced particles should depend on pseudorapidity. This pseudorapidity dependence of $\langle p_T \rangle$ could translate into a pseudorapidity dependence of the long-range correlations which also depend on p_T [40]. While

hydrodynamics predicts that the pseudorapidity dependence of $\langle p_T \rangle$ follows that of the charged particle pseudorapidity density $dN/d\eta$ which increases at negative pseudorapidity, in the CGC both a rising or a falling trend of $\langle p_T \rangle$ with pseudorapidity may be possible [38]. Thus, a measurement of the pseudorapidity dependence of the ridge may provide further insights into its origin. The pseudorapidity dependence of the Fourier coefficients extracted using the long-range two-particle correlations could also be influenced by event-by-event fluctuations of the initial energy density [41–43]. The pressure gradients that drive the hydrodynamic expansion may differ in different pseudorapidity regions, causing a pseudorapidity-dependent phase shift in the event-plane orientation determined from the direction of maximum particle emission. Evidence for such event-plane decorrelation has been found in pPb collisions [44]. Additional studies of the pseudorapidity dependence of the ridge may contribute to elucidating the longitudinal dynamics of the produced system.

The two-particle correlation measurement is performed using "trigger" and "associated" particles as described in Ref. [45]. The trigger particles are defined as charged particles detected within a given p_T^{trig} range. The particle pairs are formed by associating each trigger particle with the remaining charged particles from a certain p_T^{assoc} range. Typically, both particles are selected from a wide identical range of pseudorapidity, and therefore by construction the $\Delta\eta$ distribution is symmetric about $\Delta\eta = 0$ [29]. Any $\Delta\eta$ dependence in the ridge correlation signal would be averaged out by the integration over the trigger and associated particle pseudorapidity distributions [46]. To gain further insights about the long-range ridge correlation in the pPb system, in this paper we perform a $\Delta\eta$-dependent analysis by restricting the trigger particle to a narrow pseudorapidity range. With this method, the combinatorial background resembles the single-particle density. Therefore, the correlation function in pPb collisions is nonuniform in $\Delta\eta$.

The ridge correlation is often characterized by the Fourier coefficients V_n. The V_n values are determined from a Fourier decomposition of long-range two-particle $\Delta\phi$ correlation functions given by

$$\frac{1}{N_{\mathrm{trig}}}\frac{dN^{\mathrm{pair}}}{d\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi}\left[1 + \sum_n 2V_n \cos(n\Delta\phi)\right] \quad (1)$$

as described in Refs. [8,45], where N^{pair} is the total number of correlated hadron pairs. N_{assoc} represents the total number of associated particles per trigger particle for a given (p_T^{trig}, p_T^{assoc}) bin.

To remove short-range correlations from jets and other sources, a pseudorapidity separation may be applied between the trigger and associated particle; alternatively, the correlations in low multiplicity events may be measured and subtracted from those in high multiplicity events after appropriate scaling, to remove the short-range correlations, which are likely to have similar $\Delta\eta$-$\Delta\phi$ shapes in high- and low-multiplicity collisions. Both methods are used in this analysis.

The single-particle anisotropy parameters v_n are extracted from the particle-pair Fourier coefficients V_n, assuming that

they factorize [47]. The v_n values are then normalized by their laboratory frame midrapidity values and are studied as a function of $\eta_{\mathrm{c.m.}}$. These distributions are compared to the normalized pseudorapidity distributions of the mean transverse momentum.

II. CMS DETECTOR

A 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. [48]. The main results in this paper are based on data from the silicon tracker. This detector consists of 1440 silicon pixel and 15 148 silicon strip detector modules, and is located in the 3.8 T magnetic field of the superconducting solenoid. It measures the trajectories of the charged particles emitted within the pseudorapidity range $|\eta_{\mathrm{lab}}| < 2.5$, and provides an impact parameter resolution of $\sim 15\,\mu$m and a transverse momentum resolution of about 1% for particles with $p_T = 2$ GeV/c, and 1.5% for particles at $p_T = 100$ GeV/c.

The electromagnetic calorimeter (ECAL) and the hadron calorimeter (HCAL) are also located inside the solenoid. The ECAL consists of 75 848 lead-tungstate crystals, arranged in a quasiprojective geometry and distributed in a barrel region ($|\eta_{\mathrm{lab}}| < 1.48$) and two endcaps that extend up to $|\eta_{\mathrm{lab}}| = 3.0$. The HCAL barrel and endcaps are sampling calorimeters composed of brass and scintillator plates, covering $|\eta_{\mathrm{lab}}| < 3.0$. Iron/quartz fiber Cherenkov hadron forward (HF) calorimeters cover the range $2.9 < |\eta_{\mathrm{lab}}| < 5.2$ on either side of the interaction region. The detailed MC simulation of the CMS detector response is based on GEANT4 [49].

III. DATA SAMPLES AND EVENT SELECTION

The data used are from pPb collisions recorded by the CMS detector in 2013, corresponding to an integrated luminosity of about 35 nb^{-1} [50]. The beam energies were 4 TeV for protons and 1.58 TeV per nucleon for lead nuclei, resulting in a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV. The direction of the higher-energy proton beam was initially set up to be clockwise, and then reversed. Massless particles emitted at $\eta_{\mathrm{c.m.}} = 0$ were detected at $\eta_{\mathrm{lab}} = -0.465$ (clockwise proton beam) or at $\eta_{\mathrm{lab}} = 0.465$ (counterclockwise proton beam) in the laboratory frame. Both datasets were used in this paper. The data in which the proton beam traveled clockwise were reflected about $\eta_{\mathrm{lab}} = 0$ and combined with the rest of the data, so that the proton beam direction is always associated with the positive η_{lab} direction.

The online triggering, and the offline reconstruction and selection follow the same procedure as described in Ref. [29]. Minimum-bias events were selected by requiring that at least one track with $p_T > 0.4$ GeV/c was found in the pixel tracker for a pPb bunch crossing. Because of hardware limits on the data acquisition rate, only a small fraction (10^{-3}) of all minimum bias triggered events were recorded (i.e., the trigger was "prescaled"). The high-multiplicity triggers were implemented using the level-1 (L1) trigger and high level trigger (HLT) to enhance high multiplicity events that are of interest for the particle correlation studies. At L1, two

event streams were triggered by requiring the total transverse energy summed over ECAL and HCAL to be greater than 20 or 40 GeV/c. Charged tracks were then reconstructed online at the HLT using the three layers of pixel detectors, and requiring a track origin within a cylindrical region of 30 cm length along the beam and 0.2 cm radius perpendicular to the beam [51].

In the offline analysis, hadronic collisions were selected by requiring at least 3 GeV/c of total energy in at least one HF calorimeter tower on each side of the interaction region (positive and negative η_{lab}). Events were also required to contain at least one reconstructed primary vertex within 15 cm of the nominal interaction point along the beam axis (z_{vtx}) and within 0.15 cm distance transverse to the beam trajectory.

The pPb instantaneous luminosity provided by the LHC in the 2013 pPb run resulted in approximately a 3% probability that at least one additional interaction occurs in the same bunch crossing, i.e., pileup events. A pileup rejection procedure [29] was applied to select clean, single-vertex pPb events. The residual fraction of pileup events was estimated to be no more than 0.2% for the highest multiplicity pPb interactions studied in this paper [29]. Based on simulations using the HIJING [52] and the EPOS [53] event generators, these event selections have an acceptance of 94–97% for pPb interactions that have at least one primary particle with $E > 3$ GeV in both η_{lab} ranges of $-5 < \eta_{\text{lab}} < -3$ and $3 < \eta_{\text{lab}} < 5$. The charged-particle information was recorded in the silicon tracker and the tracks were reconstructed within the pseudorapidity range $|\eta_{\text{lab}}| < 2.5$.

A reconstructed track was considered as a primary track candidate if the impact parameter significance $d_{xy}/\sigma(d_{xy})$ and the significance of z separation between the track and the best reconstructed primary vertex (the one associated with the largest number of tracks, or best χ^2 probability if the same number of tracks was found) $d_z/\sigma(d_z)$ are both less than 3. In order to remove tracks with poor momentum estimates, the relative uncertainty in the momentum measurement $\sigma(p_{\text{T}})/p_{\text{T}}$ was required to be less than 10%. To ensure high tracking efficiency and to reduce the rate of misreconstructed tracks, primary tracks with $|\eta_{\text{lab}}| < 2.4$ and $p_{\text{T}} > 0.3$ GeV/c were used in the analysis.

The events are classified by $N_{\text{trk}}^{\text{offline}}$, the measured number of primary tracks within $|\eta_{\text{lab}}| < 2.4$ and $p_{\text{T}} > 0.4$ GeV/c (a p_{T} cutoff of 0.4 GeV/c was used in the multiplicity determination to match the HLT requirement), in a method similar to the approach used in Refs. [9,10]. The high- and low-multiplicity events in this paper are defined by $220 \leqslant N_{\text{trk}}^{\text{offline}} < 260$ and $2 \leqslant N_{\text{trk}}^{\text{offline}} < 20$, respectively. The high-multiplicity selection corresponds to an event fraction of 3.4×10^{-6} of the events. Data from the minimum bias trigger are used for low-multiplicity event selection, while the high-multiplicity triggers with online multiplicity thresholds of 100, 130, 160, and 190 are used for high multiplicity events [29].

IV. ANALYSIS PROCEDURE

The dihadron correlation is quantified by azimuthal angle ϕ and pseudorapidity differences between the two particles:

$$\Delta\phi = \phi_{\text{assoc}} - \phi_{\text{trig}}, \quad \Delta\eta = \eta_{\text{lab}}^{\text{assoc}} - \eta_{\text{lab}}^{\text{trig}},$$

where ϕ_{assoc} and $\eta_{\text{lab}}^{\text{assoc}}$ are the associated particle coordinates and ϕ_{trig} and $\eta_{\text{lab}}^{\text{trig}}$ are the trigger particle coordinates, both measured in the laboratory frame. The per-trigger normalized associated particle yield is defined by

$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{\text{trig}}} \frac{d^2N}{d\Delta\eta \, d\Delta\phi}.$$

Unlike in previous studies [4–6,9–12], the trigger particles in this analysis are restricted to two narrow η_{lab} windows: $-2.4 < \eta_{\text{lab}}^{\text{trig}} < -2.0$ (Pb side) and $2.0 < \eta_{\text{lab}}^{\text{trig}} < 2.4$ (p side). The associated particles are from the entire measured η_{lab} range of $-2.4 < \eta_{\text{lab}}^{\text{assoc}} < 2.4$.

The associated particles are weighted by the inverse of the efficiency factor, $\varepsilon_{\text{trk}}(\eta_{\text{lab}}, p_{\text{T}})$, as a function of the track's pseudorapidity and p_{T} [45]. The efficiency factor accounts for the detector acceptance $A(\eta_{\text{lab}}, p_{\text{T}})$, the reconstruction efficiency $E(\eta_{\text{lab}}, p_{\text{T}})$, and the fraction of misidentified tracks, $F(\eta_{\text{lab}}, p_{\text{T}})$,

$$\varepsilon_{\text{trk}}(\eta_{\text{lab}}, p_{\text{T}}) = \frac{AE}{1 - F}.$$

The corresponding correction function is obtained from a PYTHIA6 (tune Z2) [54] plus GEANT4 [49] simulation.

A. Quantifying the jet contributions

Figure 1 shows the two-dimensional (2D) correlated yield for the two trigger particle pseudorapidity windows in low and high multiplicity events. The same p_{T} range of $0.3 < p_{\text{T}} < 3.0$ GeV/c is used for trigger and associated particles. The peak at (0,0) is the near-side jet-like structure. In the high multiplicity events, one can notice a ridge-like structure in $|\Delta\eta|$ at $\Delta\phi = 0$ atop the high combinatorial background. A similar extensive structure can also be seen on the away side $\Delta\phi = \pi$, which contains the away-side jet. Unlike correlation functions from previous studies, the correlated yield is asymmetric in $\Delta\eta$; it reflects the asymmetric single particle $dN/d\eta$ distribution in the pPb system.

The $\Delta\phi$ distribution of the associated yield is projected within each $\Delta\eta$ bin (with a bin width of 0.2). Before quantifying jet contributions, the zero-yield-at-minimum (ZYAM) technique [55] is used to subtract a uniform background in $\Delta\phi$. To obtain the ZYAM background normalization, the associated yield distribution is first projected into the range of $0 < \Delta\phi < \pi$, and then scanned to find the minimum yield within a $\Delta\phi$ window of $\pi/12$ radians. This minimum yield is treated as the ZYAM background. The ZYAM background shape as a function of $\Delta\eta$ is similar to the shape of the single particle density.

After ZYAM subtraction, the signal will be zero at the minimum. For example, the $\Delta\phi$ distributions in high- and low-multiplicity collisions are depicted in Fig. 2 for two, short-($0 < |\Delta\eta| < 0.2$) and long-range ($2.8 < |\Delta\eta| < 3.0$), $\Delta\eta$ bins. They are composed of two characteristic peaks: one at $\Delta\phi = 0$ (near-side) and the other at $\Delta\phi = \pi$ (away-side), with a minimum valley between the two peaks. For low-multiplicity collisions at large $\Delta\eta$, no near-side peak is observed.

First, the $\Delta\eta$ dependence of the correlated yield is analyzed. In each $\Delta\eta$ bin, the correlated yield is averaged within the near
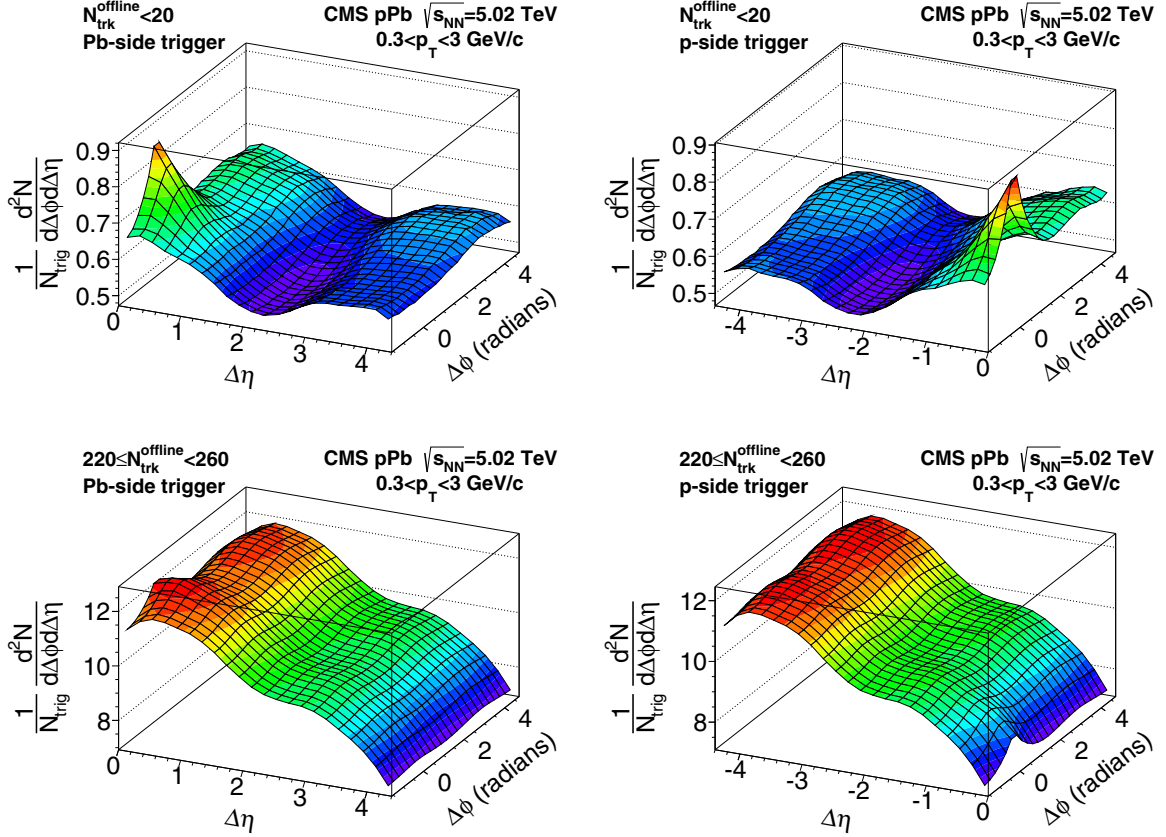
FIG. 1. Efficiency-corrected 2D associated yields with Pb-side trigger particle ($-2.4 < \eta_{\mathrm{lab}}^{\mathrm{trig}} < -2.0$, left panels) and p-side trigger particle ($2.0 < \eta_{\mathrm{lab}}^{\mathrm{trig}} < 2.4$, right panels) in low-multiplicity ($2 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 20$, upper panels) and high-multiplicity ($220 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 260$, lower panels) are shown for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The associated and trigger particle p_{T} ranges are both $0.3 < p_{\mathrm{T}} < 3$ GeV/c.

side ($|\Delta\phi| < \pi/3$. The correlated yield reaches a minimum at around $\pi/3$). The near-side averaged correlated yield per radian, $(1/N_{\mathrm{trig}})(dN)/(d\Delta\eta)$, is shown as a function of $\Delta\eta$ in Fig. 3. In low-multiplicity collisions, the near-side $\Delta\eta$ correlated yield is consistent with zero at large $\Delta\eta$. This indicates that the near side in low-multiplicity pPb collisions is composed of only a jet component after ZYAM subtraction. In high-multiplicity collisions, an excess of the near-side correlated yield is seen at large $\Delta\eta$ and it is due to the previously observed ridge [10].

In order to quantify the near-side jet contribution, the near-side correlation function is fitted with a two-component functional form:

$$\frac{1}{N_{\mathrm{trig}}} \frac{dN_{\mathrm{near}}(\Delta\eta)}{d\Delta\eta} = \frac{Y\beta}{\sqrt{2}\sigma\,\Gamma(1/2\beta)} \exp\left[-\left(\frac{\Delta\eta^2}{2\sigma^2}\right)^{\beta}\right]$$
$$+ (C + k\Delta\eta)\mathrm{ZYAM}(\Delta\eta). \quad (2)$$

The first term represents the near-side jet; Y is the correlated yield, and σ and β describe the correlation shape. Neither a simple Gaussian nor an exponential function describes the jet-like peak adequately. However, a generalized Gaussian form as in Eq. (2) is found to describe the data well. The second term on the right-hand side of Eq. (2) represents the ridge structure. Since the ridge is wide in $\Delta\eta$ and may be related to the bulk medium, its shape is modeled as dominated by

the underlying event magnitude, ZYAM($\Delta\eta$). However, the background shape multiplied by a constant is not adequate to describe the ridge in high multiplicity events. Instead, the background shape multiplied by a linear function in $\Delta\eta$, as in Eq. (2), can fit the data well, with reasonable χ^2/ndf (where ndf is the number of degree of freedom) (see Table I). Here C quantifies the overall strength of the ridge yield relative to the underlying event, and k indicates the $\Delta\eta$ dependence of the ridge in addition to that of the underlying event.

The fits using Eq. (2) are superimposed in Fig. 3 and the fit parameters are shown in Table I. For low-multiplicity collisions, the k parameter is consistent with zero and, in the fit shown, it is set to zero. For high-multiplicity collisions, the C parameter is positive, reflecting the finite ridge correlation, and the k parameter is nonzero, indicating that the ridge does not have the same $\Delta\eta$ shape as the underlying event. As already shown in Fig. 3, the ridge (correlated yield at large $\Delta\eta$) is not constant but $\Delta\eta$ dependent.

The fitted Y parameter shows that the jet-like correlated yield in high-multiplicity collisions ($Y_{220 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 260}$) is larger than that in low-multiplicity collisions ($Y_{N_{\mathrm{trk}}^{\mathrm{offline}} < 20}$). The ratio is

$$\alpha = Y_{220 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 260} / Y_{N_{\mathrm{trk}}^{\mathrm{offline}} < 20}$$
$$= \begin{cases} 3.08 \pm 0.11_{-0.31}^{+0.96} & \text{for Pb-side triggers;} \\ 3.13 \pm 0.09_{-0.28}^{+0.28} & \text{for } p\text{-side triggers,} \end{cases} \quad (3)$$
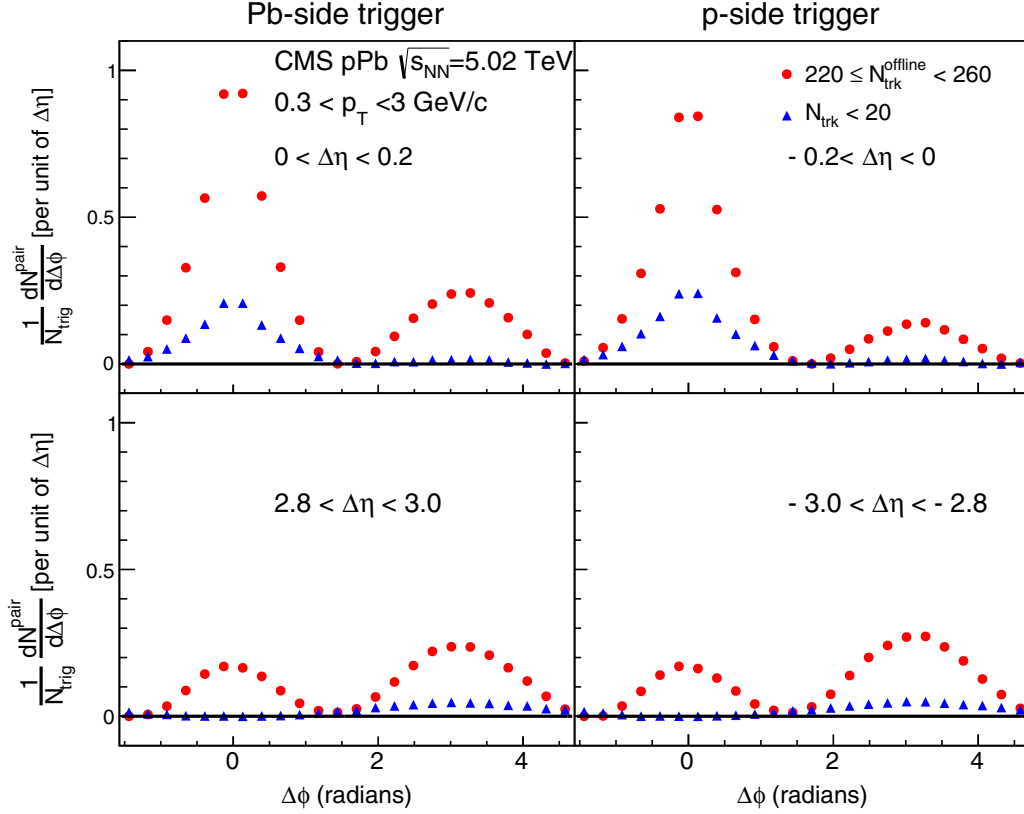
FIG. 2. Examples of the distribution of the associated yields after ZYAM subtraction for both low-multiplicity ($2 \leqslant N_{\text{trk}}^{\text{offline}} < 20$, blue triangles) and high-multiplicity ($220 \leqslant N_{\text{trk}}^{\text{offline}} < 260$, red circles) are shown for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results for Pb-side (left panels) and p-side (right panels) trigger particles are both shown; small $\Delta\eta$ in the upper panels and large $|\Delta\eta|$ in the lower panels. The trigger and associated particle p_{T} ranges are both $0.3 < p_{\text{T}} < 3$ GeV/c.

where the $\pm$ sign is followed by the statistical uncertainty from the fit. The upper "+" and lower "−" are followed by the systematic uncertainty, which is obtained by fitting different functional forms, such as Gaussian and exponential functions, and by varying the $\Delta\eta$ range to calculate the ZYAM value.

The α values are used as a scaling factor when correlations from low-multiplicity collisions are removed in determining the Fourier coefficients in high-multiplicity events.

B. Fourier coefficients

For each $\Delta\eta$ bin, the azimuthal anisotropy harmonics, V_n, can be calculated from the two-particle correlation $\Delta\phi$ distribution,

$$V_n = \langle \cos n\Delta\phi \rangle.$$

The $\langle\rangle$ denotes the averaging over all particles and all events. At large $\Delta\eta$, the near-side jet contribution is negligible, but the away-side jet still contributes. The jet contributions may be significantly reduced or eliminated by subtracting the low-multiplicity collision data, via a prescription described in Ref. [29],

$$V_n^{\text{sub}} = V_n^{\text{HM}} - V_n^{\text{LM}} \frac{N_{\text{assoc}}^{\text{LM}}}{N_{\text{assoc}}^{\text{HM}}} \alpha. \quad (4)$$

Here, LM and HM stand for low-multiplicity and high-multiplicity, respectively. $N_{\text{assoc}}^{\text{HM}}$ and $N_{\text{assoc}}^{\text{LM}}$ are the associated

particle multiplicities in a given pseudorapidity bin, and V_n^{HM} and V_n^{LM} are the Fourier coefficients in high- and low-multiplicity collisions, respectively. The α value is obtained from Eq. (3). This procedure to extract V_n is tested by studying the pPb collisions generated by the HIJING 1.383 model [52]. The basic HIJING model has no flow, so a flow-like signal is added [56] by superimposing an azimuthal modulation on the distributions of the produced particles. The measured V_2 using Eq. (4) is consistent with the input flow value within a relative 5% difference.

To quantify the anisotropy dependence as a function of η_{lab}, assuming factorization, $V_n(\eta_{\text{lab}}^{\text{trig}}, \eta_{\text{lab}}^{\text{assoc}}) = v_n(\eta_{\text{lab}}^{\text{trig}}) v_n(\eta_{\text{lab}}^{\text{assoc}})$, a self-normalized anisotropy is calculated from the Fourier coefficient V_n:

$$\frac{v_n(\eta_{\text{lab}}^{\text{assoc}})}{v_n(\eta_{\text{lab}}^{\text{assoc}} = 0)} = \frac{V_n(\eta_{\text{lab}}^{\text{assoc}})}{V_n(\eta_{\text{lab}}^{\text{assoc}} = 0)}. \quad (5)$$

Here, the $\eta_{\text{lab}}^{\text{assoc}}$ is directly calculated from $\Delta\eta$, assuming the trigger particle is at a fixed η_{lab} direction

$$\eta_{\text{lab}}^{\text{assoc}} = \Delta\eta + \eta_{\text{lab}}^{\text{trig}}, \quad (6)$$

in which $\eta_{\text{lab}}^{\text{trig}} = -2.2\,(2.2)$ for the Pb-side (p-side) trigger. Hereafter, we write only η_{lab}, eliminating the superscript 'assoc' from $\eta_{\text{lab}}^{\text{assoc}}$.

To avoid short-range correlations that remain even after the subtraction of the low-multiplicity events, only correlations
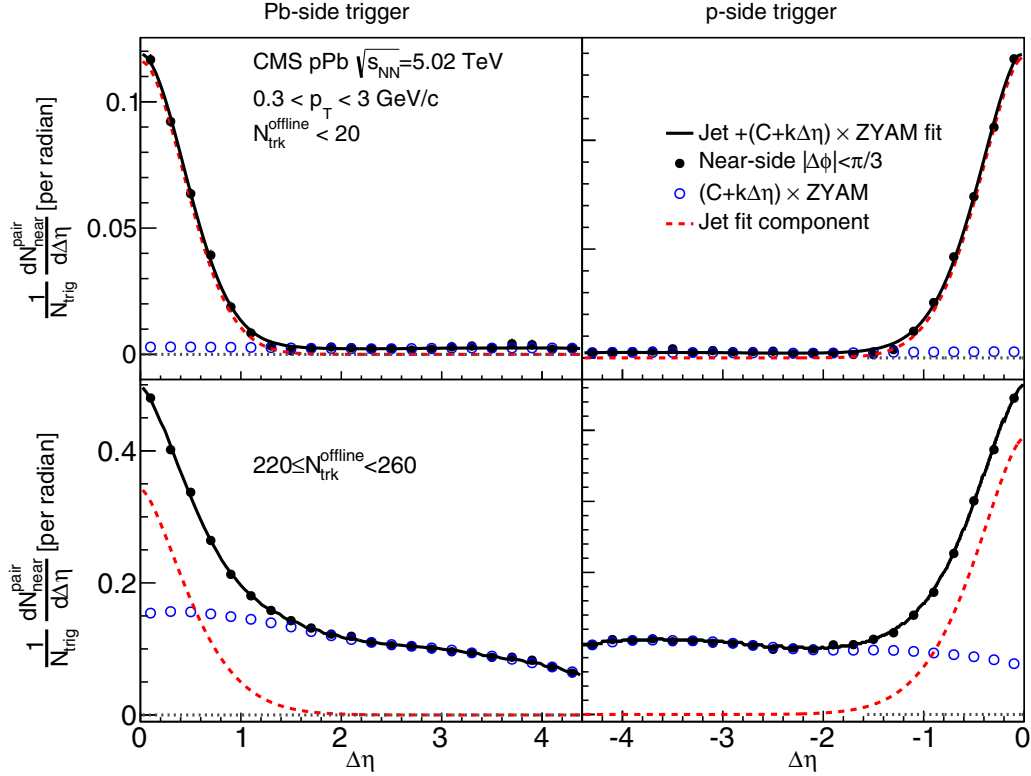
FIG. 3. The near-side ($|\Delta\phi| < \pi/3$) correlated yield after ZYAM subtraction in low-multiplicity $2 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 20$ (upper panels) and high-multiplicity $220 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 260$ (lower panels) are shown for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The trigger and associated particle p_T ranges are both $0.3 < p_T < 3$ GeV/c. The trigger particles are restricted to the Pb-side ($-2.4 < \eta_{\mathrm{lab}}^{\mathrm{trig}} < -2.0$, left panels) and the p-side ($2.0 < \eta_{\mathrm{lab}}^{\mathrm{trig}} < 2.4$, right panels), respectively. Fit results using Eq. (2) (black solid curves) are superimposed; the red dashed curve and the blue open points are the two fit components, jet and ridge, respectively.

with large $|\Delta\eta|$ are selected to construct the v_n pseudorapidity distributions.

V. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties in the Fourier coefficient V_n are estimated from the following sources: the track quality

TABLE I. Summary of fit parameters for low- and high-$N_{\mathrm{trk}}^{\mathrm{offline}}$ ranges in pPb collisions.

| Parameter | $N_{\mathrm{trk}}^{\mathrm{offline}} < 20$ | |
	Pb-side trigger	p-side trigger
Y	0.130 ± 0.003	0.156 ± 0.003
σ	0.445 ± 0.011	0.446 ± 0.010
β	0.943 ± 0.057	0.870 ± 0.043
C	0.0045 ± 0.0009	0.0045 ± 0.0010
k	0 (Fixed)	0 (Fixed)
χ^2/ndf	0.279	0.459
Parameter	$220 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 260$	
	Pb-side trigger	p-side trigger
Y	0.401 ± 0.011	0.489 ± 0.011
σ	0.457 ± 0.008	0.492 ± 0.007
β	0.757 ± 0.003	0.782 ± 0.025
C	0.0137 ± 0.0004	0.0098 ± 0.0004
k	-0.0011 ± 0.0001	0.0002 ± 0.0001
χ^2/ndf	1.074	0.463

requirements by comparing loose and tight selections; bias in the event selection from the HLT trigger, by using different high-multiplicity event selection criteria; pileup effect, by requiring a single vertex per event; and the event vertex position, by selecting events from different z-vertex ranges. In the low multiplicity V_n subtraction, the jet ratio parameter α is applied. The systematic uncertainties in α are assessed by using fit functions different from Eq. (2), as well as by varying the $\Delta\eta$ range when obtaining the ZYAM value. This systematic effect is included in the final uncertainties for the multiplicity-subtracted V_n. In addition, the effect of reversing the beam direction is studied. This is subject to the same systematic uncertainties already described above; thus it is not counted in the total systematic uncertainties, but is used as a crosscheck.

The estimated uncertainties from the above sources are shown in Table II. Combined together, they give a total uncertainty of 3.9% and 10% for V_2 and V_3 coefficients, respectively, as determined without the subtraction of signals from low-multiplicity events. For low-multiplicity-subtracted results, the systematic uncertainties rise to 5.8% and 15%, respectively.

The systematic uncertainties from the track-quality and jet-ratio selection are correlated among the pseudorapidity bins, so they cancel in the self-normalized anisotropy parameter, $v_n(\eta_{\mathrm{lab}})/v_n(\eta_{\mathrm{lab}} = 0)$. The systematic uncertainties in other sources are treated as completely independent of

TABLE II. Summary of systematic uncertainties in the second and third Fourier harmonics in pPb collisions. The label "low-mult sub" indicates the low-multiplicity subtracted results, while "no sub" indicates the results without subtraction.

	$220 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 260$			
Source	V_2 (no sub)	V_2 (low-mult sub)	V_3 (no sub)	V_3 (low-mult sub)
Track quality requirement	3.0%	3.0%	7.0%	11.0%
HLT trigger bias	2.0%	2.5%	2.0%	2.5%
Effect from pileups	1.5%	3.0%	3.5%	3.5%
Vertex dependence	0.5%	1.0%	6.0%	9.0%
Jet ratio	. . .	3.0%	. . .	3.0%
Total	3.9%	5.8%	10%	15%

pseudorapidity and are propagated in $v_n(\eta_{\mathrm{lab}})/v_n(\eta_{\mathrm{lab}} = 0)$. The estimated systematic uncertainties in $v_2(\eta_{\mathrm{lab}})/v_2(\eta_{\mathrm{lab}} = 0)$ and $v_3(\eta_{\mathrm{lab}})/v_3(\eta_{\mathrm{lab}} = 0)$ without low multiplicity subtraction are estimated to be 3.6% and 10%, respectively. For low-multiplicity-subtracted results, the systematic uncertainties rise to 5.7% and 14%, respectively.

VI. RESULTS

The V_2 and V_3 values in high-multiplicity collisions for Pb-side and p-side trigger particles are shown in Fig. 4. The strong peak is caused by near-side short-range jet contributions. The Fourier coefficients, V_2^{sub} and V_3^{sub}, after the low-multiplicity data are subtracted, are also shown. The short-range jet-like peak is largely reduced, but may not be completely eliminated due to different near-side jet-correlation shapes for high- and low-multiplicity collisions. The long-range results are not affected by the near-side jet, but the away-side jet may still contribute if its shape is different in high- and low-multiplicity collisions or if its magnitude does not scale according to α.

By self-normalization via Eq. (5), the Fourier coefficient from both trigger sides can be merged into a single distribution by combining the negative and positive η_{lab} range. The laboratory frame central value $\eta_{\mathrm{lab}} = 0$ is used so that the
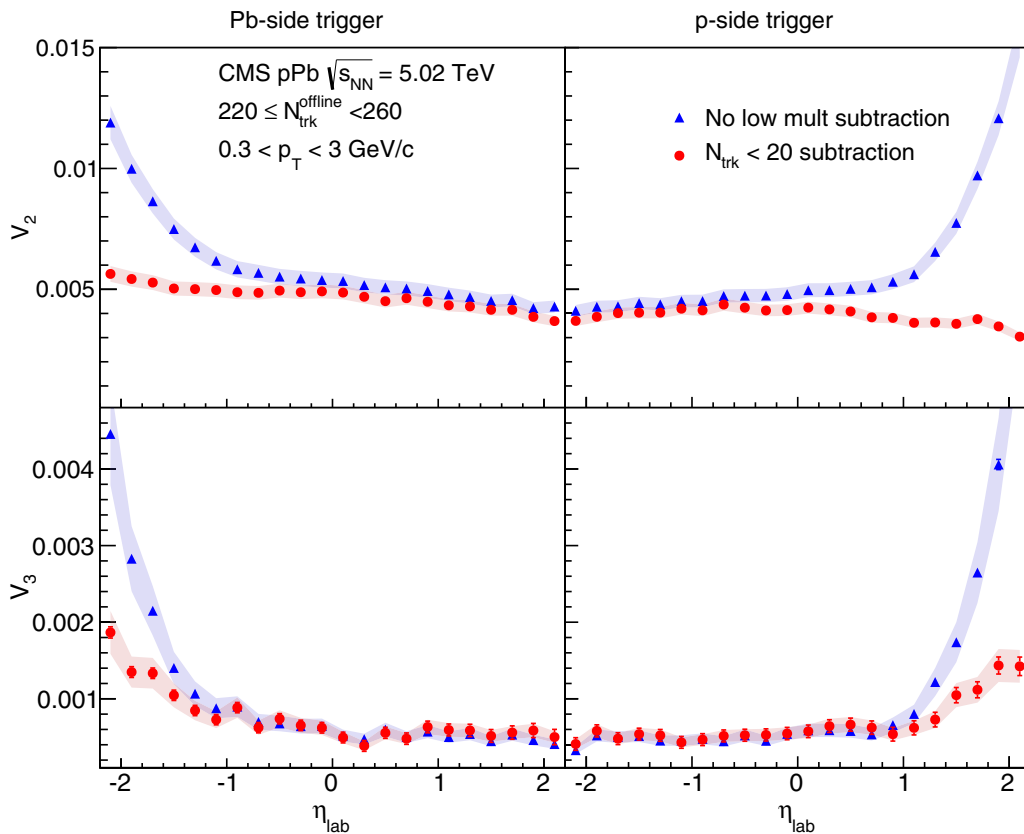

FIG. 4. Fourier coefficients, V_2 (upper) and V_3 (lower), of two-particle azimuthal correlations in high-multiplicity collisions ($220 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 260$) with (circles) and without (triangles) subtraction of low-multiplicity data, as a function of η_{lab}. Left panel shows data for Pb-side trigger particles and the right panel for the p side. Statistical uncertainties are mostly smaller than point size; systematic uncertainties are 3.9% and 10% for V_2 and V_3 without low-multiplicity subtraction, 5.8% and 15% for V_2 and V_3 with low-multiplicity subtraction, respectively. The systematic uncertainties are shown by the shaded bands.
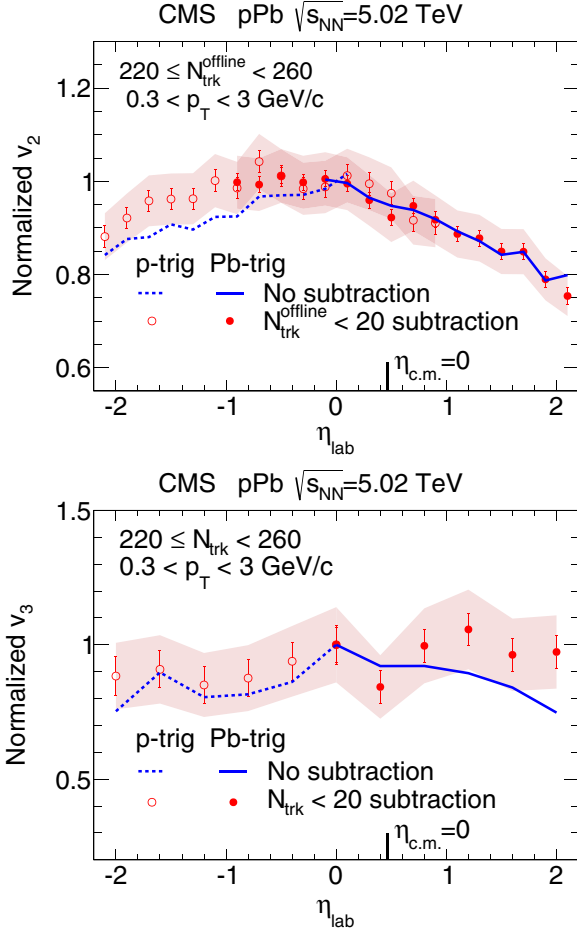
FIG. 6. $v_2(\eta_{c.m.})/v_2(-\eta_{c.m.})$, as a function of $\eta_{c.m.}$ in the center-of-mass frame. The data points are results from V_n^{sub} with low-multiplicity data subtracted. The bands show the systematic uncertainty of $\pm 5.7\%$. Error bars indicate statistical uncertainties only.

FIG. 5. Self-normalized anisotropy parameters, $v_2(\eta_{lab})/v_2$ $(\eta_{lab}=0)$ (top panel) and $v_3(\eta_{lab})/v_3(\eta_{lab}=0)$ (bottom panel), as a function of η_{lab}. Data points (curves) are results with (without) low-multiplicity data subtraction; filled circles and solid lines are from the Pb-side trigger. Open circles and dashed lines are from the p-side trigger. The bands show systematic uncertainties of $\pm 5.7\%$ and $\pm 14\%$ for $v_2(\eta_{lab})/v_2(\eta_{lab}=0)$ and $v_3(\eta_{lab})/v_3(\eta_{lab}=0)$, respectively. The systematic uncertainties in $v_n(\eta_{lab})/v_n(\eta_{lab}=0)$ without subtraction are similar. Error bars indicate statistical uncertainties only.

separation of the central value to both η_{lab}^{trig} is the same. In this way, possible contamination from jets is kept at the same level as a function of η_{lab}. This is more important for the Fourier coefficients determined without the subtraction of the low-multiplicity data.

Figure 5 shows the $v_2(\eta_{lab})/v_2(\eta_{lab}=0)$ and $v_3(\eta_{lab})/v_3(\eta_{lab}=0)$ results obtained from the corresponding V_2 and V_3 data in Fig. 4. The curves show the $v_n(\eta_{lab})/v_n(\eta_{lab}=0)$ obtained from the high-multiplicity data alone, V_n^{HM}, without subtraction of the low-multiplicity data. The data points are obtained from the low-multiplicity-subtracted V_n^{sub}; closed circles are from the Pb-side trigger particle data and open circles from the p side. To avoid large contamination from short-range correlations, only the large $|\Delta\eta|$ range is shown, but still with enough overlap in midrapidity η_{lab} between the two trigger selections; good agreement is observed. Significant
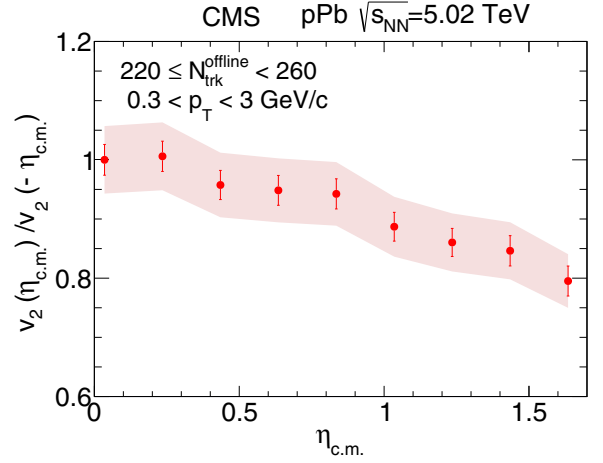
pseudorapidity dependence is observed for the anisotropy parameter; it decreases by about $(24\pm 4)\%$ (statistical uncertainty only) from $\eta_{lab}=0$ to $\eta_{lab}=2$ in the p direction. The behavior of the normalized $v_2(\eta_{lab})/v_2(\eta_{lab}=0)$ is different in the Pb side, with the maximum difference being smaller. The v_2 appears to be asymmetric about $\eta_{c.m.}=0$, which corresponds to $\eta_{lab}=0.465$. A nonzero v_3 is observed, however the uncertainties are too large to draw a definite conclusion regarding its pseudorapidity dependence.

When using long-range two-particle correlations to obtain anisotropic flow, the large pseudorapidity separation between the particles, while reducing nonflow effects, may lead to underestimation of the anisotropic flow because of event plane decorrelation stemming from the fluctuating initial conditions [42,43]. This effect was studied in pPb and PbPb collisions [44]. The observed decrease in v_2 with increasing absolute value of pseudorapidity could be partially due to such decorrelation.

The asymmetry of the azimuthal anisotropy is studied by taking the ratio of the v_n value at positive $\eta_{c.m.}$ to the value at $-\eta_{c.m.}$ in the center-of-mass frame, as shown in Fig. 6. The ratio shows a decreasing trend with increasing $\eta_{c.m.}$.

In pPb collisions, the average p_T of charged hadrons depends on pseudorapidity. As stated in Ref. [37], the pseudorapidity dependence of $\langle p_T \rangle$ could influence the pseudorapidity dependence of v_2. This may have relevance to the shape of the normalized v_2 distribution as observed in Fig. 5. To compare v_2 and the $\langle p_T \rangle$ distribution, the p_T spectra for different $\eta_{c.m.}$ ranges are obtained from Ref. [57]. The charged particle p_T spectra in minimum-bias events are then fitted with a Tsallis function, as done in Ref. [58].

The inclusive-particle p_T is averaged within $0 < p_T < 6$ GeV/c. In addition, the average momentum for the particles used in this analysis, $0.3 < p_T < 3$ GeV/c and $220 \leqslant N_{trk}^{offline} < 260$, is calculated and plotted in Fig. 7. The $\langle p_T \rangle$ as a function of $\eta_{c.m.}$ does not change for different multiplicity ranges within 1%. Thus, the minimum bias $\langle p_T \rangle$ distribution is compared directly to the high-multiplicity anisotropy v_2
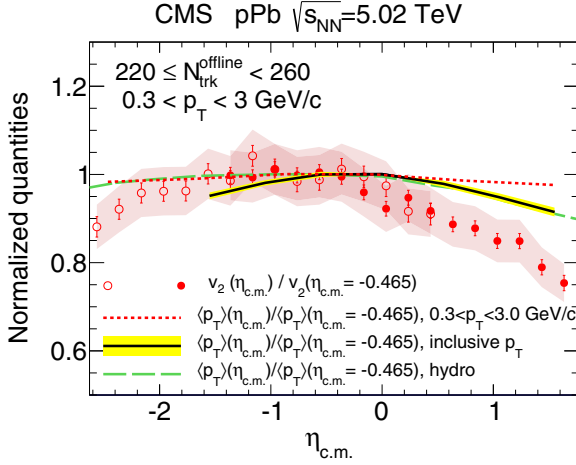
FIG. 7. Self-normalized $v_2(\eta_{\rm c.m.})/v_2(\eta_{\rm c.m.} = -0.465)$ distribution with low-multiplicity subtraction from Pb-side (filled circles) and p-side (open circles) triggers, and $\langle p_{\rm T}\rangle(\eta_{\rm c.m.})/\langle p_{\rm T}\rangle(\eta_{\rm c.m.} = -0.465)$ of $0 < p_{\rm T} < 6\,{\rm GeV}/c$ range from minimum-bias events (solid line) and $0.3 < p_{\rm T} < 3\,{\rm GeV}/c$ range from high-multiplicity ($220 \leqslant N_{\rm trk}^{\rm offline} < 260$) events (dotted line) as functions of $\eta_{\rm c.m.}$. Dashed curve is the hydrodynamic prediction for $\langle p_{\rm T}\rangle(\eta_{\rm c.m.})/\langle p_{\rm T}\rangle(\eta_{\rm c.m.} = -0.465)$ distribution.

result. The $\langle p_{\rm T}\rangle$ distribution is normalized by its value at $\eta_{\rm c.m.} = -0.465$. Self-normalized $\langle p_{\rm T}\rangle(\eta_{\rm c.m.})/\langle p_{\rm T}\rangle(\eta_{\rm c.m.} = -0.465)$ is plotted in Fig. 7, compared to the self-normalized $v_2(\eta_{\rm c.m.})/v_2(\eta_{\rm c.m.} = -0.465)$ distribution in the center-of-mass frame. The systematic uncertainty band for $\langle p_{\rm T}\rangle(\eta_{\rm c.m.})/\langle p_{\rm T}\rangle(\eta_{\rm c.m.} = -0.465)$ is obtained by averaging the upper and lower limits of the systematic uncertainty band from the underlying $p_{\rm T}$ spectra. The hydrodynamic theoretical prediction for $\langle p_{\rm T}\rangle(\eta_{\rm c.m.})/\langle p_{\rm T}\rangle(\eta_{\rm c.m.} = -0.465)$ is also plotted.

As shown in Fig. 7, the hydrodynamic calculation [37] for $\langle p_{\rm T}\rangle$ falls more rapidly than the $\langle p_{\rm T}\rangle$ for data (solid and dotted lines) towards positive $\eta_{\rm c.m.}$. The distribution is asymmetric for both data and theory. The comparison of the $\langle p_{\rm T}\rangle$ and the v_2 distributions shows that both observables have a decreasing trend towards large $|\eta_{\rm c.m.}|$, but the decrease in $\langle p_{\rm T}\rangle$ at forward pseudorapidity is smaller. The decrease of v_2 with $\eta_{\rm c.m.}$ does not appear to be entirely from a change in $\langle p_{\rm T}\rangle$; other physics is likely at play. The value of v_2 decreases by $(20 \pm 4)\%$ (statistical uncertainty only) from $\eta_{\rm c.m.} = 0$ to $\eta_{\rm c.m.} \approx 1.5$.

VII. SUMMARY

Two-particle correlations as functions of $\Delta\phi$ and $\Delta\eta$ are reported in pPb collisions at $\sqrt{s_{NN}} = 5.02\,{\rm TeV}$ by the CMS experiment. The trigger particle is restricted to narrow pseudorapidity windows. The combinatorial background is assumed to be uniform in $\Delta\phi$ and normalized by the ZYAM procedure as a function of $\Delta\eta$. The near-side jet correlated yield is fitted and found to be greater in high-multiplicity than in low-multiplicity collisions. The ridge yield is studied as a function of $\Delta\phi$ and $\Delta\eta$ and it is found to depend on pseudorapidity and the underlying background shape ZYAM ($\Delta\eta$). The pseudorapidity dependence differs for trigger particles selected on the proton and the Pb sides.

The Fourier coefficients of the two-particle correlations in high-multiplicity collisions are reported, with and without subtraction of the scaled low-multiplicity data. The pseudorapidity dependence of the single-particle anisotropy parameters, v_2 and v_3, is inferred. Significant pseudorapidity dependence of v_2 is found. The distribution is asymmetric about $\eta_{\rm c.m.} = 0$ with an approximate $(20 \pm 4)\%$ decrease from $\eta_{\rm c.m.} = 0$ to $\eta_{\rm c.m.} \approx 1.5$, and a smaller decrease towards the Pb-beam direction. Finite v_3 is observed, but the uncertainties are presently too large to draw conclusions regarding the pseudorapidity dependence.

The self-normalized $v_2(\eta_{\rm c.m.})/v_2(\eta_{\rm c.m.} = -0.465)$ distribution is compared to the $\langle p_{\rm T}\rangle(\eta_{\rm c.m.})/\langle p_{\rm T}\rangle(\eta_{\rm c.m.} = -0.465)$ distribution as well as from hydrodynamic calculations. The $\langle p_{\rm T}\rangle(\eta_{\rm c.m.})/\langle p_{\rm T}\rangle(\eta_{\rm c.m.} = -0.465)$ distribution shows a decreasing trend towards positive $\eta_{\rm c.m.}$. The $v_2(\eta_{\rm c.m.})/v_2(\eta_{\rm c.m.} = -0.465)$ distribution also shows a decreasing trend towards positive $\eta_{\rm c.m.}$, but the decrease is more significant in the case of the v_2 measurement. This indicates that physics mechanisms other than the change in the underlying particle spectra, such as event plane decorrelation over pseudorapidity, may influence the anisotropic flow.

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