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Observation of long-range, near-side angular correlations in pPb collisions at the LHC

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ABSTRACT

Results on two-particle angular correlations for charged particles emitted in pPb collisions at a nucleon–nucleon center-of-mass energy of 5.02 TeV are presented. The analysis uses two million collisions collected with the CMS detector at the LHC. The correlations are studied over a broad range of pseudorapidity, η, and full azimuth, ϕ, as a function of charged particle multiplicity and particle transverse momentum, p_T. In high-multiplicity events, a long-range ($2 < |\Delta\eta| < 4$), near-side ($\Delta\phi \approx 0$) structure emerges in the two-particle $\Delta\eta$–$\Delta\phi$ correlation functions. This is the first observation of such correlations in proton–nucleus collisions, resembling the ridge-like correlations seen in high-multiplicity pp collisions at $\sqrt{s} = 7$ TeV and in AA collisions over a broad range of center-of-mass energies. The correlation strength exhibits a pronounced maximum in the range of $p_T = 1$–1.5 GeV/c and an approximately linear increase with charged particle multiplicity for high-multiplicity events. These observations are qualitatively similar to those in pp collisions when selecting the same observed particle multiplicity, while the overall strength of the correlations is significantly larger in pPb collisions.

1. Introduction

This Letter presents measurements of two-particle angular correlations in proton-lead (pPb) collisions at a nucleon–nucleon center-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV, performed with the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC). Two-particle correlations in high-energy collisions provide valuable information for characterizing Quantum Chromodynamics and have been studied previously for a broad range of collision energies in proton–proton (pp), proton–nucleus (pA), and nucleus–nucleus (AA) collisions. Such measurements can elucidate the underlying mechanism of particle production and possible collective effects resulting from the high particle densities accessible in these collisions.

Studies of two-particle angular correlations are typically performed using two-dimensional $\Delta\eta$–$\Delta\phi$ correlation functions, where $\Delta\phi$ is the difference in azimuthal angle ϕ between the two particles and $\Delta\eta$ is the difference in pseudorapidity $\eta = -\ln(\tan(\theta/2))$. The polar angle θ is defined relative to the counterclockwise beam.

Of particular interest in studies of collective effects is the long-range (large $|\Delta\eta|$) structure of two-particle correlation functions, which is less susceptible to known sources of correlations such as resonance decays and fragmentation of energetic jets. Measurements in high-energy AA collisions have shown significant modifications of the long-range structure compared with minimum bias pp collisions [1]. Novel correlation structures extending over large $\Delta\eta$ at $|\Delta\phi| \approx 0$ and $|\Delta\phi| \approx 2\pi/3$ were observed in azimuthal correlations for intermediate particle transverse momenta, $p_T \approx 1$–5 GeV/c [2–10]. In AA collisions, long-range correlations are interpreted as a consequence of the hydrodynamic flow of the produced strongly interacting medium [11] and are usually characterized by the Fourier components of the azimuthal particle distributions [12]. Of particular importance are the second and third Fourier components, called elliptic and triangular flow, as they most directly reflect the medium response to the initial collision geometry and its fluctuations [13], and allow the study of fundamental transport properties of the medium using hydrodynamic models [14–16].

In current pp and pA Monte Carlo (MC) event generators, the dominant sources of such long-range correlations are momentum conservation and away-side ($\Delta\phi \approx \pi$) jet correlations. Measurements in pp collisions at 7 TeV have revealed the emergence of long-range, near-side ($\Delta\phi \approx 0$) correlations in a selection of collisions with very high final-state particle multiplicity [17]. A large variety of theoretical models have been proposed to explain the origin of these so-called ridge-like correlations (see Ref. [18] for a recent review). The proposed mechanisms range from color connections in hard scattering processes and collective effects in the initial interaction of the protons to hydrodynamic effects in the

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high-density system possibly formed in these collisions. It is natural to search for the possible emergence of related features in pPb collisions, where a similar range of final-state multiplicities can be explored. The first comparison of pp and pPb measurements as a function of charged particle multiplicity and particle transverse momentum, presented in this Letter, should provide valuable information for understanding the origin of the long-range, near-side correlation signal seen in high-multiplicity pp collisions.

2. Experimental setup

This analysis uses a pPb data set collected during a short run (lasting for about 8 hours) in September 2012. 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. Due to the energy difference, the nucleon–nucleon center-of-mass in the pPb collisions is not at rest with respect to the laboratory frame. Since the higher energy proton beam traveled in the clockwise direction, i.e. at $\theta = \pi$, massless particles emitted at $\eta_{\mathrm{cm}} = 0$ in the nucleon–nucleon center-of-mass frame will be detected at $\eta = -0.465$ in the laboratory frame.

A detailed description of the CMS experiment can be found in Ref. [19]. The main detector subsystem used for this analysis is the tracker, located in the 3.8 T field of the superconducting solenoid. It measures charged particles within the pseudorapidity range $|\eta| < 2.5$ and consists of 1440 silicon pixel and 15 148 silicon strip detector modules. It provides an impact parameter resolution of ∼15 μm and a transverse momentum (p_{T}) resolution of about 1.5% for 100 GeV/c particles. Also located inside the solenoid are the electromagnetic calorimeter (ECAL) and hadron calorimeter (HCAL). The ECAL consists of more than 75 000 lead-tungstate crystals, arranged in a quasi-projective geometry and distributed in a barrel region ($|\eta| < 1.48$) and two endcaps that extend up to $|\eta| = 3.0$. The HCAL barrel and endcaps are sampling calorimeters composed of brass and scintillator plates, covering $|\eta| < 3.0$. Iron forward calorimeters (HF) with quartz fibers, read out by photomultipliers, extend the calorimeter coverage up to $|\eta| = 5.0$. The detailed MC simulation of the CMS detector response is based on GEANT4 [20].

3. Event and track selection

The relatively low pPb collision frequency (about 200 Hz) provided by the LHC in this pilot run allowed the use of a track-based minimum bias trigger. For every pPb bunch crossing, the detector was read out and events were accepted if at least one track with $p_{\mathrm{T}} > 0.4$ GeV/c was found in the pixel tracker. In the offline analysis, a coincidence of at least one HF calorimeter tower with more than 3 GeV of total energy on both the positive and negative sides of HF was required to select hadronic collisions. 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 transverse distance to the beam trajectory. At least two reconstructed tracks were required to be associated with the primary vertex. Beam related background was suppressed by rejecting events with a high fraction of pixel clusters inconsistent with a single collision vertex [21]. Based on simulations using the HIJING event generator, the event selections have a total acceptance of about 96.2% for hadronic inelastic pPb interactions. A total of 2 million events passed all selection criteria, corresponding to an integrated luminosity of about 1 $\mu\mathrm{b}^{-1}$, assuming a pPb interaction cross section of 2.1 barns.

The angular correlation functions were obtained using the CMS *highPurity* [22] track selection. Additionally, a reconstructed track was only considered as a primary-track candidate if the significance of the separation along the beam axis, z, between the track and the primary vertex, $\mathrm{d}z/\sigma(\mathrm{d}z)$, and the significance of the impact parameter relative to the primary vertex transverse to the beam, $\mathrm{d}T/\sigma(\mathrm{d}T)$, were each less than 3. The relative uncertainty of the momentum measurement, $\sigma(p_{\mathrm{T}})/p_{\mathrm{T}}$, was required to be less than 10%. To ensure high tracking efficiency and low fake rate, only tracks within $|\eta| < 2.4$ and with $p_{\mathrm{T}} > 0.1$ GeV/c were used.

Table 1
Fraction of the full event sample for each multiplicity class. The last two columns show the observed and corrected multiplicities, respectively, of charged particles with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.4$ GeV/c. Systematic uncertainties are given for the corrected multiplicities, while statistical uncertainties are negligible.

Multiplicity class ($N_{\mathrm{trk}}^{\mathrm{offline}}$)	Fraction (%)	$\langle N_{\mathrm{trk}}^{\mathrm{offline}} \rangle$	$\langle N_{\mathrm{trk}}^{\mathrm{corrected}} \rangle$
Minimum bias	100.0	40.6	53.4 ± 2.9
$N_{\mathrm{trk}}^{\mathrm{offline}} < 35$	50.4	17.1	23.5 ± 1.3
$35 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 90$	41.9	56.3	75.6 ± 4.1
$90 \leqslant N_{\mathrm{trk}}^{\mathrm{offline}} < 110$	4.6	98.2	114.3 ± 6.2
$N_{\mathrm{trk}}^{\mathrm{offline}} \geqslant 110$	3.1	128.2	149.1 ± 8.1

To match the analysis used for high-multiplicity pp collisions [17], the events were divided into classes of reconstructed track multiplicity, $N_{\mathrm{trk}}^{\mathrm{offline}}$, where primary tracks with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.4$ GeV/c were counted. The fraction of events falling into each of the four multiplicity classes is listed in Table 1. The table also lists the average values of $N_{\mathrm{trk}}^{\mathrm{offline}}$ and $N_{\mathrm{trk}}^{\mathrm{corrected}}$, the event multiplicity of charged particles with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.4$ GeV/c corrected for detector acceptance and efficiency of the track reconstruction algorithm, as discussed in the following section.

4. Calculation of the two-particle correlation function

The analysis of two-particle correlations was performed in classes of track multiplicity, $N_{\mathrm{trk}}^{\mathrm{offline}}$, following the procedure established in [7,8]. For each track multiplicity class, "trigger" particles are defined as charged particles originating from the primary vertex within a given p_{T} range. The number of trigger particles in the event is denoted by N_{trig}. In this analysis, particle pairs are formed by associating every trigger particle with the remaining charged primary particles from the same p_{T} interval as the trigger particle (a minimum of two particles is required in each p_{T} bin from each event). The per-trigger-particle associated yield is defined as

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

where $\Delta\eta$ and $\Delta\phi$ are the differences in η and ϕ of the pair. The signal distribution, $S(\Delta\eta, \Delta\phi)$, is the per-trigger-particle yield of particle pairs from the same event,

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

The mixed-event background distribution, used to account for random combinatorial background and pair-acceptance effects,

$$B(\Delta\eta, \Delta\phi) = \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N^{\mathrm{mix}}}{\mathrm{d}\Delta\eta \, \mathrm{d}\Delta\phi}, \tag{3}$$

is constructed by pairing the trigger particles in each event with the associated particles from 10 different random events in the same 2 cm wide z_{vtx} range. The symbol N^{mix} denotes the number of pairs taken from the mixed event, while $B(0,0)$ represents the mixed-event associated yield for both particles of the pair going in approximately the same direction and thus having full pair acceptance (with a bin width of 0.3 in $\Delta\eta$ and $\pi/16$ in $\Delta\phi$). Therefore, the ratio $B(0,0)/B(\Delta\eta,\Delta\phi)$ is the pair-acceptance correction factor used to derive the corrected per-trigger-particle associated yield distribution. The signal and background distributions are first calculated for each event, and then averaged over all the events within the track multiplicity class.

Each reconstructed track is weighted by the inverse of an efficiency factor, which accounts for the detector acceptance, the reconstruction efficiency, and the fraction of misreconstructed tracks. Detailed studies of tracking efficiencies using MC simulations and data-based methods can be found in [23]. The combined geometrical acceptance and efficiency for track reconstruction exceeds 50% for $p_T \approx 0.1$ GeV/c and $|\eta| < 2.4$. The efficiency is greater than 90% in the $|\eta| < 1$ region for $p_T > 0.6$ GeV/c. For the multiplicity range studied here, little or no dependence of the tracking efficiency on multiplicity is found and the rate of misreconstructed tracks remains at the 1–2% level.

Simulations of pp, pPb and peripheral PbPb collisions using the PYTHIA, HIJING and HYDJET event generators, respectively, yield efficiency correction factors that vary due to the different kinematic and mass distributions for the particles produced in these generators. Applying the resulting correction factors from one of the generators to simulated data from one of the others gives associated yield distributions that agree within 5%. Systematic uncertainties due to track quality cuts and potential contributions from secondary particles (including those from weak decays) are examined by loosening or tightening the track selections on $\mathrm{d}z/\sigma(\mathrm{d}z)$ and $\mathrm{d}T/\sigma(\mathrm{d}T)$ from 2 to 5. The associated yields are found to be insensitive to these track selections within 2%.

5. Results

Fig. 1 compares 2-D two-particle correlation functions for events with low (a) and high (b) multiplicity, for pairs of charged particles with $1 < p_T < 3$ GeV/c. For the low-multiplicity selection ($N_{\mathrm{trk}}^{\mathrm{offline}} < 35$), the dominant features are the correlation peak near $(\Delta\eta, \Delta\phi) = (0,0)$ for pairs of particles originating from the same jet and the elongated structure at $\Delta\phi \approx \pi$ for pairs of particles from back-to-back jets. To better illustrate the full correlation structure, the jet peak has been truncated. High-multiplicity events ($N_{\mathrm{trk}}^{\mathrm{offline}} \geqslant 110$) also show the same-side jet peak and back-to-back correlation structures. However, in addition, a pronounced "ridge"-like structure emerges at $\Delta\phi \approx 0$ extending to $|\Delta\eta|$ of at least 4 units. This observed structure is similar to that seen in high-multiplicity pp collision data at $\sqrt{s} = 7$ TeV [17] and in AA collisions over a wide range of energies [3–10].

As a cross-check, correlation functions were also generated for tracks paired with ECAL photons, which originate primarily from decays of π^0s, and for pairs of ECAL photons. These distributions showed similar features as those seen in Fig. 1, in particular the ridge-like correlation for high multiplicity events.

To investigate the long-range, near-side correlations in finer detail, and to provide a quantitative comparison to pp results, one-dimensional (1-D) distributions in $\Delta\phi$ are found by averaging the signal and background two-dimensional (2-D) distributions over $2 < |\Delta\eta| < 4$ [7,8,17]. In the presence of multiple sources of correlations, the yield for the correlation of interest is commonly estimated using an implementation of the zero-yield-at-minimum (ZYAM) method [26]. A second-order polynomial is first fitted to the 1-D $\Delta\phi$ correlation function in the region $0.1 < |\Delta\phi| < 2$. The minimum value of the polynomial, C_{ZYAM}, is then subtracted from the 1-D $\Delta\phi$ correlation function as a constant background (containing no information about correlations) to shift its minimum to be at zero associated yield. The statistical uncertainty on the minimum level of $\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi}$ obtained by the ZYAM procedure as well as the deviations found by varying the fit range in $\Delta\phi$ give an absolute uncertainty of ±0.0015 on the associated yield, independent of multiplicity and p_T.

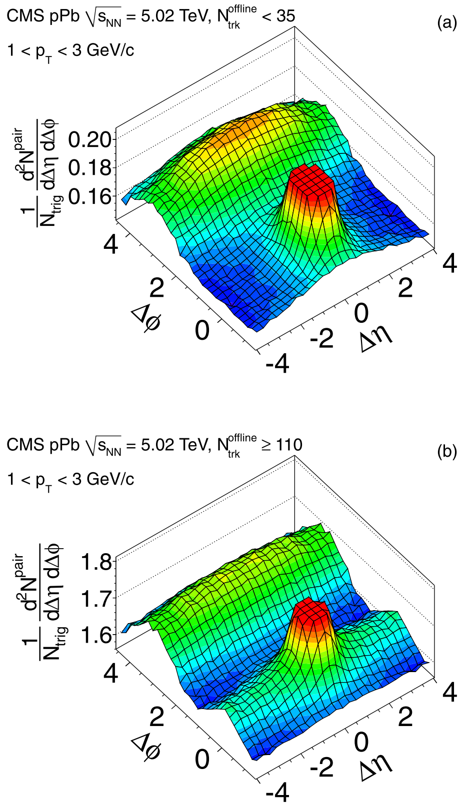

Fig. 1. 2-D two-particle correlation functions for 5.02 TeV pPb collisions for pairs of charged particles with $1 < p_T < 3$ GeV/c. Results are shown (a) for low-multiplicity events ($N_{\mathrm{trk}}^{\mathrm{offline}} < 35$) and (b) for a high-multiplicity selection ($N_{\mathrm{trk}}^{\mathrm{offline}} \geqslant 110$). The sharp near-side peaks from jet correlations have been truncated to better illustrate the structure outside that region.

Fig. 2 shows the results for pPb data (solid circles) for various selections in p_T and multiplicity $N_{\mathrm{trk}}^{\mathrm{offline}}$, with p_T increasing from left to right and multiplicity increasing from top to bottom. The results for pp data at $\sqrt{s} = 7$ TeV, obtained using the same procedure [17], are also plotted (open circles).

A clear evolution of the $\Delta\phi$ correlation function as a function of both p_T and $N_{\mathrm{trk}}^{\mathrm{offline}}$ is observed. For the lowest multiplicity selection in pp and pPb the correlation functions have a minimum at $\Delta\phi = 0$ and a maximum at $\Delta\phi = \pi$, reflecting the correlations from momentum conservation and the increasing contribution from back-to-back jet-like correlations at higher p_T. Results from the HIJING [24] model (version 1.383), shown as dashed lines, qualitatively reproduce the shape of the correlation function for low $N_{\mathrm{trk}}^{\mathrm{offline}}$.

For multiplicities $N_{\mathrm{trk}}^{\mathrm{offline}} \geqslant 35$, a second local maximum near $|\Delta\phi| \approx 0$ emerges in the pPb data, corresponding to the near-side, long-range ridge-like structure. In pp data, this second maximum is clearly visible only for $N_{\mathrm{trk}}^{\mathrm{offline}} > 90$. For both pp and pPb collisions, this near-side correlated yield is largest in the $1 < p_T < 2$ GeV/c range and increases with increasing multiplicity. While the evolution of the correlation function is qualitatively similar in pp and pPb data, the absolute near-side correlated yield is significantly larger in the pPb case.

In contrast to the data, the HIJING calculations show a correlated yield of zero at $\Delta\phi = 0$ for all multiplicity and p_T selections. The

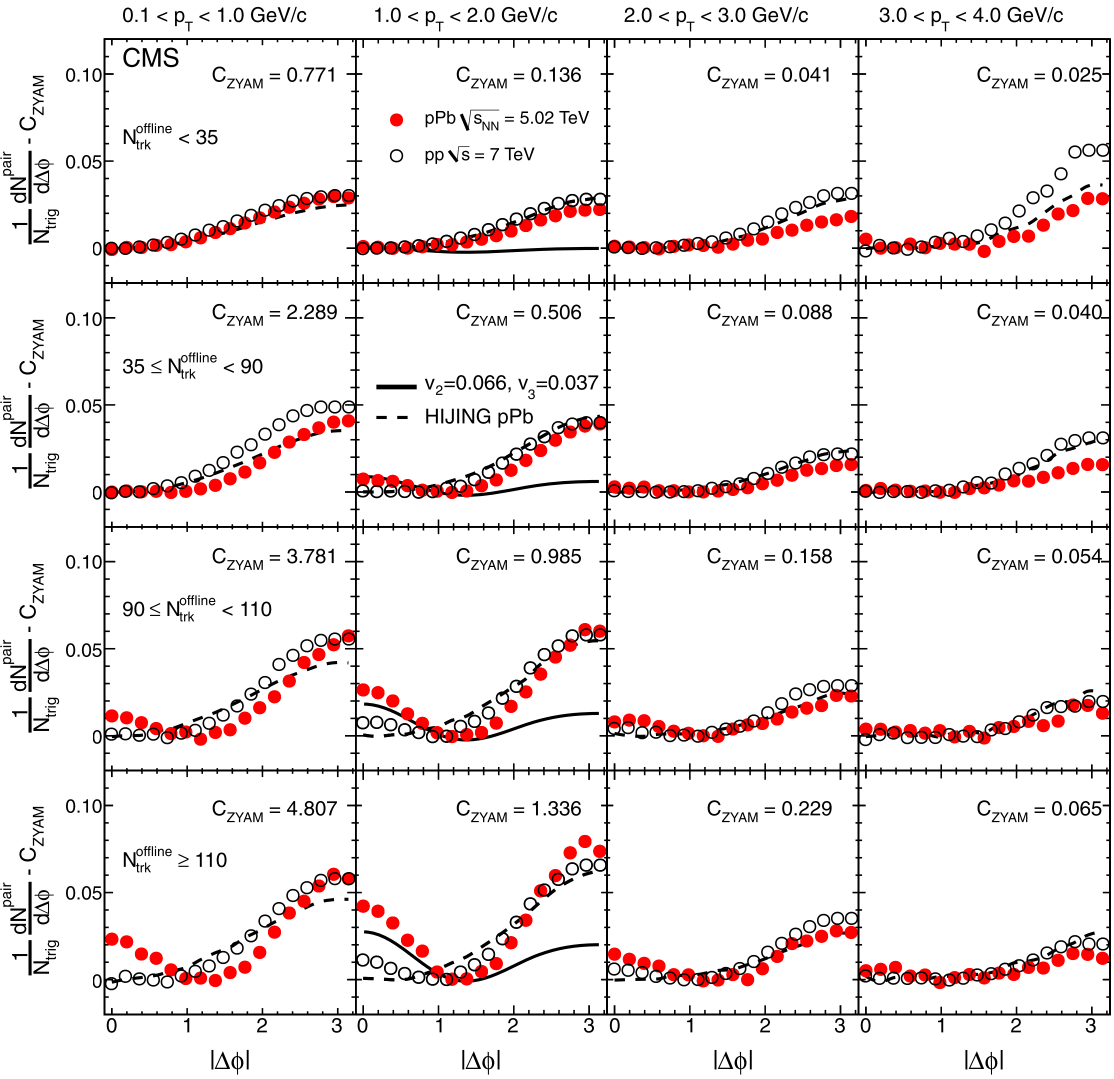

Fig. 2. Correlated yield obtained from the ZYAM procedure as a function of $|\Delta\phi|$ averaged over $2 < |\Delta\eta| < 4$ in different p_T and multiplicity bins for 5.02 TeV pPb data (solid circles) and 7 TeV pp data (open circles). The p_T selection applies to both particles in each pair. Statistical uncertainties are smaller than the marker size. The subtracted ZYAM constant is listed in each panel. Also shown are pPb predictions for HIJING [24] (dashed curves) and a hydrodynamic model [25] (solid curves shown for $1 < p_T < 2$ GeV/c).

long-range, near-side enhancement is also absent in simulated pp collision events with the PYTHIA [27,28] event generator (version 6.4.24) and in simulated pPb collisions with the AMPT [29] model (version 1.25/2.25).

Long-range correlations in pPb collisions have been quantitatively predicted in models assuming a collective hydrodynamic expansion of a system with fluctuating initial conditions [25]. The correlation resulting from the predicted elliptic and triangular flow components for pPb collisions at $\sqrt{s_{NN}} = 4.4$ TeV are compared to the observed correlation in Fig. 2 for the $1 < p_T < 2$ GeV/c selection (solid line, second column). The magnitudes for elliptic and triangular flow of $v_2 = 0.066$ and $v_3 = 0.037$ correspond to those given in Ref. [25] for the highest multiplicity selection and the average value of $p_T \approx 1.4$ GeV/c found in the data. The same v_2 and v_3 coefficients were used for all multiplicity classes, showing the multiplicity dependence of the correlated yield assuming a constant flow effect. While this provides an indicative and useful illustration of the magnitude of the observed near-side enhancement, a detailed quantitative comparison of the model and data will need to include the additional non-hydrodynamical correlations from back-to-back jets, as well as the effects of momentum conservation, which suppress the correlation near $\Delta\phi \approx 0$ relative to $\Delta\phi \approx \pi$.

The ridge-like structure in pPb collisions was also predicted to arise from initial state gluon correlations in the color-glass condensate framework, where the contribution of collimated gluon emissions is significantly enhanced in the gluon saturation regime [30]. This model qualitatively predicts the increase in the correlation strength for higher multiplicity pPb collisions, although it remains to be seen if the large associated yield seen in the highest multiplicity selection can be quantitatively reproduced in the calculation.

The strength of the long-range, near-side correlations can be further quantified by integrating the correlated yield from Fig. 2 over $|\Delta\phi| < 1.2$ using 12 classes of multiplicity. The resulting integrated "ridge yield", normalized by the width of the p_T interval, is plotted as a function of particle p_T and event multiplicity in Fig. 3 for pp (open circles) and pPb (solid circles) data. The error bars correspond to statistical uncertainties, while the shaded boxes indicate the systematic uncertainties.

Fig. 3(a) shows that the ridge yield for events with $N_{\mathrm{trk}}^{\mathrm{offline}} \geqslant 110$ peaks in the region $1 < p_T < 2$ GeV/c for both collision

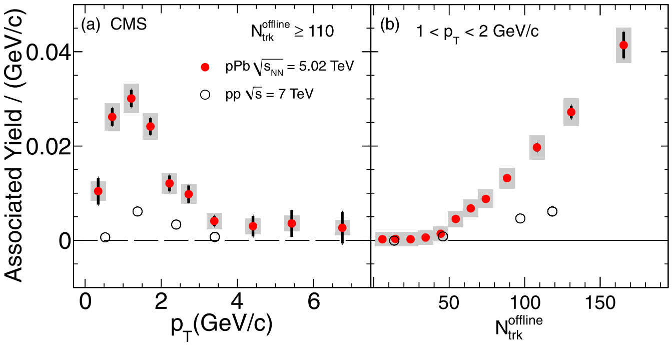

Fig. 3. Associated yield for the near-side of the correlation function averaged over $2 < |\Delta\eta| < 4$ and integrated over the region $|\Delta\phi| < 1.2$ in 7 TeV pp collisions (open circles) and 5.02 TeV pPb collisions (solid circles). Panel (a) shows the associated yield as a function of p_T for events with $N_{trk}^{offline} \geqslant 110$. In panel (b) the associated yield for $1 < p_T < 2$ GeV/c is shown as a function of multiplicity $N_{trk}^{offline}$. The p_T selection applies to both particles in each pair. The error bars correspond to statistical uncertainties, while the shaded areas denote the systematic uncertainties.

systems. However, while the yield in pp collisions is consistent with zero for the $0.1 < p_T < 1$ GeV/c selection, it remains greater than zero in pPb data even for the $0.1 < p_T < 0.5$ GeV/c range. For higher p_T, the ridge yield in pp collisions is consistent with zero for $p_T > 3$ GeV/c, while the pPb results only approach zero at $p_T \approx 4$–7 GeV/c.

The multiplicity dependence of the ridge yield for $1 < p_T < 2$ GeV/c particle pairs is shown in Fig. 3(b). For low-multiplicity collisions, the ridge yield determined by the ZYAM procedure is consistent with zero, indicating that ridge-like correlations are absent or smaller than the negative correlations expected due to, e.g. momentum conservation. At higher multiplicity the ridge-like correlations emerge, with an approximately linear rise of the ridge yield observed for $N_{trk}^{offline} \gtrsim 40$, which corresponds to $N_{trk}^{corrected} \gtrsim 53$. While the multiplicity dependence is qualitatively similar for pp and pPb collisions, a significantly larger yield per trigger particle is seen in pPb than in pp at a given multiplicity.

When interpreting the differences in the correlation structure between the two collision systems, it is important to consider the relative contributions of different particle production mechanisms to the observed particle yields. While very high multiplicity pp collisions should mainly arise from rare multiple hard-scattering processes, the high-multiplicity pPb events should mostly result from particle production in multiple soft proton–nucleon scatterings. This will in particular affect the correlations due to back-to-back jet fragmentation in the $\Delta\phi \approx \pi$ region. A simultaneous description of the measurements in pp and pPb should provide significant constraints on models of the underlying physics processes. With such an improved understanding of the smaller systems, comparisons to the PbPb data will also provide insights in understanding the similarity of the ridge-like correlations in all three systems.

6. Conclusion

The CMS detector at the LHC has been used to measure angular correlations between two charged particles with $|\eta| < 2.4$ in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Azimuthal correlations for $2 < |\Delta\eta| < 4$ in high-multiplicity pPb collisions exhibit a long-range structure at the near side ($\Delta\phi \approx 0$). This ridge-like structure is qualitatively similar to that observed in pp collisions at $\sqrt{s} = 7$ TeV and in AA collisions over a broad range of center-of-mass energies. The effect is most evident in the intermediate transverse momentum range, $1 < p_T < 1.5$ GeV/c. The near-side ridge yield obtained by the ZYAM procedure is found to be consistent with zero in the low-multiplicity region, with an approximately linear increase with multiplicity for $N_{trk}^{offline} \gtrsim 40$ (corresponding to $N_{trk}^{corrected} \gtrsim 53$). While the multiplicity and p_T dependences of the observed effect are similar to those seen in pp data at $\sqrt{s} = 7$ TeV, the absolute ridge yield in pPb is significantly larger than in pp collisions of the same particle multiplicity.

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