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Recent Results on Multi-Particle Azimuthal Correlations in High-Multiplicity pp and pPb Collisions in CMS

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In nucleus-nucleus collisions, the Quark-Gluon Plasma behaves like a perfect fluid and the azimuthal anisotropy of the observed particle final-state distributions reflects its properties. This anisotropic flow, arising mainly from initial-state geometry and its fluctuations, highlights the collective behavior of the particles produced in the collision. It is well-described by hydrodynamics and explains the long-range near-side correlations, known as the "ridge", observed experimentally in AA collisions and, more recently, in small systems such as pp or pA collisions. The CMS experiment has studied this correlation in details by extracting the momenta of the Fourier decomposition of azimuthal particle-distribution in the final state (v_{n}, n = 2 - 4). The v_{n} are extracted using di-hadron correlation and multi-particle cumulant methods in both pp and pPb collisions. In this talk, results from CMS on the ridge in small systems are shown and compared with those in PbPb collisions, demonstrating that the collective nature of the ridge is present also in small systems. The correlation between different Fourier coefficients is further investigated using a symmetric cumulant analysis and compared across colliding systems. The latest results on v_{n} correlations in pp at 13 TeV and pPb at 8.16 TeV collisions are also discussed. All these results give us a better understanding of collective effects from small to large colliding systems and provide more insights on the nature of the ridge in pp and pPb collisions.

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Similarly to high-energy nucleus-nucleus (AA) collisions, a long-range near side azimuthal correlation structure (ridge-like) was observed for high-multiplicity events in small colliding systems (such as pp and pPb collisions) [1–7]. In AA collisions, the ridge can be understood assuming the formation of a medium with properties compatible with that of an expanding, almost perfect fluid, composed of quarks and gluons, known as quark-gluon plasma [8, 9]. In order to investigate the origin and properties of the ridge in small systems, the experiments at the RHIC and the LHC are currently performing and comparing key measurements among different system sizes [10–13]. In this proceedings, some recent results from the CMS experiment [14] on long-range near-side azimuthal correlations in pp and pPb collisions are shown and compared with the corresponding results in PbPb.

Results for proton-proton collisions at $\sqrt{s} = 5$, 7 and 13 TeV, proton-lead collisions at $\sqrt{s_{\mathrm{NN}}} =$ 5.02 and 8.16 TeV and peripheral lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and 5.02 TeV are presented. In order to have meaningful comparisons, the PbPb events are reprocessed with a similar reconstruction software as in pp and pPb collisions and the same track selection is applied in all data samples. All the tracks used in this analysis are selected with tuned quality criteria [15]. The tracks used in the correlation measurements have $p_{\mathrm{T}} > 0.3$ GeV and $|\eta| < 2.4$. The event classification is done in terms of charged particle multiplicity ($N_{\mathrm{trk}}^{\mathrm{offline}}$), which is defined as the number of tracks with $p_{\mathrm{T}} > 0.4$ GeV and $|\eta| < 2.4$. These requirements are chosen to match with the online requirements (trigger) to select high-multiplicity events. Monte Carlo (MC) simulations are used to correct the measurements for detector acceptance, tracking efficiency and the rate of misreconstructed tracks. For more details on the data sets, MC simulations, reconstruction algorithms and selections, see Refs. [16, 17].

The analyses are done via the investigation of the Fourier coefficients (v_{n}) extracted from azimuthal angle (ϕ) particle distributions [18]. These coefficients can provide valuable information about the initial state geometry of the collision and its fluctuations. These measurements are sensitive to many effects, such as jets correlations and resonances decays, event and track selections, additional collisions in the same bunch crossing (pile-up) and vertex position in the beam direction. Corrections are applied to account for most of these effects, and systematic uncertainties are assigned in each case [16, 17]. In all the figures, the size of the systematic uncertainty is represented by shaded boxes around each point.

The v_2, v_3 and v_4 coefficients as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$ for PbPb, pPb and pp collisions are shown in Fig. 1. The coefficients are extracted using a two-particle correlation method that estimates and subtracts the di-jet contribution using a low-multiplicity control region, which is considered to do not give flow contributions [16, 17]. The results are presented with and without the subtraction of the di-jet correlations, which are more important in low-multiplicity events. For all v_{n}, similar trends are observed for pp and pPb, i.e., it increases and tends to saturate at higher $N_{\mathrm{trk}}^{\mathrm{offline}}$. In PbPb, v_n seems to always increase, even at higher multiplicities, and v_2 has higher magnitude than in the pPb and pp cases. In addition, almost no dependence on center-of-mass energy is observed for both v_2 and v_3 in pPb collisions.

In Fig. 2 the v_2 coefficient is obtained as a function of p_{T} for different particle species: inclusive charged hadrons, $h^{\pm}$, K_{s}^{0} and $\Lambda/\bar{\Lambda}$. For all the systems the v_2 increases with particle p_{T}, reaching maximum values around $2 < p_{\mathrm{T}} < 4$ GeV. A mass ordering (lower particle masses corresponding to higher magnitudes of v_2) for low-p_{T} particles ($p_{\mathrm{T}} < 2$ GeV) is observed for the three

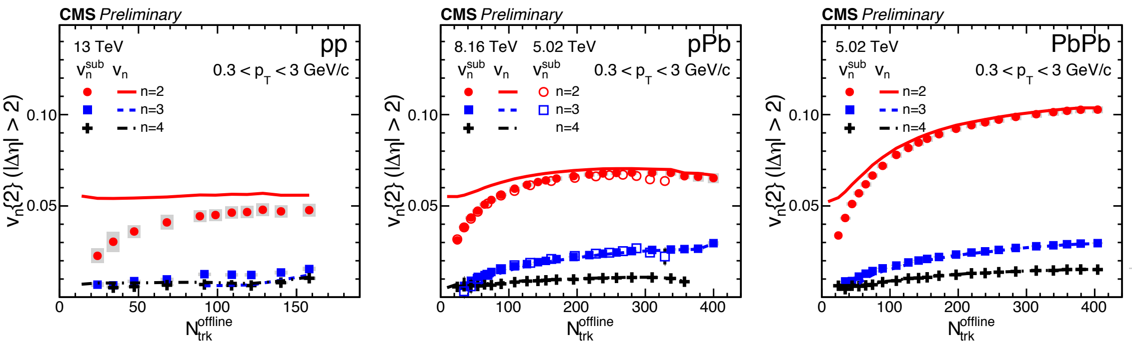

Figure 1: Fourier coefficients (v_n, n=2-4) as a function of charged particle multiplicity for pp, pPb and PbPb collisions in various center-of-mass energies. The v_n coefficients are extracted using a two-particle correlation method with (points) and without (lines) di-jet correlations subtraction [17].

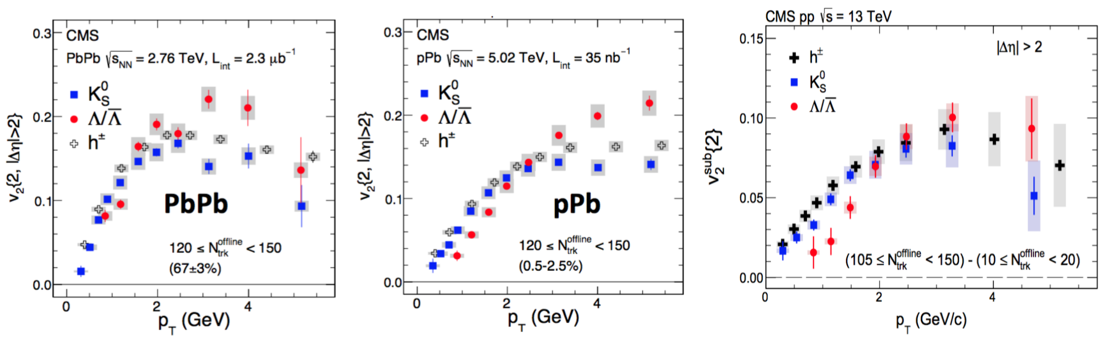

Figure 2: Fourier coefficient (v_2) as a function of p_T for different particle species and colliding systems. The measurements are performed using a two-particle correlation method with subtraction of di-jet contributions to the coefficients [16].

systems. The splitting is more pronounced in smaller systems.

The v_2 measurement from multi-particle cumulant technique [19] and the Lee-Yang Zeros (LYZ) method [20] are presented on Fig. 3. The latter considers an asymptotic form of the cumulant expansion to explore the correlation among all the particles in the event. The results are compared to v_2 values obtained with the two-particle correlation method. A similar behavior of multi-particle v_2 is observed across all colliding systems within the experimental uncertainties: $v_2\{4\} \sim v_2\{6\}$ for pp, $v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$ for pPb and $v_2\{4\} \sim v_2\{6\} \sim v_2\{8\} \sim v_2\{LYZ\}$ for PbPb. These results provide an important evidence for a collective behavior of the particles produced in the final state of small colliding systems. However, a significant splitting between $v_2\{2\}$ and $v_2\{\text{multi-particle}\}$ is observed in pPb and PbPb at high-multiplicity, while $v_2\{2\}$ and $v_2\{\text{multi-particle}\}$ are approximately equal in high-multiplicity events produced in pp collisions. In hydrodynamic models, this can be connected with differences among the systems regarding initial-state geometry fluctuations (see for example Ref. [21]).

Further studies to understand the collectivity in small systems are presented in Fig. 4. The correlations between different Fourier coefficients, v_n and v_m, are extracted using the symmetric

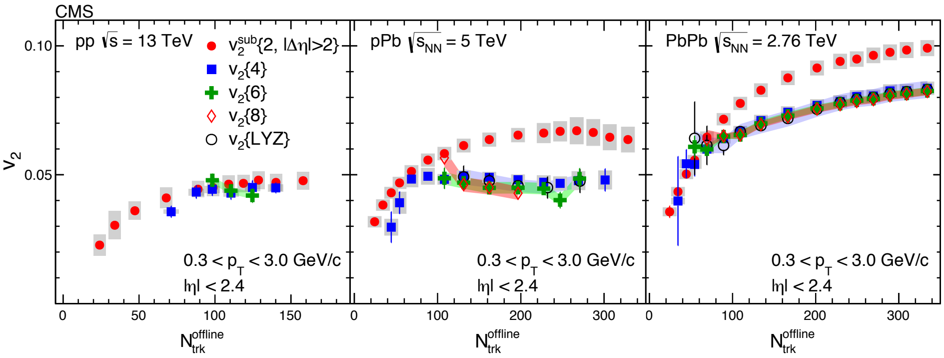

Figure 3: Fourier coefficient (v_2) as a function of charged particle multiplicity for PbPb, pPb and pp collisions. $v_2^{\rm sub}\{2, |\Delta\eta| > 2\}$ is measured using two-particle correlation method with subtraction of di-jet contributions. The $v_2\{4\}$, $v_2\{6\}$ and $v_2\{8\}$ are extracted using multi-particle cumulant method and $v_2\{\rm LYZ\}$ is obtained using the Lee-Yang Zeros technique [16].

cumulants, SC(n,m) [22]. These correlations are presented before (top plots) and after (bottom plots) normalization by the two-particle $v_{\rm n}$ from Fig. 1. A positive value of SC(n,m) means that $v_{\rm n}$ and $v_{\rm m}$ are correlated and a negative value means that they are anticorrelated. For the three systems SC(2,4) is positive for the entire multiplicity range. In pPb and PbPb collisions, SC(2,3) starts with positive values at lower multiplicities and then decreases to negative values from around $N_{\rm trk}^{\rm offline} > 60$. In pp collisions, SC(2,3) suggests to move into negative values for $N_{\rm trk}^{\rm offline} \sim 110$. Nevertheless, the current precision of the measurement does not allow for firm conclusions. As shown in Fig. 1, $v_{\rm n}$ coefficients have different magnitudes depending on the system size. This is mainly due to the initial-state geometry. Therefore, normalizing the SC(n,m) by the corresponding $v_{\rm n}$ coefficients allows a proper comparison across systems as shown in Fig. 4 bottom plots. At high multiplicities, the normalized SC(2,3) has similar behavior in pPb and PbPb, which point to similar initial state fluctuations. The normalized SC(2,4) measurements show a clear ordering between pp, pPb and PbPb systems. This could be explained by different transport properties of the created medium in the different colliding systems.

In summary, recent results on multi-particle azimuthal correlations in pp, pPb and PbPb collisions from the CMS detector at LHC are presented in a wide multiplicity range for different collision energies, particle species and $p_{\rm T}$. Measurements involving multi-particle correlations indicate that the collective behavior observed in relativistic nucleus-nucleus collisions is also present in small systems, such as pp and pPb. In addition, results presented on the correlations between different orders of Fourier harmonics provide valuable information to constrain theoretical models and deepen our knowledge of the initial state geometry and its fluctuations in hadronic colliding systems.

References

[1] CMS Collaboration, *Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC*, *JHEP* **09** (2010) 091.

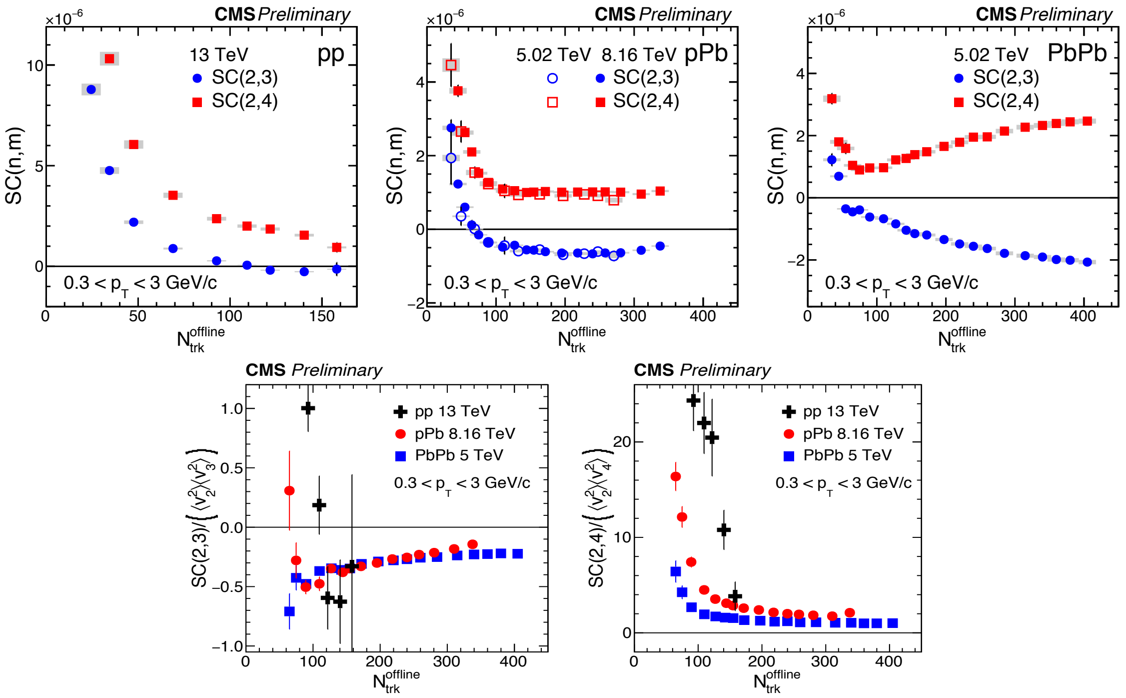

Figure 4: Correlations between v_n and v_m, SC(n,m), as a function of charged particle multiplicity for PbPb, pPb and pp collisions. Top: correlations between v_n and v_m measured with the symmetric cumulants method. Bottom: normalized correlations using the symmetric cumulants technique for the numerator and v_n from two-particle correlation for the denominator [17].

[2] ATLAS Collaboration, *Observation of Long-Range Elliptic Azimuthal Anisotropies in $\sqrt{s} = 13$ TeV and 2.76 TeV pp Collisions with the ATLAS Detector*, *Phys. Rev. Lett.* **116** (2016) 172301.

[3] CMS Collaboration, *Measurement of long-range near-side two-particle angular correlations in pp collisions at $\sqrt{s} = 13$ TeV*, *Phys. Rev. Lett.* **116** (2016) 172302.

[4] CMS Collaboration, *Observation of long-range near-side angular correlations in proton-lead collisions at the LHC*, *Phys. Lett. B* **718** (2013) 795.

[5] ALICE Collaboration, *Long-range angular correlations on the near and away side in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Phys. Lett. B* **719** (2013) 29.

[6] ATLAS Collaboration, *Observation of Associated Near-Side and Away-Side Long-Range Correlations in $\sqrt{s_{NN}} = 5.02$ TeV Proton-Lead Collisions with the ATLAS Detector*, *Phys. Rev. Lett.* **110** (2013) 182302.

[7] LHCb Collaboration, *Measurements of long-range near-side angular correlations in $\sqrt{s_{NN}} = 5$ TeV proton-lead collisions in the forward region*, *Phys. Lett. B* **762** (2016) 473.

[8] J. Y. Ollitrault, *Anisotropy as a Signature of Transverse Collective Flow*, *Phys. Rev. D* **46** (1992) 229.

[9] W. Reisdorf and H. G. Ritter, *Collective flow in heavy-ion collisions*, *Ann. Rev. Nucl. Part. Sci.* **47** (1997) 663.

[10] ALICE Collaboration, *Long-range angular correlations of π, K and p in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Phys. Lett. B* **726** (2013) 164.

[11] CMS Collaboration, *Multiplicity and transverse momentum dependence of two- and four-particle correlations in pPb and PbPb collisions*, *Phys. Lett. B* **724** (2013) 213.

[12] ATLAS Collaboration, *Measurements of long-range pseudorapidity correlations and azimuthal harmonics in $\sqrt{s_{NN}} = 5.02$ TeV proton-lead collisions with ATLAS detector*, *Phys. Rev. C* **90** (2014) 044906.

[13] CMS Collaboration, *Evidence for collective multi-particle correlations in pPb collisions*, *Phys. Rev. Lett.* **115** (2015) 012301.

[14] CMS Collaboration, *The CMS experiment at the CERN LHC*, *JINST* **3** (2008) S08004.

[15] CMS Collaboration, *Description and performance of track and primary-vertex reconstruction with the CMS tracker*, *JINST* **9** (2014) P10009.

[16] CMS Collaboration, *Evidence for collectivity in pp collisions at the LHC*, *Phys. Lett. B* **765** (2017) 193.

[17] CMS Collaboration, *Fourier harmonic correlations with symmetric cumulant in pp (13 TeV), pPb (5 TeV and 8 TeV) and PbPb (5 TeV)*, CMS PAS HIN-16-022.

[18] S. Voloshin and Y. Zhang, *Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions*, *Z. Phys. C* **70** (1996) 665.

[19] A. Bilandzic, R. Snellings, and S. Voloshin, *Flow analysis with cumulants: Direct calculations*, *Phys. Rev. C* **83** (2011) 044913.

[20] R. S. Bhalerao, N. Borghini, and J. Y. Ollitrault, *Analysis of anisotropic flow with Lee-Yang zeroes*, *Nucl. Phys. A* **727** (2003) 373.

[21] L. Yan and J. Y. Ollitrault, *Universal fluctuation-driven eccentricities in proton-proton, proton-nucleus and nucleus-nucleus collisions*, *Phys. Rev. Lett.* **112** (2014) 082301.

[22] ALICE Collaboration, *Correlated event-by-event fluctuations of flow harmonics in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *Phys. Rev. Lett.* **117** (2016) 182301.