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Measurements of flow and correlation phenomena in pp, pPb and PbPb collisions at CMS

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Many aspects of anisotropic collective flow in ultra relativistic heavy-ion collisions have been studied extensively in the past years using two or more particle correlations. An overview of collective flow and particle correlation measurements at CMS as a function of transverse momentum, pseudorapidity, event multiplicity, for both charged hadrons or identified particles will be presented. These results will be compared among pp, pPb and PbPb systems. Latest results of pp and PbPb data from 2015 run will also be discussed.

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Anisotropic azimuthal correlations are closely associated with the properties of the hot and dense medium formed in high energy heavy ion collisions. In fact, it was through their observations in the turn of the millennium that it was found at the Relativistic Heavy Ion Collider (RHIC) that the quark gluon plasma (QGP) produced in such collisions behaved as a nearly perfect fluid [1], contrary to earlier expectations that it would behave roughly as an ideal gas. Another finding at RHIC was the quench of jets traversing the hot and dense medium, mainly in the case of head-on relativistic heavy ion collisions. At the Large Hadron Collider (LHC), a plethora of complex and deeper investigations of the QGP properties has been performed over the recent years. In particular, the possibility of extending the measurement of azimuthal correlations to particles with very high transverse momentum p_T, has added significant new insights into these observations.

Another remarkable discovery in AA collisions at RHIC energies was the two-hadrons long-range azimuthal ("ridge-like") correlations, where particles very close in the azimuthal direction ($\Delta\phi \sim 0$) are correlated over a wide region in relative pseudorapidity (up to $\Delta\eta \sim 4$). Surprisingly, similar correlations were discovered in 2010 at the LHC in high multiplicity events produced in pp collisions at 7 TeV [2] and, some time later, also in pPb collisions, posing questions on the possible common nature of the systems formed in pp, pA and AA collisions.

In this paper, results related to those phenomena are reported, starting by azimuthal correlations in *PbPb* collisions at 5.02 TeV in the nucleon-nucleon center-of-mass, extending from low transverse momentum ($1 < p_T < 3$ GeV/c), associated with hydrodynamic collective flow, and up to very large p_T (up to 100 GeV/c), where anisotropic azimuthal distributions may reflect the path-length dependence of parton energy loss while traversing the medium, shedding light into the quenched jet. Several methods are used to extract the Fourier coefficients, such as the scalar product method for correlating charged tracks with the energy deposited in the hadronic forward calorimeters, as well as the multi-particle cumulant method.

Measurements of two- and multi-particle angular correlations in pp collisions at $\sqrt{s} = 5$, 7, and 13 TeV are also presented as a function of charged-particle multiplicity. The second-order (v_2) and third-order (v_3) azimuthal anisotropy harmonics of unidentified charged particles, as well as v_2 of K^0_S and $\Lambda/\bar{\Lambda}$ particles, are extracted from long-range two-particle correlations as functions of particle multiplicity and transverse momentum. For high-multiplicity pp events, a mass ordering is observed for the v_2 values of charged hadrons (mostly pions), K^0_S, and $\Lambda/\bar{\Lambda}$, with lighter particle species exhibiting a stronger azimuthal anisotropy signal below $p_T \approx 2$ GeV/c. For 13 TeV data, the v_2 signals are also extracted from four- and six-particle correlations for the first time in pp collisions, with comparable magnitude to those from two- particle correlations. These observations are similar to those seen in pPb and PbPb collisions, suggesting a collective origin for the observed long-range correlations in high-multiplicity pp collisions.

The CMS detector has nearly 4π solid angle acceptance and an extended coverage of more than ten units in pseudorapidity ($\eta = -\log[\tan(\theta/2)]$, with θ being the polar angle along the beam direction). Its large superconducting solenoid of 6 m internal diameter, with 3.8 T axial magnetic field, is surrounding the three-layer silicon pixel and the strip tracker, the crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to these detectors, CMS has extensive forward calorimetry, in particular two steel/quartz-fiber Cerenkov forward hadronic calorimeters (HF, $2.9 < |\eta| < 5.2$). A complete description of the CMS detector can be found in Ref.[3].

Spatial asymmetries reflect the eccentricities in the overlapping region of the two colliding nuclei in non-central collisions. They drive a collective anisotropic expansion after the local thermal equilibrium is attained, following the strong re-scattering of the partons in the initial state, resulting in the observed azimuthal anisotropies. The azimuthal dependence of the particle yield can be written in terms of an harmonic expansion with $E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(\sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_{EP})]\right)$ where ϕ is the azimuthal angle and $\psi_{n,EP}$ is the n^{th}-order event plane (EP) angle measured experimentaly. The event-plane is determined event-by-event and contains both the beam direction and the azimuthal direction of maximum particle density. For achieving the maximum pseudorapidity gap possible (three units in $\Delta\eta$), which reduces the non-flow contribution, elliptic flow v_2 and triangular flow v_3 event planes are defined by means of the forward calorimeter data, with HF^+ (within $3 < \eta < 5$) and HF^- (within $-5 < \eta < -3$). Another event plane using tracker data with $0.75 \leq \eta \leq 0.75$ is also defined and used in the three-subevent technique for determining the resolution corrections for HF^+ and HF^-.

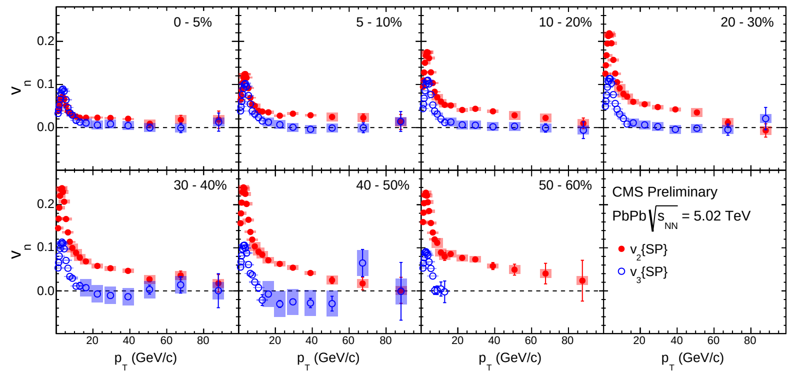

Figure 1: Results $v_2\{SP\}$ and $v_3\{SP\}$ measured in *PbPb* collisiosn at $\sqrt{s_{NN}}$ are shown in several centrality windows as a function of the transverse momentum p_T. Statistical and systematic uncertainties are represented, respectively, by bars and shaded boxes.

The scalar product method is employed for measuring the $v_2\{SP\}$ and $v_3\{SP\}$ anisotropy coefficients as a function of p_T up to 100 GeV/c, for several collision centrality intervals in the overall range 0-60%. The details about data samples, experimental procedures, the scalar product method and the systematic uncertainties, can be found in Ref. [6]. The results are shown in Fig. 1, with statistical and systematic uncertainties represented by bars and shaded boxes, respectively.

It can be seen that, for all centralities, $v_2\{SP\}$ shows a rapid rise up to $p_T \approx 3$ GeV/c and then falls fast up to $p_T \approx 10$ GeV/c, decreasing more slowly for higher p_T values. At low-p_T, $v_2\{SP\}$ increase from most central to mid-peripheral events (30-40%), and then decrease toward more peripheral ones, showing a similar p_T behavior in all measured centralities. The $v_3\{SP\}$ values are also exhibited in Fig. 1, showing a similar behavior as that of $v_2\{SP\}$ for the same centrality ranges, although being practically centrality independent for low p_T. Besides, the measured $v_3\{SP\}$ shows non-zero values up to $p_T \approx 20$ GeV/c, which is consistent with picturing the system as being subjected to fluctuating initial conditions (if the initial conditions were described by nucleons uniformly distributed in both nuclei, in a rotationally invariant way, the odd harmonics would be identically zero, by symmetry).

In order to investigate the origin of the non-zero anisotropy coefficients up to such high p_T and to explore its possible collective nature, the v_2 values are also obtained from correlations of 4, 6 and 8 particles. The Q-cumulant method is used to measure $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$, which provides a fast, exact (no approximations), and unbiased (no interference between different harmonics) evaluation of the cumulants. It is also less subjected to non-flow since, if M particles are produced in a collisions, direct k-particle correlations are of order $1/M^{k-1}$, so that they become smaller as k increases. Therefore, the 4^{th}-, 6^{th}-, 8^{th}-order cumulant, as well as and the Lee-Yang zeros (LYZ) (involving all particles in the event) methods are expected to be much less affected by non-flow contributions than the second-order one. The cumulants are expressed in terms of the moments of the magnitude of the corresponding flow vectors Q_n. The details of the technique and measurement are in Ref. [6]. The corresponding results are shown in Fig. 2.

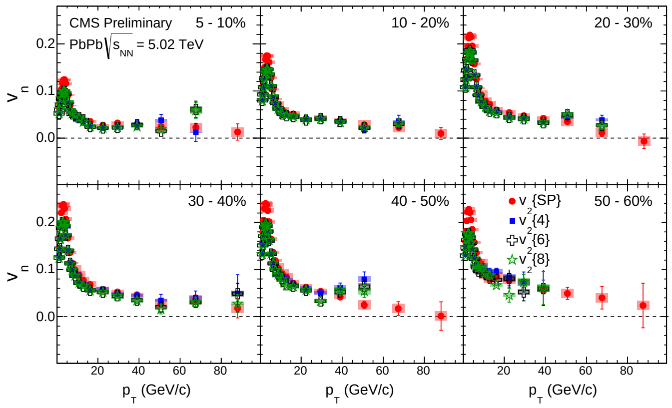

Figure 2: Results from $v_2\{SP\}$ and multi-particle cumulants $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$ are shown as a function of p_T in six centrality ranges of PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Statistical and systematic uncertainties are represented, respectively, by bars and shaded boxes.

It can be seen from Fig. 2 that, in the range $p_T < 3$ GeV/c, $v_2\{SP\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$, a result that is consistent with the expectations from hydrodynamics. For $p_T > 10$ GeV/c, $v_2\{SP\} \approx v_2\{m\}$, providing strong evidence that collective anisotropic particle emission in heavy ion collisions extends to very high p_T. Although the nature of the collectivity at high p_T may be related to the jet quenching phenomena, these observations of anisotropies at both low and high p_T are likely related to the initial state anisotropies and event-by-event fluctuations, posing a challenge to theoretical models.

Recently, the long-range two-particle correlation phenomena in high-multiplicity pp collisions had its characterization extended by a detailed investigation of two- and multi-particle azimuthal correlations with unidentified charged particles, as well as correlations of reconstructed V^0 particles (i.e., K_S^0 and $\Lambda/\bar{\Lambda}$) in pp collision at $\sqrt{s_{NN}} = 5,7$ and 13 TeV energies. The technique used for investigating two-hadrons correlations defines, for each track multiplicity class, "trigger" particles as charged particles or V^0 candidates with $|\eta| < 2.4$, originating from the primary vertex within a given p_T^{trig} range. Particle pairs are then formed by associating each trigger particle with the remaining charged primary tracks with $|\eta| < 2.4$ and from a specified p_T^{assoc} interval (which can be either the same as or different from the p_T^{trig}). A pair is removed if the associated particle is the daughter of any trigger V^0 candidate (this contribution is negligible since associated particles are mostly primary tracks). The background to such signal combination is constructed by pairing the trigger particles in each event with the associated charged particles from 20 different randomly selected events in the same 0.5 cm wide longitudinal vertex position (z_{vtx}) range and from the same track multiplicity class. The same-event and mixed-event pair distributions are first calculated for each event, and then averaged over all the events within the track multiplicity class. Details of this analysis, containing the data samples, event selections, as well as a complete description of the technique used for studying dihadron correlations, and the estimate of corresponding systematic uncertainties can be found in Ref. [9] and in references therein.

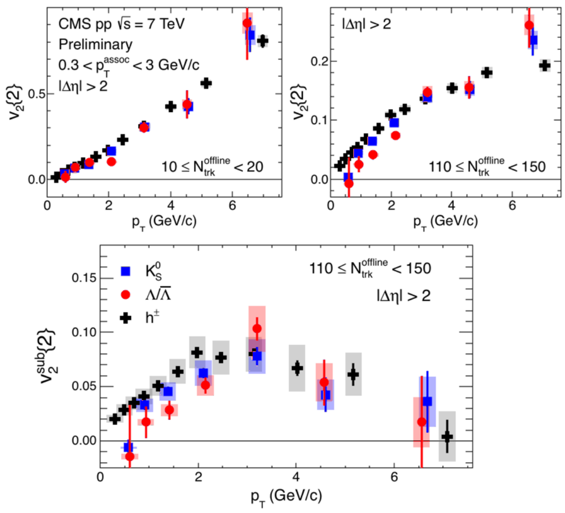

Figure 3: Results from $v_2\{2\}$ and $v_2^{sub}\{2\}$ are shown in the low-track multiplicity event, as well as in the high multiplicity case. Statistical and systematic uncertainties are represented, respectively, by bars and shaded boxes.

The v_2 and v_3 harmonics extracted from two-particle correlations are studied as functions of particle p_T and event multiplicity and are shown in Fig. 3 (top panel). The residual contribution of back-to-back jets to long-range correlations is estimated and removed by subtracting similar correlations obtained from very low multiplicity pp events, with result also shown in Fig. 3 (bottom).

No clear mass-ordering for low $N_{trk}^{offline}$ ranges is seen in Fig. 3. However, in the high multiplicity $N_{trk}^{offline}$ range, a clear mass-ordering is observed, which is indicative of the presence of radial flow. For the subtracted flow component $v_2^{sub}\{2\}$, it can also be seen that for K_S^0, $v_2^{sub}\{2\}$ is higher than for $\Lambda/\bar{\Lambda}$ at low p_T, but the order is reversed in the high-p_T range. For the subtracted flow component $v_2^{sub}\{2\}$, it can be clearly seen that the values of this variable increase up to $p_T \approx 2-3$ GeV/c, and then decrease.

Further significant results obtained in this study are shown in the panel of Fig. 4, corresponding to the elliptic flow harmonics v_2 obtained with the cumulant method for high multiplicity pp collisions at 13 TeV (left), high multiplicity pPb collisions at 7 TeV (middle) and PbPb collisions at 2.76 TeV (right) energies in the nucleon-nucleon center-of-mass. First, the similarity of the results for these very different systems is indeed remarkable, except for a smaller ratio $v_2\{2\}/v_2\{4\}$ in the case of pp collisions. This difference perhaps suggests that there would be fewer fluctuating

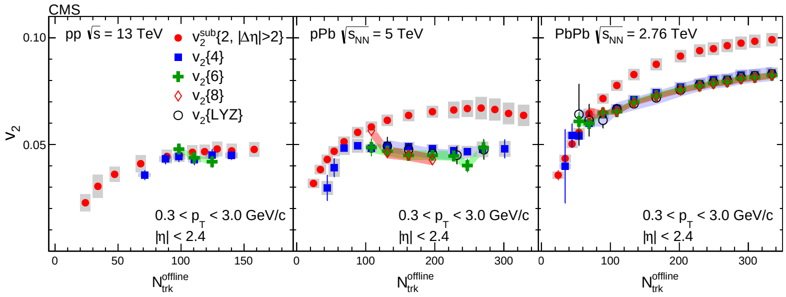

Figure 4: Results from $v_2^{sub}\{2\}$ and $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$ are shown as a function of $N_{trk}^{offline}$ for pp collisions in the high multiplicity realm, as well as for pPb and PbPb collisions at the LHC enegies, exhibiting a stricking similarity in the three systems. Shaded boxes represent systematic uncertainties. Statistical and systematic uncertainties are represented, respectively, by bars and shaded boxes.

sources in the initial conditions of pp collisions, as compared to pPb and PbPb. Finally, the most stricking result in the pp case, regarding the higher-order cumulants, with $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$, clearly shows evidence of collective behavior in pp collisions, as expected from hydrodynamics, which had been already observed earlier in the pPb and PbPb cases. These observations pose an even bigger challenge to theoretical models to explain.

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