

Flow and correlations results from CMS

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The observation of long-range two-particle correlations in high energy heavy ion collisions opens the opportunities of exploring novel QCD dynamics in quark gluon plasma (QGP), the hot dense matter created in heavy ion collisions. In particular, such correlations are sensitive to the degree of thermalization in the system. We present selected results from non-identified and identified two-particle and multi-particle correlations in PbPb collisions, as well as in lighter systems.

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1. Introduction

Ultra-relativistic heavy ion collisions are a ideal terrain for exploring strongly interacting matter under extreme conditions. A stepping stone in high energy physics is the discovery of QGP at RHIC (Relativistic Heavy-Ion Collider) [1], a new medium defined as thermally equilibrated state of matter in which quarks and gluons are deconfined from hadrons [2]. Two observables that advocate directly the existence of Quark-Gluon Plasma are measurements of flow and the suppression of high p_T hadrons. The flow, as a manifestation of non-uniform emission of final state particles, can be described successfully by relativistic hydrodynamics treating the QGP as almost a perfect liquid. Two-particle and multi-particle correlations have been used extensively at the CMS experiment in quantifying the spacial anisotropy through measurements of the flow signal v_n with identified and non-identified reconstructed particles.

2. Multi-particle correlations in PbPb and pPb

Dihadron correlations are a robust tool in handling the effects of particle production in relativistic heavy ion collisions. One significant effect that was observed in two-particle correlations is the presence of a near side ($\Delta\phi \sim 0$) "ridge-like" structure. This long range correlation was first measured at the STAR experiment [3, 4] and than extensively investigated at LHC energies [5, 6, 7, 8]. In the case of symmetrical nucleus-nucleus (AA) collisions this ridge-like structure can be explained by higher order harmonics predominantly by the triangular v_3 flow [9]. However, these long-range correlations have also been observed in smaller systems, like proton-proton (pp) [10] and proton-lead (pPb) [11, 12] collisions for high multiplicity case at the LHC. The question then arises if this long-range correlations, for smaller systems, can also be put in the context of hydrodynamic models. One way of inferring this is to investigate multi-particle correlations since, from a hydrodynamical point of view, all multi-particle azimuthal correlations stem from anisotropic collective expansion of the created medium. In figure 1 the second-order Fourier harmonic v_2 , averaged over $0.3 < p_T < 3.0$ GeV/c, is plotted as a function of multiplicity $N_{\text{trk}}^{\text{offline}}$ for PbPb (left) and pPb (right). With open symbols results of v_2 from two and four-particle correlations from CMS [13] are presented. As an extension of this analysis higher order correlations were calculated, the six- ($v_2\{6\}$) and the eight- ($v_2\{8\}$) particle case, and also the Lee-Yang zero which represents the all-particle correlation method. For both the symmetrical PbPb and asymmetrical pPb system, the v_2 falls within the $\pm 10\%$ difference range for all the methods ($v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$ and LYZ) a result that favours the collective nature of the analysed systems. Comparing the two-particle $v_2\{2\}$ results with higher order correlations we see consistent higher values which can be explained by hydrodynamical models as a consequence of event-by-event participant geometry fluctuations.

3. Two-particle correlations of strange hadrons

CMS conducted measurements of two-particle angular correlations between identified strange hadrons (K_S^0 and $\Lambda/\bar{\Lambda}$) and unidentified charged particles in PbPb and pPb collisions. The reconstruction technique for K_S^0 and $\Lambda/\bar{\Lambda}$ candidates (generally referred to as V^0 's) is described in [14]. Using the two-particle method the construction of the corresponding correlation function follows

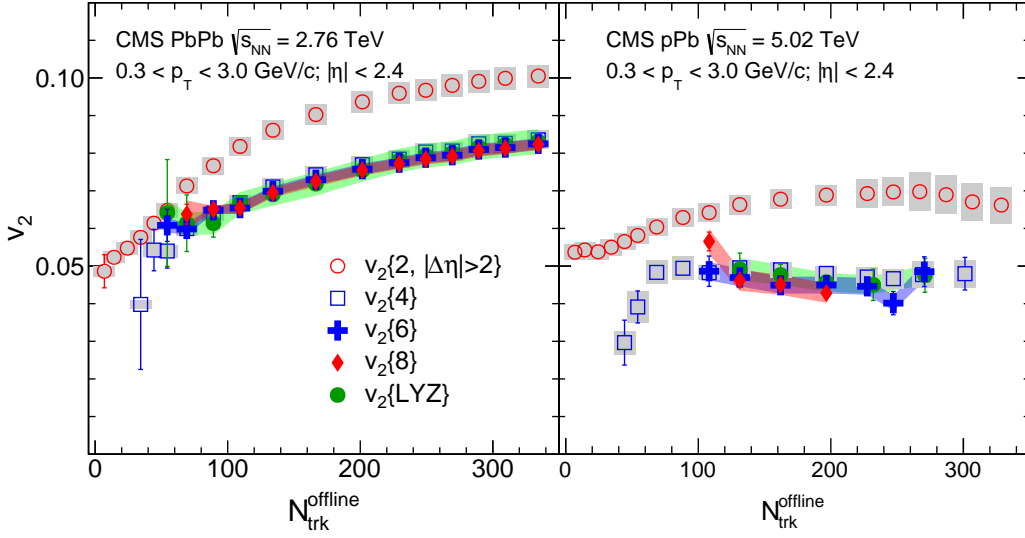


Figure 1: Values of v_2 obtained from 6-particle (blue cross), 8-particle (red diamond) cumulants, and LYZ (green filled circle) method, averaged over particle p_T range of 0.3-3.0 GeV/c, as a function of multiplicity $N_{\text{trk}}^{\text{offline}}$ in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV (left) and pPb at $\sqrt{s_{NN}} = 5.02$ TeV (right). Open data points are published two-particle and four-particle v_2 results from [13]. Shaded areas denote systematic uncertainties.

the same methodology as in [15, 16]. The azimuthal two-particle harmonics $V_{n\Delta}$ of K_S^0 and $\Lambda/\bar{\Lambda}$ are extracted through the Fourier decomposition of the correlation function averaged over $|\Delta\eta| > 2$ (in order to remove short-range correlations such as jets) as was done in [14]. Using the two-particle Fourier coefficients the single-particle harmonics are calculated as,

$$v_n(p_T^{V_0}) = \frac{V_{n\Delta}(p_T^{V_0}, p_T^{\text{ref}})}{\sqrt{V_{n\Delta}(p_T^{\text{ref}}, p_T^{\text{ref}})}}, \quad n = 2, 3. \quad (3.1)$$

Here the p_T^{ref} is the reference bin for the range $0.3 < p_T^{\text{ref}} < 3.0$ GeV/c to minimize correlations from jets at higher p_T . Figure 2 shows measured v_2 values of K_S^0 and $\Lambda/\bar{\Lambda}$ and inclusive charged

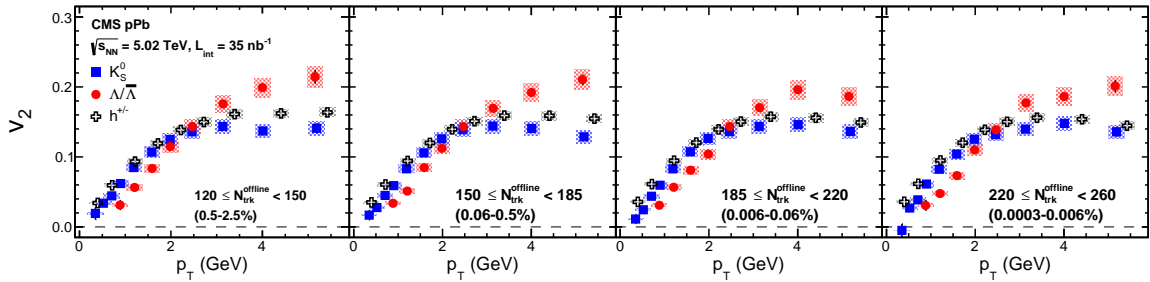


Figure 2: v_2 results for K_S^0 (filled squares), $\Lambda/\bar{\Lambda}$ (filled circles) and inclusive charged particles (open crosses) as a function of p_T for four multiplicity ranges in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

particles for pPb collisions. In the $p_T \leq 2$ GeV/c domain for all multiplicity ranges, the v_2 values for K_S^0 particles are larger than those of $\Lambda/\bar{\Lambda}$ with inclusive charged particles v_2 values being above the K_S^0 , $\Lambda/\bar{\Lambda}$ cases. For higher p_T values the mass ordering reverses for K_S^0 and $\Lambda/\bar{\Lambda}$ now with inclusive

charged particles v_2 values falling between the values of the two identified strange hadron species. Comparing the PbPb and pPb case, even though one observes qualitatively a similar particle-species mass ordering of v_2 , the mass ordering effect is found to be less clear in PbPb data than in pPb data for all multiplicity ranges [14]. In addition, the scaling effect was investigated, dividing the v_2 by the number of constituent quarks and plotting the values as a function of transverse kinetic energy per quark (KE_T) for pPb and PbPb. Figure 3 shows the v_2/n_q values for K_S^0 , $\Lambda/\bar{\Lambda}$ particles in pPb collisions. After introducing the scaling by the number of quarks the v_2 values for both particle species approximately fall on the same curve. This effect is conjectured to be connected with the quark recombination [17, 18], which postulates that collective flow is developed among constituent quarks first before they combine into final-state hadrons.

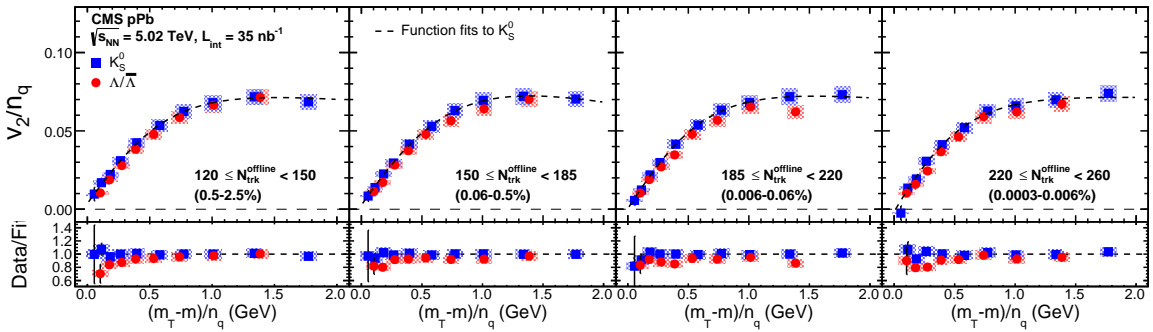


Figure 3: Ratio of v_2/n_q for K_S^0 (filled squares), $\Lambda/\bar{\Lambda}$ (filled circles) particles as a function of KE_T/n_q in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

4. Factorization breaking effect

Dealing with two-particle correlations a common assumption, in a pure hydrodynamical flow picture, is the effect of factorization. This means that the two-particle harmonic $V_{n\Delta}(p_T^a, p_T^b)$ is equal to the product of single particles anisotropies $v_n(p_T^a) \times v_n(p_T^b)$ ($n > 1$) i.e. it factorizes, explaining any deviation from this equality with contributions from non-flow effects. However, recent studies from hydrodynamics [19, 20, 21] show that this effect can follow completely from a pure flow picture induced via p_T -dependent event plane angle a dependence caused by initial state fluctuations within nuclei. This is illustrated from the following equation showing the relation between the harmonics,

$$V_{n\Delta}(p_T^a, p_T^b; \eta^a, \eta^b) = \langle v_n(p_T^a) v_n(p_T^b) \cos[n(\Psi_n(p_T^a, \eta^a) - \Psi_n(p_T^b, \eta^b))] \rangle. \quad (4.1)$$

From the last equation we can conclude that only when the event-plane angle is a global phase (no p_T and η dependence) we observe factorization. CMS conducted a detailed analysis [22] on the effect of factorization breaking focusing on both the p_T and η dependence of the event-plane angle. In order to quantify the effect for p_T case one uses the ratio r_n as in [22],

$$r_n = \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a) V_{n\Delta}(p_T^b, p_T^b)}}. \quad (4.2)$$

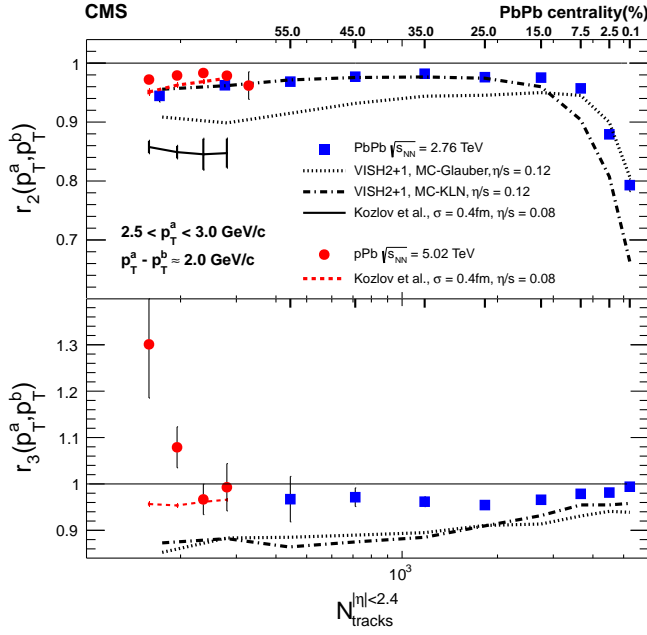


Figure 4: Ratio r_n for the elliptic and triangular case in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of centrality (multiplicity). Dashed lines show predictions of hydrodynamical models [20, 21].

In a hydrodynamical picture the ratio can only be $r_n \leq 1$, factorization breaking referring to values of r_n below unity, with $r_n > 1$ implying non-collective contributions. Figure 4 shows values of r_n for the elliptic and triangular case for PbPb and pPb collisions. The ratio is plotted versus centrality (multiplicity) including comparisons with hydro models predictions [20, 21]. In the case of PbPb collisions, looking from left to right, increasing centrality we see a steep drop of r_2 value going to around 0.8 (20% below unity) for the most central collisions (0-0.2%) where the initial state fluctuations are most dominant. Lowering the centrality and looking at peripheral collisions we observe that the effect is small and is on the level of 3-5%. Comparing the r_2 values for high multiplicity pPb collisions we see that it is similar in intensity with peripheral PbPb collisions. The triangular case r_3 shows that factorization holds better for this higher flow order. Using the hydrodynamical predictions for different initial-state conditions, we conclude that quantitatively they describe the experimental data well.

In addition, the longitudinal (η) event-plane angle dependence was investigated in PbPb and pPb collisions. The ratio r_n for the η case is defined as,

$$r_n(\eta^a, \eta^b) = \frac{V_{n\Delta}(-\eta^a, \eta^b)}{V_{n\Delta}(\eta^a, \eta^b)} \approx e^{-2F_n^\eta \eta^a}. \quad (4.3)$$

As for the p_T case, if the event-plane angle has longitudinal fluctuations the ratio $r_n(\eta^a, \eta^b)$ should have values below unity. The harmonics $V_{n\Delta}(\eta^a, \eta^b)$ are calculated in the same way as in the case of $V_{n\Delta}(p_T^a, p_T^b)$, now correlating tracks from two different (η^a, η^b) bins. Here, particle a is selected from the range $|\eta| < 2.4$ and $0.3 < p_T < 3.0$ GeV/c, while particle b is selected from the Hadron Forward Towers (total coverage of $2.9 < \eta < 5.2$) with the energy exceeding 1 GeV. In this way,

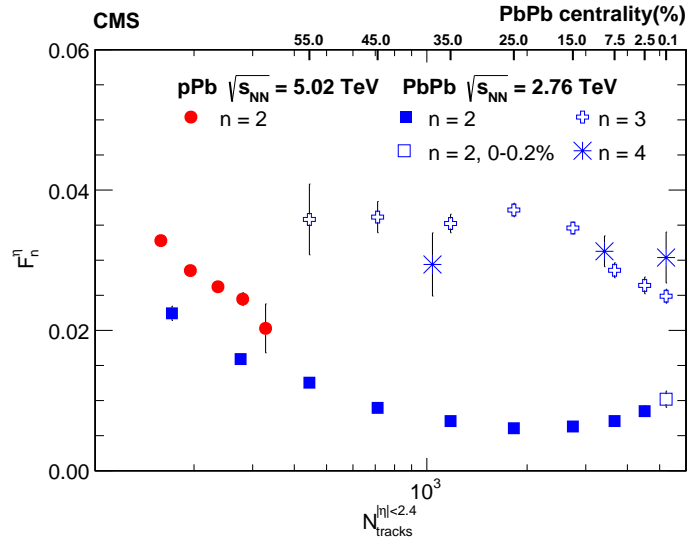


Figure 5: The F_n^η parameter as a function of multiplicity in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for $n = 2-4$ and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for $n=2$.

paring up tracks (a, b) from two sub-detectors we can apply a large $\Delta\eta$ cut between them and suppress the non-flow contributions. Observing differential values of $r_n(\eta^a, \eta^b)$ [22] we conclude that the ratio is independent of η^b , for η^a ranges where the long-range cut ($|\Delta\eta| > 2$) is valid. This can be used to introduce a parametrization of the ratio 4.3, with the assumption that relative fluctuations between two event plane angles depend only on their pseudorapidity difference. Figure 5 shows values of parameter F_n^η as a function of multiplicity, in pPb collisions for $n = 2$ and PbPb collisions for $n = 2-4$. The minimum for F_2^η is around mid-central (20%) PbPb collisions, and increases significantly for more peripheral PbPb events and also for pPb events. For the most central PbPb collisions, the F_2^η value increases slightly, although the r_2 data for 0-0.2% centrality are not well described by 4.3. For similar multiplicities, magnitude of F_2^η in pPb is significantly larger than those in PbPb. In PbPb collisions, a much stronger longitudinal factorization breakdown is seen for higher-order harmonics in comparison with $n=2$, as shown by the F_3^η and F_4^η parameters.

5. Summary

CMS conducted detailed studies in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using two- and multi-particle correlations with non-identified and identified particles. The observed long-range correlation ("ridge") in pPb is investigated with higher order cumulants, the six- ($v_2\{6\}$) and the eight- ($v_2\{8\}$) particle case and also the Lee-Yang zero which represents the all-particle case. The Fourier coefficient v_2 shows no dependence on the number of correlated particles with significant non-zero values favouring a hydrodynamical picture even for lighter systems. Two particle correlations were used in extracting single-particle anisotropy for reconstructed strange hadrons K_S^0 , $\Lambda/\bar{\Lambda}$ demonstrating important effects like "scaling" and mass ordering of v_2 . Finally, CMS investigated the effect of factorization breaking caused by the p_T and η dependent event-plane angle. The results show a clear presence of this effect for both the

transversal momentum and longitudinal case which is caused by initial state fluctuations within the nuclei.

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