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Jovan Milosevic for the CMS Collaboration

Abstract

The recent CMS results on anisotropic particle emission will be presented. Consistency between the results obtained using four-, six and eigth-particle correlation as well as the Lee-Yang zero method reveals a multi-particle nature of the long-range correlations observed in pPb collisions. By correlating an identified strange hadron (K^0_S or $\Lambda/\bar{\Lambda}$) with a charged particle, at large relative pseudorapidity, the magnitude of the elliptic and triangular flow of strange particles from both pPb and PbPb collisions have been extracted. The results for K^0_S and $\Lambda/\bar{\Lambda}$ scaled by the number of constituent quarks as a function of transverse kinetic energy per quark are in a mutual agreement (within 10) for both v_2 and v_3 over a wide range of particle transverse kinetic energy and event multiplicities. Due to the initial-state fluctuations, the event-plane angle depends on both, transverse momenta (p_T) and pseudorapidity (η), which consequently induce breaking of the factorization of the two-particle azimuthal anisotropy into a product of single-particle anisotropies. For p_T, maximal effect of factorization breaking of about 20is observed in ultra-central PbPb collisions. For η, the effect is weakest for mid-central PbPb events and gets larger for more central or peripheral PbPb collisions as well as for high multiplicity pPb collisions. The experimental results are consistent with recent hydrodynamic predictions in which the factorization breakdown effect is incorporated. It is found that the effect is mainly sensitive to the initial-state conditions rather than the shear viscosity of the medium.

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ANISOTROPY IN pPb AND PbPb COLLISIONS FROM CMS

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Abstract. The recent CMS results on anisotropic particle emission will be presented. A multi-particle nature of the long-range correlations observed in pPb collisions is revealed through consistency between the results obtained using four-, six and eight-particle correlation as well as the Lee-Yang zero method. The magnitude of the elliptic and triangular flow of strange particles from both pPb and PbPb collisions have been extracted by correlating an identified strange hadron (K^0_S or $\Lambda/\bar{\Lambda}$) with a charged particle separated by a large relative pseudorapidity. The results for strange, K^0_S and $\Lambda/\bar{\Lambda}$, particles scaled by the number of constituent quarks plotted as a function of transverse kinetic energy per number of constituent quarks are in a rather good mutual agreement for both v_2 and v_3 over a wide range of particle transverse kinetic energy and event multiplicities. The initial-state fluctuations induce that the event-plane angle is not any more a global quantity but depends on both, transverse momenta (p_T) and pseudorapidity (η), which further induces the factorization breaking of the two-particle azimuthal anisotropy into a product of single-particle anisotropies. In the p_T direction, maximal effect of factorization breaking of about 20% is observed in ultra-central PbPb collisions. In the η direction, the effect is weakest for mid-central PbPb events and gets larger for more central or peripheral PbPb collisions as well as for high multiplicity pPb collisions. The experimental results are compared with recent hydrodynamic predictions which involve the factorization breakdown effect. The effect is sensitive to the initial-state conditions rather than the shear viscosity of the medium.

1 Introduction

The methods of the two-, four-, six- and eight-particle correlations [1] as well as the Lee-Yang Zero method (LYZ) [2,3] could be used to extract the magnitude of the azimuthal anisotropy which is characterized by Fourier coefficients, v_n. The long-range ($|\Delta\eta| > 2$) correlation known as the ridge [4], observed in high-multiplicity pPb collisions using the two-particle correlations, gave a hint that such a structure could have a hydrodynamic origin. In order to give a strong evidence of the multi-particle nature of the observed long-range effect, the correlations among four or more charged particles from pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV are performed [5]. Beside charged particles, two-particle angular correlations are formed also between an identified strange hadron (K^0_S or $\Lambda/\bar{\Lambda}$) and a charged particle [6] separated by a large relative pseudorapidity ($|\Delta\eta| >$ 2). These correlations revealed similar ridge structures. The extracted Fourier coefficients, v_2 and v_3, scaled to the number of constituent quarks showed that found hydrodynamic behavior happens on the partonic level. It is shown that even in the case when the hydrodynamic flow is the only source of the long-range correlations, initial-state fluctuations makes the event plane angle dependent on both, p_T and η. This then leads to factorization breaking of the two-particle azimuthal anisotropy into a product of single-particle anisotropies [7–9].

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2 The CMS experiment and data used

A super-conducting solenoid surrounds the tracker detector of the CMS experiment [10]. Produced magnetic field of 3.8 T enabled precise measurements of p_T above 0.3 GeV/c. The data at the LHC energies of $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV in PbPb and pPb collisions with integrated luminosities of 160 μb^{-1} and 35 nb^{-1}, respectively, have been collected. The CMS detector has a wide pseudorapidity coverage ($|\eta| < 2.5$) which is excellently suited for studying the long-range correlations.

3 Results

3.1 Collectivity in pPb collisions

The magnitude of the elliptic flow, v_2, is measured using the two-, four-, six- and eight-particle correlation as well as using the LYZ method in both PbPb and pPb collisions [5]. In Fig. 1 is shown multiplicity dependence of the v_2 coefficient, averaged over $0.3 < p_T < 3.0$ GeV/c range and within $|\eta| < 2.4$.

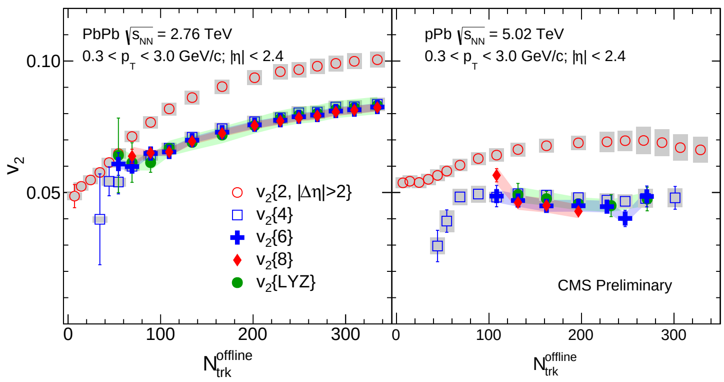

Figure 1: The v_2 values as a function of multiplicity obtained from two-, four-, six- and eight-particle cumulants, and LYZ methods in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV (left) and pPb at $\sqrt{s_{NN}} = 5.02$ TeV (right) collisions. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

In order to suppress jet-related non-flow effects, the elliptic flow magnitudes from two-particle correlations, $v_2\{2\}$, are obtained applying the $|\Delta\eta| > 2$ cut. The obtained $v_2\{2\}$ results are consistently above the results obtained from the multi-particle correlation. Such feature appeared due to the event-by-event participant geometry fluctuations of the v_2 coefficient which affect the two- and multi-particle correlations differently. Also, the v_2 results from higher order cumulants and from LYZ method are in mutual agreement within 2% and 10%

for PbPb and pPb collisions respectively. This mutual agreement between the v_2 results in high-multiplicity pPb collisions means that measured v_2 magnitude does not depend on the number of particles used in its reconstruction. This feature could be used as a strong evidence to support interpretation of the long-range correlation as a collective phenomenon not only in PbPb, but also in small systems formed in pPb collisions.

3.2 Collective flow of strange particles

Detailed description of the reconstruction technique for K_S^0 and $\Lambda/\bar{\Lambda}$ particles can be found in [6]. The magnitude of the single-particle flow coefficients, v_2 and v_3, is extracted from the two-dimensional $\Delta\phi - \Delta\eta$ distributions formed by correlating reconstructed strange particles candidates with charged particles. In order to remove short-range correlations such as jet fragmentation, a Fourier decomposition of the corresponding $\Delta\phi$ projection is applied after averaging over $|\Delta\eta| > 2$ region. The v_2 results for K_S^0 and $\Lambda/\bar{\Lambda}$ particles emitted from

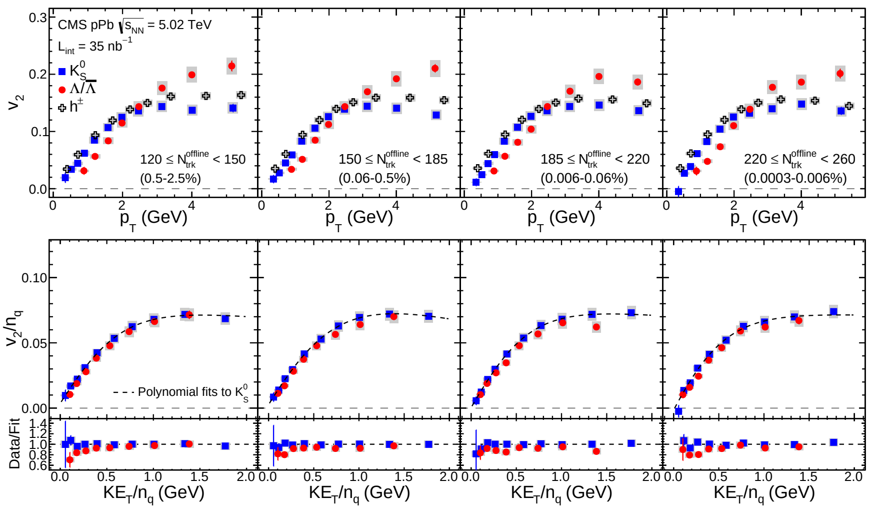

Figure 2: Top: the v_2 for K_S^0 (filled squares), $\Lambda/\bar{\Lambda}$ (filled circles), and charged particles (open crosses) as a function of p_T for four multiplicity ranges in high-multiplicity pPb events at $\sqrt{s_{NN}}$ = 5.02 TeV. Middle: the v_2/n_q ratios for K_S^0 (filled squares) and $\Lambda/\bar{\Lambda}$ (filled circles) particles as a function of transverse kinetic energy per quark KE_T/n_q. Bottom: ratios of v_2/n_q for K_S^0 and $\Lambda/\bar{\Lambda}$ particles to a smooth fit function of v_2/n_q for K_S^0 particles *vs* KE_T/n_q. The error bars correspond to statistical uncertainties, while the shaded areas denote the systematic uncertainties.

high-multiplicity pPb collisions are shown in Fig. 2. The corresponding peripheral PbPb results, obtained within the same multiplicity ranges as in the case of pPb collisions, are shown in Fig. 3. The top raw of Fig. 2 and Fig. 3 shows the v_2 in function of p_T for four high-multiplicity bins in pPb collisions and for four peripheral PbPb bins respectively. In both figures are also shown v_2

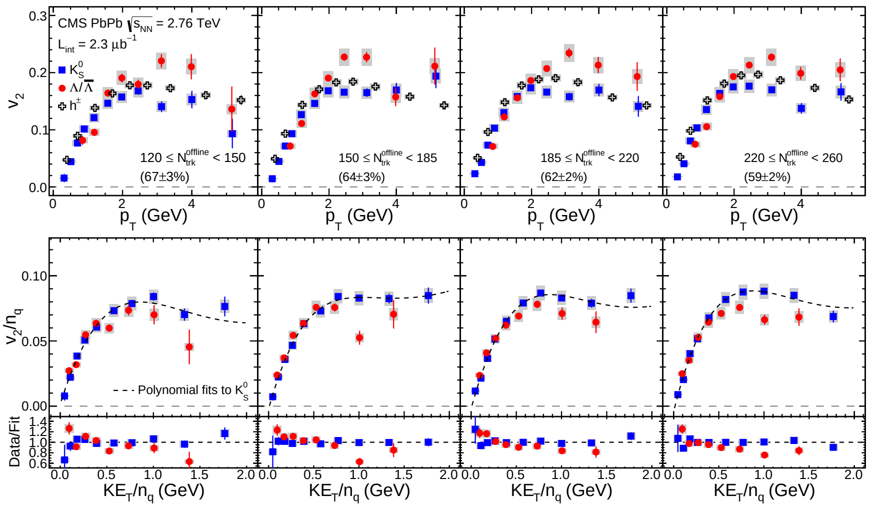

Figure 3: Top: the v_2 for K_S^0 (filled squares), $\Lambda/\bar{\Lambda}$ (filled circles), and charged particles (open crosses) as a function of p_T for peripheral PbPb events at $\sqrt{s_{NN}} = 2.76$ TeV. Middle: the v_2/n_q ratios for K_S^0 (filled squares) and $\Lambda/\bar{\Lambda}$ (filled circles) particles as a function of transverse kinetic energy per quark KE_T/n_q. Bottom: ratios of v_2/n_q for K_S^0 and $\Lambda/\bar{\Lambda}$ particles to a smooth fit function of v_2/n_q for K_S^0 particles *vs* KE_T/n_q. The error bars correspond to statistical uncertainties, while the shaded areas denote the systematic uncertainties.

results for charged particles. Huge majority of them are pions. The v_2 results exhibit a mass ordering effect: lighter particle species have a stronger azimuthal anisotropy at the given small p_T with respect to the heavier kind of particles. The effect is a bit less pronounced in PbPb collisions with respect to pPb ones. At high p_T appear two branches where the baryonic flow is greater than the mesonic v_2. In order to deeper investigate the seen effect, in the middle raw of Fig. 2 and Fig. 3 is shown the v_2 magnitude divided with the number of constituent quarks, n_q, and plotted as a function of transverse kinetic energy per quark, KE_T/n_q, with $KE_T = \sqrt{m^2 + p_T^2} - m$. This scaling makes that the v_2 of the shown particle species collapse onto a unique distribution. The bottom raw of Fig. 2 depicts the ratio between the data and a polynomial fit to the K_S^0 data which shows that the scaling is valid to better than 10% (25%) over most of the KE_T/n_q range in pPb (PbPb) collisions. For p_T values below 0.2 GeV/c the scaling breaks. The fact that the scaling behavior mainly holds could be related to the quark recombination model and suggests that the collective flow happens on the partonic level.

Beside the elliptic flow, the triangular flow, v_3, is also measured for strange

K_S^0 and $\Lambda/\bar{\Lambda}$ and charged particles in both colliding systems. Their magnitudes are depicted in Fig. 4. Due to limited statistics, the triangular flow has been analyzed within a wide multiplicity range ($185 \leq N_{trk}^{offline} < 350$) only. As in the case of the elliptic flow, a mass ordering effect is observed also for the triangular flow in both colliding systems. The distributions of the magnitude of the triangular flow scaled to the number of the constituent quarks for K_S^0 and $\Lambda/\bar{\Lambda}$ particles are in a mutual agreement better than 20% over the whole KE_T/n_q range. According to our knowledge, no calculations on the triangular flow scaled to the n_q has been performed in parton recombination models.

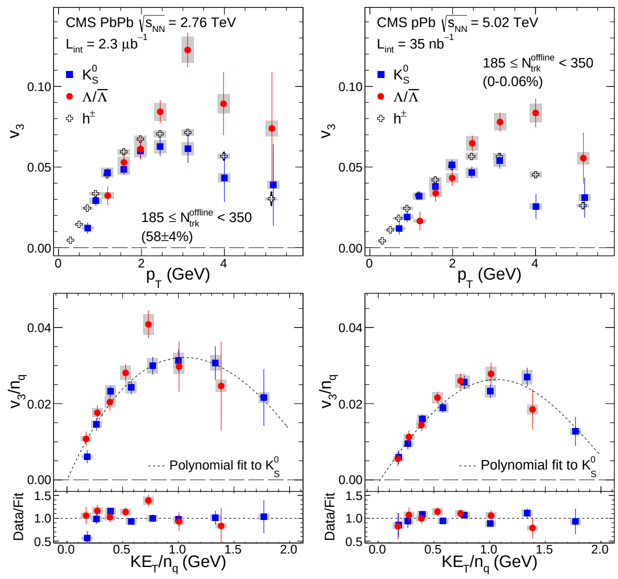

Figure 4: Top: the v_3 for K_S^0 (filled squares), $\Lambda/\bar{\Lambda}$ (filled circles), and charged particles (open crosses) as a function of p_T for the multiplicity range $185 \leq N_{trk}^{offline} < 350$ in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (left) and in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (right). Middle: the n_q-scaled v_3 values of K_S^0 and $\Lambda/\bar{\Lambda}$ particles as a function of KE_T/n_q. Bottom: Ratios of v_n/n_q to a smooth fit function of v_n/n_q for K_S^0 *vs* KE_T/n_q. The error bars correspond to statistical, while the shaded areas to systematic uncertainties.

3.3 Initial-state fluctuations and factorization breaking

Due to the event-by-event fluctuations in positions of nucleons which form the colliding nuclei, higher-order Fourier harmonics (n $\geq$ 3), measured with respect to their corresponding global event plane angles, Ψ_n, appear. Recently, it was discovered [7,8] that not only magnitudes of Fourier harmonics, v_n, but also Ψ_n could depends on p_T due to initial-state fluctuations even if the hydrodynamic flow is the only source of the correlations. It has an important consequence: the factorization of the two-particle azimuthal anisotropy, $V_{n\Delta}(p_T^{(a)}, p_T^{(b)})$, into a product of single-particle anisotropies, $v_n(p_T^{(a)}) \times v_n(p_T^{(b)})$, does not hold any more precisely. A new observable, r_n, is introduced. It is formed from the two-particle Fourier coefficients

$$r_n(p_T^{(a)}, p_T^{(b)}) \equiv \frac{V_{n\Delta}(p_T^{(a)}, p_T^{(b)})}{\sqrt{V_{n\Delta}(p_T^{(a)}, p_T^{(a)}) V_{n\Delta}(p_T^{(b)}, p_T^{(b)})}}, \tag{1}$$

and it is approximately equal to $\cos[n(\Psi_n(p_T^{(a)}) - \Psi_n(p_T^{(b)}))]$ (more details in [8,9]). If the factorization breaks (holds), then the r_n achieves value smaller (equal) than 1. If the r_n has the value greater than 1 then it means that there are unremoved non-flow effects. A most pronounced effect has been found in ultra-central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [11]. In the left (right) panel of Fig. 5 are shown p_T- (η-)dependent magnitudes of the factorization

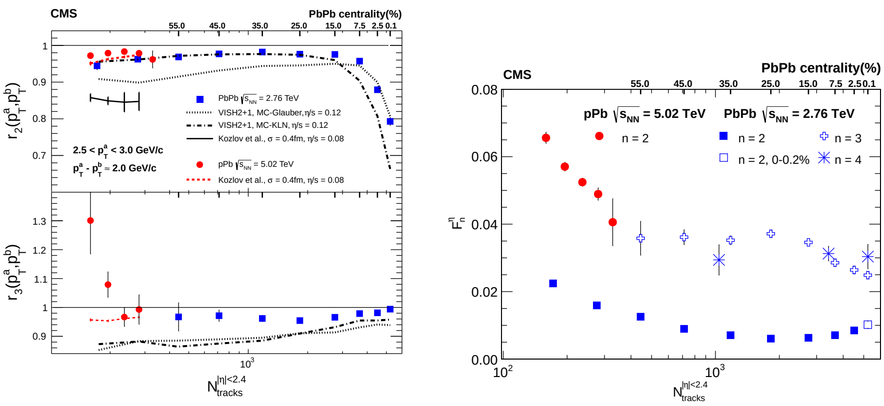

Figure 5: Left: The p_T-dependent r_2 and r_3 results as a function of multiplicity in pPb and PbPb collisions. The curves show the calculations for PbPb collisions from viscous hydrodynamics in Ref. [8] with MC-Glauber and MC-KLN initial condition models, and also hydrodynamic predictions for PbPb and pPb data in Ref. [7]. Right: The η-dependent F_n^η parameter as defined in Eq. (12) in [9] as a function of multiplicity in PbPb collisions for n = 2, 3 and 4 and pPb collisions for n = 2. The error bars correspond to statistical uncertainties, while systematic uncertainties are negligible.

breaking effect over a wide multiplicity range. The centrality axis, drawn at the top of the figures, is applicable only to the PbPb collisions. In the case of the 2nd harmonic, the smallest effect is observed for semi-central collisions, both for p_T- and η- dependencies. Going to more central or more peripheral collisions the size of the effect increases. At the same multiplicity, the size of the effect in the p_T- dependence is rather similar in the two colliding systems, while in the η- dependence the effect is much stronger in pPb than in PbPb collisions. In PbPb collisions, the size of the p_T-dependent r_3 is small and nearly independent of centrality, while in pPb collisions the r_3 approaches to 1 and then goes significantly above 1 at lower multiplicities. Oppositely to the p_T-, the η-dependence of the effect for the 3rd harmonic is stronger than for the 2nd one. The p_T-dependent data are qualitatively described by viscous hydrodynamic models [7,8] with fluctuating initial-state conditions, while they are mainly insensitive to the shear viscosity to entropy density ratio [9]. This promises of using the factorization data to disentangle contributions of the initial-state conditions and the mediums transport properties to the collective flow in the final state. The η-dependent factorization data show the influence of the initial-state fluctuations along the longitudinal direction. This could improve the three-dimensional modeling of the evolution of the strongly-coupled quark gluon medium.

Acknowledgments

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