LATEST RESULTS ON ANISOTROPY IN pPb AND PbPb COLLISIONS FROM CMS*

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In this paper, we present some of the heavy-ion results from CMS, restricting to anisotropic particle emission. Consistency between the results obtained using four-, six- and eight-particle correlations 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 ($K^0_{\rm S}$ 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 $K^0_{\rm S}$ 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 momentum ($p_{\rm T}$) and pseudorapidity (η), which consequently induce breaking of the factorization of the two-particle azimuthal anisotropy into a product of single-particle anisotropies. For $p_{\rm T}$, the maximal effect of factorization breaking of about 20% is 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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1. Introduction

The magnitude of the azimuthal anisotropy, characterized by Fourier coefficients, v_n, could be obtained using two-, four-, six- and eight-particle correlations [1] as well as the Lee–Yang Zero method (LYZ) [2,3]. The long-range correlation observed in pPb collisions from two-particle correlations, the ridge [4], gave a hint that such a structure could have a hydrodynamic origin. In order to further investigate the multi-particle nature of the observed long-range correlation, correlations among four or more charged particles for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are performed [5]. Beside charged particles, two-particle angular correlations between an identified strange hadron ($K^0_{\rm S}$ or $\Lambda/\bar{\Lambda}$) and a charged particle [6] revealed a similar ridge structure. The extracted v_2 and v_3 coefficients scaled to the number of constituent quarks showed that this hydrodynamic behavior happens on the partonic level. Even if the hydrodynamic flow is the only source of the seen correlations, initial-state fluctuations can cause that the event plane is not a global feature of the event, but that its position can depend both on $p_{\rm T}$ and η, which then leads to factorization breaking of the two-particle azimuthal anisotropy into a product of single-particle anisotropies [7–9].

2. The CMS experiment and data used

The CMS detector [10], placed within a super-conducting solenoid which produces a 3.8 T magnetic field enabling precise measurements of $p_{\rm T}$ above 0.3 GeV$/c$, collected the data at the LHC energies of $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV in PbPb and pPb with integrated luminosities of 160 μb^{-1} and 35 nb^{-1}, respectively. It has a wide pseudorapidity range ($|\eta| < 2.5$) which is excellently suited for flow measurements.

3. Results

3.1. Collectivity in pPb collisions

The elliptic flow, v_2, is measured from two-, four-, six and eight-particle correlation as well as from the LYZ method in both PbPb and pPb collisions [5]. Figure 1 shows the v_2 *vs.* multiplicity, averaged over $0.3 < p_{\rm T} < 3.0$ GeV$/c$ and within $|\eta| < 2.4$. In order to reduce jet-related non-flow effects, the $v_2\{2\}$ from two-particle correlations are obtained applying the $|\Delta\eta| > 2$ cut. These $v_2\{2\}$ data are consistently above the multi-particle correlation data due to the fact that the event-by-event participant geometry fluctuations of the v_2 coefficient affect the two- and multi-particle cumulants differently. The v_2 from higher order cumulants and from LYZ method is in mutual agreement within 2% and 10% for PbPb and pPb collisions respectively. As the v_2 in high-multiplicity pPb collisions does not depend on the number of particles used in its reconstruction, it is 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.

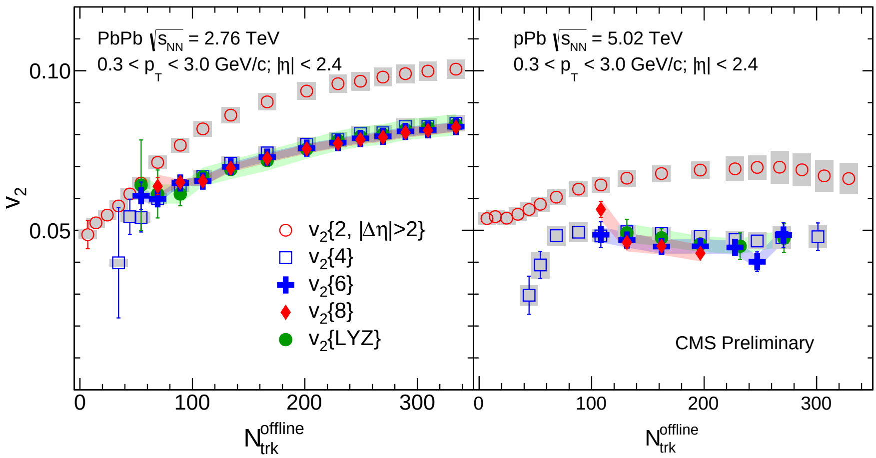

Fig. 1. The v_2 values as a function of multiplicity obtained from two-, four-, six- and eight-particle cumulants, and LYZ methods in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV (left) and pPb at $\sqrt{s_{NN}} = 5.02$ TeV (right) collisions. Statistical and systematic uncertainties are indicated by the error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

3.2. Collective flow of strange particles

The details of the reconstruction technique for K^0_{S} and $\Lambda/\bar{\Lambda}$ particles can be found in [6]. Due to the limited space, in this paper Fig. 2 is shown with the v_2 results for K^0_{S} and $\Lambda/\bar{\Lambda}$ particles emitted from high-multiplicity pPb collisions only. The corresponding peripheral PbPb results, within the same multiplicity ranges, can be found in [6]. The top row of Fig. 2 shows the v_2 in function of p_{T} for four high-multiplicity bins in pPb collisions. The majority of charged particles are pions. The v_2 results show a mass ordering effect: lighter particle species exhibit a stronger azimuthal anisotropy at the given small p_{T} with respect to the heavier ones. At high p_{T}, two branches appear where the baryonic flow is greater than the mesonic one. To investigate the seen effect deeper, in the middle row of Fig. 2 the v_2 divided with the number of constituent quarks, n_q, is shown and plotted as a function of transverse kinetic energy per quark, $\mathrm{KE_T}/n_q$, with $\mathrm{KE_T} = \sqrt{m^2 + p_{\mathrm{T}}^2} - m$. This scaling makes that the v_2 of the shown particle species collapse onto a unique distribution. The bottom row of Fig. 2 depicts the ratio between the data and a polynomial fit to the K^0_{S} data which shows that the scaling is valid to better than 10% over most of the KE_{T}/n_q range except for the values below 0.2 GeV$/c$. Similar behavior is seen in the peripheral PbPb data too [6]. The scaling behavior could be related to the quark recombination model and suggests that the collective flow happens on the partonic level.

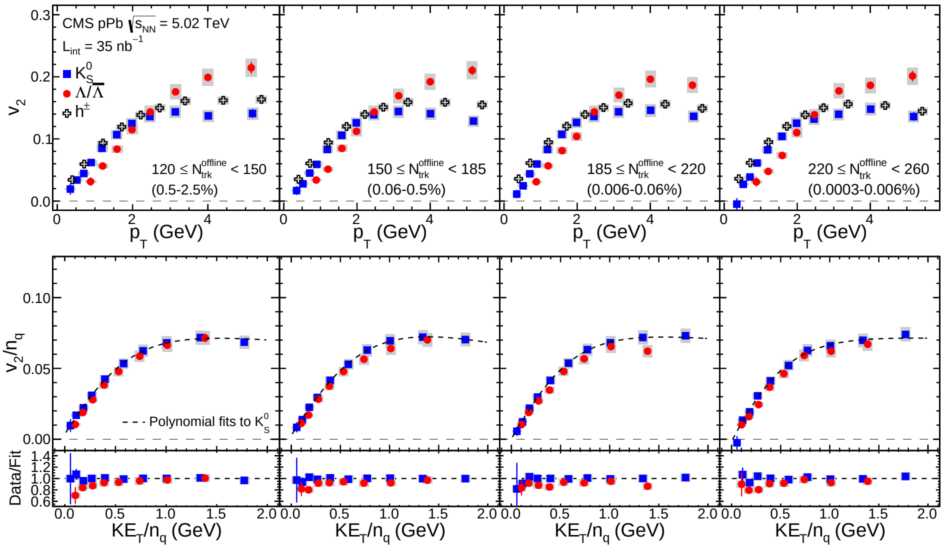

Fig. 2. Top: The v_2 for K^0_{S} (filled squares), $\Lambda/\bar{\Lambda}$ (filled circles), and charged particles (open crosses) *vs.* p_{T} for four multiplicity ranges in pPb events at $\sqrt{s_{NN}} = 5.02$ TeV. Middle: The v_2/n_q ratios for K^0_{S} (filled squares) and $\Lambda/\bar{\Lambda}$ (filled circles) particles *vs.* $\mathrm{KE_T}/n_q$. Bottom: Ratios of v_2/n_q for K^0_{S} and $\Lambda/\bar{\Lambda}$ particles to a smooth fit function of v_2/n_q for K^0_{S} particles *vs.* $\mathrm{KE_T}/n_q$. The error bars correspond to statistical uncertainties, while the shaded areas denote the systematic uncertainties.

Beside the elliptic flow, the triangular, v_3, flow is also measured for K^0_{S} and $\Lambda/\bar{\Lambda}$ particles in both colliding systems. The obtained results are presented in Fig. 3. Due to limited statistics, only the v_3 from $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 350$ multiplicity range is shown. As in the case of the v_2, a mass ordering effect is observed also for the v_3 in both systems. The distributions of the magnitude of the triangular flow scaled to the n_q for K^0_{S} and $\Lambda/\bar{\Lambda}$ particles are in a mutual agreement better than 20% over the whole $\mathrm{KE_T}/n_q$ range. According to our knowledge, no calculations on the v_3 scaling to the n_q has been performed in parton recombination models.

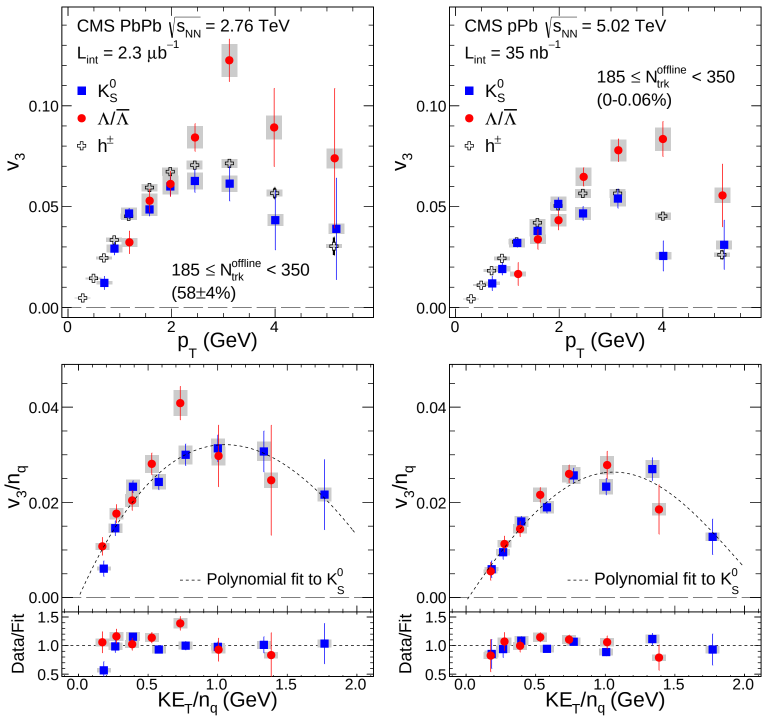

Fig. 3. Top: The v_3 for K^0_{S} (filled squares), $\Lambda/\bar{\Lambda}$ (filled circles), and charged particles (open crosses) *vs.* p_{T} for the multiplicity range $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 350$ in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (left) and in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (right). Middle: The n_q-scaled v_3 values of K^0_{S} and $\Lambda/\bar{\Lambda}$ particles *vs.* $\mathrm{KE_T}/n_q$. Bottom: Ratios of v_n/n_q to a smooth fit function of v_n/n_q for K^0_{S} *vs.* $\mathrm{KE_T}/n_q$. 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, higher-order Fourier harmonics ($n \geq 3$), measured with respect to their corresponding global event plane angles, Ψ_n, appear. It was discovered [7,8] that not only v_n, but also Ψ_n could depend on p_{T} due to initial-state fluctuations even if the hydrodynamic flow is the only source of the correlations. As a consequence, the factorization of the two-particle azimuthal anisotropy into a product of single-particle anisotropies does not hold any more precisely. A new observable, r_n, which is approximately equal to $\cos[n(\Psi_n(p_{\mathrm{T1}}) - \Psi_n(p_{\mathrm{T2}}))]$ (more details in [8,9]) is introduced. The r_n achieves value smaller (equal) than 1 when factorization breaks (holds). The value greater than 1 means that there are unremoved non-flow effects. A huge effect has been found in ultra-central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [11]. In Fig. 4, $p_{\rm T}$- and η-dependent magnitudes of the factorization breaking effect over a wide centrality/multiplicity range are shown. In the case of the 2$^{\rm nd}$ harmonic, the smallest effect is observed for semi-central collisions for both dependencies. Going to more central or more peripheral collisions, the size of the effect increases. At the same multiplicity, the size of the effect is rather similar in the two colliding systems. In PbPb collisions, the size of the $p_{\rm T}$-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 $p_{\rm T}$-, the η-dependence of the effect for the 3$^{\rm rd}$ hamonic is stronger than for the 2$^{\rm nd}$ one. The $p_{\rm T}$-dependent data are qualitatively described by viscous hydrodynamic models with fluctuating initial-state conditions, while they are largely insensitive to the shear viscosity to entropy density ratio [9]. This promises using the factorization data to disentangle contributions of the initial-state conditions and the medium's transport properties to the collective flow in the final state. The η-dependent factorization data give an indication of initial-state fluctuations along the longitudinal direction. This could improve the three-dimensional modeling of the evolution of the strongly-coupled quark–gluon medium.

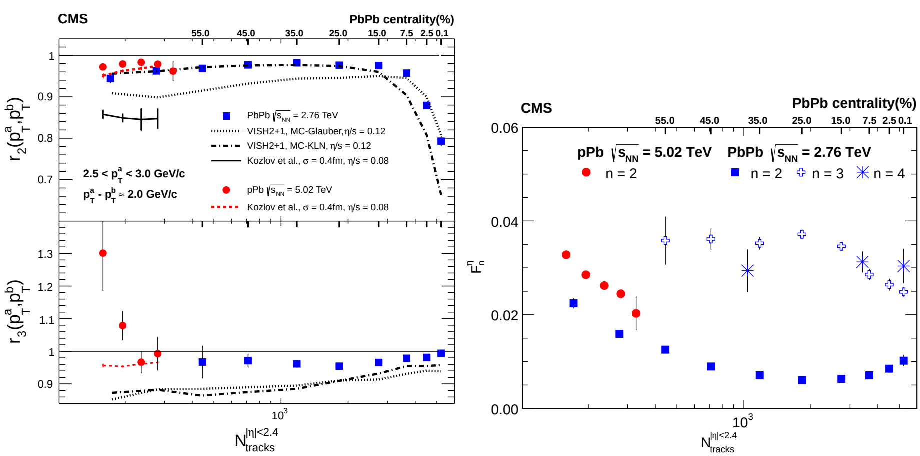

Fig. 4. Left: The $p_{\rm T}$-dependent r_2 and r_3 results *vs.* multiplicity in pPb and PbPb collisions. The curves show the calculations for PbPb collisions from viscous hydrodynamics in Ref. [8] with MC-Glauber and MC-KLN initial condition models, and also hydrodynamic predictions for PbPb and pPb data in Ref. [7]. Right: The η-dependent F_n^η parameter as defined in Eq. (12) in [9] *vs.* multiplicity in PbPb collisions for $n = 2$–4 and pPb collisions for $n = 2$. The error bars correspond to statistical uncertainties, while systematic uncertainties are negligible.

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