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New results on collectivity in small systems with CMS

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The elliptic (v_2) flow of prompt D^0 mesons, together with K^0_S, Λ, Ξ, and Ω in high-multiplicity pPb collisions at 8.16 TeV, is presented. The data are collected with the CMS detector at the LHC from the rapidity interval $-1.46 < y_{cm} < 0.54$ and transverse momentum range $1.5 < p_T < 8$ GeV. The results are compared to those from the 30–50% centrality PbPb data at 5.02 TeV. A mass-ordering behavior with a stronger v_2 of lighter species for $p_T < 2$ GeV is observed. The v_2 scaled to the number of constituent quarks vs the transverse kinetic energy per constituent quark shows that the D^0 scaled v_2 values in pPb collisions are smaller than those of light-flavor particles. Such an effect is not observed in PbPb collisions indicating a weaker collectivity of charm quarks than the one of light-flavor quarks, and a weaker coupling between heavy quarks and a possibly formed quark-gluon plasma droplet. The v_2 of prompt J/ψ mesons in high-multiplicity pPb collisions at 8.16 TeV is also measured. The J/ψ mesons are reconstructed via the dimuon channel with $1.4 <| y |< 2.4$ and $2 < p_T < 8$ GeV. This observation provides the most direct evidence for the presence of charm quark collectivity in pPb collisions. Comparison with v_2 of D^0 and strange hadrons allows a strong constraints on the dynamics of charm quarks produced in small hadronic collision systems with high multiplicities. Additionally, the standard and the subevent cumulant method is used to measure correlations between the v_2 and triangular (v_3) flow, and between the v_2 and quadrupole (v_4) flow in pPb collisions up to very low multiplicities. At high multiplicities, all methods give similar results showing that non-flow is not the dominant in this region, while at low multiplicities, the subevent method allows to strongly suppress the non-flow contribution and reveals the pure collectivity.

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1. Introduction

Particles emitted in relativistic nucleus-nucleus collisions exhibit collective azimuthal (ϕ) correlations which are long-range in pseudorapidity (η). These correlations suggest the formation of a strongly interacting quark-gluon plasma (QGP) that exhibits nearly ideal hydrodynamic behavior [1, 2]. Similar long-range collective azimuthal correlations are also observed in high-multiplicity proton-lead (pPb) events [3]. A question appears of whether a fluid-like QGP is created also in such a small system. Experimental measurements in these small systems are consistent with the hydrodynamic expansion of a tiny QGP droplet, but an alternative scenario based on gluon saturation in the initial state also claims ability to describe the main features of these correlations [4].

In the early stages of the hadronic collision, charm (c) and bottom (b) quarks are produced via hard scatterings. Thus, they could be used to study the properties and dynamics of the QGP through its entire evolution [5]. The observation of the elliptic flow (v_2) of prompt D^0 mesons in pPb collisions provided an evidence for c quark collectivity in a small system [6]. The v_2 of prompt D^0 mesons has somewhat smaller magnitude with respect to the v_2 produced by particles formed from light u and d quarks suggesting a weaker collective motion of c quarks relative to that of the bulk medium. As the D^0 meson is formed from both a light and a c quark, the relative contribution of different flavor quarks to the prompt D^0 v_2 signal is not fully constrained. Thus, the observation of the v_2 signal for J/ψ mesons in pPb collisions can provide the most direct evidence of c quark collectivity and impose new constraints on the collective dynamics of heavy quarks and their interaction with possibly formed QGP in small systems.

Additionally, in order to understand the onset of collective behavior from high- to low-multiplicity events in small systems, a subevent symmetric four-particle cumulant technique [7] has been performed using 8.16 TeV pPb data. For low-multiplicity events with $N_{trk}^{offline} \leq 80$, this method has been used to suppress non-collective contribution coming from few-particle correlations which arise from jets and thus to reveals a pure long-range azimuthal correlations up to events with $N_{trk}^{offline} \geq 50$. The method also allows to study event-by-event correlations among the v_2, and v_3 and v_4 Fourier harmonics, and to highlights its collective nature [3, 8, 9]. Namely, the correlation data are similar to those observed in PbPb collisions, where a negative correlation is found between v_2 and v_3 harmonics, while the correlation is positive between v_2 and v_4. This observation further supports the hydrodynamic origin of collective correlations in small systems.

2. Experiment and data used

The central feature of the CMS apparatus is a superconducting solenoid of 6m internal diameter, providing a magnetic field of 3.8T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcaps. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. For charged particles with transverse momentum $1 < p_T < 10$ GeV and $|\eta| < 1.4$, typical track resolution is 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [10]. Muons are measured

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in the $|\eta| < 2.4$ range. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [11].

The pPb data at $\sqrt{s_{NN}} = 8.16$ TeV used in these analyses were collected by the CMS detector, and correspond to an integrated luminosity of 186 nb^{-1}. The quantity $N_{trk}^{offline}$ is the number of primary charged-particle tracks [10] with $|\eta| < 2.4$ and $p_T > 0.4$ GeV. Events with $N_{trk}^{offline} < 35$ are used to estimate the contribution of residual non-flow back-to-back jet-like correlations. It is required that the events contain a primary vertex close to the nominal interaction point of the beams, within 15 cm along the beam direction, and 0.2 cm in the plane transverse to the beam direction.

Muon candidates are reconstructed either by finding tracks in the muon detectors, and then fitting them together with tracks reconstructed in the silicon tracker, or by extrapolating tracks from the silicon tracker to match a hit on at least one segment of the muon detectors. The muon candidates are also required to pass the identification criteria of the particle-flow algorithm [12].

The J/ψ meson candidates are formed from $\mu^+\mu^-$ pairs, originating from a common vertex. Due to the long lifetime of b hadrons compared to that of J/ψ mesons, nonprompt J/ψ components can be discriminated by measuring the displacement between the secondary $\mu^+\mu^-$ vertex and the primary collision vertex.

3. Methods used

The azimuthal anisotropy of J/ψ mesons is extracted from the long-range ($|\Delta\eta| > 1$) two-particle azimuthal correlations, following an identical procedure to that described in Refs. [3, 6, 8].

The symmetric cumulant (SC) is defined as

$$SC(n,m) = \langle\langle 4\rangle\rangle_{n,m,n,m} - \langle\langle 2\rangle\rangle_{n,n}\langle\langle 2\rangle\rangle_{m,m} \tag{3.1}$$

where 2- and 4-particle correlators are defined as

$$\langle\langle 2\rangle\rangle_{n,n} = \langle\langle e^{i(n\phi_1 - n\phi_2)}\rangle\rangle, \langle\langle 4\rangle\rangle_{n,m,n,m} = \langle\langle e^{i(n\phi_1 + m\phi_2 - n\phi_3 - m\phi_4)}\rangle\rangle \tag{3.2}$$

where n and m correspond to different harmonic order.

The $\langle\langle ...\rangle\rangle$ denotes the averaging over all events and over all particles of interest. The two-, three- and four-subevent cumulant (SC_{sub}) are then defined as

$$SC_{2sub}(n,m) = \langle\langle 4\rangle^{a,a|b^*b^*}_{n,m|n,m}\rangle - \langle\langle 2\rangle^{a|b^*}_{n|n}\rangle\langle\langle 2\rangle^{a|b^*}_{m|m}\rangle, \tag{3.3}$$

$$SC_{3sub}(n,m) = \langle\langle 4\rangle^{a^*|bb|c^*}_{n|m,n|m}\rangle - \langle\langle 2\rangle^{b|a^*}_{n|n}\rangle\langle\langle 2\rangle^{b|c^*}_{m|m}\rangle, \tag{3.4}$$

$$SC_{4sub}(n,m) = \langle\langle 4\rangle^{a^*|b|c^*|d^*}_{n|m|n|m}\rangle - \langle\langle 2\rangle^{a|c^*}_{n|n}\rangle\langle\langle 2\rangle^{b|d^*}_{m|m}\rangle. \tag{3.5}$$

where a, b, c and d denote the particles chosen in each subevent spanned over certain η window (for more details see [13]).

4. Results

The elliptic flow results corrected for residual jet correlations (v_2^{sub}) are shown in Fig. 1 (top left) for prompt D^0 mesons and for strange hadrons as functions of p_T for high-multiplicity pPb collisions. The prompt D^0 v_2^{sub} shows a p_T-dependence similar to those seen for particles made from light flavor quarks. In order to compare qualitatively the obtained results, in the top right panel of Fig. 1 are shown corresponding results extracted from PbPb collisions within centrality range of 30–50%. Collectivity at the partonic level is investigated by studying the scaling properties of v_2^{sub} divided by the number of constituent quarks (n_q) as a function of transverse kinetic energy per constituent quark, KE_T/n_q, for all measured particles. The corresponding plots for pPb (bottom left) and PbPb (bottom right panel) collisions are shown in Fig. 1. In pPb collisions, the v_2^{sub}/n_q for strange hadrons tend to follow a common trend for $0.5 < KE_T/n_q < 1.5$ GeV, while the D^0 v_2^{sub}/n_q has smaller value. This could suggest that the collective behavior of *c* quarks is weaker than that of the light-flavor *u*, *d* and *s* quarks. For KE_T/n_q above 1.5 GeV, no clear scaling of v_2^{sub}/n_q between mesons and baryons is observed. This is qualitatively different in the larger PbPb collision system with centrality between 30 and 50% where all particles show tendency to follow a universal trend.

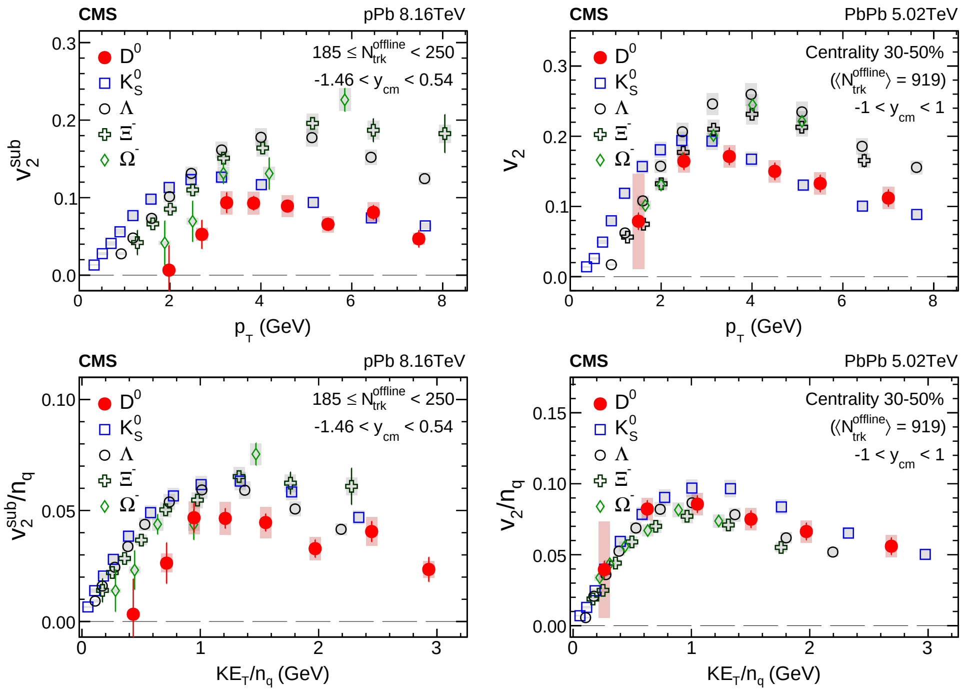

Figure 1: Top: prompt D^0 meson and strange hadrons v_2^{sub} *vs* p_T in pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV with $185 \le N_{trk} < 250$ (left) and PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with centrality of 30–50% (right) [6]. Bottom: the v_2^{sub} scaled to the number of constituent quarks [6]. The D^0 v_2^{sub} data in PbPb collisions are taken from Ref. [14]. The error bars (shaded areas) correspond to the statistical (systematic) uncertainties.

The v_2^{sub} values for prompt J/ψ mesons as a function of p_T in high-multiplicity pPb collisions are shown in Fig. 2 (top) and compared to K_S^0 and D^0 meson results. As in the case of D^0 mesons, the J/ψ v_2^{sub} exhibits a characteristic p_T dependence: first it rises, reaches a maximum and then decreases going to higher p_T values. In the context of the quark coalescence model, in Fig. 2 (bottom) are shown corresponding v_2^{sub} values scaled to the n_q and plotted *vs* KE_T/n_q to represent the collectivity at the partonic level. Over the full KE_T/n_q range, the scaled v_2^{sub} for prompt D^0 and J/ψ mesons is consistently below that of K_S^0 meson. However, no definitive conclusion can yet be claimed based on current experimental uncertainties.

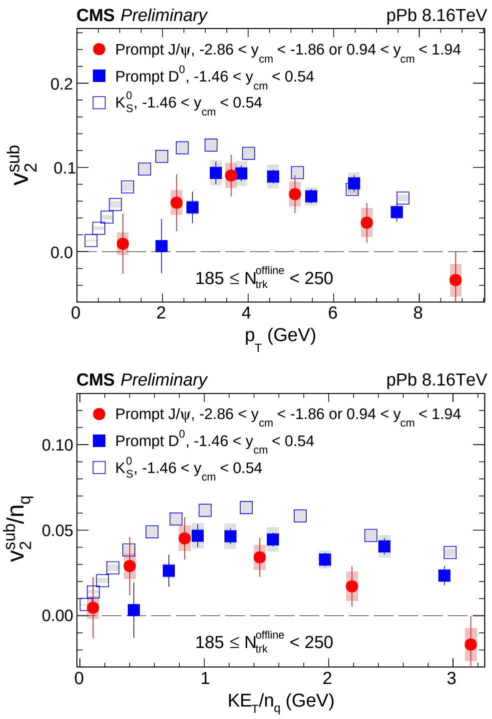

Figure 2: Top: Prompt J/ψ and D^0, as well as K^0_S v_2^{sub} *vs* p_T for pPb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV with $185 \leq N_{trk} < 250$ [15]. Bottom: the v_2^{sub} scaled to the number of constituent quarks [15]. The K^0_S and D^0 v_2^{sub} data are taken from Ref. [6]. The error bars (shaded areas) correspond to statistical (systematic) uncertainties.

Symmetric cumulants $SC(2,3)$ and $SC(2,4)$ for 2-, 3- and 4-subevents as a function of multiplicity in pPb collisions are shown in Fig. 3. For a comparison, in the same figure are also shown corresponding results with no subevents. For $N_{trk}^{offline} < 80$, both $SC(2,3)$ and $SC(2,4)$ diverge toward positive values in the no subevent case, likely because of a dominant contribution of few-particle correlations. But, in the case of using the subevent method, this trend is strongly suppressed. For $N_{trk}^{offline} > 50$ a clear negative values of $SC(2,3)$ are observed, while $SC(2,4)$ values are positive. These observations are similar to what was seen in PbPb collisions [16], and provide further evidence of collectivity observed in small systems down to events with $N_{trk}^{offline}$ of ≈ 50.

5. Summary

Significant v_2 values of prompt D^0 and J/ψ mesons in high-multiplicity pPb collisions at 8.16 TeV are measured. This observation provides an evidence for *c* quark collectivity in small collision system. The collectivity is weaker with respect to the one observed for light flavor quarks, unlike what is found in PbPb collisions. That provides strong constraints on the heavy quarks dynamics in small systems. The $SC_{sub}(2,3)$ and $SC_{sub}(2,4)$ are measured in pPb collisions at 8.16 TeV. An anti-correlation is observed between the elliptic flow v_2 and Fourier harmonic v_3, while v_2 and Fourier harmonic v_4 are positively correlated. At high multiplicities, standard and SC_{sub} give similar results for $SC(2,3)$ suggesting that non-flow is not dominant in this region,

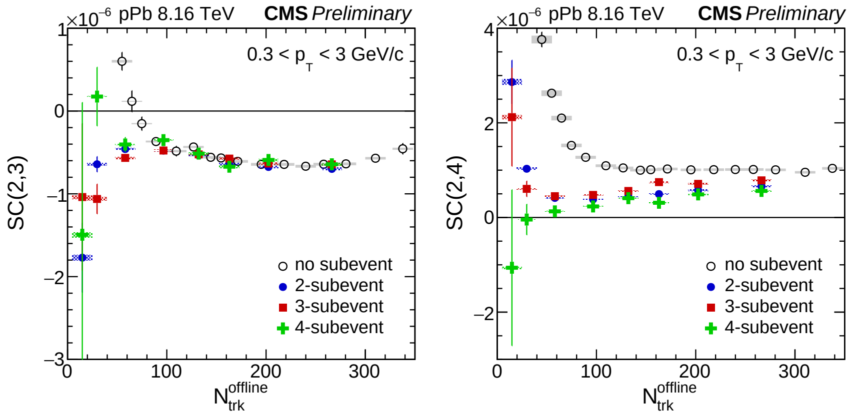

Figure 3: $SC(2,3)$ and $SC(2,4)$ *vs* $N_{trk}^{offline}$ from 2-, 3- and 4-subevents method [13]. Results taken from the Ref. [16] with no subevents are also shown. Shaded areas denote the systematic uncertainties.

while $SC(2,4)$ show a different behavior for different numbers of subevents, which emphasizes the sensitivity of $SC(2,4)$. For $50 < N_{trk}^{offline} < 80$, the subevent method suppresses the non-flow contribution and reveals the harmonic correlation from collectivity.

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