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Elliptic flow of charm and strange hadrons in high-multiplicity pPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 8.16\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

The elliptic azimuthal anisotropy coefficient (v_2) is measured for charm (D^0) and strange (K^0_S, Λ, Ξ^-, and Ω^-) hadrons, using a data sample of pPb collisions collected by the CMS experiment, at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{_{\mathrm{NN}}}} = 8.16\,\mathrm{TeV}$. A significant positive v_2 signal from long-range azimuthal correlations is observed for all particle species in high-multiplicity pPb collisions. The measurement represents the first observation of possible long-range collectivity for open heavy flavor hadrons in small systems. The results suggest that charm quarks have a smaller v_2 than the lighter quarks, probably reflecting a weaker collective behavior. This effect is not seen in the larger PbPb collision system at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$, also presented.

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There has been longstanding interest in the space-time evolution of the multiparticle production process in high energy collisions of hadrons [1]. The observation of strong collective flow, as inferred from the correlations in azimuthal angle (ϕ) of particles emitted over a wide pseudorapidity (η) range in relativistic nucleus-nucleus (AA) collisions, has been one of the key signatures suggesting the formation of a strongly interacting quark-gluon plasma (QGP) between the initial impact of the colliding nuclei and final production of particles. As observed first at the BNL RHIC [2–5] and later at the CERN LHC [6–11], the QGP exhibits nearly ideal hydrodynamical behavior [12–14]. In recent years, the observation of similar correlations in events with high final-state particle multiplicity resulting from proton-proton (pp) [15–17] and proton-lead (pPb) [18–21] collisions at the LHC has raised the question whether a fluid-like QGP is also created in these smaller collision systems [22].

The azimuthal correlation structure of emitted particles is typically characterized by its Fourier components [23]. In hydrodynamic models, the second and third Fourier components, known as elliptic (v_2) and triangular (v_3) flow, respectively, most directly reflect the QGP response to the initial collision geometry and its fluctuations [24–26]. The properties of the long-range correlation associated with light-flavor and strange hadrons in small systems are found to be similar to those observed in AA collisions. This includes, e.g., the particle species dependence [27–29] and multiparticle (or collective) nature [29–32] of the long-range correlation. More recently, such long-range correlations have also been observed in lighter systems at RHIC, including dAu [33–35] and ^{3}HeAu [36]. While these measurements are consistent with a hydrodynamic expansion, alternative scenarios based on gluon saturation in the initial state also claim to capture the main features of the correlation data (recent reviews are provided in Refs. [37, 38]).

The large masses of heavy quarks (charm and bottom) lead to their being produced in the early stages of the collision, and they thus probe the properties of the QGP through their interactions with the medium [39]. The elliptic flow results for D mesons in AA collisions measured at RHIC [40] and the LHC [41–43] suggest that charm quarks develop strong collective behavior, similar to the bulk production of light flavor particles from the QGP. In small systems, long-range correlation involving inclusive muons and J/ψ mesons have revealed hints of heavy flavor quark collectivity [44, 45]. Observation of D meson v_2 in the pPb system, and especially the comparison to the light-flavor and strange particle v_2, can impose further constraints on different interpretations related to the origin of the observed long-range collectivity. In particular, such measurements can provide key insights to properties of heavy quark interaction and thermalization within a hot QGP medium possibly formed at a significantly reduced system size.

This Letter presents the first measurements of the elliptic anisotropies of prompt D^0 mesons and strange hadrons (K^0_S, Λ, Ξ^-, and Ω^-) in pPb collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 8.16$ TeV. In all cases, particles and antiparticles are combined in the measurements. The v_2 harmonic of all particle species in high-multiplicity pPb events is determined in different intervals of transverse momentum (p_T), via long-range two-particle correlations with charged particles. The v_2 harmonics for the same strange hadrons are also measured in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for 30–50% centrality (defined as the fraction of the total inelastic cross section, with 0% denoting the most central collisions), to compare with the previously published D^0 v_2 results from these same collisions [43].

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume, there are four primary subdetectors including a silicon pixel and strip tracker detector, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Iron and quartz-fiber Cherenkov hadron forward calorimeters cover the range $2.9 < |\eta| < 5.2$. Muons are measured in gas-ionization detectors 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 $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [46]. A 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. [47].

The pPb data at $\sqrt{s_{_{\mathrm{NN}}}} = 8.16\,\mathrm{TeV}$ used in this analysis were collected by the CMS experiment in 2016, and correspond to an integrated luminosity of $186\,\mathrm{nb}^{-1}$. The beam energies are 6.5 TeV for the protons and 2.56 TeV per nucleon for the lead nuclei. Because of the asymmetric beam conditions, particles selected in this Letter from midrapidity in the laboratory frame ($|y_{\mathrm{lab}}| < 1$) correspond to rapidity in the nucleon-nucleon center-of-mass frame of $-1.46 < y_{\mathrm{cm}} < 0.54$, with positive rapidity corresponding to the proton beam direction. The event reconstruction, event selections, and triggers are identical to those described in Refs. [48, 49]. A subset of PbPb data at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ for 30–50% centrality is also used and reprocessed using the same reconstruction algorithm as the pPb data.

The pPb data are analyzed for multiplicity ranges of $N_{\mathrm{trk}}^{\mathrm{offline}} < 35$ and $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$, where $N_{\mathrm{trk}}^{\mathrm{offline}}$ is the number of primary tracks [46] with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.4\,\mathrm{GeV}$. Events in the multiplicity region of $N_{\mathrm{trk}}^{\mathrm{offline}} > 250$ is not included to avoid effects of multiple interactions in a single event (pileup). These bin boundaries correspond to fractional inelastic cross sections from 100 to 57%, and from 0.33 to 0.01%, respectively. The 30–50% centrality PbPb data have an average $N_{\mathrm{trk}}^{\mathrm{offline}}$ of 919.

The reconstruction and selection procedures for strange-hadron candidates in pPb collisions are identical to those in Refs. [28, 29, 50]. Pairs of oppositely charged particle tracks that are detached from the primary vertex (i.e., having large significance of impact parameters) are selected to determine if they point to a common secondary vertex from the decay of a $\mathrm{K_S^0}$, a Λ or a $\mathrm{D^0}$ candidate. The reconstruction efficiency for tracks with low momenta and large impact parameters is increased by using all tracks that pass the loose selection of Ref. [46]. The track pair is assumed to originate from $\pi^+\pi^-$ in $\mathrm{K_S^0}$ reconstruction, while the assumption of $\pi^-\mathrm{p}$ ($\pi^+\overline{\mathrm{p}}$) is used in the Λ ($\overline{\Lambda}$) reconstruction. To reconstruct Ξ^- and Ω^- particles, a Λ candidate is combined with an additional particle of the correct sign, assuming the pion or kaon PDG mass [51], to define an additional vertex. The $\mathrm{D^0}$ mesons are reconstructed through the hadronic decay channel $\mathrm{D^0} \rightarrow \mathrm{K}^-\pi^+$. In order to suppress the combinatorial background and improve the momentum and mass resolution, high-purity [46] tracks with $p_{\mathrm{T}} > 0.7\,\mathrm{GeV}$ and $|\eta| < 1.5$ are used. For each pair of selected tracks, two $\mathrm{D^0}$ candidates are considered by assuming one of the tracks has the pion mass while the other track has the kaon mass, and vice versa. Similar swapped-mass candidates are not required for strange hadrons since the two decay products are either the same mass (for $\mathrm{K_S^0}$) or so different in mass that momentum-sharing criteria can be used to identify which decay particle is the heavier one (for Λ, Ξ^- and Ω^-).

Several topological selections are applied to further reduce the combinatorial background. In particular, strange hadron and $\mathrm{D^0}$ candidates are selected according to the χ^2 probability of their decay vertex, the three-dimensional distance (normalized by its uncertainty) between the primary and decay vertices, and the pointing angle (defined as the angle between the line segment connecting the primary and decay vertices and the momentum vector of the reconstructed particle candidates in the plane transverse to the beam direction). The selection is optimized in each p_{T} bin, separately for different particle species, in order to maximize the statistical significance of the signal. For Ξ^- and Ω^- reconstruction, these selections are applied to both the initial decay vertex and the subsequent decay vertex of Λ.

In the case of the D^0 measurement, the selections on the pointing angle also suppress the fraction of nonprompt D^0 production (from decays of b hadrons). Simulated event samples of PYTHIA 8.209 [52, 53] D^0 signal events, embedded into EPOS LHC [54] minimum bias pPb events, are used to estimate the nonprompt D^0 contamination in data. By fitting the distributions of distance of closest approach of D^0 total momentum vector to the primary vertex, using the probability distribution functions (pdf) for prompt and nonprompt D^0 derived from simulation, the residual nonprompt fraction is found to be decreasing with p_T from 7 to 1%.

The azimuthal anisotropies of D^0 mesons and strange hadrons are extracted from their long-range ($|\Delta\eta| > 1$) two-particle azimuthal correlations with charged particles, as described in Refs. [28, 29]. Taking the D^0 meson as an example, the two-dimensional (2D) correlation function is constructed by pairing each D^0 candidate with reference primary charged-particle tracks with $0.3 < p_T < 3.0$ GeV (denoted "ref" particles), and calculating

$$\frac{1}{N_{D^0}} \frac{d^2 N^{pair}}{d\Delta\eta \, d\Delta\phi} = B(0,0) \, \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}, \tag{1}$$

where $\Delta\eta$ and $\Delta\phi$ are the differences in η and ϕ of each pair. The same-event pair distribution, $S(\Delta\eta, \Delta\phi)$, represents the yield of particle pairs normalized by the number of D^0 candidates from the same event. The mixed-event pair yield distribution, $B(\Delta\eta, \Delta\phi)$, is constructed by pairing D^0 candidates in each event with the reference primary charged-particle tracks from 20 different randomly selected events, from the same $N_{trk}^{offline}$ range, and with a primary vertex falling in the same 2 cm wide range of reconstructed z coordinate. The analysis procedure is performed in each D^0 candidate p_T range by dividing it into intervals of invariant mass. The correction for acceptance and efficiency (derived from PYTHIA+EPOS simulations) of the D^0 meson yield is found to have negligible effect on the measurements, and thus is not applied. The $\Delta\phi$ correlation functions averaged over $|\Delta\eta| > 1$ (to remove short-range correlations such as jet fragmentation) is then obtained from the projection of 2D distributions and fitted by the first three terms of a Fourier series (including additional terms has a negligible effect):

$$\frac{1}{N_{D^0}} \frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi} \left[1 + \sum_{n=1}^{3} 2 V_{n\Delta} \cos(n\Delta\phi) \right]. \tag{2}$$

Here, $V_{n\Delta}$ are the Fourier coefficients and N_{assoc} represents the total number of pairs per D^0 candidate. By assuming $V_{n\Delta}$ to be the product of single-particle anisotropies [55], $V_{n\Delta}(D^0, \text{ref}) = v_n(D^0) v_n(\text{ref})$, the v_n anisotropy harmonics for D^0 candidates can be extracted as a function of invariant mass, $v_n(D^0) = V_{n\Delta}(D^0, \text{ref}) / \sqrt{V_{n\Delta}(\text{ref}, \text{ref})}$. Because of the limited amount of available data, only the elliptic anisotropy harmonic is measured. The residual contribution of back-to-back dijets to the measured v_2 results is corrected by subtracting correlations from low-multiplicity pPb events, following an identical procedure established in Refs. [29, 55]. The Fourier coefficients, $V_{n\Delta}$, extracted from events with $N_{trk}^{offline} < 35$ are subtracted from those extracted from events with $185 \leq N_{trk}^{offline} < 250$ after accounting for the jet yield ratio of the selected events. The subtraction is not performed for PbPb results as the back-to-back jet correlations are found to be negligible in events with centrality between 30 and 50% [49].

To extract the v_2 values of the D^0 meson signal (v_2^S), a simultaneous fit to the invariant mass spectrum of D^0 candidates and their v_2 as a function of the invariant mass, $v_2^{S+B}(m_{inv})$, is performed in each p_T interval. The mass spectrum fit function is composed of three components: the sum of two Gaussian functions with the same mean but different widths for the D^0 signal,

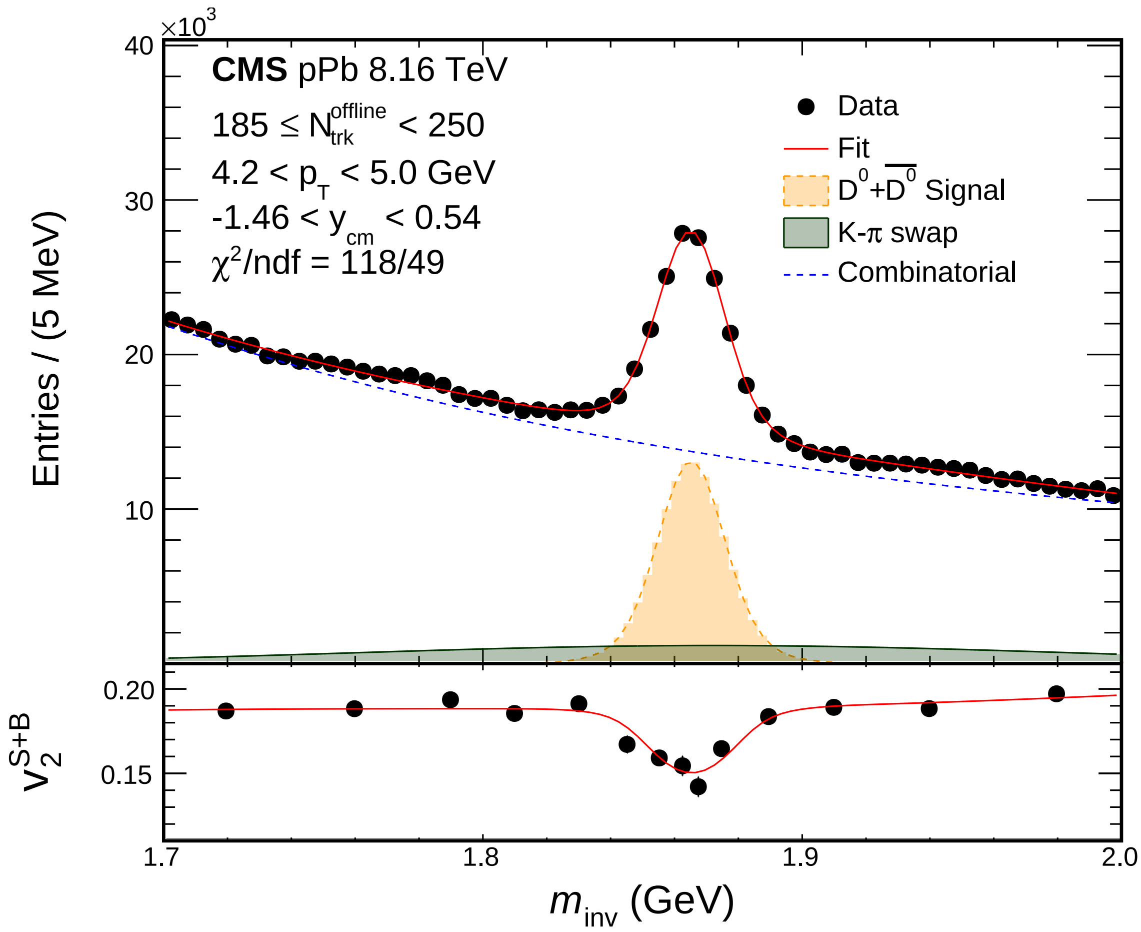

Figure 1: Example of the simultaneous fit to the invariant mass spectrum and $v_2^{S+B}(m_{\mathrm{inv}})$ in the p_{T} interval 4.2–5.0 GeV for events with $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$.

$S(m_{\mathrm{inv}})$, an additional Gaussian function to describe the invariant mass shape of D^0 candidates with an incorrect mass assignment from the exchange of the pion and kaon designations, $SW(m_{\mathrm{inv}})$, and a third-order polynomial to model the combinatorial background, $B(m_{\mathrm{inv}})$. The width of $SW(m_{\mathrm{inv}})$ and the ratio of the yields of $SW(m_{\mathrm{inv}})$ and $S(m_{\mathrm{inv}})$ are fixed according to results obtained from PYTHIA+EPOS simulation studies. The $v_2^{S+B}(m_{\mathrm{inv}})$ distribution is fitted with

$$v_2^{S+B}(m_{\mathrm{inv}}) = \alpha(m_{\mathrm{inv}})v_2^{S} + [1 - \alpha(m_{\mathrm{inv}})]v_2^{B}(m_{\mathrm{inv}}), \tag{3}$$

where

$$\alpha(m_{\mathrm{inv}}) = \frac{S(m_{\mathrm{inv}}) + SW(m_{\mathrm{inv}})}{S(m_{\mathrm{inv}}) + SW(m_{\mathrm{inv}}) + B(m_{\mathrm{inv}})}. \tag{4}$$

Here $v_2^{B}(m_{\mathrm{inv}})$ for the background D^0 candidates is modeled as a linear function of the invariant mass, and $\alpha(m_{\mathrm{inv}})$ is the D^0 signal fraction. The K-π swapped component is included in the signal fraction because these candidates are from genuine D^0 mesons and should have the same v_2 value as that of the non-swapped D^0 signal. Figure 1 shows an example of a simultaneous fit to the mass spectrum and $v_2^{S+B}(m_{\mathrm{inv}})$ in the p_{T} interval 4.2–5.0 GeV for the multiplicity range $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$ in pPb collisions. The v_2 values for the strange hadrons are extracted in the same way although no swapped-mass component is required.

As the residual contribution from nonprompt D^0 mesons is small, no explicit correction is applied and a systematic uncertainty is quoted instead. Based on the prediction for AA collisions

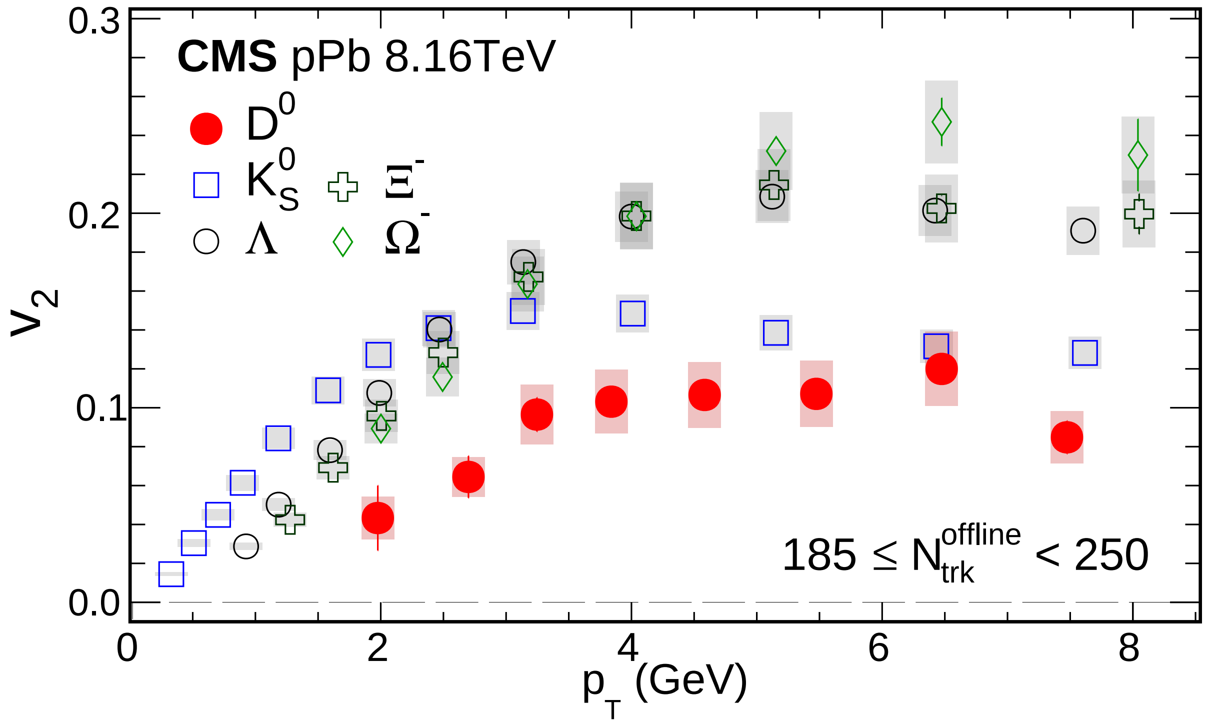

Figure 2: Results of elliptic flow (v_2) for D^0 mesons, as well as K^0_S, Λ, Ξ^-, and Ω^- particles, as functions of p_T for $-1.46 < y_{cm} < 0.54$, with $185 \leq N_{trk}^{offline} < 250$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. The error bars correspond to statistical uncertainties, while the shaded areas denote the systematic uncertainties.

that B mesons have a smaller v_2 than light-flavor particles, due to the larger mass of the b quark [56–58], the nonprompt D^0 v_2 values are assumed to lie between 0 and those of strange hadrons. The maximum effect from nonprompt D^0 mesons is thus estimated using the extracted nonprompt D^0 fraction and the change in v_2^S is found to be smaller than 6%.

Other sources of systematic uncertainty in the D^0 v_2 measurement in this analysis include the background mass pdf, the D^0 meson yield correction (acceptance and efficiency correction), selection of the D^0 candidates, and the background v_2 pdf. No systematic effect has been observed while changing the background mass pdf to a second-order polynomial or an exponential function. To evaluate the uncertainties arising from the D^0 meson yield correction, the v_2 values are extracted from the corrected signal D^0 distributions and compared to the uncorrected v_2 values, yielding an uncertainty of 2%. The selection criteria for D^0 candidates are also varied to tighter and looser values such that the D^0 signal fraction, $\alpha(m_{inv})$, changes by 50% and a systematic uncertainty of 14% is evaluated from the variations of v_2. The systematic uncertainties from the background v_2 pdf (20% for $p_T < 2.4$ GeV and 4% for $p_T > 2.4$ GeV) are evaluated by changing $v_2^B(m_{inv})$ to a second-order polynomial function of the invariant mass and a constant value. Systematic uncertainties from trigger bias and effects of pileup are negligible.

For K^0_S, Λ, and Ξ^- particles, the systematic uncertainties related to selection of reconstructed candidates (2% for K^0_S and Λ particles and 6% for Ξ^- particles) are evaluated in the same way as for D^0 mesons. To test the procedure of extracting the signal v_2, a study using EPOS LHC [54] pPb events is performed and the extracted values are compared to the generator-level values. The agreement is found to be better than 6%. Systematic uncertainties for Ω^- particles are quoted to be the same as those of Ξ^- particles.

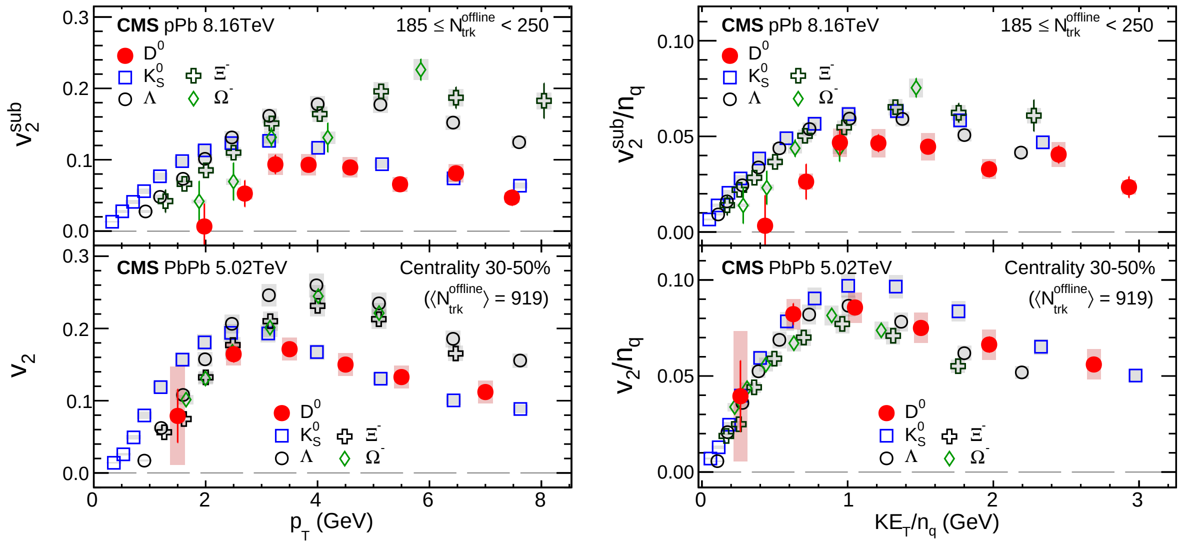

Figure 3: Left: the $v_2^{\rm sub}$ results for prompt D^0 meson, as well as for strange hadrons, as functions of p_T, for $-1.46 < y_{\rm cm} < 0.54$ in pPb collisions at $\sqrt{s_{\rm NN}} = 8.16\,\rm TeV$ with $185 \leq N_{\rm trk}^{\rm offline} < 250$ (upper) and for $-1 < y_{\rm cm} < 1$ in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02\,\rm TeV$ for 30–50% centrality (lower). Right: the n_q-scaled $v_2^{\rm sub}$ results. The D^0 v_2 data in PbPb are taken from Ref. [43]. The error bars correspond to statistical uncertainties, while the shaded areas denote the systematic uncertainties.

Figure 2 shows the results of the v_2 measurement of the prompt D^0 meson with $-1.46 < y_{\rm cm} < 0.54$ for high-multiplicity ($185 \leq N_{\rm trk}^{\rm offline} < 250$) pPb collisions. The v_2 results for strange hadrons are also shown for comparison. A clear mass ordering in the elliptic flow is observed in the low-p_T region of $\lesssim 2.5\,\rm GeV$, where heavier particle species have a smaller v_2 signal at a given p_T value. For $p_T > 2.5\,\rm GeV$, v_2 values for Λ, Ξ^-, and Ω^- baryons, which are similar to each other, all become larger than those of D^0 and K_S^0 mesons, a trend which is also observed in 5.02 TeV pPb collisions [28].

The elliptic flow results corrected for residual jet correlations ($v_2^{\rm sub}$) are shown in Fig. 3 (upper left) for prompt D^0 mesons as well as for strange hadrons as functions of p_T for pPb collisions with $185 \leq N_{\rm trk}^{\rm offline} < 250$. The reduction in the v_2 values resulting from the correction is most significant in the high-p_T region, with a 30–40% reduction found for $p_T > 5\,\rm GeV$. The prompt D^0 $v_2^{\rm sub}$ results show a clear trend of rising and declining with p_T. The same ordering in particle mass as seen in Fig. 2 is observed in the $v_2^{\rm sub}$ values in the lower-p_T region. This behavior is consistent with the expectation of particle emission from a collective expanding source, which might indicate significant collective behavior of charm quarks in high-multiplicity pPb systems at LHC energies. Previously published v_2 data for D^0 meson in 30–50% centrality PbPb collisions [43], together with new results for strange hadrons obtained in this Letter, are shown in Fig. 3 (lower left). A similar mass ordering to that in pPb collisions is seen, although the multiplicity range is much larger.

Motivated by the quark coalescence model [59–63], collectivity at the partonic level is investigated by studying the scaling properties of $v_2^{\rm sub}$ divided by the number of constituent quarks, n_q, as a function of transverse kinetic energy per constituent quark, KE_T/n_q (where $KE_T = \sqrt{m^2 + p_T^2} - m$), for all hadronic species and systems measured (Fig. 3, right). In high-multiplicity pPb collisions, the results for strange hadrons tend to follow a universal trend in the region $0.5 < KE_T/n_q < 1.5\,\rm GeV$, while the elliptic flow for D^0 mesons is found to have smaller values. This could suggest that the collective behavior of charm quarks is weaker than that of the light-flavor and strange quarks in high-multiplicity pPb collisions at the LHC. For $KE_T/n_q >$ 1.5 GeV, no clear universal scaling of v_2/n_q between mesons and baryons is observed. The behavior is qualitatively different in the larger PbPb collision system with centrality between 30 and 50%. The results for all particle species tend to follow a common trend in the $KE_T/n_q <$ 1 GeV region, indicating that D^0 mesons develop a strong collective behavior similar to the bulk of the QGP.

In summary, the first measurements of elliptic azimuthal anisotropies for prompt D^0 mesons, as well as K^0_S, Λ, Ξ^-, Ω^- hadrons, in high-multiplicity pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV are presented. Significant positive v_2 values are observed for D^0 mesons with $p_T > 2$ GeV. Comparing to strange-hadron results, the D^0 v_2 values are found to be smaller at a given p_T, or at similar transverse kinetic energy per constituent quark, after normalizing v_2 by the number of constituent quarks. The latter effect is not observed in the larger PbPb collision system. A possible interpretation is that, in high-multiplicity pPb collisions, in contrast to larger nucleus-nucleus collision systems, the collective behavior of charm quarks is weaker than that of the light-flavor quarks.

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