PROCEEDINGS OF SCIENCE

Recent results of D^0 mesons azimuthal anisotropy using the CMS detector

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In a relativistic heavy ion collision, heavy flavor (charm and bottom) quarks are mostly created via hard processes at the early stage of the collisions. We present the latest results of the azimuthal anisotropy coefficients v_{n} for prompt and nonprompt D^0 mesons in PbPb, pPb, and pp collisions from the CMS experiment. The studies are about collectivity phenomena in smaller systems (pp and pPb collisions), searches for the effects of very strong electromagnetic fields created in the initial stages of ultrarelativistic PbPb collisions, and charm quark energy loss in the quark-gluon plasma.

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In ultrarelativistic nucleus-nucleus collisions at BNL RHIC and CERN LHC, strongly interacting matter with quarks and gluons as degrees of freedom (quark-gluon plasma, QGP) is produced at time scales of $\sim 1 - 10$ fm$/c$. The azimuthal particle correlations observed in such collisions are used to study the properties of the QGP. A parametrization by a Fourier expansion, with Fourier coefficients, v_{n}, gives information about the initial collision geometry and its fluctuations. The second order (v_2) coefficient is mostly related to the almond-shaped geometry of the overlapping region in the collisions, while the third order (v_3) coefficient is associated with fluctuations in the position of the nuclei constituents [1]. Heavy flavor quarks, charm and bottom, are mostly produced via hard parton scattering processes in such collisions, being mostly produced right after the collisions. In addition, because of their larger masses compared to typical temperatures of any stage of the system evolution, heavy-flavor quarks are expected to experience the full evolution of the collision system until the hadronization phase [2].

The heavy-flavor quarks are excellent probes of the effects from initial stages of the collisions, such as the ones from very strong and transient ($\sim 10^{-1}$fm$/c$) electromagnetic fields (EM) hypothesized to be created by spectators and participants of the collisions [3]. They can also be used as probes for event-by-event flow fluctuations caused by initial conditions at low transverse momentum (p_{T}) and also by variations of particle energy loss at high-p_{T} [4]. In addition, heavy-flavor quarks are used in the study of the origin of collectivity phenomena (similar to the ones in nucleus-nucleus collisions) observed in small colliding systems, like proton-proton (pp) and proton-lead (pPb) collisions, with the potential to discriminate contributions to v_{n} coefficients from initial and final-state effects [5].

In this proceedings, measurements of prompt and nonprompt (from decays of beauty hadrons) D^0 mesons azimuthal anisotropy are presented. The data from lead-lead (PbPb, at nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}}$ = 5.02 TeV), pPb at $\sqrt{s_{NN}}$ = 8.16 TeV, and pp at $\sqrt{s}$ = 13 TeV collisions at the LHC are collected using the CMS experiment [6]. The events from PbPb collisions are from minimum bias (MB) triggered data samples, while events from pp and pPb collisions are from both MB and high multiplicity (HM) triggers. The prompt and nonprompt D^0 mesons are identified using multivariate selections. To measure the flow harmonic coefficients, different methods were used depending on the collision system and type of study. For the results in the PbPb collisions, scalar product and cumulant methods are used to measure v_{n} from two-and four-particle correlations, while in pp and pPb collisions the two-particle correlation method is employed. The signal v_{n} from D^0 mesons are extracted by fitting the invariant mass (m_{inv}) distribution of the D^0 candidates and v_{n} values as a function of m_{inv}. The main systematic uncertainties are obtained by studying the D^0 mesons reconstruction and identification selection efficiency, the fit modeling of the m_{inv} and v_{n}, the contamination of nonprompt D^0 particles in the prompt D^0 mesons samples, and contributions from hadronic jets for the measurements in small colliding systems. For details about the procedures described above, see Refs. [5, 7, 8].

The v_2 and v_3 results in Fig 1 extend previously published data from CMS [9], by enlarging the p_{T} range up to $\sim$60.0 GeV$/c$ and by providing finer p_{T} bins with much smaller statistical uncertainties. Similar trends as in charged particles is observed for D^0 mesons, showing that heavy-flavor quarks flow together with lighter quarks. The theoretical calculations also provide good qualitative description of the data, in special, the TAMU SMCs model [10] shows considerable improvements with respect to TAMU model [11] in the p_{T} range $3 - 10$ GeV$/c$, by considering

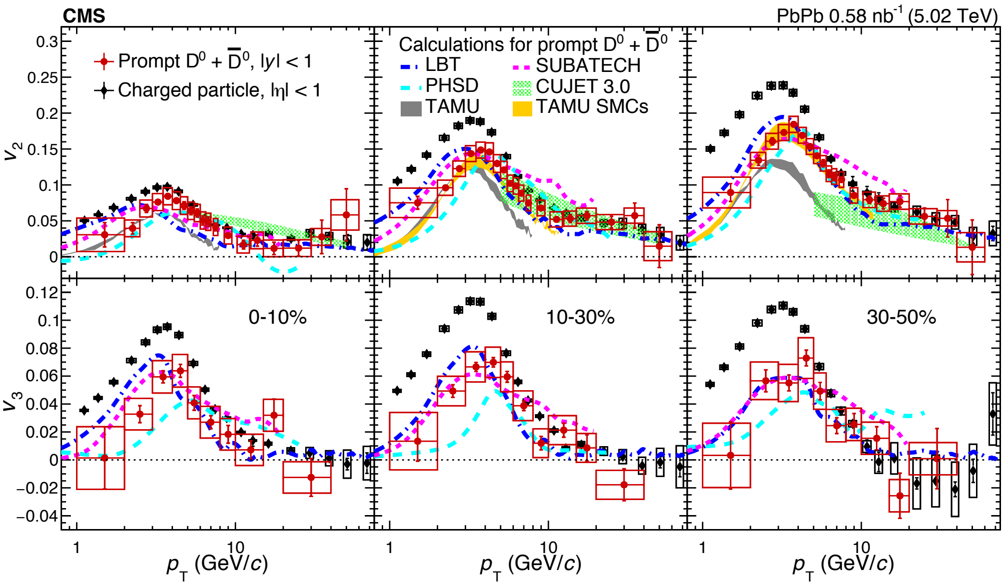

Figure 1: Flow coefficients v_2 (upper) and v_3 (lower) of prompt D^0 mesons (with rapidity $|y| < 1.0$) and charged particles (with pseudorapidity $|\eta| < 1.0$) in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The vertical bars are statistical uncertainties, while open boxes represent systematic uncertainties. Several theoretical calculations of v_n of prompt D^0 mesons are shown for comparison [7].

space-momentum correlations (SMCs) between charm quarks and high-flow quarks in the QGP.

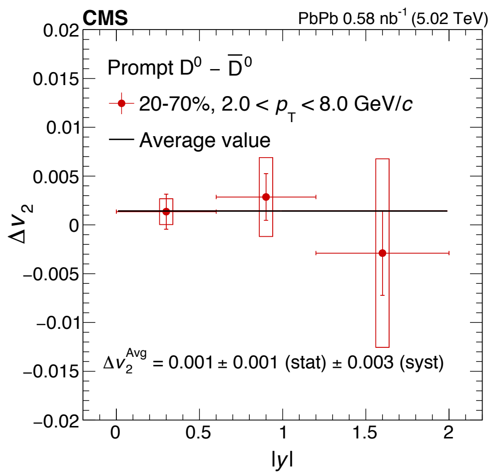

Figure 2: Prompt D^0 mesons Δv_2 (between D^0 and $\overline{\mathrm{D}}^0$ particles) as a function of rapidity in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The vertical bars are statistical uncertainties, while open boxes represent systematic uncertainties [7].

In ultrarelativistic nucleus-nucleus collisions, very strong and transient ($\sim 10^{-1}\,\mathrm{fm}/c$) EM fields are hypothesized to be induced by the collision participants and spectators. There are predictions indicating that such strong EM fields can produce a difference in the v_n coefficients for positively and negatively charged particles. In particular, the Coulomb field created by collision participants is expected to create a difference in v_2 [3]. To search for such effects, the difference Δv_2 between the v_2 values of D^0 and $\overline{D}^0$ mesons is measured, as shown in Fig. 2. The extracted average in the full rapidity region is $\Delta v_2^{\rm Avg} = 0.001 \pm 0.001(\rm stat) \pm 0.003(\rm syst)$, which is compatible with zero. Currently there is no prediction for such effects in charm quarks v_n coefficients, but they are expected to be larger than for lighter quarks (predicted to be of the order of ~0.001 at the LHC energies [3]). This is because heavy-flavor quarks are in general produced much earlier in the collision than light quarks, when the magnitude of the EM fields is larger [12]. Therefore, such small value of Δv_2 can pose constraints on possible EM effects on charm quarks.

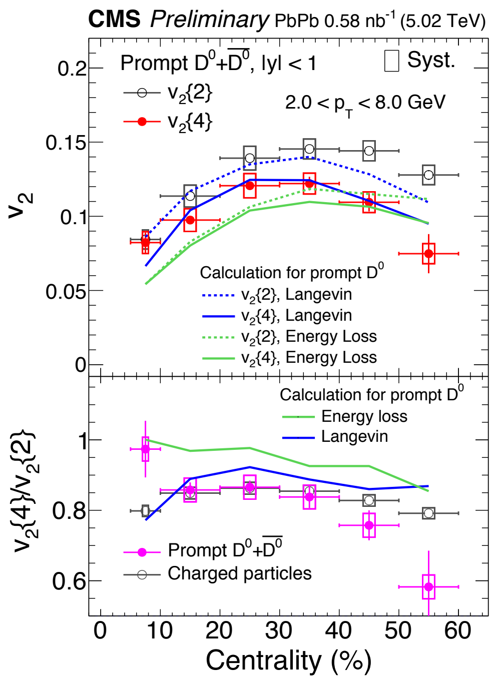

Figure 3: Upper panel: prompt D^0 mesons $v_2\{2\}$ and $v_2\{4\}$ as function of centrality in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The blue solid and dashed lines denote DABMod model calculations with Langevin dynamics for $v_2\{4\}$ and $v_2\{2\}$, respectively. The green solid and dashed lines denote DABMod model calculation including radiative energy loss. Lower panel: ratio of $v_2\{4\}/v_2\{2\}$ for D^0 mesons ($|y| < 1.0$) and charged particles ($|\eta| < 1.0$). The vertical bars are statistical uncertainties, while open boxes represent systematic uncertainties [8].

In the Ref. [8], the v_2 coefficient of prompt D^0 mesons is measured for the first time using a four particle cumulant technique, $v_2\{4\}$. These measurements allow to access the magnitude of the event-by-event fluctuations of the flow harmonics from heavy-flavor quarks. In particular, the ratio $v_2\{4\}/v_2\{2\}$ is predicted to be sensitive to energy-loss fluctuations for high-p_T heavy-flavor quarks [4]. Figure 3 shows results of $v_2\{4\}$ and $v_2\{2\}$ (from scalar product method) as a function of centrality from 5 to 60% and $2 < p_T < 8$ GeV/c. The $v_2\{4\}$ shows similar trends as $v_2\{2\}$, but with smaller magnitude. In the lower panel, the ratio $v_2\{4\}/v_2\{2\}$ shows a hint of different trends in peripheral events, which could indicate that fluctuations in hard processes become visible for charm mesons, but the uncertainties are large for a firm conclusion. The measurements are compared with DABMod model [4], showing a better description from Langevin dynamics calculations for

$2 < p_T < 8$ GeV$/c$. Measurements at higher p_T are also presented in Ref. [8], but are not shown in this proceedings.

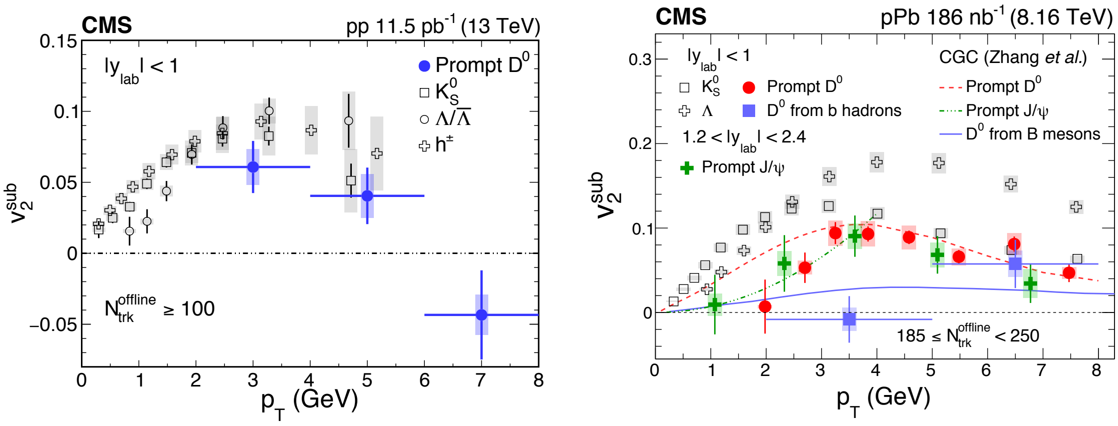

Figure 4: Left: Measurements of $v_2^{\rm sub}$ for prompt $\rm D^0$ mesons as a function of p_T in pp collisions at $\sqrt{s} = 13$ TeV. Published results for charged particles, $\rm K^0_s$ mesons, Λ baryons are also shown for comparison. Right: Measurements of $v_2^{\rm sub}$ for prompt and nonprompt $\rm D^0$ mesons, $\rm K^0_s$ mesons, Λ baryons, and prompt J/Ψ mesons in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. The lines show theoretical calculations within the CGC framework. The vertical bars are statistical uncertainties, while shaded areas represent systematic uncertainties. [5]

Similarly to nucleus-nucleus collisions, long-range collective azimuthal correlations are observed in small colliding systems with high final-state particle multiplicity ($N_{\rm trk}^{\rm offline}$). Figure 4 (left) shows results for the $v_2^{\rm sub}$ (corrected for residual jet correlations [5]) of prompt $\rm D^0$ mesons in pp collisions at $\sqrt{s} = 13$ TeV as a function of p_T. A positive value of the v_2 signal (0.061 ± 0.018(stat)$\pm$ 0.013(syst)) is observed over a p_T range of $\sim 2-4$ GeV$/c$, going to zero at higher p_T. This indicates that charm quarks also present such collectivity signatures in pp collisions. In Ref. [5] results of $v_2^{\rm sub}$ as a function of $N_{\rm trk}^{\rm offline}$ in pp and pPb are also presented in order to investigate possible system size dependence of collectivity for charm quarks.

Figure 4 (right) shows results for nonprompt $\rm D^0$ mesons as a function of p_T in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. For $p_T \sim 2-5$ GeV$/c$, nonprompt $\rm D^0$ mesons show a considerably smaller value of v_2 as compared to prompt $\rm D^0$ particles, with a significance of 2.7 standard deviations. Comparison with calculations from the color glass condensate (CGC) framework [13, 14] are also presented, where sizeable v_2 signals are generated by correlations between partons in the initial stages of the collisions, showing a good qualitative description of the results for J/Ψ mesons and prompt and nonprompt $\rm D^0$ mesons.

In summary, recent results on the prompt and nonprompt $\rm D^0$ mesons azimuthal anisotropy in pp, pPb, and PbPb collisions using the CMS experiment are presented. Collectivity effects observed in small systems (pp and pPb collisions) are investigated by measuring the elliptic flow coefficient (v_2) as a function of the $\rm D^0$ mesons transverse momentum and flow fluctuation effects in PbPb collisions are studied by comparing v_2 measured using two-and four-particle cumulant techniques. In addition, a search for hypothesized electromagnetic fields created at the initial stages of PbPb collisions is performed by measuring the difference in v_2 between $\rm D^0$ and $\overline{\rm D}^0$ mesons as a function of rapidity.

Acknowledgments

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