STUDIES OF HEAVY QUARK DIFFUSION IN QGP WITH NONPROMPT D^0 COLLECTIVITY AND JET–D^0 ANGULAR CORRELATIONS IN PbPb COLLISIONS*

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Measurements of the correlations of the final-state heavy flavor hadrons are of great interest since they provide information about the initial collision geometry and its fluctuation. More importantly, those measurements could reveal the mass dependence of parton energy loss and quark diffusion in the Quark–Gluon Plasma (QGP). In this paper, we report on the first measurement of the azimuthal anisotropy of nonprompt D^0 in PbPb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV. The elliptic (v_2) and triangular (v_3) coefficients are performed as functions of D^0 transverse momentum p_{T}, in three centrality classes. Compared to the results from promptly produced D^0, the nonprompt D^0 v_2 flow coefficients are systematically lower. However, those results have a similar dependence on p_{T} and centrality. A non-zero v_3 coefficient of the nonprompt D^0 is seen in PbPb data. We also present the first azimuthal angular correlation measurement between jets and D^0 mesons in pp and PbPb collisions. The jet–D^0 correlation measurement is performed using jets with $p_{\mathrm{T}} > 60$ GeV/c and D^0 mesons with $4 < p_{\mathrm{T}} < 20$ GeV/c. In PbPb collisions at 5.02 TeV, compared to the pp, the D^0 distribution hints at the diffusion of charm quarks in the medium, created in heavy-ion collisions. The results could provide new constraints on the mechanism of the heavy quark diffusion and energy loss in the QGP.

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1. Introduction

The final-state correlations between heavy and light flavor hadrons emitted in high-energy nuclear collisions could reveal information on mass dependence of various processes in Quark–Gluon Plasma, such as parton energy loss and diffusion [1]. The azimuthal anisotropy Fourier coefficients

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v_2 (elliptic flow) and v_3 (triangular flow) of charm (c) quark have shown a great similarity with light hadrons in transverse momentum (p_{T}) and centrality dependence. The magnitude of flow coefficients, however, is smaller in the case of c quarks, particularly in the low- and intermediate-p_{T} range ($p_{\mathrm{T}} < 15$ GeV/c), where it is believed that charm quark suffers thermalization [2, 3]. Due to the larger bottom (b) quark mass as compared to the charm quark mass, b hadron azimuthal anisotropy measurement can shed new light on understanding the heavy quark and medium interaction. In addition to the correlation with bulk-produced particles, azimuthal angular correlation measurement between heavy flavor hadrons and jets can further improve that understanding.

In this contribution, we report on the first measurement of the second, v_2, and third, v_3, azimuthal anisotropy coefficient of D^0 mesons that come from b-hadron decays in lead–lead (PbPb) collisions. Results are shown as a function of D^0-meson transverse momentum, in three centrality intervals. The azimuthal angular correlation measurement between jets and D^0 mesons in proton–proton (pp) and PbPb collisions, integrated in centrality, is also shown.

2. Dataset and analysis details

This analysis uses PbPb and pp collisions data at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV collected with the CMS detector [4] with a total integrated luminosity of 0.58 pb^{-1} (v_n measurement), 404 μb^{-1} (jet–D^0 correlations in PbPb), and 27.4 pb^{-1} (jet–D^0 correlations in pp). Inclusive D^0 ($\bar{D}^0$) meson candidates reconstruction is done via decay channel $D^0 \rightarrow \pi^+ + K^-$ ($\bar{D}^0 \rightarrow \pi^- + K^+$) by pairing particles of opposite charge. The both possible particle assignments are considered for each pair. A boosted decision tree (BDT) algorithm, from the tmva package [5], is applied in order to suppress the background (both combinatorial background and prompt D^0 component).

The inclusive D^0-meson yield, in each bin of scalar product (v_n^i) for the v_n measurement or in each bin of the distance from the jet axis (r) for the jet–D^0 correlation measurement, is obtained from the fit of the invariant mass spectrum [6]. The fraction of nonprompt D^0 mesons is extracted from the template fit of the distribution of the distance of the closest approach (DCA) between the collision point and the direction of the D^0 momentum vector. In this procedure, the DCA distribution of data is fitted with a linear combination of prompt and nonprompt D^0 DCA simulated templates. The v_n coefficients are measured by taking the mean of the nonprompt D^0-mesons scalar product distribution in each bin of p_{T} and centrality.

3. Results

The results of v_2 and v_3 azimuthal anisotropy coefficients for nonprompt D^0 mesons, compared with previously published values for prompt D^0 from Ref. [3], are shown in Fig. 1. The results show non-zero values of the elliptic flow of b-hadron daughters, although the flow magnitude is significantly smaller than in the prompt D^0 case. The difference is more evident in the low- and intermediate-p_{T} range and it is in agreement with the mass ordering observed in pPb collisions [7], as well as the mass ordering observed in leptonic channels in PbPb collisions [8, 9]. At larger D^0 transverse momentum, elliptic flow values from c and b quarks start converging. The v_2 coefficients of nonprompt D^0 mesons exhibit very weak dependence on centrality and p_{T}, unlike flow of promptly produced D^0 mesons where those dependencies are strongly expressed. The nonprompt v_3 Fourier coefficients have large statistical fluctuations so that neither the transverse momentum nor the centrality dependence can be determined. However, results suggest a non-zero value in the $4 < p_{\mathrm{T}} < 6$ GeV$/c$ range for all centralities. As was the case for elliptic flow, the magnitude of v_3 is lower for nonprompt than for prompt D^0 mesons.

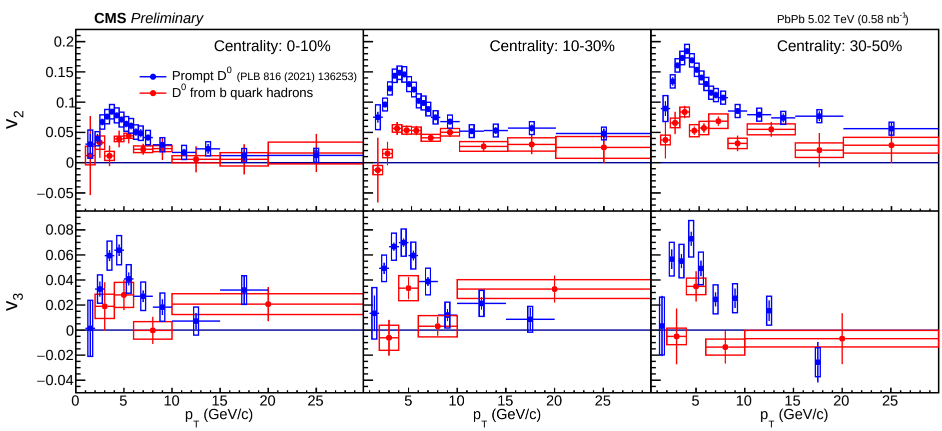

Fig. 1. The elliptic, v_2 (top panel), and the triangular, v_3 (bottom panel), flow coefficients of nonprompt and prompt D^0 mesons as functions of p_{T} and in three bins of centrality. The bars and the boxes represent statistical and systematic uncertainties, respectively. The figure is taken from Ref. [6].

The comparison between the measured nonprompt D^0 v_n coefficients and theoretical calculations that have different modeling of the b quark flow is shown in Fig. 2. While all models show qualitative agreement with the measured p_{T} dependence of the elliptic flow, there are quantitative discrepancies which could provide constraints on the description of b-quark interactions with the medium. In the low- and intermediate-$p_{\rm T}$ regime, for the centrality range of 30–50%, the LGR model [10, 11] is favored by the measurements, while for the most central events (0–10%), the same model does not predict a peak structure seen in the data. The PHSD model [12] gives a good description of the data for centrality ranges of 0–10% and 10–30%, but shows higher discrepancies in semi-peripheral collisions, 30–50% centrality range. A larger disagreement was observed between this model and the data for prompt D^0, where the PHSD calculations underestimate the v_2 Fourier coefficient [3]. For the TAMU model [13], the direct comparison with data is not possible since it provides predictions in the centrality range of 20–40% only. However, the model describe well the measurement performed in the centrality range of 10–30%. At higher $p_{\rm T}$, in the regime where D^0-mesons anisotropy is driven by the path-length dependence of parton energy loss, the LBT model [14, 15] is slightly closer to the data than the CUJET3.0 model [16, 17], which is systematically above the experimental results, but still within uncertainties. The PHSD model is the only one that has calculations for v_3 coefficients. Similar as for the v_2 case, the model is consistent with measurement, except that position of the maximum is shifted towards higher $p_{\rm T}$.

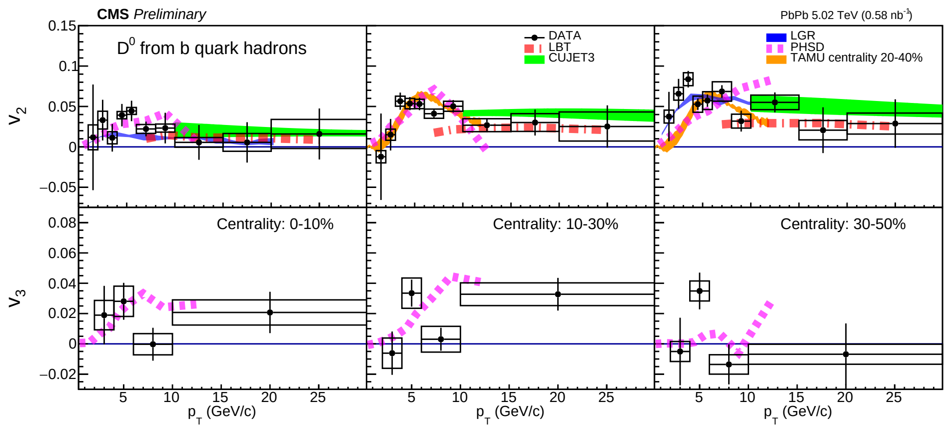

Fig. 2. (Color online) The elliptic, v_2 (top panel), and the triangular, v_3 (bottom panel), flow coefficients of nonprompt D^0 mesons as functions of transverse momentum and in three bins of centrality. The bars and the boxes represent statistical and systematic uncertainties, respectively. The colored bands show theoretical predictions [10–17]. The figure is taken from Ref. [6].

The top panel of Fig. 3 shows the measured D^0-meson radial distributions in pp and PbPb collisions, while the PbPb/pp ratio is shown in the middle panel. The measurement is performed in the D^0 and jet transverse momentum range $4 < p_{\rm T} < 20$ GeV/c and $p_{\rm T} > 60$ GeV/c, respectively.

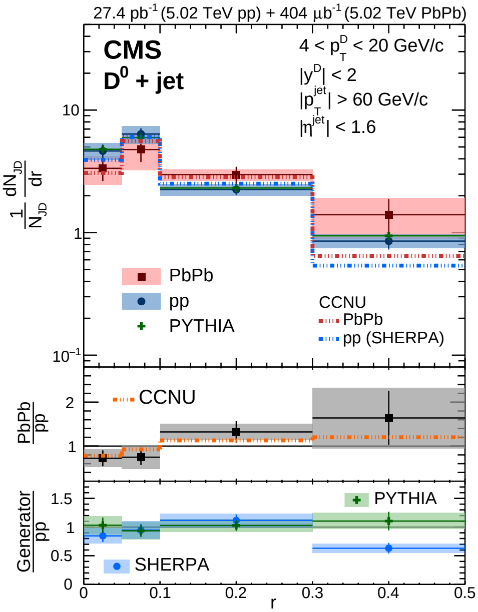

Fig. 3. Distribution of prompt D^0 mesons in jets as a function of the r measured in pp and PbPb collisions. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The ratios of the D^0-meson radial distributions in PbPb and pp data are shown in the middle panels. The experimental results are compared with theoretical predictions [18–20]. In the bottom panels, the ratios of the D^0-meson radial distributions of pp over the two MC event generators are presented. The figure is taken from Ref. [21].

This result indicates that D^0 mesons at low-p_T are farther away from the jet axis in PbPb compared to pp collisions. The CCNU [18] calculation predicts a small increase of the D^0-meson yield with r in PbPb compared to pp collisions, which is consistent with the data. The pp results are compared to calculations from the PYTHIA [19] and SHERPA [20] event generators in the bottom panel of Fig. 3. The measured spectrum in pp collisions for $r < 0.3$ is consistent with both models. For the larger values of r, PYTHIA captures the features of the data better than SHERPA, which underpredicts the pp spectrum.

4. Summary

In summary, the elliptic (v_2) and triangular (v_3) Fourier harmonics of D^0 mesons that come from b-hadron decays (nonprompt D^0) are measured in lead–lead (PbPb) collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The v_2 results suggest a transverse momentum dependence and a slight increase for less central collisions, while the magnitudes are lower as compared with the promptly produced D^0 mesons. An indication of non-zero triangular flow is found in the transverse momentum range of $4 < p_{\mathrm{T}} < 6$ GeV$/c$. The jet–D^0 correlations are studied by measuring the radial distributions of D^0 mesons with respect to the jet axis in PbPb and proton–proton collisions. The comparison hints at a modification of the distribution in PbPb collisions at $4 < p_{\mathrm{T}} < 20$ GeV$/c$. The new measurements place additional constraints on the theoretical understanding of heavy quark interactions with the medium.

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