Event-by-event correlations between soft hadrons and D^0 mesons in 5.02 TeV PbPb collisions at the CERN Large Hadron Collider

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In this paper heavy quark energy loss models are embedded in full event-by-event viscous hydrodynamic simulations to investigate the nuclear suppression factor and the azimuthal anisotropy of D^0 mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the p_T range 8–40 GeV. In our model calculations, the R_{AA} of D^0 mesons is consistent with experimental data from the CMS experiment. We present the first calculations of heavy flavor cumulants $v_2\{2\}$ and $v_3\{2\}$ (and also discuss $v_2\{4\}$), which is also consistent with experimental data. Event-shape engineering techniques are used to compute the event-by-event correlation between the soft hadron v_n and the heavy meson v_n. We predict a linear correlation between these observables on an event-by-event basis.

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I. INTRODUCTION

In the last decade, remarkable progress has been made towards understanding the properties of the strongly interacting quark-gluon plasma (QGP) produced in ultrarelativistic heavy ion collisions [1,2]. A defining feature of the QGP is its ability to flow as a nearly perfect liquid where the shear viscosity to entropy density ratio $\eta/s \sim 0.1$ is an order of magnitude smaller than in ordinary fluids such as water [3].

Event-by-event relativistic viscous hydrodynamic simulations [4] have revealed that in this QCD liquid viscous effects are so small that the spatial inhomogeneities present in the initial state are efficiently converted into final state momentum space anisotropy [5,6]. One finds that the low-p_T elliptic and triangular flows of all charged particles, v_2 and v_3, are linearly correlated with the corresponding eccentricities of the initial state, ε_2 and ε_3 [7–10], while higher order flow harmonics exhibit some degree of nonlinear response [11–14].

In contrast, the physical mechanism responsible for azimuthal anisotropies at high p_T ($p_T \gtrsim 10$ GeV) relies not on pressure and flow gradients but rather on differences in the path length of highly energetic probes quenched by the expanding medium [15,16]. This qualitative understanding has been recently confirmed by the first jet-energy-loss plus event-by-event viscous hydrodynamic calculations performed in [17,18]. A novel feature found in [17,18] is that the approximate linear response between v_2 and ε_2 also holds at high p_T on an event-by-event basis. This implies that the quantum randomness in the position of the nucleons in the incident nuclei, which determines the fluctuations of the initial conditions used in the subsequent hydrodynamic evolution, significantly affects the distribution of path lengths traversed by jets in the medium.

The observation of large azimuthal anisotropy of open heavy flavor mesons [19–21] adds important new elements to the overall picture discussed above. Heavy quarks are produced by hard processes in the initial stages of the collision with a nonthermal transverse momentum spectrum, which is expected to relax towards a nearly thermal distribution within a relaxation time scale $\tau_R \sim \frac{M}{T}\frac{\eta}{sT}$ [22] (M is the heavy quark mass). The difference between the charm and bottom quark masses suggests that, at low p_T, the D^0 meson v_n should be larger than the corresponding coefficients for B^0 mesons [23]. Additionally, at low-p_T quark coalescence [24–26] between heavy and light flavors [27,28] can substantially increase the elliptic flow of heavy mesons [29,30], as well as various effects such as Langevin type behavior and hadronic rescattering.

For $p_T \gtrsim 10$ GeV heavy quarks hadronize mostly via fragmentation[1] and the various low-p_T effects can be neglected. This provides a simpler scenario for studying how initial state spatial anisotropies are mapped into the final state heavy flavor azimuthal anisotropy. We address this problem by exploring new techniques that connect soft physics and heavy flavor observables. A heavy quark energy loss model is embedded on top of event-by-event viscous hydrodynamic backgrounds to study the nuclear suppression factor and v_n of D^0 mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for 8–40 GeV. We do not intend to find constraints in the chosen energy loss models but rather to discuss the sensitivity of the presented observables that could be used to better understand the physics of heavy quarks on an event-by-event basis. Our event-by-event approach predicts a linear correlation between the soft hadron and the heavy meson v_2 and v_3, which could be verified at the CERN Large Hadron Collider (LHC). This linear relationship is not an obvious feature, as the anisotropies

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[1]We neglect possible D-like states that might form in the QGP [31].

in the soft and heavy sectors emerge from two very different production, interaction, and hadronization mechanisms.

In fact, nonlinearities have already been observed in a study using all charged particles at high p_T [18]. The degree of linear correlation between $\varepsilon_n \to v_n^{\text{hard}}$ can be quantified through a Pearson coefficient, Q_n,

$$Q_n = \frac{\langle \varepsilon_n v_n(p_T) \cos n[\phi_n - \psi_n(p_T)] \rangle}{\sqrt{\langle \varepsilon_n^2 \rangle \langle v_n(p_T)^2 \rangle}}, \tag{1}$$

that demonstrates the correlation between two vectors; i.e., both the magnitude ε_n and angle ϕ_n of the initial condition and how that maps onto the final magnitude v_n and angle ψ_n of the azimuthal anisotropy. Then a value of $Q_n = (-)1$ implies a perfect (anti)linear correlation whereas $Q_n = 0$ implies absolutely no correlation. For all charged particles at high p_T, Q_2 for $\varepsilon_n \to v_n^{\text{hard}}$ is shown in Fig. 6 from [18] where $Q_2 \gtrsim 0.9$, which indicates a quite linear correlation. However, compared to the soft sector it is clear that more nonlinearities appear at high p_T because Q_2 is smaller at high p_T. Furthermore, Q_2 demonstrates even more nonlinearities for a larger η/s and for peripheral collisions. Finally, higher order flow harmonics demonstrate even larger nonlinearities demonstrated by values of $Q_3 \approx 0.7$–0.9. The implications of these nonlinearities and how they may vary depending on the mass of the particle still remains an interesting question that we will start to explore in this paper.

II. DETAILS OF THE MODEL

To simulate the propagation of heavy quark jets in the medium, we developed a modular Monte Carlo code in C++, named DABMod, combined with ROOT [32] and PYTHIA8 [33] libraries, that allows for a variety of energy loss models to be implemented. Starting from the initial conditions, we sample charm quarks (c) inside the medium with initial momentum distribution given by pQCD FONLL calculations [34,35] and random initial direction. We neglect effects of the jets on the medium [36], but the local space-time dependence of the hydrodynamic fields is considered in the energy loss calculations.

For this first study we employ the following simple parametrization for the heavy quark energy loss per unit length [37]: $\frac{dE}{dx}(T,v) = -f(T,v)\,\Gamma_{\text{flow}}$, where T is the temperature experienced by the heavy quark, v is the heavy quark velocity, $\Gamma_{\text{flow}} = \gamma[1 - v_{\text{flow}} \cos(\varphi_{\text{quark}} - \varphi_{\text{flow}})]$ with $\gamma = 1/\sqrt{1 - v_{\text{flow}}^2}$ takes into account the boost from the local rest frame of the fluid [38], φ_{quark} is the angle defined by the propagating jet in the transverse plane, and φ_{flow} is the flow local azimuthal angle. The jet propagates only in the transverse plane, starting from a production point $\boldsymbol{x}_0$, moving in the direction defined by φ_{quark}.

We investigate the cases where $f(T,v) = \xi T^2$ and $f(T,v) = \alpha$, with ξ and α being constants. Both forms are simplified approximations for the interactions between heavy quarks and the strongly interacting QGP. The first choice is inspired by anti–de Sitter/conformal field theory correspondence (AdS/CFT) calculations [39] (for nonconformal plasma see [40]). The second choice is inspired by Ref. [41] which showed that a nondecreasing drag coefficient near the phase transition is favored for a simultaneous description of heavy flavor $R_{AA}(p_T)$ and $v_2(p_T)$ (this is also supported by T-matrix calculations [42,43]). These models are fairly simple to implement and they give a good description of R_{AA}.

Our calculations use hydrodynamical profiles to provide the temperature and flow fields at each time step for each event. We generate hydrodynamic profiles using the (2+1)-dimensional event-by-event relativistic viscous hydrodynamical model, v-USPhydro [44–46], which passes standard accuracy tests [47]. Our setup is the same as [17,46] (MCKLN initial conditions at PbPb $\sqrt{s_{NN}} = 5.02$ TeV [48–50], $\eta/s = 0.05$, and initial time $\tau_0 = 0.6$ fm), which describes experimental data in the soft sector, such that all the hydrodynamic parameters are fixed in the present study. The heavy quarks are evolved on top of hydrodynamic backgrounds until they reach the jet-medium decoupling temperature T_d, below which hadronization is performed using the Peterson fragmentation function [51]. This parameter encodes the large uncertainties regarding hadronization of jets in the QGP and is set to vary between $T_d = 120$ MeV and $T_d = 160$ MeV, inspired by [18,52,53]. The parameter for the Peterson fragmentation function is fixed so that the heavy meson spectra matches FONLL calculations. Coalescence is not taken into account but it will be implemented in future work to extend the validity of our calculations to low p_T. Hadronic rescattering is not significant at high p_T [54,55] and is neglected here.

In this work, an event-by-event analysis is possible by oversampling each individual hydro event with millions of heavy quarks. From each individual event, $R_{AA}^c(p_T,\varphi)$ for charm quarks is obtained and the corresponding azimuthal coefficients

$$v_n^c(p_T) = \frac{\frac{1}{2\pi}\int_0^{2\pi} d\varphi \cos\left[n\varphi - n\psi_n^c(p_T)\right] R_{AA}^c(p_T,\varphi)}{R_{AA}^c(p_T)} \tag{2}$$

are calculated based on [56] with

$$\psi_n^c(p_T) = \frac{1}{n}\tan^{-1}\left(\frac{\int_0^{2\pi} d\varphi \sin(n\varphi)\, R_{AA}^c(p_T,\varphi)}{\int_0^{2\pi} d\varphi \cos(n\varphi)\, R_{AA}^c(p_T,\varphi)}\right). \tag{3}$$

In reality, there are very few heavy quarks per event, and our approach gives the probability for an event with a certain v_n and ψ_n in the soft sector to produce the heavy flavor quantities $v_n^c(p_T)$ and $\psi_n^c(p_T)$. To compare with experimental data, the scalar product method [57,58] is used to calculate the two- and four-particle cumulants with the inclusion of multiplicity weighting and centrality class rebinning as described in [18,59]. We have at least a couple of thousand hydrodynamic events in each centrality class, and we checked that our statistical error bars (computed using jackknife resampling [60]) are on the order of 10^{-4}.

The free parameters ξ and α that define our two energy loss scenarios are determined by matching our model calculations for D^0 R_{AA} to experimental data at $p_T \gtrsim 10$ GeV in the 0–10% centrality class. The same procedure has been used to fix the jet-medium coupling in the light sector in [17,18,37]. The parameters must be fixed for every decoupling temperature T_d

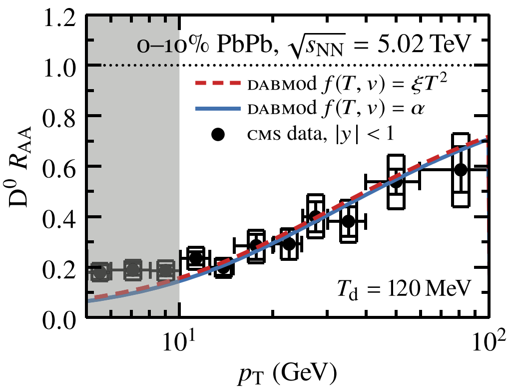

FIG. 1. R_{AA} for D^0 mesons in 0–10% PbPb collisions at $\sqrt{s_{NN}} =$ 5.02 TeV and decoupling temperature $T_d = 120$ MeV comparing two energy loss models with experimental data from the CMS Collaboration [61].

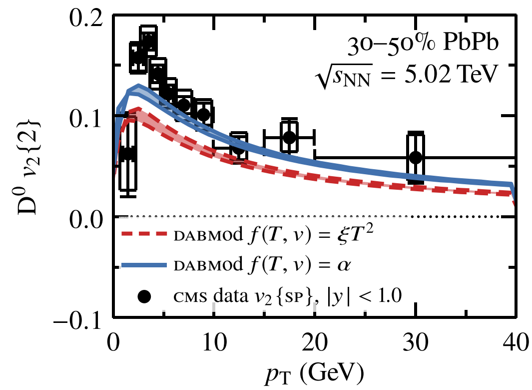

FIG. 2. $v_2\{2\}$ of D^0 mesons in 30–50% PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV comparing two energy loss models with CMS data [64]. The band corresponds to the decoupling temperature interval $120 \leqslant T_d \leqslant 160$ MeV.

separately. With these parameters fixed[2] we can perform a full simulation across all p_T and centralities.

III. NUMERICAL RESULTS

Figure 1 shows our results for D^0 R_{AA}, together with run 2 LHC CMS data [61]. In this plot we use the decoupling temperature $T_d = 120$ MeV and compare the two energy loss scenarios. One can observe that both energy loss models give the same nuclear modification factor in the p_T range considered. These results are robust with respect to variations in T_d, by appropriately fixing ξ and α. Finally, since we do not use the same p_T dependence, our results differ from previous implementations of AdS/CFT-inspired energy loss calculations such as [62,63].

We compute the differential $v_2\{2\}$ [17,18] for D^0 meson at 30–50% centrality and compare it to experimental data in Fig. 2. At intermediate and high p_T, the temperature dependent energy loss model clearly underestimates the data, whereas the constant model $f(T,v) = \alpha$ is within the uncertainties. Both energy loss models underestimate the data at low p_T, where effects such as coalescence, shadowing, and stochastic dynamics could play a significant role. The constant model gives the largest elliptic flow (as it occurred in [41]) while the bands illustrate the dependence of these observables with T_d. We find that $v_2\{2\}$ increases when T_d is lowered from 160 to 120 MeV, which is expected due to the larger time available to build up the azimuthal anisotropy. Moreover, we note that even though the chosen T_d range is large, our results are quite robust concerning this parameter.

Our calculations for the corresponding $v_3\{2\}$ of D^0 can be found in Fig. 3, together with experimental data for comparison. $v_3\{2\}$ is a factor ~3 smaller than the corresponding $v_2\{2\}$ shown in Fig. 2 and falls slightly below the experimental data at low p_T. By considering event-by-event simulations, one sees that a nondecreasing drag coefficient [41] gives not only the largest $v_2\{2\}$ but also the largest $v_3\{2\}$, thereby amplifying the survival of the initial state fluctuations perceived by heavy flavor. Also, $v_3\{2\}$ is particularly sensitive to the decoupling between heavy quarks and the medium in comparison with $v_2\{2\}$ as the bands almost overlap. We find a slightly smaller D^0 triangular flow than Refs. [29,52], which is likely due to the event-plane decorrelation effect present at high p_T [17,18,65]. Finally, our calculations in Fig. 1–3 show that v_n are more sensitive to the energy loss models than R_{AA}.

Azimuthal anisotropy fluctuations can be systematically investigated using multiparticle cumulants [66,67] which, in the present context of heavy-light flavor flow correlations, should give valuable information about the spectrum of path length fluctuations of heavy quark jets in the medium. However, it is not clear whether current statistics allows for proper measurement of higher order heavy flavor cumulants at high p_T at LHC (or even $v_3\{2\}$ with small enough error bars). Because we oversample each event, we have enough statistics to compute multiparticle cumulants such as $v_2\{4\}$, which measures the correlation between a heavy flavor candidate and

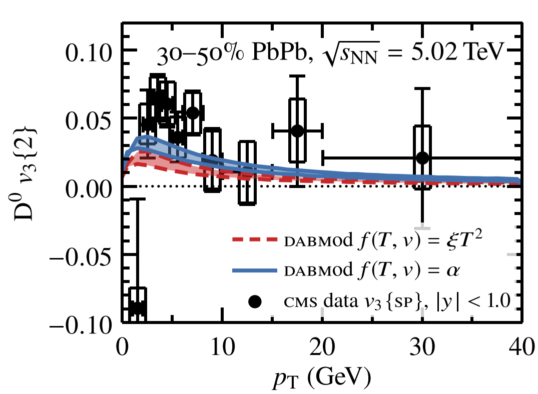

FIG. 3. $v_3\{2\}$ of D^0 in 30–50% PbPb collisions at $\sqrt{s_{NN}} =$ 5.02 TeV comparing two energy loss models with CMS data [64]. The band corresponds to the decoupling temperature interval $120 \leqslant T_d \leqslant 160$ MeV.

[2]We use $\xi = (16.000, 18.500)$ and $\alpha = (0.764, 1.087)$ MeV, where the first term in the parentheses represents $T_d = 120$ MeV while the second represents $T_d = 160$ MeV.

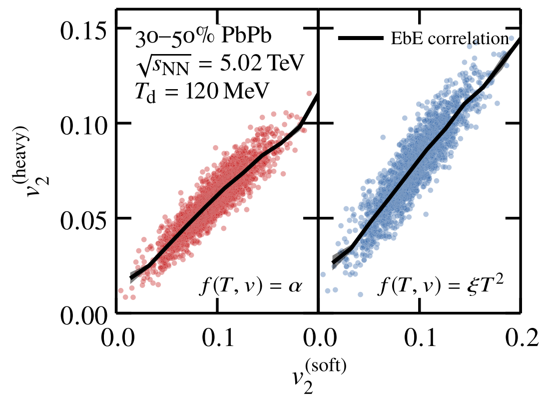

FIG. 4. Event-by-event correlation between D^0 v_2 in the p_T range 8–13 GeV and the soft hadron v_2 for two energy loss models in 30–50% PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The solid lines stem from binning the heavy meson result by the soft hadron v_2.

three soft particles [18]. For the 30–50% centrality class and p_T range 8–40 GeV we find that $v_2\{4\}/v_2\{2\} \sim 0.95$ within statistical error bars regardless of variations in the energy loss, T_d, and quark flavor. A similar value, in the case of light flavor jets, was reported in [18]. The $v_2\{4\}/v_2\{2\}$ ratio is related to the variance of the $v_2^2(p_T)$ distribution, which reflects the event-by-event fluctuations in the hard sector due to the initial density fluctuations within our model. Therefore, this ratio probes the magnitude of the initial density fluctuations and the role they play in the energy loss process. A more detailed study, involving the centrality dependence of $v_2\{4\}/v_2\{2\}$ and also the calculation of even higher order heavy flavor cumulants, will be presented elsewhere.

We now propose a new observable that encodes the event-by-event fluctuations of heavy flavor v_n at high-p_T that does not require the challenging high statistics needed in multiparticle cumulants analyses. For a given hydrodynamic event characterized by a soft hadron $v_n\{2\}$, we calculate the corresponding coefficient for D^0 in each event (this would be akin to the probability that a certain soft event corresponds to this particular heavy flavor v_n), which is shown in the scatter plot in Fig. 4 for v_2. This plot shows that the soft and the heavy elliptic flow are correlated event by event within a given centrality class. Experimentally, one can bin the soft $v_2\{2\}$ and calculate the corresponding heavy meson v_2 for that set of events, as was done for high-p_T identified hadrons by ATLAS [68]. This type of event-shape engineering procedure [69] gives rise to the solid black lines in Fig. 4. If there were no v_2 fluctuations in the heavy flavor sector one would see a flat, horizontal line. Rather, our calculations predict a clear linear correlation between the heavy meson v_2 and the elliptic flow of all charged hadrons.

This correlation is investigated in detail in Fig. 5 for v_2 (top panel) and v_3 (bottom panel) where we binned soft vs heavy v_n and varied the energy loss model as well as T_d. Similar separations between the energy loss models are observed for the cumulants, in Figs. 2 and 3, and the correlations, though the latter are highly dependent on the integrated p_T range and should be investigated experimentally in order to determine an optimal choice given the error bars. Also, even though the

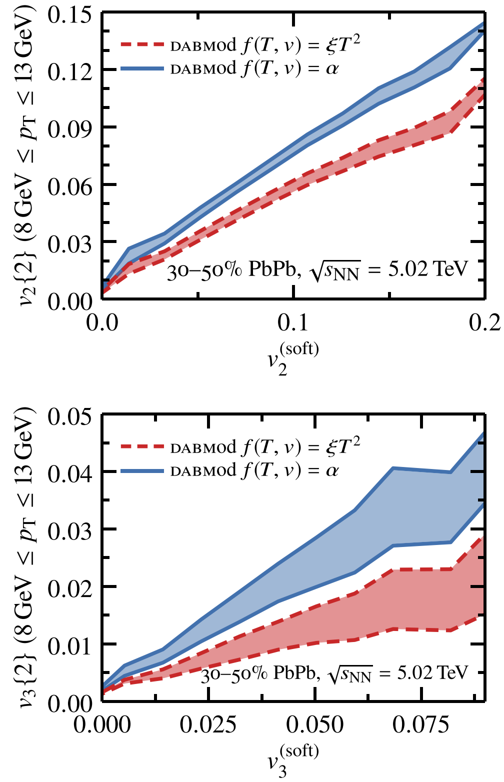

FIG. 5. Correlation between $v_n^{(heavy)}\{2\}$ for p_T in 8–13 GeV and $v_n^{(soft)}$ for D^0 in 30–50% PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using two energy loss models. The bands represent the variation of the decoupling temperature in $120 \leqslant T_d \leqslant 160$ MeV.

widths of the T_d bands are equivalent, v_3 is more sensitive to it than v_2. These results indicate that novel event-shape engineering techniques involving the flow of soft hadrons and heavy flavor will be instrumental in determining the collective behavior of heavy quarks in the QGP.

IV. LINEAR SCALING WITH ECCENTRICITIES

While there are clear qualitative differences between the two energy loss models, the understanding of how a single energy loss model leads to the development of the final azimuthal anisotropy can be further explored. It is clear from Fig. 4 that a nearly linear relationship exists between v_n^{soft} and v_n^{heavy}. Considering that in the soft sector elliptical and triangular flow are developed from a nearly linear relationship between $\varepsilon_n \to v_n^{soft}$, one then expects that the relationship between $\varepsilon_n \to v_n^{heavy}$ is also nearly linear.

In order to quantify this, we return to the Pearson coefficient in Eq. (1) and study Q_2 and Q_3 for the two different energy loss models as well as the range of T_d. In Fig. 6 one can see that, indeed, Q_2 has a nearly linear relationship between $\varepsilon_2 \to v_2^{heavy}$. Central collisions do experience some nonlinearities, which is to be expected since they are highly fluctuations-driven. Additionally, we find that $f(T,v) = \xi T^2$ has a more linear relationship between $\varepsilon_2 \to v_2^{heavy}$, whereas $f(T,v) = \alpha$ has more nonlinearities, especially in central collisions.

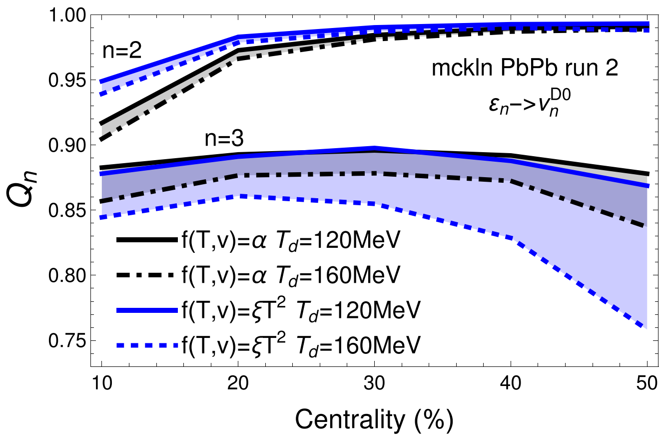

FIG. 6. Pearson coefficient described in Eq. (1) for Q_2 and Q_3 for $f(T,v)=\alpha$ and $f(T,v)=\xi T^2$ varying the decoupling temperature $T_{\rm d}=120$–160 MeV. Integrated $v_n^{\rm heavy}$ is used with the cut of $8 < p_{\rm T} < 13$ GeV.

Triangular flow experiences more nonlinearities between $\varepsilon_3 \to v_3^{\rm heavy}$ than elliptical flow does. Our results appear to be equivalent to the same effect seen in [18] for the order of magnitude of Q_2 and Q_3.

We note also that the longer the heavy quarks are coupled to the medium, the more linear the relationship between $\varepsilon_n \to v_n^{\rm heavy}$. For Q_2 this is not a large effect. However, Q_3 is strongly dependent on the decoupling temperature and this plays a larger role in determining the linearity than the energy loss model itself. This implies that v_2 is a better constraint for dE/dx whereas v_3 could provide more information about the time that heavy quarks are coupled to the QGP medium.

V. CONCLUSIONS

In summary, we presented the first theoretical calculations of D^0 multiparticle flow cumulants in heavy ion collisions performed using realistic event-by-event viscous hydrodynamics. Our calculations with the constant energy loss model $f(T,v)=\alpha$ are consistent with the published R_{AA}, v_2, and v_3 for PbPb run 2 LHC data for $p_{\rm T}=8$–40 GeV, whereas the temperature dependent energy loss model $f(T,v)=\xi T^2$ underestimates the v_2 data. We computed for the first time the heavy flavor four-particle cumulant $v_2\{4\}$, which paves the way for experimental and theoretical studies of heavy flavor elliptic flow fluctuations.

Hydrodynamic viscosity was constrained here by soft bulk flow modeling, and further investigation is needed to gauge its effect on our analysis. In [18] it was observed that an increase from 0.05 to 0.12 in η/s changed cumulants by at most 5%. Energy loss fluctuations, though not shown in this paper, have been considered following an approach similar to [37], and we observed that reasonable fluctuations affect the results for the azimuthal coefficients by a few percent. Further analysis on energy loss fluctuations will be presented elsewhere.

The linear correlation predicted here between the D^0 v_n and the underlying soft hadron v_n provides a novel signature of collectivity in the heavy flavor sector, event by event. Experimental confirmation of this behavior requires extending the current cutting edge event-shape engineering techniques [68,70] to consider soft-heavy correlations, which should be feasible during the LHC runs 2 and 3. This would not only allow for a comparison between the azimuthal anisotropies of heavy quarks and charged hadrons on an event-by-event basis but also give new insight into how the ubiquitous quantum mechanical fluctuations present in the initial state affect the energy loss experienced by heavy quarks in the plasma.

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