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Heavy - light flavor correlations of anisotropic flows at LHC energies within event-by-event transport approach

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ABSTRACT

The heavy quarks (HQs) are a unique probe of the hot QCD matter properties and their dynamics are coupled to the locally thermalized expanding quark gluon plasma. We present here a novel study of the event by event correlations between light and heavy flavor flow harmonics at LHC energy within a transport approach. Interaction between heavy quarks and light quarks have been taken into account to explore the impact of different temperature dependence for transport coefficients D_s and Γ. Our study indicates that $v_n^{heavy} - v_n^{light}$ correlation and the relative fluctuations of anisotropic flows, $\sigma_{v_n}/\langle v_n\rangle$, are novel observables to understand the heavy quark-bulk interaction and are sensitive to the temperature dependence even to moderate differences of $D_s(T)$, or $\Gamma(T)$. Hence, the comparison of such new HQ observables to upcoming experimental data at both RHIC and LHC energies can put further constraints on heavy quark transport coefficients and in particular on its temperature dependence toward a solid comparison between phenomenological determination and lattice QCD calculations.

The main goal of the ongoing nucleus-nucleus collision programs at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) is to create and characterize a state of matter that behaves like a nearly perfect fluid having a remarkably small value of shear viscosity to entropy density ratio, $\eta/s = 0.1$. The bulk properties of such a state of matter, called Quark Gluon Plasma (QGP) [1,2], are governed by the light quarks and gluons. Remarkable progress has been made towards the understanding of the properties of strongly interacting QGP. Heavy quarks [3–10], namely charm and bottom, thanks to their large masses, are considered as a solid probe to characterize the matter created in the QGP phase. They are produced in the early stage of the collisions and witness all the entire space-time evolution of QGP. In the recent past, several phenomenological studies on heavy-hadron spectra and elliptic flow with different theoretical models have been performed to extract HQ spatial diffusion coefficient at zero momentum which is within the current lattice QCD (lQCD) uncertainties [5,6,9,10]. A further step towards a better comprehension would be the inclusion of more exclusive observables for the determination of transport coefficients.

One of the observable, the heavy mesons nuclear suppression factor [11–13], $R_{AA}(p_T)$, the ratio between the hadrons produced in nucleus-nucleus collisions with respect to those produced in proton-proton collisions, has been extensively used as a probe of QGP along with the elliptic flow [14,15], $v_2(p_T) =< cos(2\phi) >$, a measure of the anisotropy in the angular distribution of heavy mesons in momentum space, as a response to the initial anisotropy in coordinate space in non-central collisions. Several attempts have been made in this direction to theoretically study both these observables with the aim to understand heavy quark dynamics in QGP [16–30]. In the recent past, a simultaneous study of both these observables, $R_{AA}(p_T)$ and $v_2(p_T)$, received significant attention as it has the potential to constrain the temperature dependence of heavy quark transport coefficient in QGP [27]. This is mainly caused by the different formation times of these observables which is useful to probe different stages of the fireball evolution. The large elliptic flow [14,15], v_2, and small nuclear suppression factor [11–13], R_{AA}, of the heavy flavor (HF) mesons observed at RHIC and LHC colliding energies are considered as an

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indication that the heavy quark interact strongly with the bulk medium.

In ref. [31], it has been shown that quasi particle model (QPM) can reproduce the lattice QCD pressure, energy density and interaction measure $T^{\mu}_{\mu} = \epsilon - 3P$. The main feature of this QPM approach is that the resulting coupling is significantly stronger than the one coming from pQCD running coupling, particularly at $T \to T_c$. This feature of QPM has been observed by other groups [32] also when quasi-particle widths (off-shell dynamics) are accounted for. The recent success of QPM to describe the heavy quark-bulk interaction in the QGP has been credited to the large enhancement of the coupling near T_c. A similar mechanism acts also in the T-matrix approach of TAMU [16,17,33,34] and the PHSD transport of Frankfurt [24] and more recently has been investigated by the LBL-CCNU collaboration [35]. Therefore, the temperature dependence of heavy quark transport coefficients is a key ingredient for the simultaneous description of heavy meson $R_{AA}(p_T)$ and $v_2(p_T)$. This dependence has also been observed in the high p_T range and in the light sector ref. [36–38], independently. Recent studies based on T-dependence K factor [35] and Bayesian model-to-data analysis [39] has also obtained similar conclusions from different viewpoints. This effect along with hadronization via coalescence plus fragmentation is the main underlying ingredient for a simultaneous description of heavy quark R_{AA} and v_2 observed experimentally [40].

Most of the studies on heavy flavor v_2 have been pursued discarding the more realistic dynamics on an event-by-event fluctuation framework with some exceptions. Recently, the triangular flow v_3 has been investigated in theoretical studies based on Langevin approach on an event-by-event analysis [41–45]. The present work is an extension of our recent works presented in Ref. [25,27,40] introducing an event-by-event fluctuating initial condition [46,47] which allows us to study also the odd harmonics. However, the main aim is, for the first time, to focus on the $v_n^{heavy} - v_n^{light}$ correlations up to 5th order harmonic. We show that within this approach with hadronization by coalescence plus fragmentation we are able to describe the experimental data not only for v_1 and v_2 of D mesons at LHC energy, as done in previous works [25,27,40,48,49], but also v_3 for different collision centralities. We also study the correlations that take place between the heavy quarks and the bulk that consists of light quarks and gluons. Finally, we show how the study of heavy-light correlations and the v_n distributions can give information about the heavy quark interaction with the QGP. In particular, we show that the linear correlation coefficient of $v_n^{heavy} - v_n^{light}$ (a measure of the degree of correlation) and the relative variance $\sigma_{v_n}/\langle v_n \rangle$ are observables highly sensitive to the temperature dependence of the transport coefficients.

The momentum evolution of the charm quark distribution function in QGP is obtained by solving the relativistic Boltzmann transport equations [40,50]:

$$\begin{aligned} p^{\mu}\partial_{\mu} f_Q(x,p) &= \mathcal{C}[f_q, f_g, f_Q](x,p) \\ p^{\mu}_q\partial_{\mu} f_q(x,p) &= \mathcal{C}[f_q, f_g](x_q,p_q) \\ p^{\mu}_g\partial_{\mu} f_g(x,p) &= \mathcal{C}[f_q, f_g](x_g,p_g) \end{aligned} \quad (1)$$

where $f_i(x,p)$ is the on-shell phase space one-body distribution function for the i parton and $\mathcal{C}[f_q, f_g, f_Q](x,p)$ is the relativistic Boltzmann-like collision integral. The phase-space distribution function of the bulk medium consists of quark and gluons entering the equation for charm quarks as an external quantities in $\mathcal{C}[f_q, f_g, f_Q]$. We assume that the evolution of f_q and f_g are independent of $f_Q(x,p)$ and discard collisions between charm quarks which is by far a solid approximation to study the D meson dynamics while it would be relevant for the J/Ψ production due to the recombination mechanism [51–53]. We are interested in the evolution of the HQ distribution function $f_Q(x,p)$ scattering with the bulk medium. The evolution of the bulk is instead given by the solution of the other two transport equations where the $\mathcal{C}[f_q, f_g]$ is tuned to a fixed $\eta/s(T)$, as discussed in detail in ref. [54].

For bulk modeling, we adopted the same approach described in Refs. [46,47]. To set the initial geometry the nucleons within the two nuclei have been distributed according to a Woods-Saxon distribution. In this way, a discrete distribution for these nucleons is generated. A geometrical method is used to determine if the two nucleons, one from the nucleus A and the other one from the nucleus B, are colliding. The two nucleons collide if the relative distance in the transverse plane is $d_T \le \sigma_{NN}/\pi$ where σ_{NN} is the nucleon-nucleon cross-section. In our calculations we use $\sigma_{NN} = 7.0\, fm^2$. The discrete distribution for the nucleons is converted into a smooth one by assuming for each nucleon a Gaussian distribution centered in the nucleon position. Finally, we convert the nucleon distribution into the parton density distribution in transverse plane $\rho_T(x,y)$, which is given by $\rho_T(x,y) = K\sum_{i=1}^{N_{part}} \exp\Big[-((x-x_i)^2+(y-y_i)^2)/(2\sigma_{xy}^2)\Big]$ where the proportionality coefficient K is fixed by the experimental longitudinal distribution dN/dy, while σ_{xy} is the Gaussian width which regulates the smearing of the fluctuations and has been fixed to $\sigma_{xy} = 0.5$ fm, as done also in the hydrodynamics framework [55,56]. In our calculation we have assumed initially a longitudinal boost invariant distribution from $y = -2.5$ to $y = 2.5$. We initialize the charm quark distribution in the coordinate space in accordance with the number of binary nucleon-nucleon collisions, N_{coll}, from the Monte Carlo Glauber model. For the momentum distribution, we use charm quark production in Fixed Order + Next - to - Leading Log (FONLL) [57] which describes the D-meson spectra in proton-proton collisions after fragmentation. For details we refer to our earlier work in Ref. [40]. For the heavy quark bulk interaction, we consider a QPM whose main feature is that the resulting coupling is significantly stronger than the one coming from pQCD running coupling, particularly as $T \to T_c$. The scattering matrix $\mathcal{M}_{(q,g)+Q\leftrightarrow(q,g)+Q}$ has been evaluated considering the leading-order diagram with the effective coupling $g(T)$ that leads to effective vertices and a dressed massive gluon propagator for $gQ \leftrightarrow gQ$ and massive quark propagator for $qQ \leftrightarrow qQ$ scatterings. For the scattering matrix, we are using the Cambridge matrix [58] that includes s, t, u channel and their interference terms. For detail, we refer to our earlier work [27,40]. Once the temperature of the QGP phase goes below the quark-hadron transition temperature, $T_c = 155$ MeV, we hadronize the charm quark to D-meson. For heavy quark hadronization, we consider an hybrid approach of hadronization by coalescence plus fragmentation. We use Peterson fragmentation function [59]: $f(z) \propto [z[1-\frac{1}{z}-\frac{\epsilon_c}{1-z}]^2]^{-1}$ where $z = p_D/p_c$ is the momentum fraction of the D-meson fragmented from the charm quark and ϵ_c is a free parameter to fix the shape of the fragmentation function, so that one can describe D-meson production in proton-proton collisions [4]. For the coalescence we use a model where the particle production is given by the coalescence integral based on a Wigner formalism, where the widths of the Wigner function are fixed by the mean square radius of the D meson, for detail we refer to our earlier work [49].

In Fig. 1, we have shown the variation of triangular flows as a function of transverse momentum in $Pb+Pb$ collisions at $\sqrt{s} = 5.02$ ATeV. We have shown explicitly the contributions of different hadronization processes which allow direct access to the role played by coalescence and fragmentation. The blue dashed lines indicate the $v_3(p_T)$ for D mesons that we obtain considering only the fragmentation as hadronization mechanism, while the green dashed line corresponds to the case via the only coalescence. The v_3 developed by the only coalescence is larger than the v_3

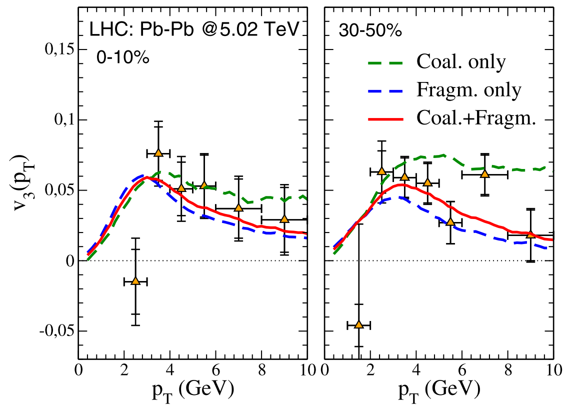

Fig. 1. D^0 meson $v_3(p_T)$ at mid-rapidity for the two centralities classes $(0-10\%)$ (left) and $(30-50\%)$ (right). Green dashed lines correspond to D mesons produced only via coalescence while blue dashed line via only fragmentation. The red solid line refers to the case with both coalescence plus fragmentation. Data taken from [60].

developed by only fragmentation. This difference originates from the fact that the anisotropic flows of D meson formed via coalescence reflect both heavy quark and bulk anisotropies in momentum space and this leads to an enhancement of the $v_3(p_T)$. Finally, the solid red line shows the $v_3(p_T)$ of D mesons produced via coalescence plus fragmentation. The underlying fraction of coalescence and fragmentation is the one that allows a good description of D meson spectra and the recently measured Λ_c/D^0 ratio at RHIC and LHC energies [61,62], see Ref. [49]. In recent past, the correlation between integrated v_2 and high order harmonics v_3, v_4 for light hadrons with the initial asymmetry in coordinate space ϵ_2, ϵ_3 and ϵ_4 have been studied within the event-by-event ideal hydrodynamics, viscous hydrodynamics and transport framework [46,63–65]. In this paper, we extend these studies to the heavy quark sector with the main novelty of considering the correlations between charm quarks and light quarks within an event-by-event transport approach. In Fig. 2, we have show the density-plot expressing the correlation between the integrated flow v_n^{heavy} for heavy quarks as a function of the corresponding final integrated flow coefficients v_n^{light} for light quarks. The results are obtained for $Pb+Pb$ collisions at $\sqrt{s_{NN}}=5.02$ TeV for two different centralities $(0-0.2)\%$ and $(30-50)\%$. The viscosity has been fixed to $4\pi\eta/s=1$ plus a kinetic f.o. realized by the increase in $\eta/s(T)$, for more details see [46,47]. As shown in the right panel we observe a strong linear correlation between $v_2^{(heavy)}$ and $v_2^{(light)}$ at both central and peripheral collisions. For the higher harmonics, we observe a reduction of the linear correlation in comparison to the second harmonic.

A measure of the linear correlation is given by the correlation coefficient $C(n,m)$ expressed as:

$$C(n,m) = \frac{\sum_i (v_n^{L,i} - \langle v_n^L \rangle)(v_m^{H,i} - \langle v_m^H \rangle)}{\sqrt{\sum_i (v_n^{L,i} - \langle v_n^L \rangle)^2 \sum_i (v_m^{H,i} - \langle v_m^H \rangle)^2}} \tag{2}$$

where $v_n^{L,i}$ and $v_m^{H,i}$ are the values of anisotropic flows corresponding to the event i for light and heavy quarks respectively. A $C(n,m) \approx 1$ corresponds to a strong linear correlation between light and heavy anisotropic flows. The results shown in this section have been obtained with a number of events $N_{event}=5000$ for each centrality class and a total number of test particles per event $N_{test}=2 \cdot 10^6$.

In the left panel of Fig. 3, we have shown the $C(n,n)$ between the initial ϵ_n and final v_n of charm quarks as a function of impact parameter, while in the right panel is shown the correlation coefficient between final heavy quarks $v_n^{(heavy)}$ and light quarks $v_n^{(light)}$. Note that the coefficients ϵ_n have been calculated using the definition given in [46] by

$$\epsilon_n = \sqrt{\langle r_T^n \cos(n\phi)\rangle^2 + \langle r_T^n \sin(n\phi)\rangle^2} / \langle r_T^n \rangle \tag{3}$$

where $r_T = \sqrt{x^2+y^2}$ and $\phi = arctan(y/x)$ are the polar coordinates in the transverse plane. As shown in the left panel, the linear correlation coefficient is a decreasing function with respect to the impact parameter for all the harmonics. Moreover, we observe that only v_2 is strongly correlated with the corresponding initial eccen-

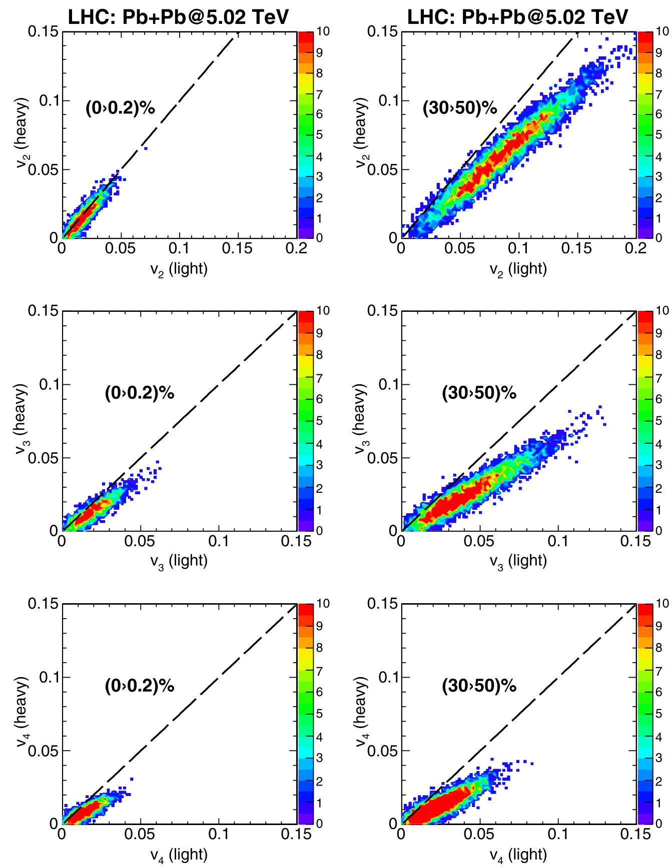

Fig. 2. Event-by-event correlation between $v_n^{(heavy)}$ and $v_n^{(light)}$ for $n=2,3,4$ for $Pb+Pb$ collisions at $\sqrt{s}=5.02$ TeV for $(30-50\%)$ and $(0-0.2\%)$ centrality cuts.

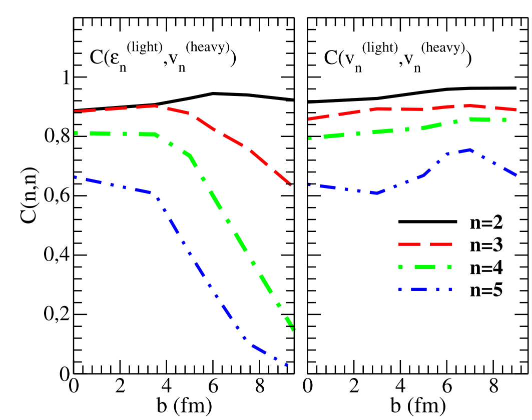

Fig. 3. Left panel: correlation coefficient between the initial ϵ_n and v_n of charm quarks at different impact parameters. Right panel: correlation coefficient between heavy quarks v_n and light quarks v_n at different impact parameters. Different colors are for different harmonics. These results have been obtained with QPM.

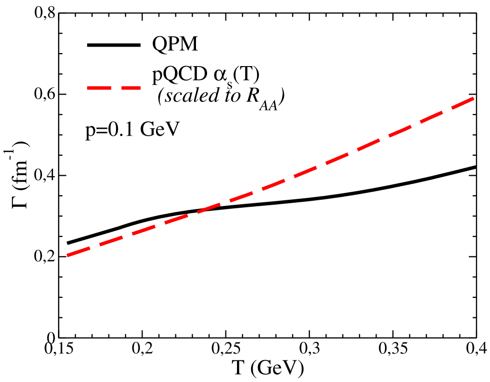

Fig. 4. Temperature dependence of the drag coefficient Γ. Black solid line corresponds to QPM. The red dashed lines correspond to pQCD interaction scaled in order to reproduce the same R_{AA} as of QPM.

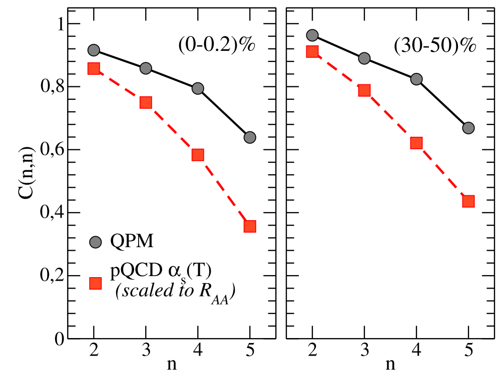

Fig. 5. Event-by-event correlation coefficient between D-meson v_n and light hadron v_n as a function of the order of the harmonic n obtained within QPM (black solid line) and pQCD (red dashed line).

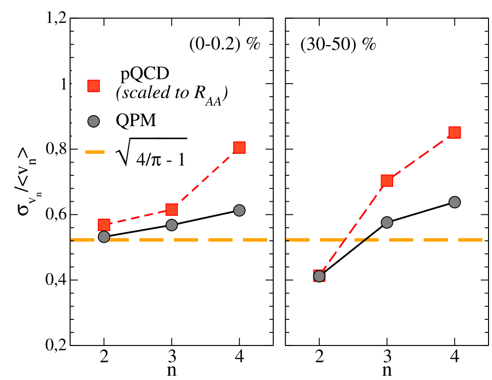

Fig. 6. $\sigma_{v_n}/\langle v_n\rangle$ as a function of the order of harmonics n for QPM (black solid line) and pQCD (red dashed line). The orange dashed lines indicate the value $\sqrt{4/\pi - 1}$ expected for a 2D Gaussian distribution.

tricities ϵ_2. On the other hand, in the right panel of Fig. 3 (black solid line), the correlation coefficient $C(2,2) \approx 0.95$ and it remains almost flat and independent of impact parameter. We observe for v_2 and v_3 approximatively the same degree of correlation, while a lower degree of correlation is shown for higher harmonics $n = 4, 5$. However, the main original finding is that the $v_n^{(heavy)}$ remains, at least up to $n = 4$, strongly correlated to $v_n^{(light)}$ at different impact parameters in variance with the correlation to the initial ϵ_n. This means that the building up of $v_n^{(heavy)}$ is driven by the v_n of the bulk, while the correlation to the initial eccentricities is nearly lost for $b \geq 5$ fm. This suggests that for noncentral collisions a strong correlation between heavy quarks v_n and light quarks v_n originates from the heavy quarks and bulk interaction. Of course, the experimental observation of these patterns would give a strong confirmation that the mechanism of v_2 build-up is the one essentially underlying most of the present theoretical description. In addition to this we will address the effect of the temperature dependence of the interaction, namely the drag coefficient, on both the correlations and v_n distribution. Several theoretical attempts have been made to study the T dependence of heavy quark drag coefficient, and it has been shown that the temperature dependence of the heavy quark interaction is an important aspect to reproduce both R_{AA} and v_2 simultaneously. However, at present, other aspects like the initial conditions, the details of the bulk expansion, or the details of the hadronization can add significant uncertainty on the T dependence of $\Gamma(T)$ or $D_s(T)$.

In Fig. 4 the black solid line shows the behavior of the drag coefficient, Γ, with temperature obtained within QPM. By red dashed line we show the same coefficient obtained within the framework of pQCD with a temperature dependent coupling, $\alpha_s(T)$. We use the same bulk for both QPM and pQCD but we upscale the interaction of pQCD case in order to reproduce the same $R_{AA}(p_T)$ obtained within the QPM case. Here we present a study of the impact of a moderate difference in the T dependence of $\Gamma(T)$ exploring a range that is even narrower than the current uncertainties [5,10]. The $\Gamma(T)$ has been tuned to reproduce the same $R_{AA}(p_T)$ of D mesons and exhibit a similar $v_2(p_T)$.

In Fig. 5 we present the correlation coefficient $C(n,n)$ as a function of the order of the harmonic n. We have computed $C(n,n)$ for both QPM and pQCD to understand the impact of the temperature dependence of heavy quark transport coefficients on the heavy-light $v_2^{HF} - v_2^{LF}$ correlation coefficients. In this figure the hadron anisotropic flows have been obtained using the parton-hadron duality scheme as done also in other approaches [46,47]. As shown in Fig. 3, the correlation coefficient decrease with the order of harmonics for both pQCD and QPM. However, the correlation is stronger for QPM than pQCD for all the harmonics considered in this manuscript for both centralities. This highlights the impact of the temperature dependence of heavy quark transport coefficients on event-by-event D-meson v_n and light hadron v_n correlation coefficients especially for semi-peripheral collisions.

Notice that different harmonics have different formation time [46]. This implies correlation coefficients of different harmonics have different sensitivity to the temperature dependence of the transport coefficients. In fact, we see that the QPM $\Gamma(T)$ induce a stronger $C(n,n)$ because it has a larger drag at $T \leq 1.5T_c$ where most of v_n develop, and this effect increase with n. Therefore, this study suggests that the comparison of theoretical results with the upcoming experimental data will put a robust constraint on the T dependence of the HQ transport coefficient, considering the moderate difference in $\Gamma(T)$ shown in Fig. 4 can induce quite different $C(n,n)$.

We have also computed the heavy quarks normalized v_n variances. In fact, some interesting properties of heavy quarks v_n distributions can be inferred by studying the centrality dependence of the relative fluctuations $\sigma_{v_n}/\langle v_n\rangle$, where σ_{v_n} are the standard deviation for v_n. In Fig. 6 we have shown the ratios $\sigma_{v_n}/\langle v_n\rangle$ for two different centralities obtained within both QPM and pQCD. Notice that we have checked that the numerical systematic error in the variance is between $5 - 10\%$ going from the one for v_2 up to v_4. As shown in Fig. 3, the second and third harmonics are the most correlated ones $C(2,2) \approx C(3,3) \approx 0.9$. Therefore, the HF $p(v_n)$ distributions tend to reflect the $p(v_n)$ distributions of the bulk, which are strongly correlated to the initial eccentricity distributions [46]. The $\sigma_{v_2}/\langle v_2\rangle$ is a decreasing function with the centrality, while $\sigma_{v_3}/\langle v_3\rangle$ is almost independent to centrality for the QPM case, and it is very close to the value $\sqrt{4/\pi - 1}$ shown by the orange dashed lines. These results imply that the distributions of v_3 are consistent with the fluctuation-only scenario discussed in [66], while the distribution of v_2 is close to this limit for most central collisions. On the other hand, for mid-peripheral collisions, the impact of global average geometry decreases the fluctuations for $n = 2$. Looking at the evolution of $\sigma_{v_n}/\langle v_n \rangle$ with n, it emerges a strong sensitivity to the T-dependence of Γ. This sensitivity constitutes a further novel way to get information on charm interaction. We also notice that, for charm quark, it seems possible to have normalized variance for $n \geq 3$ that are even quite large than the Gaussian fluctuations only scenario (shown by orange dashed lines in Fig. 6).

In summary, for heavy quark momentum evolution, we have solved the relativistic Boltzmann transport equation, where HQ-bulk interaction has been treated within both QPM and pQCD. For the bulk initialization, we introduce an event-by-event fluctuating initial condition, which allows us to access the study of the odd harmonics. We have evaluated the heavy-light correlation coefficients $C(v_n^{(heavy)}, v_n^{(light)})$ as a function of impact parameter and order of the harmonic n. We see that for $n \leq 4$ it increases with the order of the harmonics and as a function of centrality it remains flat. This trend, if observed experimentally, will be a signature that the HQ anisotropies are driven by the bulk ones. Moreover, we have found a strong impact of temperature dependence of heavy quark transport coefficients on $C(v_n^{(heavy)}, v_n^{(light)})$ and $\sigma_{v_n}/\langle v_n \rangle$ as a function of the order of harmonics n. Comparison of results presented in this manuscript with the upcoming experimental data will help to constrain heavy quark transport coefficients and disentangle different energy loss models.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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