Heavy flavor R_{AA} and v_n in event-by-event viscous relativistic hydrodynamics

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Abstract. Recently it has been shown that a realistic description of the medium via event-by-event viscous hydrodynamics plays an important role in the long-standing R_{AA} vs. v_2 puzzle at high p_T. In this proceedings we begin to extend this approach to the heavy flavor sector by investigating the effects of full event-by-event fluctuating hydrodynamic backgrounds on the nuclear suppression factor and $v_2\{2\}$ of heavy flavor mesons and non-photonic electrons at intermediate to high p_T. We also show results for $v_3\{2\}$ of B^0 and D^0 for PbPb collisions at $\sqrt{s} = 2.76$ TeV.

1. Introduction

Heavy quarks, such as bottom and charm, are very useful probes of Quark-Gluon Plasma (QGP) dynamics. Because of their large mass, these quarks are produced at the very early stages of the collision via hard processes and their subsequent propagation through the hot and dense medium is sensitive to the whole hydrodynamic evolution of the system. The energy loss experienced by the heavy quarks during their path within the plasma has been studied using the nuclear modification factor (at mid-rapidity), defined as

$$R_{\mathrm{AA}}(p_T, \varphi) = \frac{\frac{\mathrm{d}N_{\mathrm{AA}}}{\mathrm{d}p_T\,\mathrm{d}\varphi}}{N_{\mathrm{coll}}\frac{\mathrm{d}N_{\mathrm{pp}}}{\mathrm{d}p_T}}, \tag{1}$$

where $\mathrm{d}N_{\mathrm{AA}}/\,\mathrm{d}p_T = \frac{1}{2\pi}\int_0^{2\pi} d\varphi \frac{\mathrm{d}N_{\mathrm{AA}}}{\mathrm{d}p_T\,\mathrm{d}\varphi}$ is the spectrum of heavy quarks in AA collisions while $\mathrm{d}N_{\mathrm{pp}}/\,\mathrm{d}p_T$ is the corresponding proton-proton yield, φ is the azimuthal angle in the plane transverse to the beam direction, and N_{coll} is the number of binary collisions (computed within the Glauber model).

The dependence of $R_{\mathrm{AA}}(p_T, \varphi)$ on the azimuthal angle φ can be used to study the energy loss and its path length dependence in the plasma. The degree of anisotropy in $R_{\mathrm{AA}}(p_T, \varphi)$ is determined via the v_n^{heavy} coefficients of its Fourier expansion

$$\frac{R_{\mathrm{AA}}(p_T, \varphi)}{R_{\mathrm{AA}}(p_T)} = 1 + 2\sum_{n=1}^{\infty} v_n^{\mathrm{heavy}}(p_T)\cos\left[n\varphi - n\psi_n^{\mathrm{heavy}}(p_T)\right] \tag{2}$$

where $R_{\mathrm{AA}}(p_T) = \frac{1}{2\pi}\int_0^{2\pi} d\varphi\, R_{\mathrm{AA}}(p_T,\varphi)$ is the azimuthal average and

$$v_n^{\mathrm{heavy}}(p_T) = \frac{\frac{1}{2\pi}\int_0^{2\pi} d\varphi\, \cos\left[n\varphi - n\psi_n^{\mathrm{heavy}}(p_T)\right]\, R_{\mathrm{AA}}(p_T,\varphi)}{R_{\mathrm{AA}}(p_T)} \tag{3}$$

and

$$\psi_n^{\mathrm{heavy}}(p_T) = \frac{1}{n}\tan^{-1}\left(\frac{\int_0^{2\pi} d\varphi\, \sin(n\varphi)\, R_{\mathrm{AA}}(p_T,\varphi)}{\int_0^{2\pi} d\varphi\, \cos(n\varphi)\, R_{\mathrm{AA}}(p_T,\varphi)}\right). \tag{4}$$

As pointed out in [1, 2], quantities such as $v_n^{\mathrm{heavy}}(p_T)$ do not actually correspond to what is measured. In fact, just as it is done in the soft sector, the harmonic flow coefficients either at high p_T or in the heavy flavor sector are defined via correlation functions between a soft particle (event plane) with a high p_T particle or a heavy flavor candidate. This intrinsic correlation necessarily requires [1, 2] the use of event-by-event viscous hydrodynamic simulations for the QGP to correctly describe the underlying flow, and its fluctuations, in the soft sector. Through such an approach one can obtain a nonzero triangular flow at high p_T, as shown in [1, 2].

In this proceedings we initiate the investigation of event-by-event viscous hydrodynamic fluctuations on observables in the heavy flavor sector for PbPb collisions at $\sqrt{s} = 2.76$ TeV, as very briefly described below.

2. Simulation

We developed a new framework to describe the propagation of heavy quarks on top of energy density and hydrodynamic flow profiles obtained via event-by-event viscous hydrodynamics. The simulation follows a modular paradigm, which allows for the separate study of different aspects of the collision. We simulate the propagation of heavy quarks (bottom and charm) in an expanding (boost invariant) medium described by the v-USPhydro code [3, 4] on an event-by-event basis for PbPb collisions at $\sqrt{s} = 2.76$ TeV. Only shear viscosity effects are taken into account and we assume $\eta/s = 0.11$ [1]. MCKLN initial conditions [5] are used for the hydrodynamic evolution. The system is evolved separately from the heavy quark propagation, which are treated as probes, and thus we neglect any effect of the probes on the medium, unlike [6]. The hydrodynamic evolution takes place until the complete freeze-out of the system, with the freeze-out temperature set as $T_{\mathrm{FO}} = 140$ MeV, occurs. The hydrodynamic simulation gives evolving profiles on the transverse plane for the energy density ε (and temperature T) and the components of the transverse velocity v_x and v_y on an event-by-event basis.

Heavy quarks are sampled at the beginning of every hydrodynamic event (1000 events for each centrality class). The initial position of the quarks is defined by the number of binary collisions in the event. We set a random initial propagation direction φ_{quark} and the initial momentum distribution of the quarks is given by a pQCD calculation (FONLL) [7]. The heavy quarks lose energy to the evolving medium via the simple energy loss model [8]

$$\frac{\mathrm{d}E}{\mathrm{d}x} = \alpha\Gamma_{\mathrm{flow}} f(T,E,x), \tag{5}$$

where $\Gamma_{\mathrm{flow}} = \gamma\left[1 - v\cos(\varphi_{\mathrm{quark}} - \varphi_{\mathrm{flow}})\right]$ takes into account the local flow boost of the medium [1], $f(T,E,x)$ is a function that specifies the energy loss model dependence with the medium temperature, heavy quark energy E, and path length x. The coupling constant parameter α is found by comparison to data and here we use the D^0 meson R_{AA} spectrum for central collisions to obtain it for the charm quark. After fixing the value of α for charm, we take the electron contribution of both heavy quarks and fit the parameter for the bottom quark using electron R_{AA} data. The heavy quarks propagate in the QGP until they find a region where the local temperature is smaller than a certain value, which we call the jet-medium decoupling parameter, $T_d = 120$ MeV, below which energy loss stops and fragmentation is employed. We do not include coalescence effects in this paper [9] and, thus, we will restrict ourselves to the high p_T region where these effects are minimal. The final electron spectra is obtained from the meson decays, calculated using PYTHIA8 [10]. The calculation of the differential flow coefficients follows Ref. [11] where here the soft and heavy flow harmonics are correlated, which is only possible in event-by-event calculations.

3. Results

In Fig. 1 our results for the nuclear modification factor are compared to D^0 meson and heavy flavor electron data for central PbPb collisions at $\sqrt{s} = 2.76$ TeV. The plot presents results for two different energy loss models where $\mathrm{d}E/\mathrm{d}x \sim T^2$ and $\mathrm{d}E/\mathrm{d}x = \text{constant}$. The 2-particle elliptic flow cumulant $v_2\{2\}$ for non-central collisions is presented in Fig. 2 for D^0 meson and heavy flavor electrons. At intermediate $p_T < 10$ GeV our results are comparable to previous calculations [9, 12] when coalescence effects are not present. The two energy loss models that yielded the same nuclear modification factor give slightly different results for $v_2\{2\}$, which shows the sensitivity of the azimuthal distribution with the energy loss mechanisms.

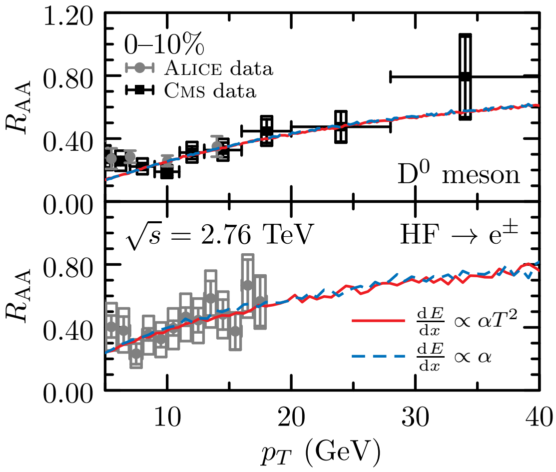

Figure 1. R_{AA} for D^0 meson (top) and heavy flavor electron (bottom) for $\sqrt{s} = 2.76$ TeV PbPb collisions and two different energy loss models. Data from ALICE and CMS [13–15] are presented with the simulation results.

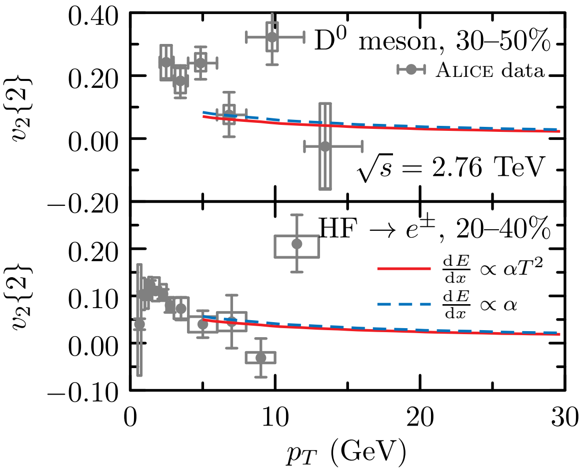

Figure 2. Differential $v_2\{2\}$ for D^0 meson (top) and heavy flavor electron (bottom) for $\sqrt{s} = 2.76$ TeV PbPb collisions and two different energy loss models. Data from the ALICE experiment [13, 16] is also presented.

Fig. 3 presents the first calculation of the 2-particle cumulant of triangular flow $v_3\{2\}$ for D^0 meson and heavy flavor electrons for non-central PbPb collisions at $\sqrt{s} = 2.76$ TeV for two energy loss models (we note that heavy flavor triangular flow, defined by the event plane method, has been computed in [17]). We see that the distinction between the energy loss models is even more significant than what is found in the case of $v_2\{2\}$ in Fig. 2 and, thus, $v_3\{2\}$ may be an even better tool than $v_2\{2\}$ to learn about jet-medium interactions.

4. Conclusions

We developed a new framework to study heavy probes in an event-by-event hydrodynamically expanding viscous QGP. Results for R_{AA} and $v_2\{2\}$ in the heavy flavor sector from this approach

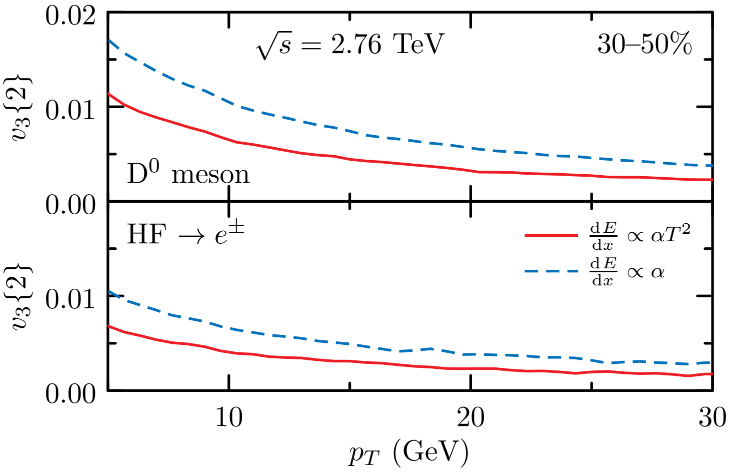

Figure 3. Differential $v_3\{2\}$ for D^0 meson (top) and heavy flavor electron (bottom) for $\sqrt{s} = 2.76$ TeV PbPb collisions and two different energy loss models.

were compared to available experimental data. We also presented the first calculation of $v_3\{2\}$ for heavy flavor, which revealed to be more sensitive to the choice of energy loss than $v_2\{2\}$. Future work includes the calculation of multiple-particle cumulants of harmonic flow and the inclusion of coalescence effects to also describe the intermediate p_T sector.

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