Event-by-event $v_n$ correlations of soft hadrons and heavy mesons in heavy ion collisions

Caio A. G. Prado$^a$, Jacquelyn Noronha-Hostler$^b$, Roland Katz$^a$, Jorge Noronha$^a$, Marcelo G. Munhoz$^a$, Alexandre A. P. Suaide$^a$

$^a$Instituto de Física, Universidade de São Paulo, C.P. 66318, 05315-970 São Paulo, SP, Brazil
$^b$Department of Physics, University of Houston, Houston TX 77204, USA

Abstract
Combining event-by-event hydrodynamics with heavy quark energy loss we compute correlations between the heavy and soft sectors for elliptic and triangular flow harmonics $v_2$ and $v_3$ of $D^0$ mesons in PbPb collisions at 2.76 TeV and 5.02 TeV. Our results indicate that $v_3$ is strongly influenced by the fragmentation temperature and that it builds up later than $v_2$ during the evolution of the system.

Keywords: heavy flavor, anisotropic flow, event-by-event viscous hydrodynamics, event shape engineering

1. Introduction
It is known that final state flow anisotropies are converted from medium density gradients present in early stages of heavy ion collisions due to the nearly perfect fluidity property of the Quark-Gluon Plasma ($qgp$). Event-by-event viscous hydrodynamics has been shown to accurately describe the anisotropic flow coefficients, $v_n$, in the soft limit ($p_T < 2$ GeV) [1]. However, at high $p_T$ the underlying physical mechanism behind anisotropic flow changes and $v_n$ is driven by differences in the path length of jets flowing through the plasma [1, 2], a picture that has been confirmed by event-by-event jet energy loss combined with viscous hydrodynamics calculations [3]. In this picture, there is an approximate linear response relation between the high $p_T$ $v_2$ and the initial state eccentricity $e_2$.

Recent calculations using event shape engineering techniques [4, 5] has shown that heavy flavor meson azimuthal anisotropy at high $p_T$ are linearly correlated with the anisotropy in the soft sector [5]. Following these calculations, in this proceeding, we further investigate the correlations between $D^0$ mesons with $p_T \gtrsim 10$ GeV to all charged particles in the soft sector for PbPb at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 5.02$ TeV collisions. This is done by combining a heavy quark energy loss model with event-by-event viscous hydrodynamic backgrounds, which allows for computing the nuclear modification factor, $R_{AA}$, and the corresponding flow coefficients $v_2$ and $v_3$.

2. Development of the simulation
In order to study the evolution of the heavy quarks inside the $qgp$ we developed the so-called DAB-MOD [6], a modular Monte Carlo simulation program written in C++, using root [7] and PYTHIA8 [8] libraries. The
modular characteristic of the program allows for one to select different energy loss models, medium backgrounds or hadronization processes while studying the evolution of the system. In the simulation, bottom and charm quarks are sampled within the transverse plane at midrapidity of the qgp medium with their initial momentum given by pQCD calculation using FONLL [9,10]. Each sampled heavy quark travels along the transverse plane with a velocity v and a constant direction $\varphi_{\text{quark}}$. We implement a simple parametrization of the energy loss per unit length given as:

$$\frac{dE}{dx}(T,v) = -f(T,v)\Gamma_{\text{flow}},$$

(1)

where T is the local temperature, $\Gamma_{\text{flow}} = \gamma(1 - v_{\text{flow}} \cos(\varphi_{\text{quark}} - \varphi_{\text{flow}}))$ (with $\gamma = 1/\sqrt{1 - v_{\text{flow}}^2}$) is the flow factor with $\varphi_{\text{flow}}$ the local azimuthal angle of the underlying flow.

In this work we consider $f(T,v) = \alpha$, inspired by the study performed in Ref. [11], which showed that a non decreasing drag coefficient near the phase transition is favored for a simultaneous description of heavy flavor $R_{AA}(p_T)$ and $v_2(p_T)$. The free parameter $\alpha$ in the energy loss expression is fixed by matching the $D^0$ $R_{AA}$ computed by DIF-MOD to data for $p_T \sim 10 \text{ GeV}$ in the central collisions.

We use the v-usphydro event-by-event relativistic viscous hydrodynamical model [12,13,14] for the temperature and flow profiles of the medium. For initial conditions, MClm [15] is used with $\eta/s = 0.11$ and an initial time $t_0 = 0.6 \text{ fm}$, which leads to a good description of experimental data for the flow harmonics at low $p_T$. Currently, no coalescence is implemented in the code and hadronization of the heavy quarks is assumed to occur when the local temperature reaches a chosen temperature $T_{d_i}$, at which fragmentation [16] is performed. Also, no effect on the medium from the traversing heavy quarks is considered during this calculation and the heavy quarks are treated as probes.

The event-by-event analysis uses a couple of thousand hydro events in each centrality bin. Heavy quarks are oversampled for each event. That allows us to compute the nuclear modification factor $R_{AA}(p_T, \varphi)$, for a given heavy quark flavor $q$ or heavy meson from $q$, and its corresponding flow coefficients $v_n$.

3. Results

We show in Fig. 1 a comparison of $D^0$ $R_{AA}$ computed by DAB-MOD with experimental data [20,21,22] for both $\sqrt{s} = 2.76 \text{ TeV}$ and $\sqrt{s} = 5.02 \text{ TeV}$ PbPb central collisions. In the considered region of $p_T \gtrsim 10 \text{ GeV}$ our results lead to a good agreement with the data and are similar for both fragmentation temperatures of $T_d = 120 \text{ MeV}$ and $T_d = 160 \text{ MeV}$. 

![Fig. 1](image-url) (Color online) $D^0$ nuclear modification factor $R_{AA}$ computed by DAB-MOD for $\sqrt{s} = 2.76 \text{ TeV}$ (left) and $\sqrt{s} = 5.02 \text{ TeV}$ (right) PbPb 0–10% central collisions. Gray area indicates $p_T$ region where effects of coalescence may be significant. Experimental data from Refs. [20,21,22].
In Fig. 2 we compute the multi-particle cumulants $v_2(n)$ of $D^0$ mesons for the same collision energies at a different centrality range of 30–40% and compare with currently available experimental data \[23, 24\]. One can see that our results are consistent with data at high $p_T$ for the two collision energies. At low $p_T \lesssim 10$ GeV one must consider that coalescence is not negligible and our results fall below experimental data. Furthermore, different energy loss mechanisms come into play in the low $p_T$ regime \[25\], which may contribute to the overall magnitude of the computed flow harmonics.

Using event-by-event correlations \[6\] one can examine different parameters of the simulation and study their effects. In Fig. 3, we show the correlations for PbPb at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 5.02$ TeV semi-central collisions. The left (right) plots show the correlation for the elliptic (triangular) flow. The figure exhibits a clear difference of the slopes for the two chosen fragmentation temperatures in the case of $v_3$, which is not observed for $v_2$. That might be related to the build up time of each harmonic, since, the higher the $T_d$, the less time the quark has to interact with the medium before hadronization occurs. The plots indicate that for this energy loss parametrization, $v_3$ takes longer to build up than $v_2$, which should get most of its effect from the initial interaction with the medium.

4. Conclusions

This work combines event-by-event hydrodynamic flow and temperature profiles with a parametrization for heavy quark energy loss, which allows for the computation of $R_{AA}$ and $v_2$ of $D^0$ mesons at high $p_T$. By
implementing these calculations into a Monte Carlo simulation, called dar-mod, we were able to obtain the correlations between the heavy flavor and soft sectors for the elliptic and triangular flow harmonics $v_2$ and $v_3$ using an event engineering technique first described in [6]. Our results show that the $v_3$ magnitude is highly affected by the fragmentation temperature which indicates that it might be built up at later stages during the evolution of heavy quarks within the medium when compared to $v_2$.

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