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Heavy Flavor Production, Flow and Energy Loss

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Abstract

An overview of the current status of the heavy quarks as probe of the hot QCD in-medium interaction is presented. Heavy quarks that produced out-of-equilibrium but strongly interacting with the created quark-gluon plasma (QGP) bulk medium offer the unique opportunity to have a probe that thermalize in a time scale comparable with the lifetime of the QGP. Finally, the possible role of heavy quark for probing the initial strong electromagnetic field created in relativistic heavy-ion collisions is discussed.

Keywords: Open Heavy Flavor, Transport Coefficients, Elliptic flow, Directed Flow, Magnetic Field

1. Introduction

Heavy quarks (HQs), mainly charm and bottom, play a crucial role for probing the Hot QCD matter interaction in a regime where also lattice QCD can access its in medium properties like transport coefficients and spectral functions [1] . In the context of ultra-relativistic heavy-ion collisions (uRHICs), there are two reasons why HQs can be considered "heavy"; the first, typical of particle physics is that $M_Q >> \Lambda_{QCD}$ which allows to compute the initial spectrum within next-to-leading order (NLO) calculations; the second, typical of plasma physics, is that $M_Q >> T$ the temperature of the bulk matter which means that the HQ production is set by the initial hard scattering and subsequent thermal production can be neglected. So at variance with the light quark-gluon sector the initial distribution function are known from pp and pA collisions [2, 3] and these initial HQs with a formation time $\tau_0 \sim 1/2M_Q \lesssim 0.1$ fm/c are witness of the entire evolution of the QGP fireball. Also, in the light quark sector the dynamical evolution can be described within the hydrodynamics framework, while for HQs is required a transport approach able to describe the evolution toward thermalization as they are not expected to thermalize in a timescale $\tau_{th}^{qg} \lesssim 1\, fm/c$. The comparison between theoretical models and experimental data on D mesons (or their semileptonic decay) has made manifest that HQs interaction, parametrized in terms of a drag γ coefficient, is quite stronger than the pQCD one. The last in fact would predict an R_{AA} quite larger than the one of light mesons in strike contrast with experimental observations. This means also that pQCD scheme, giving $\tau_{th} = \gamma^{-1} \approx 10 - 20$ fm/c for charm and $25 - 50$ fm/c for bottom (roughly scaling with the mass) [4, 5] largely overestimates the thermalization time. Even if still significant uncertainties are present there is quite some evidence, as I will discuss in the following, that $\tau_{th}^c \approx 5$fm/c $\sim \tau_{\rm QGP} >> \tau_0$, i.e. quite comparable with the lifetime of the QGP already at RHIC energies. This offers a probe carrying more information on the dynamical evolution of the interaction,

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which translate into information on the temperature dependence of the interaction. In this respect there is another scale that plays an important role being associated with the momentum transfer per collision: gT. Ideally for HQs we have also $M >> gT$, but such a condition is marginally satisfied for charm quarks at the temperature of $T \sim 300 - 400\,\mathrm{MeV}$ reached at both RHIC and LHC energies. In fact the coupling is $g \sim 2$ already within the context of pQCD and could be even larger as estimated by lQCD or non-perturbative approaches. This challenges the standard lore that considers the motion of charm quarks of Brownian type [6], an assumption that however has allowed to get significant insight into the physics of HQs.

2. Dynamical evolution of HQ in the QGP

The study of HQs dynamics in uRHICs can be divided in three stages: initial hard production, dynamical evolution in the QGP medium, hadronization and hadronic rescattering.

The first stage can be constraining by pQCD at NLO and by experimental data from pp and pA collisions. The recent developments has shown that the upper limit of Fixed Order Next Leading Logarithm (FONLL) predictions and the lower limit of General Mass-Variable Fixed Number Scheme (GM-VFNS) are able to give a correct prediction of the experimental data for pp collisions at RHIC and LHC energies. This confirms that charm and bottom can be considered "heavy" even if the inherent uncertainties for charm quarks at low p_T are quite large. For more details including also other approaches the reader can refer to the excellent recent review [2]. It is also important to notice that the prediction from the Statistical Hadronization Model on the yield of D meson appear in reasonable agreement with the yield observed in AA collisions within the uncertiantes entailed by the current knoweledge of the charm cross section [7, 8]. This is of particular interest because as discussed in the following also the p_T spectra appear to be close to thermalization in the low p_T region. In this respect the measurement of the Λ_c yield will be a further key test for the understanding of hadronization in the heavy quark sector.

The main part of the dynamics of interest for the physics of open heavy flavor is the one describing the interaction of charm quarks with the QGP medium. This can be divided in two regimes. Low p_T allows to access the transport coefficient of Hot QCD matter and the related thermalization dynamics, at high p_T one can study the jet-quenching process and in particular the mass and color dependence of the in medium energy loss. There are two main scattering processes that take place in this stage: collisional and radiative energy loss. There are several approaches to them (pQCD+HTL, QPM, T-matrix, DGLV, WHDG,HT, ...) that we can certainly cannot review here, see [2, 9, 10, 11, 12, 13, 14, 15, 16]. We only mention that a main issue it has been to understand if the main scattering channel is the collisional or the radiative. There is now a large consensus that at up to $p_T \approx 3M_{HQ}$ the collisional mechanism is dominant [11, 17] and at $p_T >> M_{HQ}$ the radiative dominates but is still not negligible its contribution if one calculates both in a self-consistent scheme.

We only mention some very recent main progress that has been achieved fo collisional scattering. An approach that more than a decade ago supplied the prediction most close to the first experimental data at RHIC energy has been the T-matrix one [10, 18]. The main idea is to study the collisional scattering process under a $\hat{V}$ potential kernel ($\hat{T} = \hat{V} + \hat{V}\hat{G}_0\hat{T}$) that one extracts from lattice QCD calculation of the free energy F of HQ. Such an approach has the advantage to account for non-perturbative physics, but has the drawback that a potential V cannot be unambiguously extracted from F that contains also a TS entropy contribution. However a main new approach to the problem has been developed that assumes a Cornell potential whose parameter are fitted to reproduce the F evaluated in lQCD [19]. In such a way self-consistently within the T-matrix approach one can evaluate both the free energy and the HQ transport coefficients. Such an approach has essentially confirmed the presence of a resonant in-medium scattering that strongly enhances the interaction as the $T \to T_c$. The strength of the approach is that without adding further parameters one can evaluate quarkonia correlators, HQ susceptibility, spectral functions; the extension to three-body radiative scatterings presently missed would strongly enhance its predicting power also in a wider p_T range. In the high p_T regime a main development has been the derivation of a soft collinear effective theory (SCET) for describing the evolution of the in-medium splitting function. Such an approach has shown to correctly predict the suppression at high $p_T > 20\,\mathrm{GeV}$ [16].

2.1. Boltzmann vs Langevin dynamics

The evolution of HQs in the expanding QGP matter is usually treated by mean of a Fokker-Planck equation often solved by mean of a stochastic Langevin approach. The first justification of this approach relies on the soft-scattering approximation of a Boltzmann collision integral which is parametrically justified if $M_{HQ}, p_T >> \vec{q}^2 \sim gT$. Such a condition however can be marginally satisfied for charm quarks, especially if we consider that there are at low p_T evidences of non-perturbative interaction which would correspond to effective large coupling g. Also, while the first studies about the evolution of HQ were based on the Fokker-Planck approach [5, 4, 20, 12], in the recent years there has been a growing of modelings based on the Boltzmann relativistic transport equation [6, 21, 22, 23, 24] and even the Kadanoff-Baym one [25]. For all these reasons it is of interest, when comparing different approaches, to understand what comes from differences in the underlying interaction or from the different transport approach employed. A study of the difference between a Boltzmann and Langevin approach starting from the same scattering matrix. For charm quark, $m_c = 1.35\,\text{GeV}$ one finds that both approaches predict a nearly identical $R_{AA}(p_T)$, but the interaction in the Langevin has to be reduced by a quantity that varies from a 15% to 50% depending on the angular dependence of the differential scattering cross section, the effect being maximal for an isotropic cross section [6]. If the two approaches are tuned to the same $R_{AA}(p_T)$ then the Boltzmann equation gives rise to a large elliptic flow v_2 of at most a 35%. For realistic models like the Quasi-Particle-Model (QPM) the Boltzmann approach give rise to a about a 30% larger Drag coefficient and to about a 20% larger v_2 at $p_T \sim 2\,\text{GeV}$, see also Fig.2 and the discussion in the next section. This tells us that differences coming from an underlying different transport approach is quite well understood and is more a quantitative question while the qualitative features are quite similar. For bottom quarks it has also been seen that the Boltzmann and Langevin approach give rise to nearly identical dynamical evolution of the spectra.

Despite these similarities it has also been observed that at the level of the energy loss of a single HQ in a Boltzmann approach can still be quite different even if the resulting $R_{AA}(p_T)$ appears to be quite similar. In fact as noticed in [6, 26] the diffusion implied by a Boltzmann dynamics is largely non gaussian, differently w.r.t. the standard Langevin approach unless $M/T \gtrsim 8 - 10$. The nuclear modification factor R_{AA} and the elliptic flow v_2 are not able to discriminate this difference in the microscopic dynamics. However in the upcoming future it should be possible to measure the $D - \bar{D}$, or at least the $D - h$, triggered angular correlation. Such and observable, even if the interaction is tuned to give the same $R_{AA}(p_T)$, appears to be quite different in a Boltzmann and in a Langevin approach has shown in Fig.1. Therefore considering

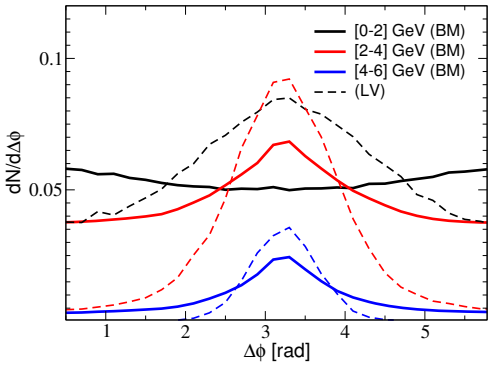

Fig. 1. (Color line) - Comparison between Boltzmann (solid line) and Langevin (dashed lines) results for angular distributions of charm quarks associated to a trigger charm with $p_T = 10\,\text{GeV}$ in different p_T as in the labels for $Pb + Pb$ at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ for $10 - 20\%$ centrality.

that we are going to more differential observables and that measurement are being available in wide p_T range were radiative energy loss is dominant, the Boltzmann approach appears to be a more suitable for a comprehensive study of open charm physics.

2.2. Impact of the temperature dependence of the interaction

One of the main goal of the HQ program at uRHICs is to study the heavy quark interaction in terms of the drag coefficient γ or the diffusion coefficient D that can be related each other by the fluctuation-dissipation theorem (FDT): $\gamma = D/ET$. In the recent years it has become more clear a link between the temperature dependence of the interaction and the formation of R_{AA} and v_2 whose simultaneous description has been a challenge for all the models since the first measurements. To describe this features going beyond the details of the specific modelings it turns out to be useful to consider three different dependences of the γ. A first case is the T^2 dependence, typical of AdS/CFT [27, 28] or pQCD with a constant coupling α_s, the second a T dependence that is close what one gets in pQCD inspired model with a strong running of α_s, and third a nearly constant drag that is close to one gets in QPM modeling [29]. The T-matrix approach, mentioned above, give rise to a T dependence that interpolates between a constant and a linear rise with T. Playing the game to tune the strength of the γ one realizes that the $R_{AA}(p_T)$ of charm quarks at RHIC can be described in a nearly identical way by all of them, see Fig.2 (left panel). Nonetheless in Fig. 2 (right panel) we can see that different T dependence can generate very different v_2 despite the $R_{AA}(p_T)$ is essentially the same [29]. We can see that a nearly constant drag γ is much more favored by the data while a simple T^2 generates a too small elliptic flow, at least for $p_T < 3$ GeV. We mention that it has been recently found that for v_3 the impact of the T dependence of γ extends at much larger p_T [30]. In Fig.2 we also show the results for a constant

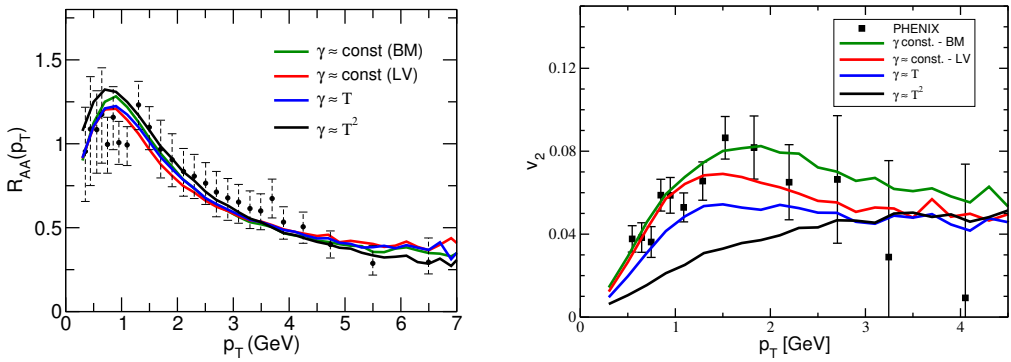

Fig. 2. (Color line) - Left panel: Nuclear modification factor R_{AA} for single $e^{\pm}$ from D meson decays in $Au + Au$ at $\sqrt{s_{NN}} = 200$ GeV for 0 – 10% centrality for different temperature dependences of the drag γ with a Langevin (LV) and a Boltzmann (BM). Right panel: Elliptic flow in 20 – 30% centrality for the corresponding cases in the left panel.

γ with a Boltzmann evolution for HQs that explicitly show what described in the previous section, i.e. that in general a Boltzmann evolution generates a larger elliptic flow, but the interaction has to be increased by about a 30%, see also Fig.3. Even if the size and the temperature dependence of the interaction is the main ingredient, an important role is played by the hadronization mechanism by coalescence [41] (or modified in medium fragmentation [42]) that enhancing both R_{AA} and v_2 allows a fair agreement with the experimental data. Also hadronic rescattering, while generally not affecting R_{AA}, give a further contribution to v_2 that is in the range of 10 – 20% [18, 31, 24] depending also on the T_c assumed that is generally in the range 155-175 MeV [1].

We note that in the HQ sector the relevance of a temperature dependence of the drag or diffusion coefficient has a larger impact than the shear viscosity to entropy density ratio η/s for the v_2 of the bulk QGP. We can see this as an consequence of the larger thermalization time for HQs that entails a stronger dependence

[1] Most recent lattice QCD with realistic quark mass now indicates $T_c \simeq 150 - 155$ MeV and also statistical model analysis indicates a very similar temperature [32], so it would be desirable to have a standard definition that considers hadronic the dynamics below such a temperature.

of the equilibration dynamics making easier to pin-down a temperature dependence of the Drag or Diffusion coefficient even without a Bayesian analysis, that however in the upcoming future will allow to put much better and quantitative constraints [33].

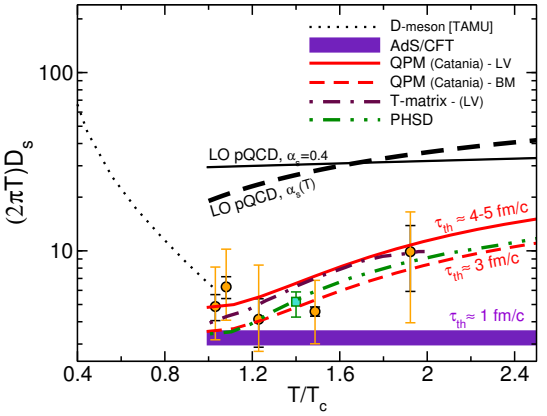

Fig. 3. (Color line) - Charm-quark diffusion coefficients from quenched lQCD [34] (circles) [35] (square), compared to model calculations based on different elastic interactions in the QGP: LO pQCD [4, 5] (solid and dashed lines), QPM calculations tuned to reproduce the R_{AA} of D meson at RHIC energy with a Boltzmann (BM) dynamics (dashed line) and with a Langevin (LV) one (solid line) [29]; PHSD transport calculation based on a dynamical QPM [25] (dash double dot line) and T-matrix approach [18] (dash-dot line). In dotted line is shown the D_s coefficient for D meson in hadronic matter [38, 39].

The diffusion coefficient D_s of the the HQ which represents a measure of the hot QCD matter and can be compared to lattice QCD calculations. Within the validity of the FDT we have $D_s(p = 0) = T/(M_{HQ}\gamma) = T/M_{HQ} \cdot \tau_{th}$ that relates the diffusion constant to the thermalization time. It is interesting to notice that τ_{th} is expected to scale with the mass, hence D_s provides a measure of the QCD interaction ideally independent on the mass of the quark. In Fig.3 we show $2\pi T D_s$ for different models that provide a fairly good description of R_{AA} and v_2 along with data from lQCD [34, 35], LO pQCD (solid lines) and AdS/CFT (violet band) [28]. The red solid and dashed line represents the D_s within a QPM model respectively with a Langevin and a Boltzmann transport equation. We also indicate the corresponding τ_{th} that along these lines stays nearly constant. We report also the D_s for the T-matrix [36] and PHSD [25] approaches. It is interesting that close to T_c the phenomenology lead to values that are quite close to AdS/CFT. We mention that the Nantes approach [11] lead to similar values but with a quite weaker T dependence, which is probably due to the gain in R_{AA} and v_2 that a stronger coalescence mechanism can supply. This is one source of uncertainty that can be expected to be reduced by a comparison of the different model predictions for the Λ_c/D ratio; a first experimental measurement has been presented at this Conference by STAR [37].

Finally we mention that the results shown in Fig.3 are not a result of a quantitative fit analysis and the different cases does not lead to the same quality of predictions, the figure is meant to be indicative of the current status from different modelings and their comparison to lQCD data. In the upcoming future a comparative Bayesian analysis [33] among different approaches would be a more powerful tool.

3. Main news from parallel talks

One of the goal of HQs physics is to investigate the mass and color effect of the jet quenching mechanism, of course for solid conclusions this require the treatment of both light and HQ jet energy loss in a common framework. This has been firstly developed in the DGLV approach, especially after the development that goes beyond the static scatterers approximation [9, 43, 44], but it lacks from the development of a realistic expanding bulk matter that allows to predict both R_{AA} and v_2. This last aspect realized in a transport model for the first time within the Linearized Boltzmann Transport framework [17, 23] in which both heavy

and light partons are treated on the same footing and the radiative energy loss is treated in a Higher-Twist formalism [15]. Such an approach is able to give a quite good prediction over wide range of energy and momenta, for both π and D mesons, including the most recent ones at 5.02 ATeV for $Pb + Pb$. The model exploits p_T and T dependent K-factors that has confirmed the need for strong non-perturbative effect in the low momentum region, $p_T \lesssim 5$ GeV.

First preliminary results from the CUJET3.0 approach, based on a microscopic picture of monopoles in the plasma, has been presented showing a reasonable good agreement with LHC data [45]. Interestingly from the point of view of the Diffusion coefficient D_s such an approach leads to a behavior similar to the one discussed in the previous section, i.e. about linearly increasing with T.

A main new direction presented at QM2017 is the study of the correlations between the v_2 of D,B mesons and the v_2 of soft bulk matter. First results both theoretically [30, 46] and experimentally confirm that the v_2 of HQs is significantly correlated with the bulk. The strength of this correlation, the coefficient linking v_2^{bulk} with $v_2^{D,B}$ as well as the size of the dispersion around this correlation are quite unknown and its study will certainly allow to acquire a much stronger insight into the HQs dynamics and the determination of $D_s(T)$.

4. Impact of initial strong magnetic field

In the recent past it has been recognized that a very strong magnetic field [47, 48] is created at early times of uRHICs. Since HQs are produced at the very early stage they will be directly affected by such a strong magnetic field. The $\vec{B}$ field is dominated by the component along the $\vec{y}$ axis, so its main effect is the induction of a current in the xz plane. On the other hand the time dependence of $\vec{B}$ generates a electric field by Faraday's law, $\vec{\nabla} \times \vec{E} = -\partial\vec{B}/\partial t$. As pointed out in [49] for the light quark sector, this results in a finite directed flow $v_1 =< p_x/p_T >$. Employing the same the space-time solution developed in Ref. [49], the resulting directed flow $v_1$for $Au + Au$ at $\sqrt{s} = 200$ AGeV at $b = 7.5$ fm is shown in Fig. 4 (left) for D and $\bar{D}$ mesons. The v_1 at forward rapidity is positive for the meson with the charm which means that the displacement induced by the Faraday current wins over the Hall drift of the magnetic field. It has to be noticed that a 1% directed flow is about 50 times larger than the one predicted for light mesons. For details we refer to Ref. [50]. In Fig.4 (right panel) the role of the thermalization time is quantified

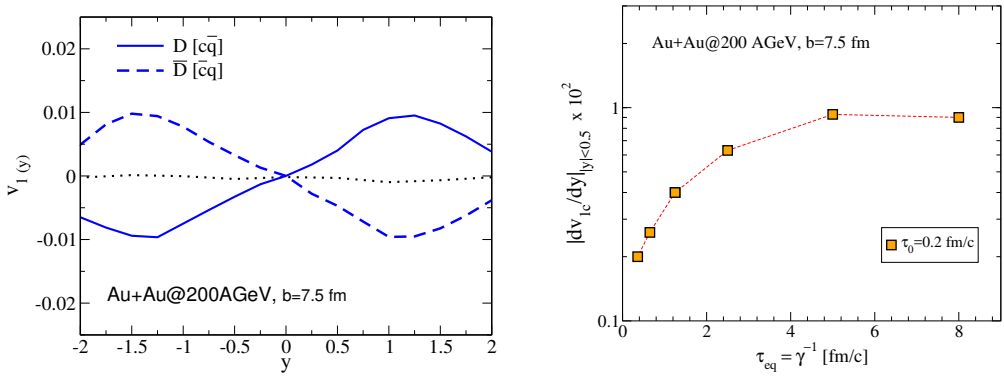

Fig. 4. (Color line) - Left panel: Directed flow v_1 of D mesons for $Au + Au$ at $\sqrt{s} = 200$ AGeV at $b = 7.5$ fm; dotted line is the results without e.m. fields. Right panel: slope parameter $|dv_{1c}/dy|$ at mid rapidity, for the same system in the left panel, as a function of the thermalization time, i.e. drag γ, assumed for the HQ in medium interaction.

showing the variation of the slope $|dv_{1c}/dy|$ with $\tau_{th} = \gamma^{-1}$. We can see that $|dv_{1c}/dy|$ decrease by about a factor of 5 decreasing the τ_c^{th} down to values $\tau_{th} \sim 0.6$ fm/c typical of light quarks. This is due to the fact that the transverse kick exerted by the e.m. field during the time interval, $\tau_{e.m.}$ is damped by its random

interaction in the medium if $\tau_{th} \simeq \tau_{e.m.}$. However, the lowest points in Fig.4 still cannot be taken as a realistic estimate for v_1 of light quarks, because the dynamics of light quarks cannot be appropriately studied by using Langevin dynamics as is done usually for heavy quarks, the light hadrons originate abundantly also from the hadronization of gluons which are not directly affected by the electromagnetic interaction and their initial momentum distributions is quite different from that of HQ. All these aspects cause a further significant reduction of v_1 of light hadrons, and make HQs a more suitable probe of the initial magnetic field. Thus, HQs could provide an independent way to scrutinize and quantify the initial magnetic field which can in turn also contribute to a more quantitative assessment of the Chiral Magnetic Effect [47].

5. Conclusions

Open Heavy Flavor is certainly an excellent probe of the Hot QCD matter that has the potential to link the phenomenology to lattice QCD data. It has generated observables not easy to predict correctly like R_{AA} and v_2. This has not to be considered as drawback because it has revealed strong non-perturbative physics in the low p_T region and is bringing key information on the temperature dependence of the interaction. This is also revealing a thermalization time τ_{th} for charm that is intermediate between the fast thermalization in the soft bulk QGP matter and the lifetime of the QGP created at ultra-relativistic energies. This feature induces also a stronger sensitivity to the initial strong electromagnetic field. Certainly the possibility to extend the measurements and the theoretical approaches to v_3 [51] and to the correlation the v_2 of HQs with the one the soft bulk as well as to have exclusive measurements on triggered angular correlation [52], will allow to acquire a solid knowledge of the HQ interaction in the Hot QCD medium.

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