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# Theoretical approaches to describe open charm hadron production in heavy-ion collisions

**Joerg Aichelin** [a]

[a] *Subatech, Univeristy of Nantes, IN2P3/CNRS, IMT Atlantique, Rue A. Kastler , 44000 Nantes, France*

*E-mail:* aichelin@subatech.in2p3.fr

Open charm mesons are considered as one of the most promising probes to study the properties of the Quark-Gluon-Plasma (QGP) which is created in relativistic heavy-ion collisions. For the description of the interaction of charm quarks with the QGP, for the hadronization and for the interaction of heavy mesons in the hadronic matter dynamical models are needed. The theoretical basis for the description of the medium evolution and charm interactions in such models are rather different - from the solution of the Langevin equation over hydrodynamic models to microscopic transport approaches. Moreover, the models differ even in the assumption of the underlying degrees-of-freedom of the QGP - from pQCD massless partons to dressed heavy quasiparticles. In spite of that differences the models show a good description of the experimental observables such as $R_{AA}$ and $v_2$. This motivated different groups, working on these charm transport approaches, to combine efforts in order to establish what one has learned so far from the comparison of the model predictions with the experimental data as well as to establish theoretical constraints on the models description of the charm dynamics. This contribution summarizes shortly this model comparison. For more details I refer to the original articles [1–4].

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## 1. Introduction

Since it has been established that in relativistic heavy-ion collisions a QPG is created, the study of its properties is of central interest. It turned out that the majority of hadrons, those which are composed of light (u,s,d) quarks, can provide only very limited information because their multiplicity is well described assuming a hadron gas with a temperature of T= 158 MeV. This temperature coincides with the inflection point of the pressure predicted by lattice gauge calculations, which solve the Lagrangian of strongly interacting matter on the computer. Among the light hadrons only those with a high $p_T$, called jets, or collective observables may therefore carry information on the time evolution of the QGP.

Presently open heavy flavor mesons (which carry a c or b quark) are considered as the most promising probe for the study of the properties of the QGP from its creation until its final stage when quarks are converted into hadrons. Heavy quarks have the advantage, that due to their large mass they are created in hard processes which can be reliably calculated in perturbative QCD (pQCD). This has been confirmed by the agreement of the first order next to leading log (FONLL) [5] calculations when compared to data.

If one wants to describe the transport of heavy quarks from their creation to the detector one is confronted with a rather complex scenario.

- One has to know when the QGP is formed and when interactions between heavy quarks and the QGP start.
- The expansion of the QGP itself has influence on the heavy meson observables.
- One has to model the interaction of heavy quarks with the QGP. Most of the approaches assume that the QGP is composed of quarks and gluons in thermal equilibrium and use Born matrix elements to calculate the cross sections between the QGP partons and the heavy quarks or use these cross sections to calculate the transport coefficients. However, even if one has agreed on the Feynman diagrams, quantities like the asymptotic mass of the QGP partons, the parameter dependence of the strong coupling constant and the mass of the exchanged gluons have to be quantified. .
- Besides elastic collisions also radiative collisions, in which a gluon is emitted, may be of importance. Their importance depends on the mass of the QGP gluons.
- When the QGP arrives the transition region heavy quarks have to be converted into heavy hadrons, either by coalescence with partons from the QGP or by fragmentation.
- The heavy mesons have a non negligible cross section with light hadrons, so in the expanding hadronic matter they may scatter.

Many of these processes are only vaguely known ( it is exactly the goal of these heavy-in experiments to determine them) and therefore it is not surprising that different transport approaches have advanced different solutions for them.

In addition, different transport equations for the heavy quarks have been advanced. Some of the groups employ a relativistic Boltzmann equation with a collision terms which calculates explicitly

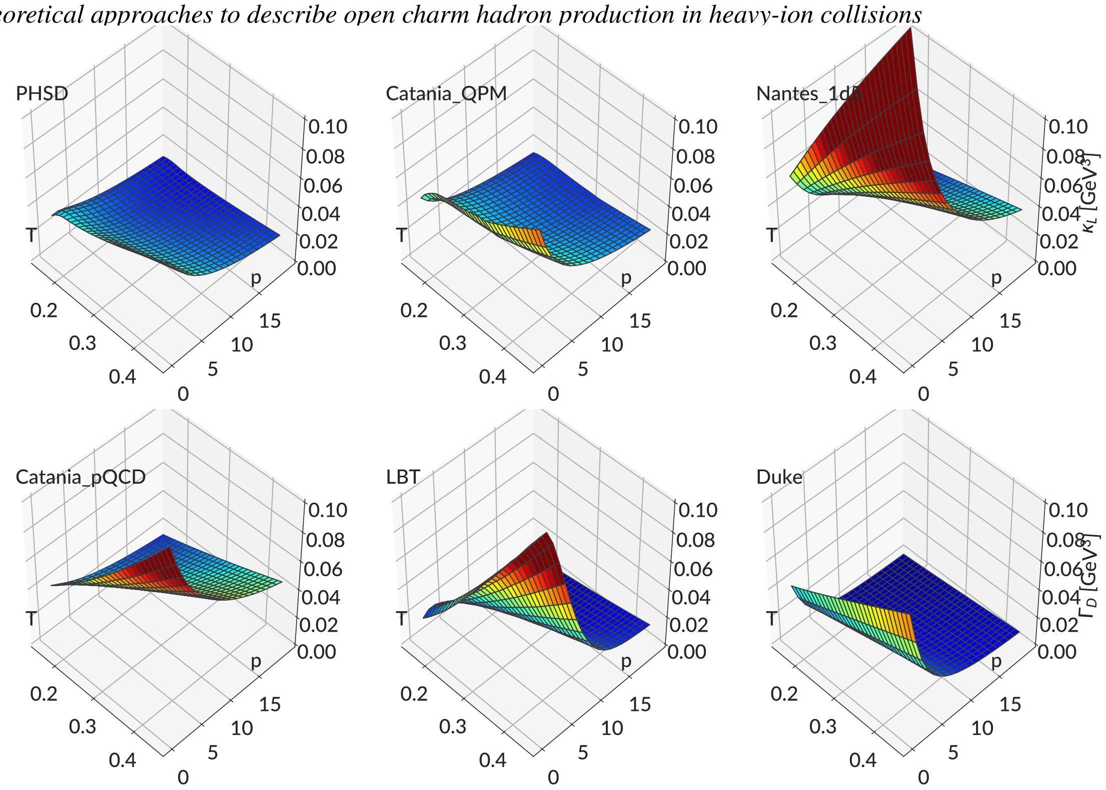



**Figure 1:** (Color online) Leading order charm quark transport coefficients (drag coefficients $\eta_D$). For approaches based on the Boltzmann equation the coefficient is calculated with the cross section which the different groups apply to describe the $D$-meson $R_{AA}$ and $v_2$ at AuAu and/or PbPb collisions at RHIC and the LHC [4].

the kinematics of the collision of a heavy quark with a QPG hadron other employ a Fokker Planck equation which can be converted into a Langevin equation. A Fokker Planck equation one obtains if one develops the collision integral of the Boltzmann equation up to the second order in the scattering angle [6]. The pQCD cross section, do not look Gaussian and therefore both approaches may lead to different results.

## 2. Transport coefficients

One of the possibilities to compare approaches based either on the Langevin or on the Boltzmann equation are transport coefficients which are an input in Langevin equations (or related to the input) and can be calculated from the Boltzmann collision integral. Here we concentrate on the drag and diffusion coefficients which are defined as [7]:

$$\begin{cases} \frac{d}{dt}\langle p\rangle \equiv \eta_D p, \\ \frac{1}{2}\frac{d}{dt}\left\langle (\Delta p_T)^2\right\rangle \equiv \kappa_T, \\ \frac{d}{dt}\left\langle (\Delta p_z)^2\right\rangle \equiv \kappa_L. \end{cases} \tag{1}$$

The Langevin equation

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi}. \tag{2}$$

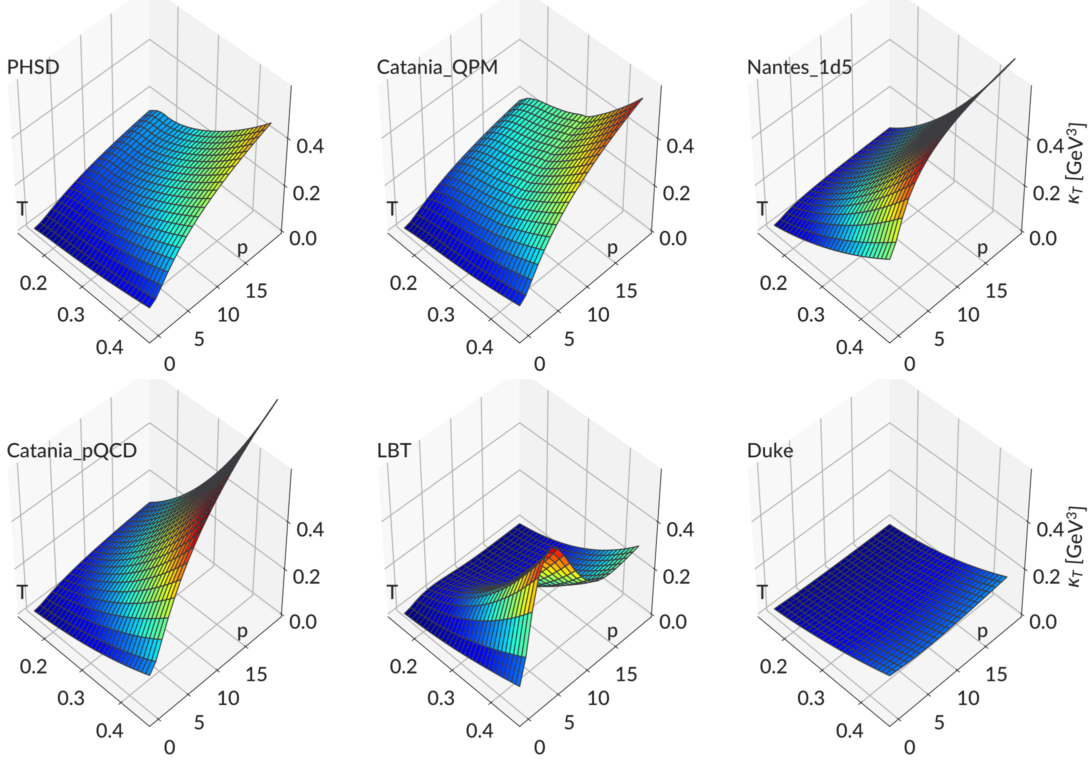
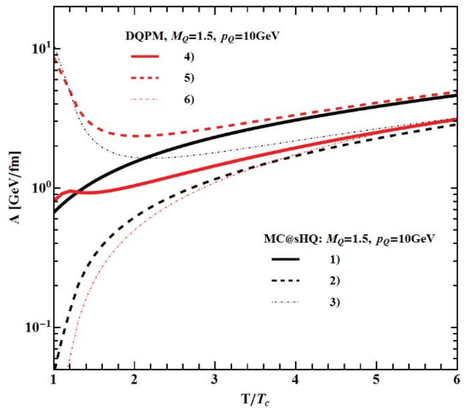



**Figure 2:** (Color online) Same as Fig. 1, but for the transverse diffusion coefficient coefficient $\kappa_T$ [4].




| | coupling | mass in gluon propagator | mass in external legs |
|---|---|---|---|
| 1) | $\alpha(Q^2)$ | $\kappa = 0.2, m_D$ | $m_{q,g} = 0$ |
| 2) | $\alpha(Q^2)$ | $\kappa = 0.2, m_D$ | $m_{q,g} = m_{q,g}^{DQPM}$ |
| 3) | $\alpha(T)$ | $\kappa = 0.2, m_D$ | $m_{q,g} = 0$ |
| 4) | $\alpha(T)$ | $m_g^{DQPM}$ | $m_{q,g} = m_{q,g}^{DQPM}$ |
| 5) | $\alpha(T)$ | $m_g^{DQPM}$ | $m_{q,g} = 0$ |
| 6) | $\alpha(Q^2)$ | $m_g^{DQPM}$ | $m_{q,g} = m_{q,g}^{DQPM}$ |

**Figure 3:** (Color online) The drag force A as a function of $T/T_c$, $T_c$ = 158 MeV, for different choices of the parameters for the calculation of the pQCD cross section in Borm approximation.

describes the movement of a particle in a medium which gets decelerated due to the drag force $\eta_D \vec{p}$ and due to thermal random kicks with the medium, described by $\vec{\xi}$ which satisfies

$$\langle \xi_i(t)\xi_j(t')\rangle = \left(\kappa_L \hat{p}_i \hat{p}_j + \kappa_T(\delta_{ij} - \hat{p}_i \hat{p}_j)\right)\delta(t-t'). \tag{3}$$

For the Boltzmann equation these transport coefficients can directly be obtained from the collision integral, see ref. [8], eq.6. The dependence on the temperature and on the heavy quark momentum of $\eta_D$ and $\kappa_T$, calculated in the different approaches, we display in Figs 1 and 2, respectively.

As can be seen, the dependence of these transport coefficients on the temperature and the

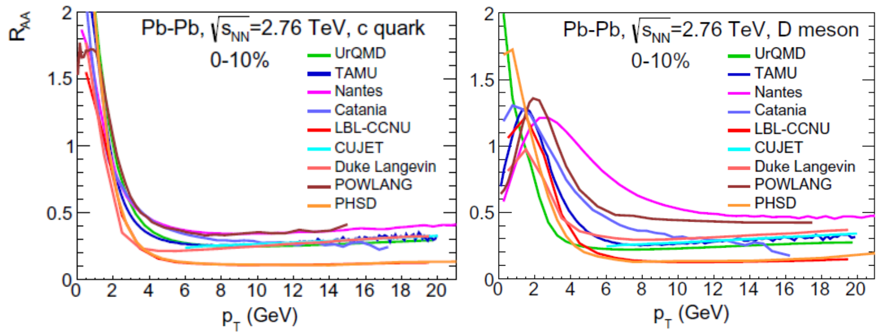



**Figure 4:** (Color online) $R_{AA}$ as a function of the heavy quark (meson) momentum p of the different approaches before hadronization (left) and after hadronization (right) [3].

momentum of the heavy quark differs substantially in the different approaches. A part of this difference come from the fact that in some approaches radiative and collisional energy loss is included whereas other limit themselves to collisional (elastic) energy loss only. This explains, however, only a part of the difference. A second reason for this difference is that the pQCD cross sections (which are calculated in Born approximation) may differ substantially depending on the parameters which have been chosen. In order to quantify the cross section, the coupling constant, the mass of the asymptotic particles and the mass of the exchanged gluon have to be specified. The influence of this choice on the drag force A is demonstrated in Fig; 3 which is based on the PHSD collision integral [9]. If the coupling constant $\alpha(T)$ is temperature dependent and the gluon mass is finite as in the Dynamical Quasi Particle Model (DQPM), the basis of the standard PHSD calculations, we obtain for the drag coefficient the read line, If, on the other side, we have massless asymptotic particles, a momentum transfer dependent coupling constant $\alpha(t)$ and a gluon mass of $m_g = 0.2gT$ for the exchanged gluon, the standard Nantes set up [10], we obtain the dotted line. The other curves show the influence of the choice of each of these parameters on the result for the drag force.

The different transport coefficients are partially compensated by different scenarios for the expansion of the QGP so if one considers both together the differences between the different approaches become smaller [4].

Another difference between the different models is the modeling of the hadronization at the end of the life time of the QGP [3]. Since heavy hadrons are not in thermal equilibrium with the QGP a standard Cooper Frye approach is not applicable. At high $p_T$ usual fragmentation functions are employed but at low $p_T$ all models employ some kind of coalescence. The details of the employed coalescence approaches have also a considerable influence of the final observables as is shown in Fig. 4. For this investigation the different models employed the same cross section and therefore $R_{AA}$ for heavy quarks at low $p_T$ is rather similar, Fig 4, left. After hadronization, Fig 4, right, some of the approaches show a maximum of $R_{AA}$ at different places, whereas other do not have a maximum at all.

## 3. Conclusions

In conclusion we have found that different transport approaches, which agree quite reasonable with the experimental data, show in detail considerable differences - in the treatment of charm propagation and interaction with the medium as well as on the description of the properties of the medium itself. In future we will discuss them further and will try to identify the most convincing solutions. At the moment we have concentrated on the available data, mainly $R_{AA}$ and $v_2$. The next runs at LHC will increase the available data set and will add other observables. This will certainly help to clarify the complex description of heavy quarks from their creation to their arrival as heavy hadrons in the detector and to exploit the power of this probe to study the properties of the QGP.

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