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EPJ featured talk: Theory of open heavy-flavor as probes for deconfinement

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Abstract. An overview of heavy quarks (HQs) as probes of hot QCD matter is presented. Although HQ production IS described within perturbative QCD, their interaction with the evolving quark-gluon plasma (QGP) occurs in a strongly coupled regime. HQs provide a unique opportunity to investigate in-medium dynamics, making them useful probes for constraining transport properties. Recent lattice QCD results have shown that HQ interactions are largely non-perturbative, particularly near T_c, where the extracted spatial diffusion coefficient, $2\pi T D_s \approx$ 1-2, suggests rapid HQ thermalization. This opens the way for a new theoretical predictions and phenomenological studies. In parallel, there is increasing interest in using HQs to probe the early stages of heavy-ion collisions, in particular, to study the role of Glasma fields in HQs dynamics. This provides new opportunities to relate the HQ phenomenology with early-stage. Finally, the large heavy-baryon production observed from pp to AA collisions challenges hadronization scenarios and highlights the importance of recombination mechanisms, particularly in light of recent experimental measurements of collective flow for charmed hadrons.

1 Introduction

Ultra-relativistic heavy-ion collisions (uRHICs) provide a powerful framework for studying and characterizing the properties of the quark-gluon plasma (QGP). To characterize the QGP, a good observable must be able to survive during its whole evolution keeping information about its microscopic interaction. Heavy quarks (HQs), namely charm and bottom quarks, due to their large mass m_Q, are particularly well suited for this purpose. In fact, HQs, with $m_Q \gg \Lambda_{\text{QCD}}$, T_{QGP}, are predominantly produced in the early stage of the collision via initial hard partonic scatterings in uRHICs. The production of HQs in pp collisions can be reliably described within perturbative QCD (pQCD) using different schemes such as the Fixed-Flavor Number Scheme (FFNS), the General-Mass Variable Flavor Number Scheme (GM-VFNS), and the Fixed-Order plus Next-to-Leading Logarithms (FONLL) approaches. For further details, see [1]. Their large masses ensure that they are created before the QGP thermalizes ($\tau \lesssim 0.1, \text{fm}/c$) and subsequently experience the full evolution of the medium. On the other hand, $m_Q \gg gT$ leads to a small momentum transfer, resulting in a Brownian-like motion, especially at low p_T. Therefore, their dynamics can be characterized by two transport coefficients (drag and diffusion) that can be related to lattice QCD (lQCD) calculations. Two

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main approaches have been used to describe the HQ evolution: the relativistic Boltzmann and the Fokker-Planck approaches. To investigate the dynamics of heavy quarks (HQs) in the quark-gluon plasma (QGP), several effective models have been developed to incorporate the non-perturbative behavior of the interaction. In literature many approaches have been proposed to describe both the in-medium evolution and the hadronization of HQs. In recent years, significant efforts have been made by the community to try to disentangle the differences among these models and to study respective phenomenological implications. For comprehensive reviews see [1–5].

2 Heavy quarks transport coefficients

In recent years, great efforts have been made with the aim of systematically identifying and reducing uncertainties that affect the extraction of transport coefficients, specifically the spatial diffusion coefficient D_s [2, 3]. One of the main challenges in the extraction of D_s is related to the limit $p \to 0$ to obtain a direct comparison with lQCD results. From phenomenological analyses the D_s can be constrained by two main observables: the nuclear modification factor $R_{AA}(p_T)$ and elliptic flow $v_2(p_T)$ in the range $p_T \sim$ 2–6 GeV. First comparisons using R_{AA} and $v_2(p_T)$ have supported the conclusion that HQ interaction with the QGP is the non-perturbative regime. The extracted values of the spatial diffusion coefficient were predicted in the range $2\pi T D_s \approx 2 - 5$ at temperatures $T \sim T_c$, consistent with expectations from the AdS / CFT correspondence. However, there are different sources of uncertainty that can affect the comparison of heavy-flavor observables. One arises from the hadronization mechanism, which significantly affects both the nuclear modification factor R_{AA} and the elliptic flow $v_2(p_T)$. In particular, the observed enhancement in Λ_c production, first observed in heavy-ion (AA) collisions and more recently also in proton-proton (pp) collisions, suggests that baryon formation plays a non-negligible role and this enhancement indirectly affects the R_{AA} of D mesons [5]. However, another source of uncertainty arises from the early stages of the collision, such as the impact of the Glasma on heavy-quark dynamics. The Glasma phase is expected to play a role in less than $1 fm/c$, inducing early stage momentum broadening and diffusion. Therefore, the glasma dynamics can affects the subsequent evolution of heavy quarks in the medium and consequently the extraction of D_s. However, the impact of these effects on heavy flavour final-state observables remains to be constrained.

On the other hand, recent studies, that combine Non-Relativistic Effective Field Theory (NREFT) with lQCD with dynamical fermions, have provided a new estimation of the D_s, providing new insight into the interaction of HQs with the QGP and the thermalization time scale [6–8]. The latest lQCD/NREFT results have shown a weak mass dependence of D_s from the charm mass to the static limit. These new results provide significantly smaller values of D_s compared to earlier quenched estimates [9–12], suggesting short thermalization times, $\tau_{\text{th}} \approx 1.4$ fm/c at $T \approx 1.2\, T_c$, even for charm quarks in the limit $p \to 0$. On the other hand, predictions from the Quasi-Particle Model (QPM) have exhibited a pronounced mass dependence [13]. Recently, an extended formulation of QPM, denoted as QPM_p, has been proposed to include momentum-dependent quasi-particle masses, which asymptotically approach the current quark mass in the high-momentum limit [14]. The QPM_p approach is able to reproduce the lQCD equation of state but also to describe light and strange quark susceptibilities, which are typically underestimated in the original QPM based on temperature-dependent masses [13]. The extracted $D_s(T)$ within the QPM_p framework exhibits a strong non-perturbative behavior at low temperatures [15], see Fig. 1. In particular, the bottom quark diffusion coefficient near T_c shows good agreement with the new lQCD/NREFT results, approaching the value expected from the AdS/CFT correspondence [18–20]. On the

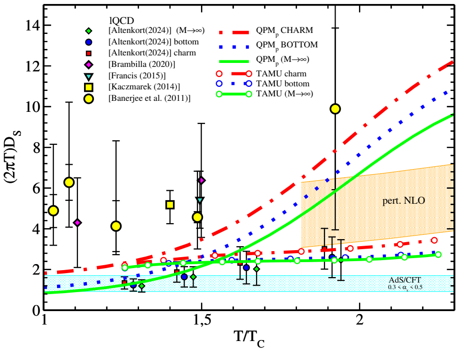

Figure 1. Spatial diffusion coefficient $2\pi T D_s$ as a function of T/T_c in QPM_p [15] and T-matrix approaches [16, 17] for charm quark compared to available lQCD data [6–12]. The cyan band is the $2\pi T D_s$ expected from the AdS/CFT correspondence [18–20]. The orange band correspond to perturbative Next-to-Leading Order predictions for $2\pi T D_s$ [21].

other hand, for charm quarks, QPM_p predictions deviate by approximately 30% for the explored temperature range. Recent T-matrix approach based on an in-medium heavy-light quark scattering amplitude including interaction kernel with both color-electric and spin-dependent forces, derived from lattice-QCD, have shown that the extracted $D_s(T)$ shows a good agreement with recent lQCD/NREFT results. In particular, spin interactions are shown reduce D_s approaching the static limit for T close to T_c, highlighting their relevance in transport coefficient extractions [16]. Recently, an updated T-matrix framework has been proposed, combining in-medium T-matrix calculations with lQCD results for the heavy-quark current correlator [17]. The in-medium potential is constrained by recent lattice data and incorporates a consistent treatment of relativistic corrections and medium-induced screening effects. Although earlier T-matrix studies successfully captured non-perturbative dynamics near T_c in the static limit, the updated approach extends the formalism by directly comparing T-matrix predictions with Euclidean correlators and spectral functions extracted from lQCD. The extracted D_s is in good agreement with recent lQCD/NREFT results, reproducing the weak mass dependence observed in lQCD data and estimating a $D_s(2\pi T) \sim$ 2-2.5 near T_c. However, other studies of D_s have been performed within the dynamical quasi-particle model (DQPM) by including inelastic $2 \to 3$ processes with massive gluon radiation, in addition to elastic $2 \to 2$ parton scattering [22].

New developments have been proposed within the framework of strongly coupled $\mathcal{N} = 4$ SYM theory to investigate HQ momentum broadening and thermalization [23]. It has been shown that non-Gaussian corrections to the heavy-quark distribution function, encoded in non-vanishing fourth-order cumulants, play a crucial role in driving the system toward thermal equilibrium. This behavior resembles what has been observed in relativistic Boltzmann transport when compared to Langevin dynamics where the Boltzmann equation include non-Gaussian deviations in the distribution function, which play a key role in faster thermalization [24].

3 Heavy quarks dynamics

The description of uRHICs requires a detailed understanding of the space-time evolution of the QGP from the early stages to the final hadron dynamics. It is expected that the early stage of URHIC is characterized by the formation of Glasma, consisting of strong chromo-fields, that in about 1 fm/c decay into the thermalized QGP. In recent decades, various approaches have been developed, using Langevin or Boltzmann transport and non-perturbative T-matrix approaches, to study HQ dynamics and provide predictions for observables such as nuclear modification factor R_{AA} and elliptic flow v_2. The role of the early stage on HQ dynamics has been investigated with the aim of studying their role in the final-state heavy-flavor observ-

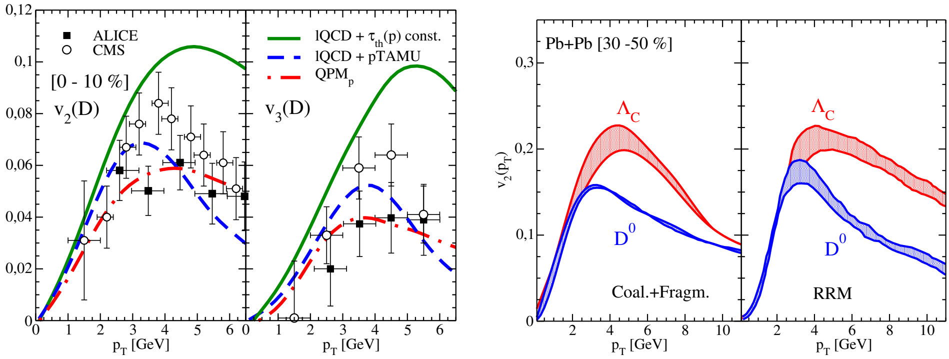

Figure 2. Left panel: D meson $v_2(p_T)$ and $v_3(p_T)$. Experimental data from [33] (ALICE coll.) and [34] (CMS Coll.). Right panel: $v_2(p_T)$ for D and Λ_c. It is shown a comparison between prediction of RRM [35] and Catania coalescence+fragmentation model [36].

ables [25–27]. It was found that Glasma phase induces transverse momentum broadening, corresponding to strong diffusion that dominates the drag force during this early evolution [27–29]. However, the role of early stage dynamics, including the influence of Glasma phase and out-of-equilibrium effects, has often been neglected or treated approximately. Recent developments aim to incorporate these initial conditions more consistently trying to identify heavy-flavor observables that are potentially sensitive to the Glasma stage. In particular, studies employing $SU(3)$ lattice gauge simulations combined with classical transport via the colored particle-in-cell method have investigated the nuclear modification factor and azimuthal correlations of heavy-quark pairs in the presence of Glasma [30, 31]. It has been shown that HQ pairs with low initial transverse momentum in a Glasma and saturation scales Q_s relevant to LHC energies undergo azimuthal decorrelation. The magnitude of this decorrelation is comparable to that generated during the QGP phase [32]. These studies currently focus solely on the Glasma stage, without the subsequent QGP evolution or hadronization phases. However, recently it has been explored the HQ dynamics throughout both the pre-equilibrium Glasma phase and the QGP, employing Langevin simulations initialized with IP-Glasma conditions within the IP-Glasma + MUSIC + MARTINI framework [37]. The Glasma stage induces momentum broadening and early energy loss, producing a non-negligible effect in the nuclear modification factor R_{AA} and elliptic flow v_2 of D mesons before the QGP phase takes place. However, the momentum dependence of the drag and diffusion coefficients and hadronization play a key role in describing the development of elliptic flow. On the other hand, other studies have investigated the implications of the new lQCD calculations of the HQ spatial diffusion coefficient $D_s(T)$ on heavy-flavor observables. The small value obtained, $2\pi T D_s \approx$ 1-2 at $T \approx T_c$, suggests a fast thermalization. These results open the way to a new wave of predictions for HQ observables while challenging conventional modeling approaches. Using an event-by-event Langevin framework, it has been shown that agreement with experimental data on R_{AA} and v_n requires a strong momentum dependence of the drag coefficient [15]. Furthermore, such a fast thermalization implies that the memory of the initial HQ momentum distribution is lost for $p_T \lesssim M_c$, suggesting the emergence of a universal behavior [38–40].

4 Heavy quarks Hadronization

Experimental measurements at RHIC and LHC have shown an enhancement of the charm baryon/meson ratio, Λ_c/D^0, in AA collisions, reaching values close to unity [5]. These values are significantly higher than those observed in elementary collisions such as e^+e^- and ep. Similar enhancements have been observed in high-multiplicity pp events ($\Lambda_c/D^0 \approx 0.6$) [5, 41, 42], challenging hadronization descriptions based solely on vacuum fragmentation and suggesting the possible formation of a hot QCD medium even in small systems. Furthermore, recent results have shown enhancement in Ξ_c/D^0 and Ω_c/D^0 ratios in pp collisions compared to that expected from fragmentation. However, the study of heavy quarks hadronization has stimulated further developments in different theoretical frameworks. These include: (i) Independent string fragmentation, as implemented in Pythia, introducing the color reconnection mechanisms [43]; (ii) In-medium hadronization with cluster decay, as in the POWLANG setup [44, 45], applied to both AA and pp collisions, where local color neutralization occurs via recombination of charm quarks with nearby opposite-color partons from the medium; (iii) Statistical Hadronization Models (SHM), extended to pp collisions for both charm and bottom hadrons [46, 47]; (iv) Coalescence/Recombination models, in which charm quarks combine with thermal light quarks to form hadrons [48, 49]; and (v) The Resonance Recombination Model (RRM), which extends coalescence by employing Breit–Wigner cross sections, enabling hadron formation via intermediate diquark states. For reviews on HF hadronization, see [4, 5]. The coalescence mechanism naturally accounts for the observed baryon enhancement in both AA and pp collisions, predicting large Λ_c/D^0 and Ξ_c/D^0 ratios in agreement with ALICE data. In the bottom sector, the coalescence+fragmentation approach predicts a ratio $\Lambda_b/B^0 \sim 0.9$ at low p_T, about 50% higher than the charm counterpart, while Ξ_b/B^0 remains smaller by $\sim 30\%$ [49]. In small systems (pp, pA), mechanisms such as Pythia color reconnection, rope hadronization, and local color neutralization in POWLANG are consistent with coalescence mechanism, leading to enhanced baryon yields and collective flow signatures. Recently, EPOS4 has been extended to incorporate coalescence into its full dynamical evolution, allowing simultaneous constraints from yields, baryon/meson ratios, and $v_2(p_T)$ across different collision systems, predicting a finite $v_2(p_T)$ for D mesons even in pp collisions [50, 51].

Finally, the coalescence mechanism predicts a larger $v_2(p_T)$ for baryons than for mesons, due to the additive elliptic flow of their constituent quarks [35]. Recent ALICE results presented at Quark Matter 2025 show that at LHC energies $v_2(\Lambda_c) > v_2(D^0)$ for $p_T \gtrsim 3$ GeV, in good agreement with predictions from the RRM [35] and the coalescence+fragmentation framework [36, 52].

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