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Open Issues in Open Heavy-Flavor Physics in High-Energy Nuclear Collisions

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1. Introduction

The production of heavy-flavor (HF) particles, containing one or more charm and/or bottom quarks, in high-energy hadronic collisions has a long history of probing fundamental aspects of Quantum Chromodynamics (QCD). The key property of the charm and bottom quarks is that their mass is much larger than the typical QCD scale, $m_{c,b} >> \Lambda_{QCD}$. For example, the yields of the pairwise produced $c\bar{c}$ or $b\bar{b}$ quarks in the hard primordial collisions of the incoming hadrons are a rich testing ground for perturbative QCD (pQCD) calculations, while they also depend on the nonperturbative parton distribution functions (PDFs) within the incoming hadrons. The short time scale of the pair production, $\tau_{prod} \sim 1/2m_Q$, is followed by a much longer duration of their nonperturbative hadronization process, for which various approaches have been employed, e.g., string fragmentation, statistical hadronization models (SHM), quark coalescence models (QCM), or independent fragmentation (usually applicable at high momentum).

The power of HF probes is also being utilized in ultra-relativistic heavy-ion collisions (URHICs) where a hot and dense QCD medium is formed that rapidly expands and cools, cf. Fig. 1. Of particular interest in this context are the diffusion properties of heavy quarks in the possibly formed quark-gluon plasma (QGP), allowing access to fundamental transport coefficients of the medium, and their hadronization, allowing novel insights into its mechanisms.

In the following, we will focus on two specific issues in the interpretation of charm-hadron production from small to large nuclear collisions systems (proton-proton (pp) via proton-nucleus (pA) to AA collisions), namely the hadro-chemistry of the different charm-hadron species (Section 2) and the so-called collectivity in their transverse-momentum spectra (Section 3), usually associated with the expanding QCD medium in large collision systems.

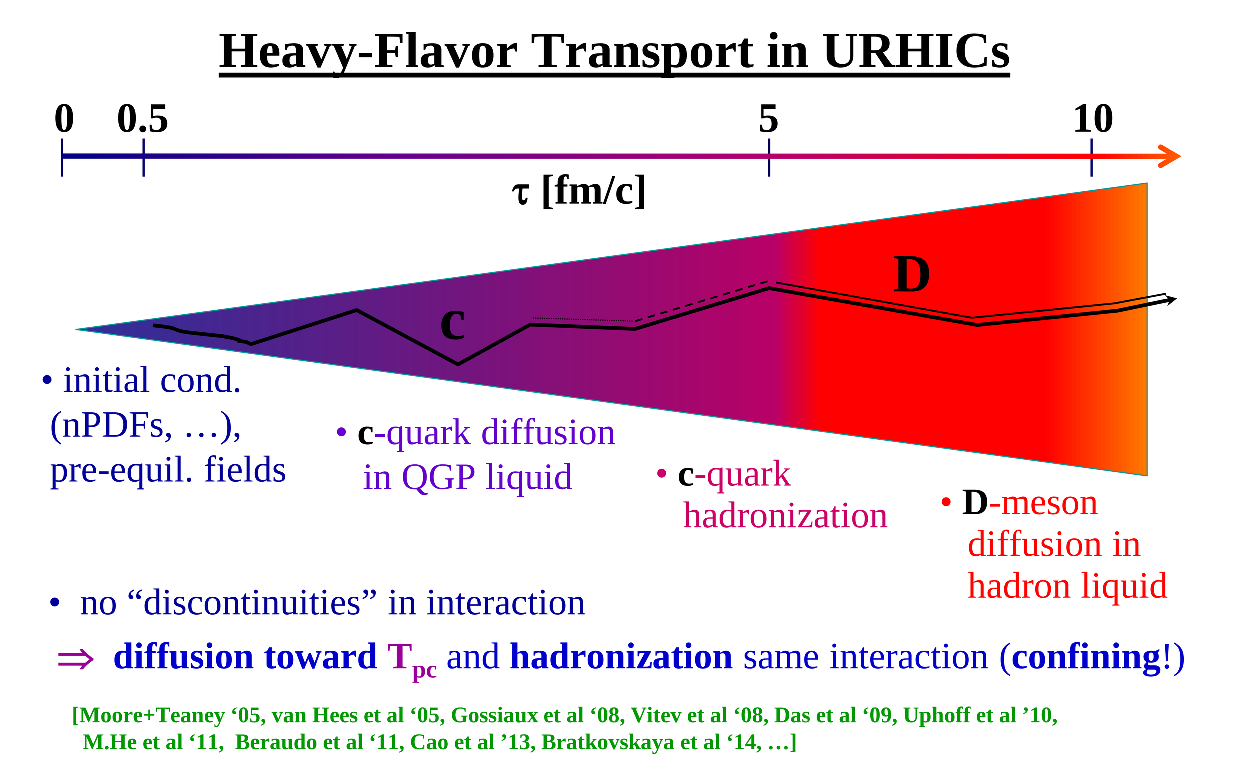

Figure 1. *Time evolution of HF particles in URHICs: initial production of heavy quarks, possibly modified by nuclear effects in PDFs, is followed by a brief exposure to a pre-equilibrium phase, diffusion through the QGP, hadronization, and diffusion in the hadronic medium until kinetic freezeout.*

2. Hadro-Chemistry

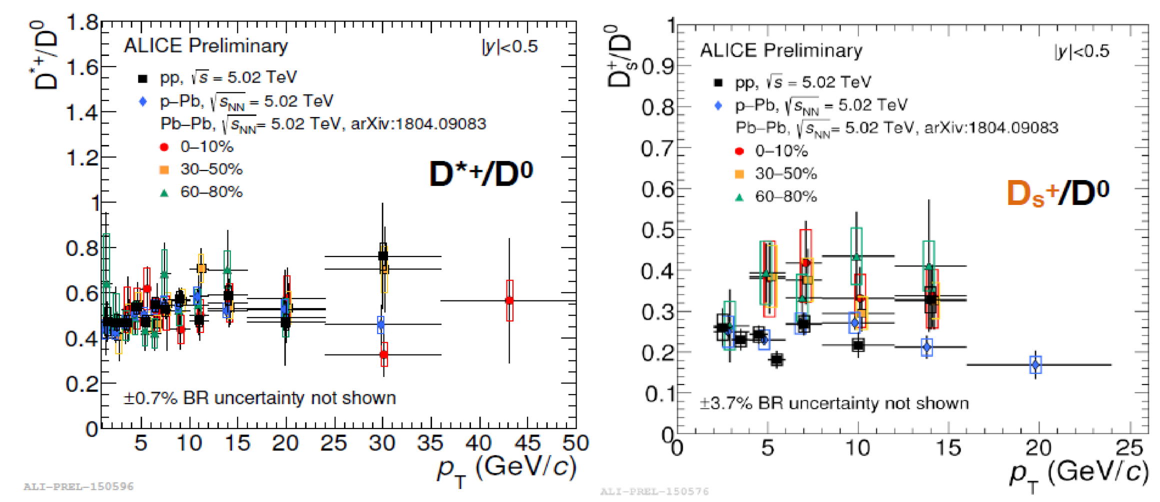

Figure 2. *The D^{*+}/D^0 (left) and D_s/D^0 (right) ratios in pp, pPb and PbPb collisions as measured by ALICE.*

We start our discussion with the D*/D ratio, cf. left panel of Fig. 2. The inclusive yields measured in pp collisions at LHC energies are consistent with the value of ca. 0.42 obtained from the SHM at T~160MeV, where the yields are simply evaluated from thermal densities including an overall charm-quark fugacity to match the total charm yield from hard production. The data show a weak p_T dependence and vary little when going to pPb and PbPb collisions. Is this agreement a coincidence, given that in the latter a system, hadronization is expected to occur from a hot QGP, rather than in the vacuum?

The D_s/D ratio, on the other hand, shows a significant enhancement when going from pp (or pPb) to PbPb collisions, cf. right panel of Fig. 2. The SHM predicts a ratio of about 0.44, which agrees with the heavy-ion data. Recalling the well-known suppression factor (or fugacity) of γ_s ~ 0.6 for anti-/strange quarks in strange-hadron production in pp collisions, the measured D_s/D^0 ratio is also consistent with the SHM in the latter.

However, for charm-baryon production, recent ALICE data have posed a puzzle, cf. Fig. 3. None of the standard event generators, nor the SHM in its baseline version (including feeddown from charm baryons as listed by the PDG) with a ratio of ~0.24 at T~160MeV, can account for the measured inclusive ratio of ~0.54. However, when augmenting the SHM with additional charm baryons as predicted by lattice-QCD and the relativistic quark model (RQM), the ALICE data can be largely explained [1]. A caveat here is the lower ratio measured by LHCb at forward rapidity.

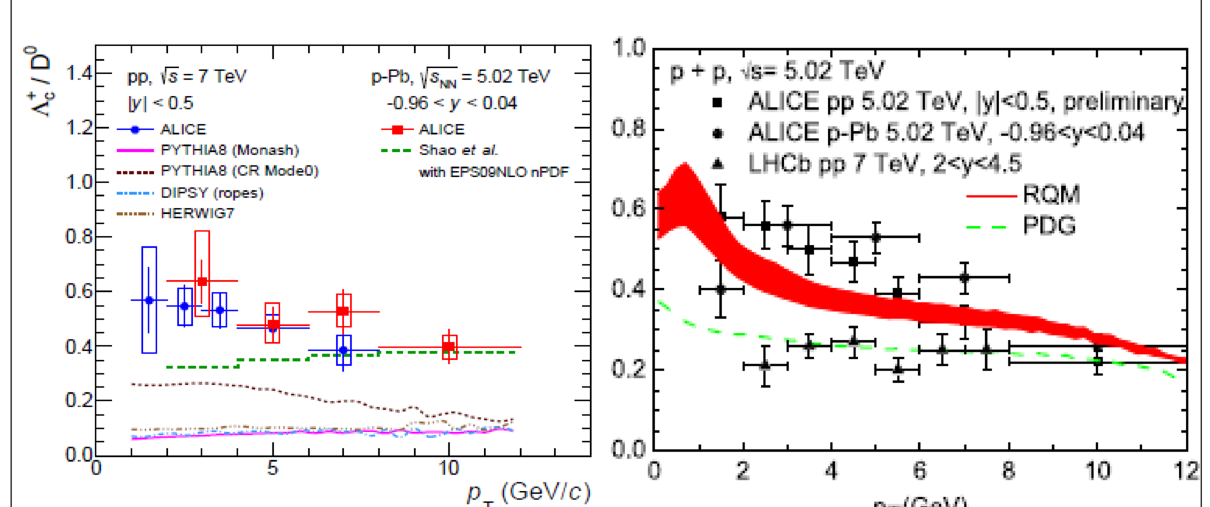

Figure 3. *Λ_c/D^0 ratio in pp and pPb collisions, compared to results from event generators (left) and the SHM with an augmented charm-baryon spectrum (right).*

New measurements of the L_c/D^0 ratio in heavy-ion collisions have posed further challenges. The STAR data from AuAu(0.2TeV) collisions at RHIC suggest a further increase of this ratio, rising above one toward low p_T, while the ALICE data in PbPb(5TeV) collisions at the LHC only show a moderate increase at intermediate p_T, suggesting a collective flow effect pushing the heavier charm baryons to higher p_T relative to mesons, cf. Fig. 4.

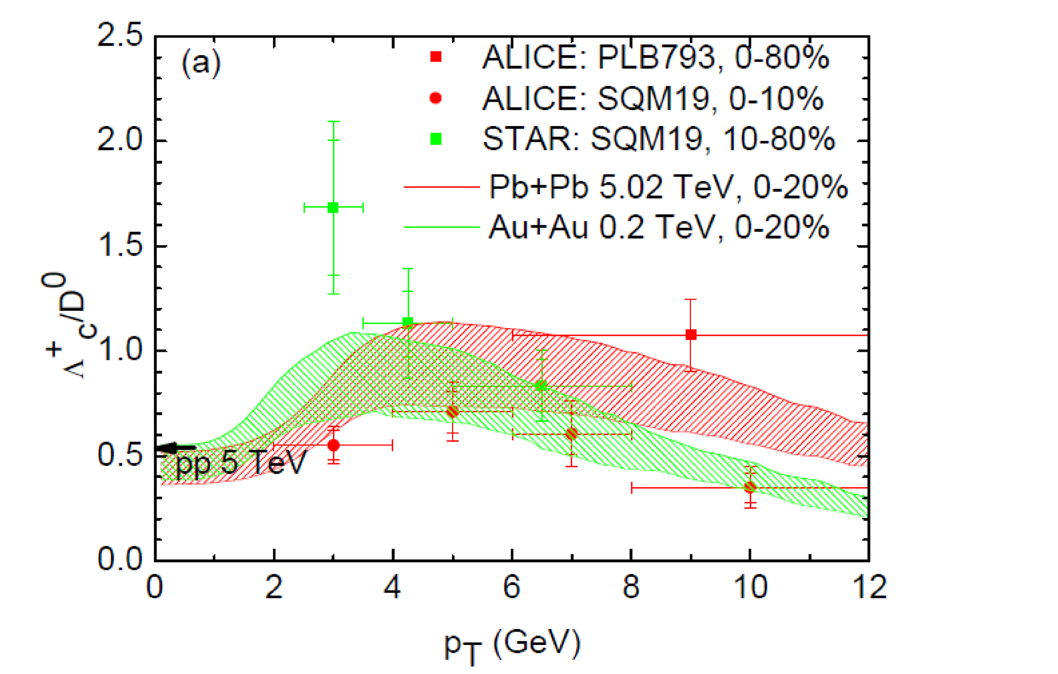

Figure 4. *The Λ_c/D^0 ratios in AuAu collisions at RHIC (green) and PbPb collisions at the LHC (ref). The bands of the theoretical curves represent the uncertainty in the decay branching of the excited charm baryons into a Λ_c final state (as opposed to DN), assumed to be 50-100%.*

The data are compared to recent comprehensive transport calculations [2] of charm-hadron observables, implementing the improved hadro-chemistry for baryons as discussed above, and a systematic treatment of space-momentum correlations in the coalescence processes (which has been a long-standing problem in the field). The results roughly reproduce the data, but a tension seems to emerge in a simultaneous description of the RHIC and LHC data (the bands reflect the uncertainty in the branching ratios of the additional baryon states and, as such, are fully correlated).

3. Collectivity

The baseline observables to quantify the modifications of the momentum spectra of HF particles in the hot QCD medium are the nuclear modification factor, R_{AA}, and the elliptic flow coefficient , v_2. In heavy-ion collisions, the R_{AA} of charm hadrons shows a suppression at high p_T and a maximum at low p_T, characteristic for an approach to thermalization, while their v_2 reaches large values near the ones in the light-hadron sector, characteristic for a strong coupling of the HF particles to the expanding medium, cf. Fig. 5 bottom row. Quantitative comparisons to model calculations allow for an extraction of the HF diffusion coefficient, resulting in minimum values of $D_s(2\pi T)=3\pm1$ near T_c, close to the conjectured quantum lower bound of 1.

It is currently an open question whether a collectively expanding medium forms in pA collisions. The D-meson

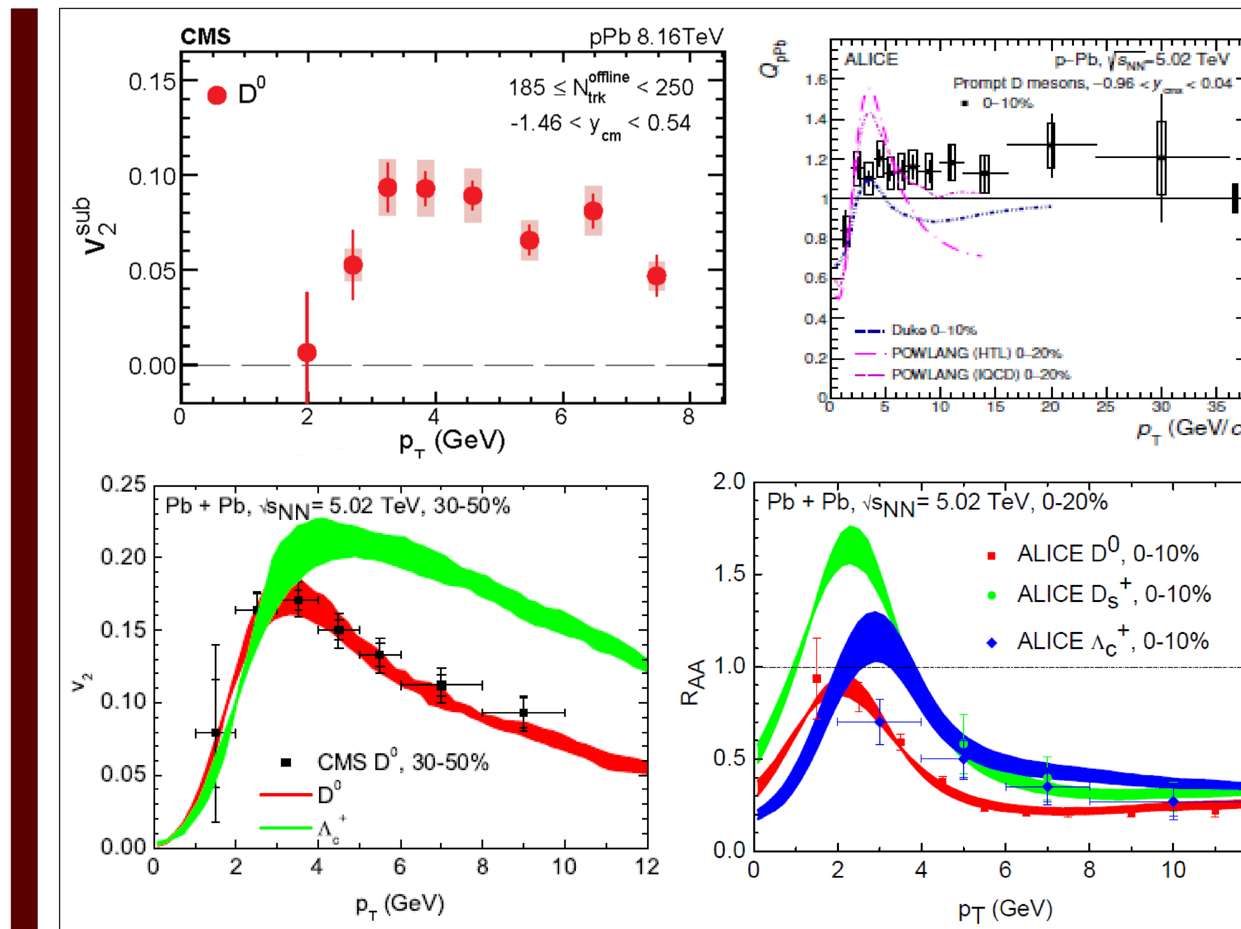

Figure 5. *Elliptic flow coefficient (left panels) and nuclear modification factor (right panels) in pPb (top row) and PbPb collisions (bottom row) measured at the LHC. The theory curves correspond to HF transport calculations [2,4,5].*

R_{AA} measured in these systems is compatible with initial-state effects only (shadowing and p_T broadening) [3]. On the other hand, for high-multiplicity pPb collisions a substantial v_2 is observed (see upper left panel of Fig. 5), while the R_{AA} is still rather close to one, incompatible with the results of HF transport calculations [4,5]. This suggests that the v_2 receives substantial contributions from initial-state correlations. Similar conclusions have been reached in the charmonium sector [6].

Open Questions

- What is the nature of heavy-quark hadronization in pp collisions? Is there a rapidity and/or transverse-momentum dependence?
- How do heavy quarks hadronize from a QGP? Can we learn about the confining interaction from HF observables in heavy-ion collisions?
- What is the origin of the large D-meson v_2 in high-multiplicity pA collisions? How can it be reconciled with the small modifications observed in their R_{AA}?

Acknowledgements

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