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Charm-hadron production in *pp* and AA collisions

Min He

Department of Applied Physics, Nanjing University of Science and Technology, Nanjing 210094, China

Ralf Rapp

Cyclotron Institute and Department of Physics & Astronomy, Texas A&M University, College Station, TX 77843, USA

Abstract

Recent measurements of various charm-hadron ratios in pp, p-Pb and Pb-Pb collisions at the LHC have posed challenges to the theoretical understanding of heavy-quark hadronization. The Λ_c/D^0 ratio in pp and p-Pb collisions shows larger values than those found in e^+e^- and ep collisions and predicted by Monte-Carlo event generators based on string fragmentation, at both low and intermediate transverse momenta (p_T). In AA collisions, the D_s/D ratio is significantly enhanced over its values in pp, while the Λ_c/D^0 data indicates a further enhancement at intermediate p_T. Here, we report on our recent developments for a comprehensive description of the charm hadrochemistry and transport in pp and AA collisions. For pp collisions we find that the discrepancy between the Λ_c/D^0 data and model predictions is much reduced by using a statistical hadronization model augmented by a large set of "missing" states in the charm-baryon spectrum, contributing to the Λ_c via decay feeddown. For AA collisions, we develop a 4-momentum conserving resonance recombination model for charm-baryon formation implemented via event-by-event simulations that account for space-momentum correlations (SMCs) in transported charm- and thermal light-quark distributions. The SMCs, together with the augmented charm-baryon states, are found to play an important role in describing the baryon-to-meson enhancement at intermediate momenta. We emphasize the importance of satisfying the correct (relative) chemical equilibrium limit when computing the charm hadrochemistry and its momentum dependence with coalescence models.

Keywords: Charm quarks, Quark-Gluon Plasma, Hadronization, Recombination

1. Introduction

Heavy quarks (*i.e.*, charm, c, and bottom, b), ever since their discovery, have served as a versatile tool to test Quantum Chromodynamics (QCD), mainly facilitated by their masses which are large compared to the nonperturbative scale of QCD: $m_{c,b} \gg \Lambda_{\rm QCD}$. This renders their pairwise production ($c\bar{c}$ or $b\bar{b}$) perturbative, which must be followed, however, by a nonperturbative hadronization process at large distances. In pp collisions, the conventional hadronization mechanism for heavy quarks is fragmentation modeled by empirical functions. On the other hand, in relativistic heavy-ion (AA) collisions, the formation of a hot and dense deconfined Quark-Gluon Plasma (QGP) enables heavy quarks to hadronize through recombination with nearby light (anti-) quarks in the medium. Furthermore, since heavy quarks participate in the full evolution history of the fireball, via diffusion in the QGP, hadronization and further diffusion in the hadronic

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phase, they act as powerful tags of the properties of QCD matter, allowing for quantitative extractions of fundamental transport coefficients [1, 2].

Recent measurements of the charm hadrochemistry at RHIC and the LHC, in particular the ratios D_s/D^0 and Λ_c/D^0, have found intriguing patterns from pp (and p-Pb) [3, 4, 5] to Pb-Pb (and Au-Au) [6, 7, 8, 9, 10, 11] collisions. The Λ_c/D^0 ratio measured in pp and p-Pb collisions at the LHC is significantly larger than that measured in e^+e^- and ep collisions, and both Λ_c/D^0 and D_s/D^0 are seen to be further enhanced at intermediate momenta in AA collisions. These enhancements are not easily explained by Monte-Carlo event generators based on string fragmentation (for pp) [12] and by conventional coalescence models for AA collisions [13, 14], and thus provide a unique opportunity for a deeper understanding of charm-quark hadronization [2]. In the following, we report on our recent developments on charm hadronization, mostly focusing on the transverse-momentum (p_T) dependent charm-hadron ratios in both pp and AA collisions. For pp collisions, we show that the surprisingly large Λ_c/D^0 ratio can be largely explained within an augmented statistical hadronization model (SHM) that accounts for "missing" states to the charm-baryon spectrum [15] which are well motivated by both relativistic quark models (RQMs) and lattice QCD (lQCD). For AA collision, we extend our previously employed momentum conserving resonance recombination model (RRM) to the formation of charm baryons. In particular, an event-by-event implementation of the RRM allows to incorporate space-momentum correlations (SMCs) in charm- and light-quark distributions that, together with the additional charm-baryon states, are essential to provide a baryon-to-meson enhancement at intermediate p_T [16].

2. Charm hadrochemistry in *pp* collisions

The SHM has been successfully applied to light- and strange-hadron production in both elementary and heavy-ion collisions, and also works for charm-meson ratios, such as D^*/D or D_s/D (the latter requiring a strangeness fugacity $\gamma_s \simeq 0.6$) [17]. However, the standard SHM prediction of the cross section ratio of prompt Λ_c over D^0, $\Lambda_c/D^0 \simeq 0.22$ [18], based on charm-hadron states listed by the particle data group (PDG), is substantially below the measured value by the ALICE collaboration in $\sqrt{s}$ = 5 and 7 TeV pp collisions [4]. To study this puzzle, we have augmented the SHM by introducing a large set of "missing" charm-baryon states that have not been measured (and are thus not listed by PDG) but have been predicted by the relativistic quark model (RQM) [19]. As a result, the Λ_c^+/D^0 ratio, at a hadronization temperature T_H = 170(160) MeV reaches $\sim$ 0.57(0.44)([15], *i.e.*, a factor $\sim$ 2 enhancement relative to the PDG scenario. To calculate the p_T differential cross sections, we have performed a hadronization of the FONLL charm-quark spectrum into charmed mesons and baryons using the pertinent fragmentation functions of the FONLL framework [20]. The parameter r in the fragmentation function for the ground-state D^0 and Λ_c^+ has been tuned to fit the slope of the measured p_T spectra. The spectra of all excited states are then decayed into ground-state particles. The resulting p_T differential D_s^+/D^0 and Λ_c^+/D^0 ratios in $\sqrt{s}$ = 5.02 TeV pp collisions are shown in Fig. 1. While both the PDG and RQM scenarios (with a fitted total charm cross section of $d\sigma^{c\bar{c}}/dy$ = 0.855 mb and 1.0 mb, respectively) work well for the mesonic ratio D_s^+/D^0, the RQM scenario with augmented charm-baryon states is favored when confronted with the ALICE mid-rapidity data of Λ_c^+/D^0. We note that a lower ratio of about 0.35 is measured by LHCb at forward rapidity [21], possibly indicating that the applicability of the SHM is compromised if the hadron multiplicity becomes too low.

3. Charm hadrochemistry and collectivity in *AA* collisions

In heavy-ion collisions, where a hot and dense QGP forms and collectively expands, the enhancement of baryon-to-meson ratios in the light and strange sector at intermediate momenta, $p_T \simeq 2-6$ GeV, has been attributed to quark coalescence processes. A similar enhancement has now been observed in the charm sector by the ALICE and STAR collaborations [8, 11]. The p_T-dependent modification of the charm hadrochemistry, together with a simultaneous description of individual charm-hadron observables ($R_{\rm AA}$ and v_2), turns out to be a non-trivial task for theoretical modelling of charm transport and hadronization in the fireball.

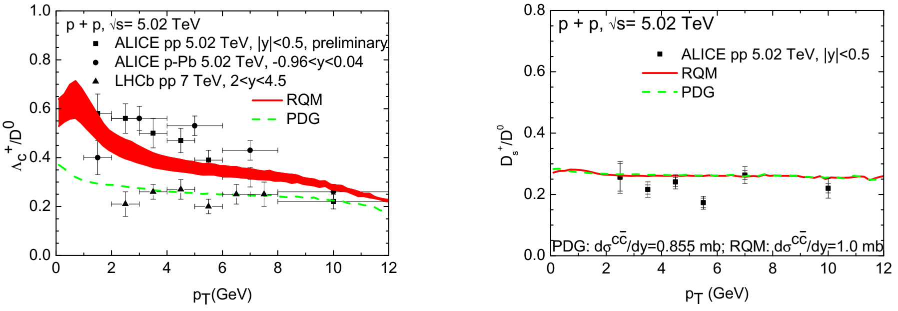

Fig. 1: The p_T-dependent D_s^+/D^0 and Λ_c^+/D^0 ratios in $\sqrt{s}$ = 5.02 TeV pp collisions. The red band for Λ_c^+/D^0 in the RQM scenario represents the uncertainty in the decay branching ratios of excited Λ_c's and Σ_c's into Λ_c^+ final states above the DN threshold, varying between 50% and 100%.

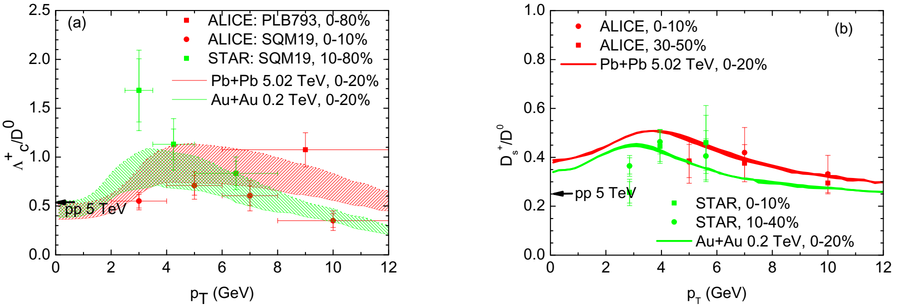

Fig. 2: (a) Λ_c^+/D^0, and (b) D_s^+/D^0 ratio, compared to LHC [6, 7] and RHIC [10, 11] data. The uncertainty bands in the Λ_c^+/D^0 ratios are due to a 50-100% BR for Λ_c feeddown from excited states above the DN threshold [15], and due to hadronic diffusion in the D_s^+/D^0 ratio. The horizontal arrows indicate the pp data.

In our recent work we have developed a 3-body resonance recombination model (RRM), taking advantage of the diquark correlation in the charm-baryon sector [16]. In addition, within the RRM, we have devised a method that incorporates space-momentum correlations (SMCs) between the phase space distributions of the charm quarks (as obtained through Langevin diffusion simulations in the QGP) and light quarks (as following from the same QGP background medium as used for the diffusion simulations). The SMCs cause, *e.g.*, fast moving quarks to hadronize preferentially in the outer regions of the fireball, where the hydrodynamic flow velocity tends to be larger. Importantly, our event-by-event implementation of the RRM not only obeys exact charm-number conservation, but also satisfies both kinetic and chemical equilibrium limits when using thermal quark distributions as input, resolving a long-standing problem of the fragility of coalescence model for the v_2 of the formed hadrons in the presence of SMCs [22]. These features are pivotal for controlled predictions of the p_T-dependence of the charm hadrochemistry, in particular pertinent ratios.

Our resulting predictions for the Λ_c^+/D^0 and D_s^+/D^0 ratios, including the augmented charm-baryon spectrum as done for pp baseline calculation, are summarized in Fig. 2. The low-p_T value of ~ 0.5 of the Λ_c^+/D^0 is essentially the same as that for pp, governed by the correct RRM relative chemical equilibrium limit between baryons and mesons. The ensuing enhancement at intermediate p_T is due to a stronger flow effect especially on the more massive charm baryons (feeding down to the Λ_c), as well as due to the SMCs captured by the improved RRM which render the higher (lower) p_T charm/light quarks more populated in the outer (central) region of the fireball at the time of hadronization. The overall enhancement of the D_s^+/D^0

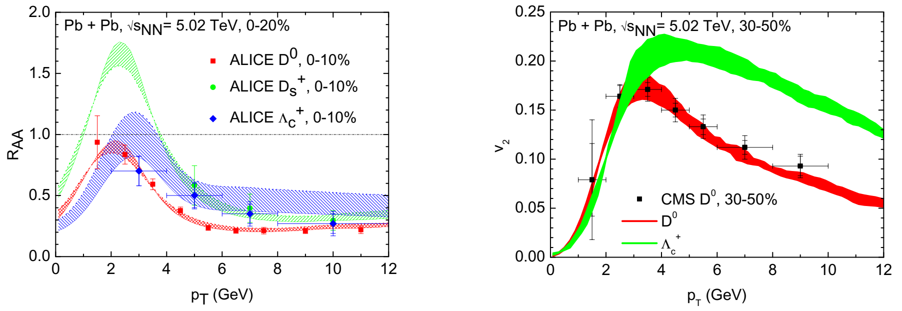

Fig. 3: R_{AA} (left panels) and v_2 (right panels) of D^0, D_s^+ and Λ_c^+ in Pb-Pb(5.02 TeV), compared to data [6, 7, 8]. The uncertainty bands for the Λ_c^+ R_{AA} are due to a 50-100% BR for feeddown from excited states above the DN threshold [15], and for the other observables due to the effects of hadronic diffusion.

relative to the pp case is a result of charm recombination in a strangeness-equilibrated environment (where the fugacity $\gamma_s \simeq 1$) [23]. We also note that the SMCs extend the reach of recombination out to significantly larger p_T which much improves the description of the D-meson v_2 at $p_T \gtrsim 4$ GeV, while the charm-hadron R_{AA} data are also well reproduced, cf. Fig. 3.

4. Conclusions

We have investigated the charm hadrochemistry in high-energy pp and heavy-ion collisions. The role of "missing" charm-baryons and a controlled implementation of space-momentum correlations in charm-quark recombination processes (a long-standing problem in the field) have been highlighted, in particular the importance of recovering both kinetic and chemical equilibrium limits in a flowing medium. The SMCs are found to significantly extend the p_T reach of recombination processes. The resulting p_T-dependent charm hadrochemistry and v_2 observables computed within our Langevin-RRM approach show a promising degree of agreement with existing data.

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