Charm-hadron production in \( pp \) and AA collisions

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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 \( \Lambda_c/D^0 \) 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 \( \Lambda_c/D^0 \) 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 \( \Lambda_c/D^0 \) 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 \( \Lambda_c \) via decay feeddown. For AA collisions, we develop a 4-momentum conserving 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: \( m_{c,b} \gg \Lambda_{\text{QCD}} \). 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
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 $\Lambda_{c}/D^{0}$, 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 $\Lambda_{c}/D^{0}$ 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 $\Lambda_{c}/D^{0}$ 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 $\Lambda_{c}/D^{0}$ 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 collisions, 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 $D^{0}/D$ or $D_{s}/D$ (the latter requiring a strangeness fugacity $\gamma_{s} \approx 0.6$) [17]. However, the standard SHM prediction of the cross section ratio of prompt $\Lambda_{c}$ over $D^{0}$, $\Lambda_{c}/D^{0} \approx 0.22$ [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 $\Lambda_{c}/D^{0}$ 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 $\Lambda_{c}$ 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 $D^{0}_{s}/D^{0}$ and $\Lambda_{c}/D^{0}$ 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 $d\sigma/dy = 0.855$ mb and 1.0 mb, respectively) work well for the mesonic ratio $D^{0}_{s}/D^{0}$, the RQM scenario with augmented charm-baryon states is favored when confronted with the ALICE mid-rapidity data of $\Lambda_{c}/D^{0}$. 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, $p_{T} \approx 2–6$ 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 [5, 11]. The $p_{T}$-dependent modification of the charm hadrochemistry, together with a simultaneous description of individual charm-hadron observables ($R_{AA}$ and $v_{2}$), turns out to be a non-trivial task for theoretical modelling of charm transport and hadronization in the fireball.

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 [18]. In addition, within the RRM, we have
Fig. 1: The $p_T$-dependent $D_s^+ / D^0$ and $\Lambda_c^+ / D^0$ ratios in $\sqrt{s} = 5.02$ TeV $pp$ collisions. The red band for $\Lambda_c^+ / D^0$ in the RQM scenario represents the uncertainty in the decay branching ratios of excited $\Lambda_c^+$ and $\Sigma_c^+$ into $\Lambda_c^+$ final states above the $DN$ threshold, varying between 50% and 100%.

Fig. 2: (a) $\Lambda_c^+ / D^0$, and (b) $D_s^+ / D^0$ ratio, compared to LHC [6] and RHIC [10,11] data. The uncertainty bands in the $\Lambda_c^+ / D^0$ ratios are due to a 50-100% BR for $\Lambda_c$ feeddown from excited states above the $DN$ threshold [13], and due to hadronic diffusion in the $D_s^+ / D^0$ ratio. The horizontal arrows indicate the $pp$ data.

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 the 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 $\Lambda_c^+ / D^0$ 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 $\sim 0.5$ of the $\Lambda_c^+ / D^0$ 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 $\Lambda_c$), 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 $D_s^+ / D^0$ relative to the $pp$ case is a result of charm recombination in a strangeness-equilibrated environment (where the fugacity $\gamma_s \approx 1$) [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
Fig. 3: \( R_{AA} \) (left panels) and \( v_2 \) (right panels) of \( D^0, D^+ \) and \( \Lambda_c^+ \) in Pb-Pb (5.02 TeV), compared to data [6, 7, 8]. The uncertainty bands for the \( \Lambda_c^+ R_{AA} \) 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.

\( R_{AA} \) 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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