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Heavy hadron production with a coalescence plus fragmentation hadronization approach: AA system size scan down to pp collisions

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Heavy baryon production in various collision systems, from RHIC to LHC energies, is a challenge for theoretical understanding of heavy quarks (HQs) hadronization. An hadronization via coalescence-fragmentation predicts large Λ_c/D^0 from AA collisions at RHIC and LHC to pp collisions at top LHC energies. The model shows significant enhancements in Ξ_c/D^0 and Ω_C/D^0 in pp collisions in agreement with ALICE data. We extend this approach to multi-charmed baryons: Ξ_{cc} and Ω_{ccc}. Investigating the impact of system size from *PbPb*, *KrKr*, *ArAr*, and *OO* as planned by ALICE3 will permit to study the role of non-equilibrium in charm quark distribution. We show that in *PbPb* collisions it resembles SHM predictions under full thermalization, but baryons like Ω_{ccc} are sensitive to HQ thermalization. Predictions for B mesons, Λ_c, and Ξ_b in *PbPb* and *pp* collisions at top LHC energies are presented. The study of heavy hadron production could sheds light on hadronization and equilibration of HQ in the QGP.

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1. Introduction

Data from RHIC and LHC experiments have provided evidence for the creation of a quark-gluon plasma (QGP). Heavy quarks (HQs) are created in the early collision stages from well-understood production mechanisms via perturbative QCD (pQCD), and because of their large masses can be probes throughout the full QGP evolution. One interesting aspect of the HQ phenomenology is the hadronization process, in particular the formation of heavy hadrons, such as D and B mesons and Λ_c or Λ_b baryons. The hadronization process affects key observables in the study of QGP such as the transverse momentum spectra and the nuclear modification factor (R_{AA}) of heavy hadrons, which provide insights on the features of the medium created and the heavy quarks interactions with it. The $R_{AA}(p_T)$ and the elliptic flow ($v_2(p_T)$) of D mesons, as measured in the experiments, suggest that charm quarks lose their energy in the QGP and take part also in the collective flow of the medium [1–12]. Recent experimental results at LHC energies have shown an enhancement of Λ_c/D^0, both in $PbPb$ and in high multiplicity proton-proton collisions (pp). The baryon over meson ration comes from an Λ_c production much larger than the one that is predicted by the fragmentation process, an enhancement that is reflected bu the differences with the fragmentation fractions measured in e^+e^- and ep collisions. These findings suggest that hadronization, like hybrid approaches via coalescence plus fragmentation, which generally assume a medium creation, is applicable in heavy-ion collisions and also in small systems like pp collisions, as shown in recent studies that have shown a good qualitative agreement with experimental data [14–16]. In literature several models, with and without recombination, have been proposed to explain these phenomena, see ref. [13] for a recent systematical comparison.

2. Hadronization model

The coalescence approach was initially introduced as a hadronization mechanism for Heavy Ion collisions at RHIC, to explain the p_T spectra, baryon-to-meson ratio, and elliptic flow splitting between mesons and baryons [17, 18]. It has been applied successively at LHC energies with a successful description of light hadron spectra and baryon-to-meson ratios [19] and then extended to heavy-flavor hadronization in AA collisions [20–23] and recently including multi-charmed hadrons like Ξ_{cc} and Ω_{ccc} [24]. The model of recombination that we use is based on the Wigner formalism for quark coalescence.

In this approach the momentum spectrum of hadrons formed by coalescence of quarks can be written as:

$$\frac{dN_H}{dyd^2P_T} = g_H \int \prod_{i=1}^{N_q} \frac{d^3p_i}{(2\pi)^3E_i} p_i \cdot d\sigma_i \; f_{q_i}(x_i, p_i) C_H(x_1...x_{N_q}, p_1...p_{N_q}) \, \delta^{(2)}\left(P - \sum_{i=1}^{n} p_i\right)$$

The statistical factor g_H represents the probability of forming a colorless hadron from quarks and antiquarks with spin 1/2. $d\sigma_i$ refers to an element of a space-like hypersurface at a fixed proper time τ theat corresponds to the QGP lifetime, while f_{q_i} denotes the quark (anti-quark) phase-space distribution functions for the i-th quark (anti-quark). The function $C_H(x_1...x_{N_q}) = C^{N_q-1} f_H(x_1...x_{N_q}, p_1...p_{N_q})$ is expressed in terms of the Wigner function $f_H(x_1...x_{N_q}, p_1...p_{N_q})$ that describes the spatial and momentum distribution of quarks in a hadron, and the factor C^{N_q-1}

which is fixed to impose that the total coalescence probability gives $\lim_{p\to 0} P^{tot}_{coal} = 1$. The Wigner function assumed here is a Gaussian in both position and momentum space, i.e. $f_H(...) = \prod_{i=1}^{N_q-1} 8\exp\left(-\frac{xri^2}{\sigma_{ri}^2} - p_{ri}^2\sigma_{ri}^2\right)$, where x_{ri} and p_{ri} represent the relative coordinates. The widths σ_{ri} are connected to the the root mean square charge radius of the hadron produced, for details see refs.[14, 21, 24, 25]. As highlighted in a series of previous studies on HQ recombination[4, 19–21, 26], the probability of coalescence as a function of quark transverse momentum is described as a decreasing function, this behaviour leads to the dominance of independent fragmentation for hadron production in the region of high p_T. In our model, a smooth transition between the low and high p_T regimes is achieved by introducing a fragmentation probability $P_{frag}(p_T)$. Therefore, HQ with non-zero p_T undergoes hadronization via coalescence or fragmentation following the coalescence probability $P_{coal}(p_T)$ and the complementary fragmentation probability defined as $P_{frag}(p_T) = 1 - P_{coal}(p_T)$. The fragmentation process that we apply here is based on the Peterson fragmentation funcrions for charmed hadrons [27] and the Kartvelishvili fragmentation functions for bottom hadrons [28].

3. Single and multi-charmed hadrons from AA to pp collisions

The effect of Heavy Quarks hadronization via coalescence plus fragmentation in AA collisions, at both RHIC and LHC energies, is to enhance the baryon production, notably increasing Λ_c yields for $p_T < 3-4$, GeV, with a resulting rise-and-fall behaviour of heavy flavour baryon-to-meson ratio [20, 21]. In pp collisions, with the assumption of QGP medium formation [30, 31], the model's predictions for D^0, D^+, D^*, and Λ_c [14] are similar with Statistical Hadronization Model with enhanced set of baryons [32], but significant differences are present for Ξ_c and Ω_c production. In

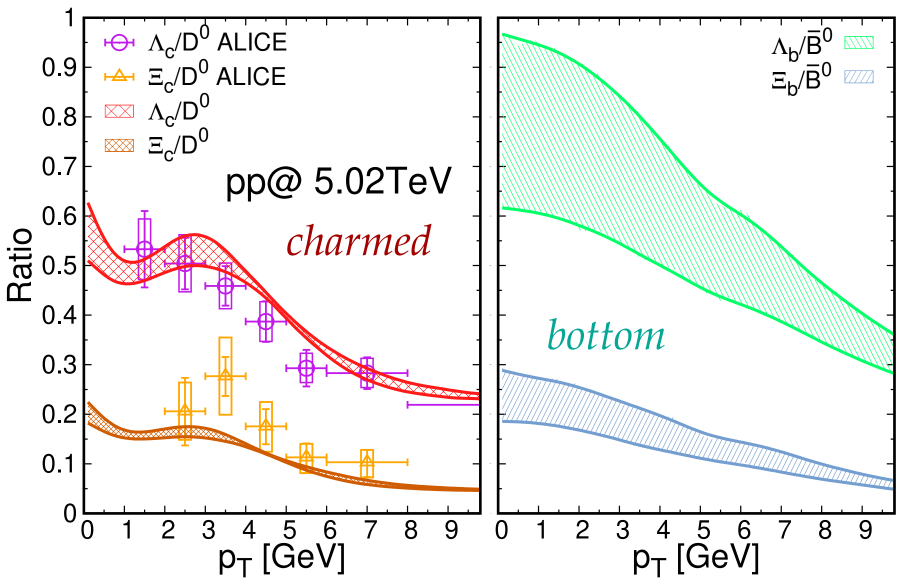

Figure 1: Comparison between (left) Λ_c/D^0, Ξ_c/D^0 and (right) Λ_b/B^0, Ξ_b/B^0 as a function of the transverse momentum for pp collision at 5.02 TeV. The bands correspond to the sensitivity of the ratio with a variation of the Wigner widths. Experimetal data from [33, 34]

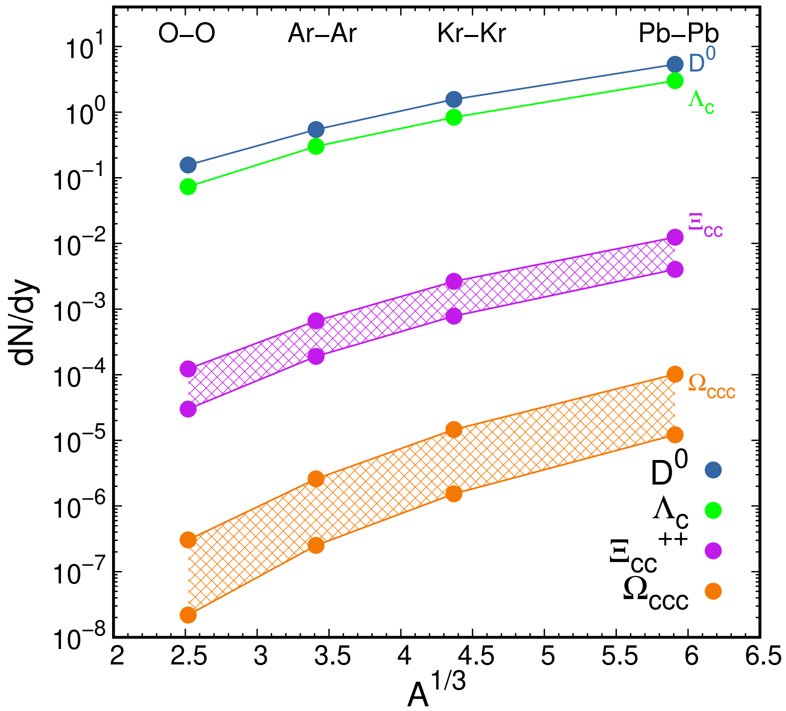

Figure 2: dN/dy at mid-rapidity of single and multi-charmed hadrons as a function of the size of the systems obtained with coalescence plus fragmentation.The band corresponds to the yields obtained with realistic distribution for the lower limit and the one obtained with thermal distribution for the upper limit.

the left panel of Fig.1 it is shown that coalescence plus fragmentation approach predicts a charmed baryon/meson ratio consistent with the recent experimental data available for pp collisions at LHC energies [33, 34]. In the right panel of Fig.1 it is shown the baryon-to-meson ratios for $\Lambda_b/\bar{B}^0$, $\Xi_b^0/\bar{B}^0$ in pp collisions at $\sqrt{s} = 5.02$ TeV. The hybrid coalescence-plus-fragmentation model predicts higher baryon ratios in the bottom sector w.r.t. the one in the charm sector. The Λ_b production obtained enhances the Λ_b/B^0 ratio to a value that is ≈ 0.9 in the low p_T region. This ratio is about 50% larger than the charmed one, but it preserves the decreasing trend at higher p_T shown by the charmed baryons. The $\Xi_b^0/\bar{B}^0$ ratio is ≈ 0.3 at low momenta, smaller than $\Lambda_b/\bar{B}^0$ of about 30%, with a similar proportion shown by the Λ_c and Ξ_c baryon over meson ratio for charmed hadrons.

We have studied further the production in AA collisions for charmed and multi-charmed hadrons, changing the size of the system, looking at $PbPb$, $KrKr$, $ArAr$ and OO collisions systems. In Fig.2, the yields for single and multi-charmed hadrons in $PbPb$ collisions at mid-rapidity $(0-10\%$ centrality) are shown by the set of point on the right of the plot. The bands represents the yield range, where the lower limit corresponding to a realistic charm distribution and the upper limit to a thermal distribution, the effect in the changing distribution is not relevant for D^0 and Λ_c, but has a large effect in the multicharmed hadrons, when a thermalized charm distribution is chosen the coiche leads to bigger yields. This behaviour is related to the fact that when more charms are clustering at low momentum, as it happens in a scenario with thermal distribution, the recombination is facilitated. The observed behaviour of these yields confirms the intuitive idea that the yields for multi-charmed baryons are more sensitive to the charm distribution compared to single-charmed hadrons. The Fig.2 illustrates also the production of single and multi-charmed hadrons in different collision systems, including $Kr + Kr$, $Ar + Ar$, and $O + O$. The initial p_T distribution for these systems is based on FONLL calculations, evolving in a QGP medium described by a relativistic Boltzmann approach, as discussed in [24]. The mean difference between the charm distribution changing the collision system, is that when the system size decreases, the fireball's lifetime and the charm quark's time in the QGP are reduced leading to a smaller energy loss, therefore, as a consequence, smaller systems exhibit flatter final p_T distributions compared to larger systems [24]. The dN/dy yield, derived from coalescence plus fragmentation for each species (shown as different bands), is plotted against the system size $A^{1/3}$. As said above, the upper band limit is for a full charm thermalization, while the lower limit comes from distributions evaluated with a Boltzmann transport approach. Comparison with SHM and consideration about the expected scaling of these yields with the system size can be found in [24].

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