Coalescence plus fragmentation approach for the hadronization mechanism of heavy hadrons from AA to pp collisions

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Abstract. One of the present challenge for the theoretical understanding of heavy-quark hadronization is represented by the description of the measurements of heavy hadron production in *pp*, *pA* and *AA* collisions from RHIC to top LHC energies. The Λ_c/D^0 ratio observed in *AA* collisions has a value of the order of the unity, and experimental measurements in *pp* collisions at both $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV have shown ratios for charm baryons Λ_c, Ξ_c^0 and Ω_c^0 respect to D^0 meson larger than that measured and expected in e^+e^-, ep collisions. We present an hadronization mechanism based on the coalescence and fragmentation processes, and the results obtained in *AA* collisions for D^0 and Λ_c related baryon to meson ratios at RHIC and LHC. We present moreover results obtained for the charmed hadron production in *pp* collisions at LHC energies assuming the formation of an hot QCD matter at finite temperature.We calculate the heavy baryon/meson ratio and the p_T spectra of charmed hadrons D^0, Λ_c^+ and the recently measured Ξ_c baryon, finding an enhancement in comparison with the ratio observed for e^+e^-, ep collisions; with this approach we also predict a significant production of Ω_c.

1 Introduction

A new state of matter composed of deconfined quark and gluons that strongly interact, called Quark-Gluon Plasma (QGP), has been studied, over the years, in the ultra-relativistic heavy ion collision at Large Hadron Collider (LHC) and at Relativistic Heavy-Ion Collider (RHIC). The bulk properties of this state of matter is characterized by the characteristics of light-quark and gluons. Instead, because of their large mass, the heavy quarks, i.e. charm and bottom, can be used as probes of the QGP properties Recently, the relation between the heavy-quark dynamics in the QGP and the bulk properties has been studied with a lot of theoretical efforts [1–10]. The experimental data have shown, for heavy ion collisions in the intermediate region of momenta, a $\Lambda_c/D^0 \sim 0.8 \div 1.5$ at RHIC and $\Lambda_c/D^0 \sim 0.2 \div 1.2$ at LHC [11–13], with an enhancement of the baryon/meson ratio in the heavy flavor sector similar to the one observed for light and strange hadrons, and larger than the one expected from the simple fragmentation in collision systems as e^+e^-, $e^\pm p$ [14]. We study the heavy hadrons production using for the hadronization process a coalescence plus fragmentation model. [15–17]. The

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different heavy hadron species produced manifests into a baryon-to-meson enhancement for charmed hadrons. [18–21] Measurements of heavy baryon production in pp collisions, at LHC energies, have recently attracted interest [22]. It represents, at the moment, a challenge for the heavy-quark hadronization theoretical understanding. In fact, at the energy of $\sqrt{s} = 5TeV$ and $13TeV$, the Λ_c/D^0 ratio has been measured with a value of about 0.6 in the low p_T region that is larger than the one evaluated in [14]. Furthermore the measured production of other single-charmed baryons with content of strangeness, i.e. Ξ_c and Ω_c, and their ratios to D^0 and Λ_c show an unexpected behavior in pp collision [23].

2 Coalescence plus Fragmentation hadronization model

The hadron production that comes from coalescence, in the model that we use, is based on the Wigner formalism, and is evaluated with the following coalescence integral:

$$\frac{d^2N_H}{dP_T^2} = g_H \int \prod_{i=1}^{n} \frac{d^3p_i}{(2\pi)^3E_i} p_i \cdot d\sigma_i \; f_{q_i}(x_i,p_i) f_H(x_1...x_n,p_1...p_n)\, \delta^{(2)}\left(P_T - \sum_{i=1}^{n} p_{T,i}\right) \quad (1)$$

where $d\sigma_i$ denotes an element of a space-like hypersurface, g_H is the statistical factor to form a colorless hadron while f_{q_i} are the quark (anti-quark) phase-space distribution functions for i-th quark (anti-quark). $f_H(x_1...x_n,p_1...p_n)$ is the Wigner function and describes the distribution of quarks, in space and momentum, within an hadron. In the case of charm hadrons we use a Wigner function that is a Gaussian distribution in relative space and momentum, $f_H(x_1...x_{N_q};p_1...p_{N_q}) = \prod_{i=1}^{N_q-1} A_W \exp\left(-\frac{x_{r_i}^2}{\sigma_{r_i}^2} - p_{r_i}^2\sigma_{r_i}^2\right)$ where x_{r1} and p_{r1} are the 4-vectors for the relative coordinates of the N_q quarks. The covariant width parameter σ_r can be related to the oscillator frequency ω by $\sigma = 1/\sqrt{\mu\omega}$ where $\mu = (m_1m_2)/(m_1+m_2)$ is the reduced mass, and is related to the root mean square charge radius of the meson. For D^+ meson $\langle r^2\rangle_{ch} = 0.184\,fm^2$ corresponds to a $\sigma_p = \sigma_r^{-1} = 0.283\,\mathrm{GeV}$; for Λ_c^+ the mean square charge radius is $\langle r^2\rangle_{ch} = 0.15\,fm^2$ with the related widths $\sigma_{p_1} = \sigma_{r_1}^{-1} = 0.251\,\mathrm{GeV}$ and $\sigma_{p_2} = \sigma_{r_2}^{-1} = 0.424\,\mathrm{GeV}$. We assign a fragmentation probability as $P_{frag}(p_T) = 1 - P_{coal}(p_T)$, after the evaluation of the coalescence probability P_{coal} for each charm quark. Based on the constraint of confinement and with the physical motivation that a quark with zero momentum cannot fragment into an hadron at lower momentum; we determine the normalization constant A_W in order to have, in the limit $p \to 0$, that all the charm quarks hadronize via coalescence. Then we can evaluate the final hadron fragmentation momentum spectra, coming from the charm quarks; it is given by the convolution of the parton spectrum that do not undergo to coalescence with the fragmentation function $D_{had}(z,Q^2) \propto 1/\left[z\left[1-\frac{1}{z}-\frac{\epsilon_c}{1-z}\right]^2\right]$. In this case we employ the Peterson fragmentation function [24], where ϵ_c is a parameter determined in order to well reproduce, with the fragmentation, the high momenta tails of the D and Λ_c production in $p+p$ collisions. [4, 21]. The relative fragmentation fractions of charm quarks into different hadron channels are used according to the fractions evaluated in [14]. In our model we use a fireball formed by a thermalized system of gluons and u, d, s quarks and anti-quarks at a temperature of $T_C = 165\,\mathrm{MeV}$, that form the bulk of particles. The fireball is considered at $\tau = 8.\,fm/c$ for LHC Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02\,TeV$, and $\tau = 4.5\,fm/c$ for RHIC Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. In $p+p$ collisions at LHC at $\sqrt{s_{NN}} = 5.02\,TeV$ we fix the parameter according to hydro-dynamical simulations [25] with $\tau = 2.5\,\mathrm{fm}/c$. The collective flow is considered assuming a radial flow profile as $\beta_T(r_T) = \beta_{max}\frac{r_T}{R}$, where R is the transverse radius of the fireball and β_{max} is the radial flow value on the external surface of the fireball. For partons at low transverse momentum, $p_T < 2\,\mathrm{GeV}$, hence we consider a thermal distribution, instead for $p_T > 2.5\,\mathrm{GeV}$, we consider the minijets that have undergone the jet

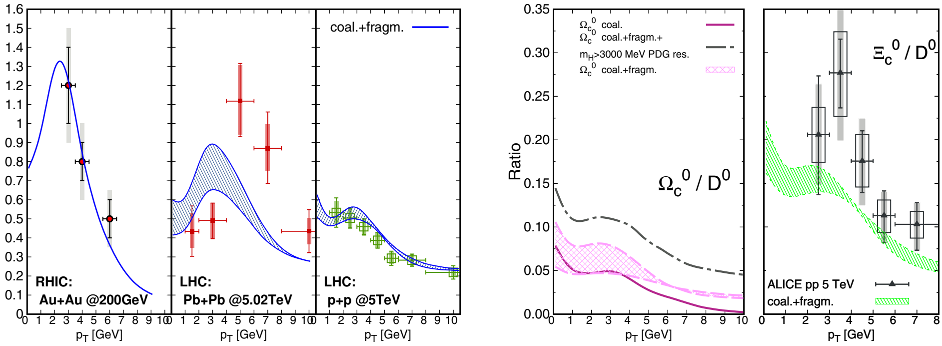

Figure 1: Λ_c^+ to D^0 ratio as a function of p_T and at mid-rapidity for (left panel) $Au + Au$ collisions at $\sqrt{s} = 200\,\text{GeV}$ [11] for (middle panel) $Pb + Pb$ collisions at $\sqrt{s} = 5.02\,\text{TeV}$ [13] and for (right panel) pp collisions at $\sqrt{s} = 5\,\text{TeV}$ [22].
(left) Ratios at mid-rapidity for pp collisions at $\sqrt{s} = 5.02\,\text{TeV}$. Ω_c/D^0 ratio considering Ω_c with: only coalescence (purple solid line), coalescence plus fragmentation (pink band), resonances (black dot-dashed lines). D^0 coming from coalescence plus fragmentation. (right) $\Xi_c^{0,+}/D^0$ with both coalescence and fragmentation, data from [23]

quenching mechanism. For heavy quarks, in heavy ion collisions, the distribution is obtained by solving the relativistic Boltzmann equation [4] giving a good description of R_{AA} and v_2 for D mesons. For $p + p$ collisions, the charm quark spectrum have been taken according to Fixed Order + Next-to-Leading Log (FONLL) distribution [26]

3 Results

Our model with coalescence plus fragmentation predicts a rise and fall of the baryon/meson ratio. The left and middle panel in Fig.1 show the comparison between RHIC and LHC for the Λ_c^+/D^0 ratio. The production ratio between coalescence and fragmentation is smaller at LHC than at RHIC. At LHC the larger contribution in particle production from fragmentation leads to a final ratio that is smaller than at RHIC [19]. Experimental data of the Λ_c^+ to D^0 ratio have been released, in the past years, for pp collisions at LHC [22, 29], and show an unexpected excess of production of Λ_c with respect to the simple fragmentation, with values of the ratio of ~ 0.6 in the region at low momenta.We have applied our model in the case of pp collisions at mid-rapidity at $\sqrt{s} = 5.02\,TeV$, assuming the formation of a QGP medium like the one simulated in hydrodynamics calculations [25] and we obtain a good description of the Λ_c/D^0 ratio, see Fig.1 (right panel), with the band determined including the uncertainties given by a 20% variation of the Wigner function widths. Our calculations describe the disappearance of the peak, and an enhancement that is significantly different from the ratio obtained with the only fragmentation [21]. In Fig. **??**, we show the Ξ_c and Ω_c to D^0 ratios in pp collisions at $\sqrt{s} = 5.02\,TeV$. In the left panel we show the Ω_c^0/D^0 ratio having considered, for the D^0 meson, the contribution that comes from both coalescence and fragmentation; while, for the Ω_c^0, we show three cases: only coalescence contribution (purple line), coalescence plus fragmentation (pink band) and including some resonance states in addition to the ground state (i.e. $\Omega_c(3000)^0$, $\Omega_c(3005)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$, $\Omega_c(3120)^0$.) (black dash-dotted line). In the right panel, we show the Ξ_c/D^0 ratio (green band) in comparison with recent data from ALICE collaboration [23], where we have included the contribution from the main existing Ξ_c resonance states.

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