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The surprising heavy hadrons production in pp and AA collisions: hadronization within coalescence and fragmentation

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Abstract. The hadronization process of heavy hadrons with bottom and charm quarks, especially for baryons Λ_c and Λ_b , in a dense QGP medium is largely not understood. We present within a coalescence plus fragmentation model the predictions for D^0 , Ds, Λ_c , B and Λ_b spectra and the related baryon to meson ratios at RHIC and LHC in a wide range of transverse momentum region up to 10 GeV, moreover we show the effect of the hadronization mechanism which plays a fundamental role to describe simultaneously the experimental data for the nuclear suppression factor R_{AA} and the elliptic flow $v_2(p_T)$ of heavy hadrons from RHIC to LHC energies. In particular, we show the considerable change of the Nuclear modification factor of D mesons due to the large Λ_c production, explaining the $R_{AA}(p_T) < 1$ observed by STAR at low momenta. We will discuss how our model can naturally predict values of the order of O(1) for Λ_c / D^0 as recently measured at both RHIC and LHC, and we present the novel predictions for Λ_b/B not yet measured, which are much larger than the expectations from fragmentation. Moreover assuming that at the LHC top energies there can be the formation of QGP, we show that in the same scheme due to considerable volume effect a still large $\Lambda_c / D^0 \approx 0.5$ is predicted as seen by ALICE in pp and pA collisions. Furthermore in the same scheme can be predicted a baryon to meson ratio Λ_c / D^0 in pp collisions assuming that at the LHC top energies there can be the formation of QGP matter. The results show a considerable volume effects that significantly reduce the ratios, but still predict quite larger values with respect to fragmentation, in agreement with recent data from ALICE in pp collisions.

1. Introduction

A new state of matter composed of a strongly interacting plasma of deconfined quark and gluons called Quark-Gluon Plasma (QGP) is created and studied in Ultra-relativistic heavy ion collision at Large Hadron Collider (LHC) and at Relativistic Heavy-Ion Collider (RHIC).

Heavy quarks like charm or bottom quarks, characterized by a large mass, are used as useful probes of the QGP properties. Information about heavy quarks are also compared to the bulk properties of this new state of matter that are governed by the light quarks and gluons, in recent years a lot of efforts have been made to study the heavy quark dynamics in the QGP [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12].



The final observable states that contain charm quarks are the charmed hadrons, mainly D mesons and Λ_c, Σ_c baryons. Recent experimental results from STAR and ALICE collaborations have shown an enhancement of the baryon/meson ratio in the heavy flavor sector like the one observed for light and strange hadrons compared to the one for p-p collision [13, 14, 15]. In particular the experimental data have shown a $\Lambda_c/D^0 \sim 0.8 \div 1.5$ for $2.5 < p_T < 6 \text{ GeV}$ at RHIC and $\Lambda_c/D^0 \sim 0.2 \div 0.8$ for $2.5 < p_T < 10 \text{ GeV}$ at LHC which is a very large enhancement compared to the value predicted by the charm hadron fragmentation ratio for p+p collisions [16] that is also smaller than the recently measured ratio in p+p collision at LHC collisions at the energy of $\sqrt{s} = 5 \text{ TeV}$ that is ~ 0.6 at very low momentum and ~ 0.3 at $p_T = 7 \text{ GeV}$. The explanation of the hadronization process through the recombination mechanism starts from the idea that the final state particles are formed by comoving partons in the QGP that combine their transverse momentum to produce a meson or a baryon with an higher transverse momentum [17, 18, 19, 20]. The relative abundance of the different heavy hadron species produced can manifests a baryon-to-meson enhancement for charmed hadrons. [21, 22, 23]

2. Coalescence plus Fragmentation Model

Our coalescence model is based on the Wigner formalism, the resolution of the coalescence integral gives the momentum spectrum of hadrons that can be written as:

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

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). $f_H(x_1 \dots x_n, p_1 \dots p_n)$ is the Wigner function and describes the spatial and momentum distribution of quarks within an hadron and can be related to the hadron wave function. The Wigner distribution function used has a Gaussian shape in space and momentum, $f_M(x_1, x_2; p_1, p_2) = A_W \exp\left(-\frac{x_{r1}^2}{\sigma_r^2} - p_{r1}^2 \sigma_r^2\right)$ where x_{r1} and p_{r1} are the 4-vectors for the relative coordinates. A_W is a normalization constant fixed to guarantee that in the limit $p \rightarrow 0$ we have all the charm hadronizing. While σ_r is the covariant width parameter and it can be related to the oscillator frequency ω by $\sigma = 1/\sqrt{\mu\omega}$ where $\mu = (m_1 m_2)/(m_1 + m_2)$ is the reduced mass. The width of f_M is related to the size of the hadron and in particular to the root mean square charge radius of the meson. For D^+ meson $\langle r^2 \rangle_{ch} = 0.184 \text{ fm}^2$ corresponding to a $\sigma_p = \sigma_r^{-1} = 0.283 \text{ GeV}$; for Λ_c^+ the widths are fixed by the mean square charge radius of Λ_c^+ which is given by $\langle r^2 \rangle_{ch} = 0.15 \text{ fm}^2$.

We compute the coalescence probability P_{coal} for each charm quark then we can assign a probability of fragmentation as $P_{frag}(p_T) = 1 - P_{coal}(p_T)$. Therefore the hadron momentum spectra from the charm spectrum $dN_{fragm}/d^2 p_T dy$ that do not undergo to coalescence is given by the convolution with the fragmentation function, for D and Λ_c^+ we employ the Peterson fragmentation function [24] $D_{had}(z, Q^2) \propto 1/\left[z \left[1 - \frac{1}{z} - \frac{\epsilon_c}{1-z}\right]^2\right]$, where ϵ_c is a free parameter to fix the shape of the fragmentation function and is determined assuring that the experimental data on D and Λ_c production in $p + p$ collisions are well described by a fragmentation hadronization mechanism. The value it has been fixed to $\epsilon_c = 0.06$ and $\epsilon_c = 0.12$ as discussed in [5]. The relative ratios between different hadron channels are properly calculated and normalized according to the ratio of fragmentation fraction in [16].

2.1. Fireball parameters and quark distribution

Our approach is based on a fireball where the bulk of particles is a thermalized system of gluons and u, d, s quarks and anti-quarks at a temperature of $T_C = 165 \text{ MeV}$. The fireball is considered

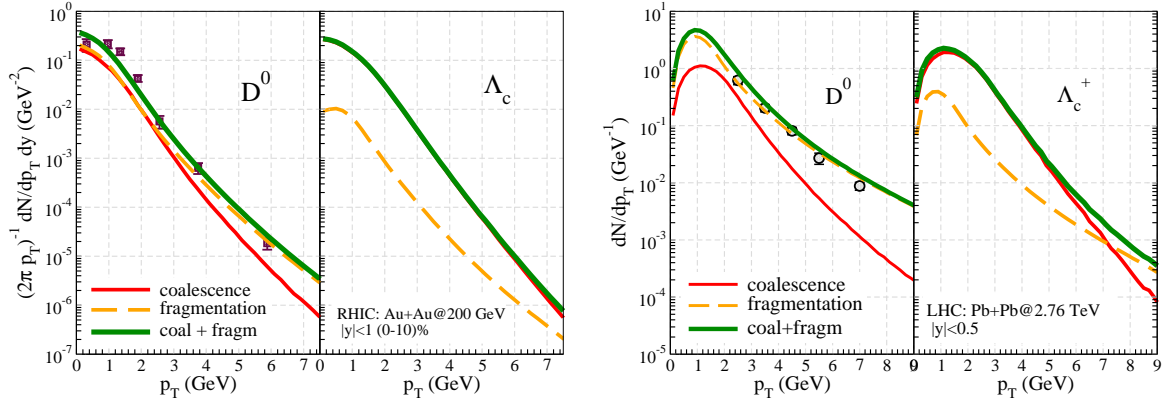


Figure 1. (Color online) (a)(left) Transverse momentum spectra at mid-rapidity for $Au + Au$ collisions at $\sqrt{s} = 200$ GeV and for (0 – 10%) centrality for D^0 meson (left panel) and for Λ_c^+ baryon (right panel). Experimental data taken from [25] (b)(right) Transverse momentum spectra at mid-rapidity for $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ TeV and for (0 – 10%) centrality for D^0 meson (left panel) and for Λ_c^+ baryon (right panel). Experimental data taken from [26]

at $\tau = 7.8$ fm/c, for LHC Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, and $\tau = 4.5$ fm/c, for RHIC Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. To take into account for the collective flow, we assume a radial flow profile as $\beta_T(r_T) = \beta_{max} \frac{r_T}{R}$, where R is the transverse radius of the fireball. For partons at low transverse momentum, $p_T < 2$ GeV, hence we consider a thermal distribution, instead for $p_T > 2.5$ GeV, we consider the minijets that have undergone the jet quenching mechanism. For heavy quarks we use the transverse momentum distribution obtained by solving the relativistic Boltzmann equation [5] giving a good description of R_{AA} and v_2 for D mesons. The heavy quark numbers are estimated to be $dN_c/dy \simeq 2$ at RHIC and $dN_c/dy \simeq 15$ at LHC. In the following calculation the charm quark mass used is $m_c = 1.3$ GeV.

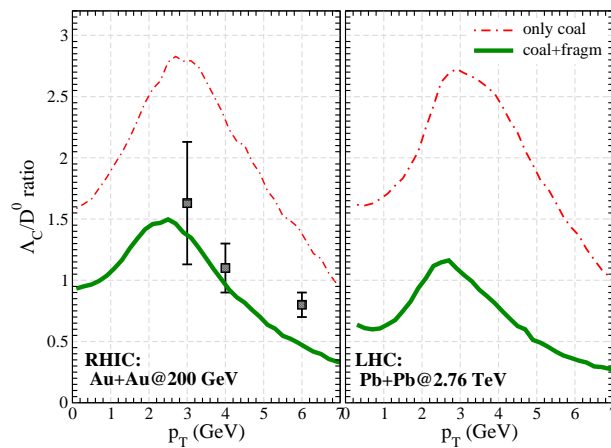


Figure 2. (Color online) Λ_c^+ to D^0 ratio as a function of p_T and at mid-rapidity for (left panel) $Au + Au$ collisions at $\sqrt{s} = 200$ GeV [15, 27] and for (right panel) $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ TeV .

3. Results

In Fig.1 (a) (left) are shown the transverse momentum spectra at midrapidity for $Au + Au$ collisions at $\sqrt{s} = 200$ GeV and for (0 – 10%) centrality for D^0 meson (left panel) and for Λ_c^+ baryon (right panel). The contribution from coalescence (red solid line) and fragmentation (orange dashed line) for D^0 production is about similar at momenta in the region $p_T < 3$ GeV. The two production differs at higher momenta where fragmentation becomes dominant for the yield. The coalescence (red solid line) mechanism appears as the dominant mechanism for the Λ_c^+ production for $p_T < 7$ GeV and it is mainly related to the fragmentation fraction of charmed hadrons formed via fragmentation from charm quarks, as showed in the analysis in Ref. [16], where this fraction is about the 6% of the total produced heavy hadrons. We have also considered for Λ_c^+ and D^0 the yield that comes from the decay of the main hadronic channels, *i.e.* D^{*0} , D^{*+} , $\Sigma_c^*(2520)$ and $\Sigma_c(2455)$.

In Fig.1 (b) (right) are shown the transverse momentum spectra at midrapidity for $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ TeV and for (0 – 10%) centrality for D^0 meson (left panel) and for Λ_c^+ baryon (right panel). In this case the contribution from coalescence (red solid line) is smaller than the one from fragmentation (orange dashed line) in all the momentum region considered, thus fragmentation is dominant for the overall yield. For the Λ_c^+ production the coalescence (red solid line) mechanism appears still the dominant mechanism up to $p_T = 7$ GeV

In the left panel of Fig.2 we show the Λ_c^+/D^0 ratio in comparison with the STAR experimental data shown by squares [15, 27]. Coalescence by itself predicts a rise and fall of the baryon/meson ratio, the inclusion of fragmentation reduces the ratio, and we can see a quite good agreement with the experimental data in the peak region (green solid line). The two panels in Fig.2 show the comparison between RHIC and LHC for the Λ_c^+/D^0 ratio. Coalescence predicts a similar ratio for both energies, in the fragmentation case the ratio is established from the experimental measured fragmentation fraction and remains exactly the same also changing the collision energy. Even if the only coalescence and the only fragmentation ratio remain similar, the combined ratio is different because, for each species, the production ratio between coalescence and fragmentation is smaller at LHC than at RHIC as can be seen from the spectra in Fig.1. Therefore, at LHC the larger contribution in particle production from fragmentation [22] leads to a final ratio that is smaller than at RHIC. As a consequence a baryon over meson ratio that is so large at low momenta, can lead also to a smaller $D^0 R_{AA}$ in this region. It is motivated by the charm quark number conservation and the dominance of D mesons in the total particle production in pp collisions.

Recently new experimental data of the Λ_c^+ to D^0 ratio have been released for pp collisions at LHC [28, 29, 30], and show an unexpected excess of production of Λ_c respect to the simple fragmentation, with values of the ratio of ~ 0.6 in the region at low momenta below 2 GeV, and a value of ~ 0.2 at 10 GeV. Assuming the formation of a QGP system also in this extremely small system we have applied our model in the case of pp collisions, assuming the formation of a medium like the one simulated in hydrodynamics calculations [31]. In Fig.3 is shown with the red dashed line the Λ_c^+/D^0 ratio obtained for this kind of system. Our calculations predict the disappearance of the peak, but an enhancement at low momenta that is significantly different from the ratio obtained with the only fragmentation. Also other possible scenarios have been studied from other groups [32] for this subject. Moreover, the presence of a coalescence mechanism can have a deep impact on the pp baseline used to evaluate theoretically the R_{AA} and R_{pA} for the different species, in particular, in the case of Λ_c , the presence of coalescence implies a different behavior especially at low momenta. Recently released data from ALICE for the Λ_c nuclear modification factor [30] can lead to a better understanding of the surprising heavy hadrons production in both small system created in pp collisions and the one created in heavy ion collision.

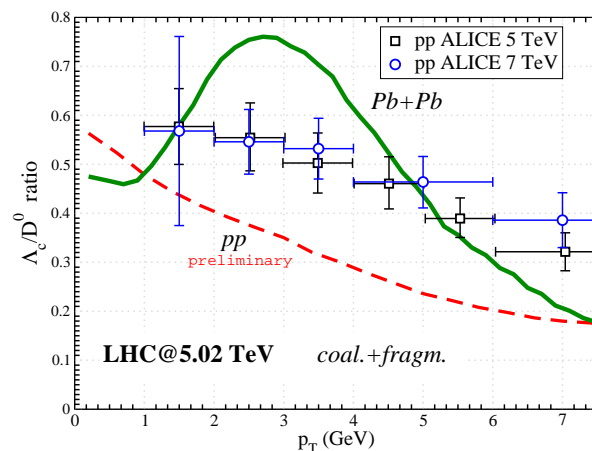


Figure 3. (Color online) Λ_c^+ to D^0 ratio as a function of p_T and at mid-rapidity for $Pb + Pb$ and pp collisions at $\sqrt{s} = 5.02$ TeV with a coalescence plus fragmentation model, experimental data for pp at collisions $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 7$ TeV [29, 30]

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