

## Heavy flavour hadronization in ultra-relativistic heavy ion collisions: from AA to pp

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**Summary.** — The  $\Lambda_c/D^0$  ratio observed in AA collisions at RHIC and LHC energies have a value of the order of the unity. On the other hand, the recent experimental measurements in pp collisions at both  $\sqrt{s} = 5.02 \text{ TeV}$  and  $\sqrt{s} = 13 \text{ TeV}$  have shown ratios for charm baryons/mesons  $\Lambda_c/D^0$  and  $\Xi_c/D^0$  larger than that measured and expected in elementary collisions  $e^+e^-$  collisions. We present an hadronization mechanism based on the coalescence and fragmentation processes and we show that this model gives a consistent description of several observables involving heavy-flavour hadrons from AA collision to pp collisions. The results obtained within this approach suggest that a description of charmed hadron production in pp collisions require the assumption of the formation of an hot QCD matter at finite temperature. Finally, extending this approach to study the production of hadrons containing multiple charm quarks,  $\Xi_{cc}$ ,  $\Omega_{cc}$  and  $\Omega_{ccc}$  we provides the predictions of multi-charmed hadrons in different collision systems like  $Pb+Pb$ ,  $Kr+Kr$ ,  $Ar+Ar$  and  $O+O$ .

### 1. – Introduction

The main goal of the ongoing heavy-ion collisions program at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) is the characterization of the state of matter created in these collisions, named Quark-Gluon Plasma (QGP). Many probes have been proposed to achieve this scope and among them the heavy quark hadron production have been considered one of the most useful probes to characterize the QGP [1, 2, 3]. The large mass of Heavy Quarks (HQs) imply that they are produced by pQCD processes with a formation time  $\tau_0 < 0.08 fm/c \ll \tau_{QGP}$  that permits to probe initial stage of the

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collision [4, 5, 6]. On the other hand, this large mass implies a larger thermalization time compared to the lifetime of the fireball produced, therefore HQs can probe the whole evolution of the plasma and conserve memory of the history of the system evolution to the final hadrons [7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. The study of Heavy Flavour (HF) production can provides information about heavy-flavor transport coefficients in the QGP and at the same time can gives information about the hadronization mechanism. In recent years, the experimental data on charmed hadrons have shown an enhancement of the charmed baryon/meson ratio similar to the one observed for light and strange hadrons, and larger than the one expected in collision systems as  $e^+e^-$ ,  $e^\pm p$  [17]. The recent experimental observation seems to indicate that in smaller collision systems like proton-proton and proton-nucleus collisions the heavy flavour production is strongly consistent with the formation of an Hot QCD matter [18, 19]. From theoretical point of view, recently this analysis has been extended to bottom hadrons in pp collisions [20] and to multi-charmed hadrons [21, 22] in different collisions systems.

## 2. – Hadronization by coalescence and fragmentation

The coalescence model is one of the possible microscopic description for the hadronization process in QGP. This model was able to explain the baryon to meson spectra and the splitting of elliptic flow of light and heavy mesons and baryons produced in heavy ion collisions at top RHIC and LHC energies [23, 24] predicting recently a large  $\Lambda_c/D^0 \sim 0.5 - 1$  in AA collisions [25, 26]. In this section we recall the basic elements of the coalescence model. The momentum spectrum of hadrons composed by  $N_q$  quarks can be written as:

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

where  $g_H$  is the statistical factor to form a colorless hadron from quarks and anti-quarks. The  $d\sigma_i$  denotes an element of a space-like hypersurface while  $f_{q_i}$  are the quark (anti-quark) phase-space distribution functions for i-th quark (anti-quark) and  $f_H(x_1 \dots x_{N_q}, p_1 \dots p_{N_q})$  is the Wigner function which describes the spatial and momentum distribution of quarks in a hadron. For  $N_q = 2$  the above formula describes meson formation, while for  $N_q = 3$  the baryon one. The Wigner function adopted has a Gaussian shape in space and momentum,  $f_H(\dots) = \prod_{i=1}^{N_q-1} A_W \exp\left(-\frac{x_{ri}^2}{\sigma_{ri}^2} - p_{ri}^2 \sigma_{ri}^2\right)$  where  $x_{ri}$  and  $p_{ri}$  are the 4-vectors for the relative coordinates and  $A_W$  is a normalization constant fixed to guarantee that in the limit  $p \rightarrow 0$  all the charm quarks hadronize by coalescence. The widths  $\sigma_{ri}$  of  $f_H(\dots)$  are related to the size of the hadron by the root mean square charge radius of the meson, for details see Ref.s [26, 18]. In our approach a charm quark with  $p_T \neq 0$  can hadronize in two ways or by coalescence or by fragmentation. Using the hadronization probability  $P_{coal}(p_T)$  to hadronize by coalescence one can associate a finite probability to hadronize by fragmentation according to the probability  $P_{frag}(p_T) = 1 - P_{coal}(p_T)$ . Finally, the hadron momentum spectra from fragmentation is given by  $\frac{dN_{had}}{d^2p_T dy} = \sum \int dz \frac{dN_{frag}}{d^2p_T dy} \frac{D_{had/c}(z, Q^2)}{z^2}$  where  $D_{had/c}(z, Q^2)$  is the fragmentation function and  $z = p_{had}/p_c$  is the momentum fraction of heavy quarks transferred to the final heavy hadron. In the calculations shown the Peterson fragmentation function is used [27].

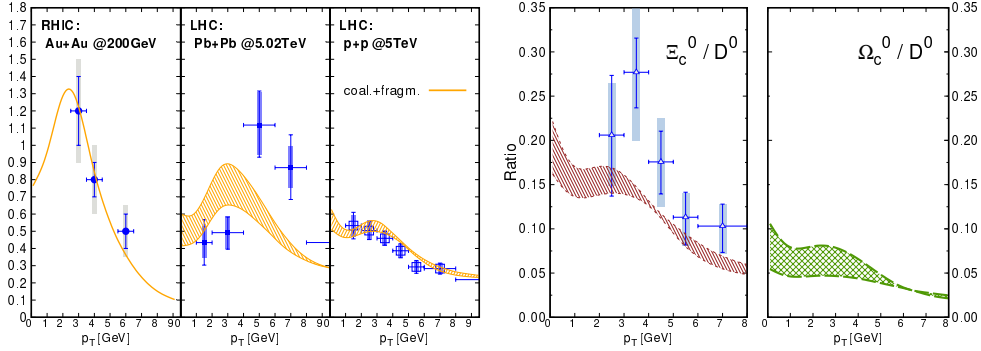


Fig. 1. – Left:  $\Lambda_c/D^0$  ratio as a function of the transverse momentum at mid-rapidity for  $Au+Au$  at  $\sqrt{s} = 200 \text{ GeV}$  [32] (left panel), for  $Pb+Pb$  at  $\sqrt{s} = 5.02 \text{ TeV}$  [33] (middle panel) and  $p+p$  at  $\sqrt{s} = 5 \text{ TeV}$  [28] (right panel). Right:  $\Omega_c/D^0$  and  $\Xi_c/D^0$  ratios as a function of the transverse momentum at mid-rapidity for  $p+p$  at  $\sqrt{s} = 5 \text{ TeV}$ . Data taken from Ref. [34]. The upper and lower limit of the bands correspond to the maximum and minimum value of the baryon/meson ratio obtained increasing and decreasing the Wigner function widths by 20%.

### 3. – Charmed hadrons from AA to pp collisions

As shown in [26] at RHIC energies the coalescence plus fragmentation approach predict for  $D$  meson with  $p_T < 3 - 4 \text{ GeV}$  a similar contribution from coalescence and fragmentation. The model predicts a different behaviour at LHC energies where fragmentation play a dominant role to the  $D$  meson production because of the large number of minijet at higher collision energies. At higher  $p_T$ , the  $D$  meson production is dominated by fragmentation mechanism at both energies. This different behaviour between coalescence and fragmentation produces a baryon enhancement that correspond to an enhancement of the  $\Lambda_c$  production for  $p_T < 3 - 4 \text{ GeV}$  at both RHIC and LHC energies. Therefore, in AA collisions this model predicts a rise and fall of the baryon/meson ratio. In the left and middle panel of Fig.1 it is shown the comparison between RHIC and LHC for the  $\Lambda_c/D^0$  ratio. We observe a reduction of the baryon/meson ratio between RHIC and LHC energies. This behaviour is mainly due to the larger number of minijets at LHC respect to RHIC where  $\Lambda_c$  baryons get a larger contribution from fragmentation leading to a smaller  $\Lambda_c/D^0$  ratio compared to the one at RHIC. On the other hand, as shown in the right panel of Fig.1, coalescence plus fragmentation approach predict in a natural way a system size dependence of the charmed baryon/meson ratio which is consistent with the recent experimental data available for pp collisions at LHC energies [28]. The calculations for pp collisions assume the formation of a QGP medium like the one simulated in hydrodynamics and transport calculations [29, 30]. In pp collisions the results of coalescence plus fragmentation model are similar to the Statistical Hadronization Model (SHM) ones, within the uncertainties, in the case of  $D^0, D^+, D^*$  and  $\Lambda_c$  but exhibit a significant difference for  $\Xi_c$  and  $\Omega_c$  considering statistical models with the same number of resonances [18, 31].

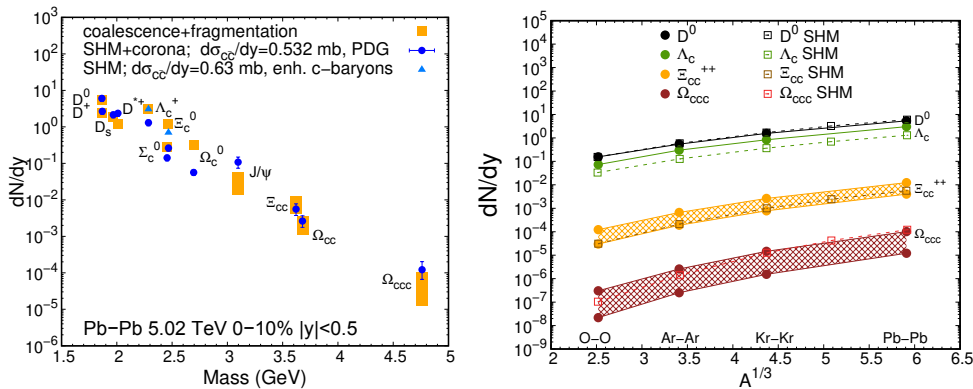


Fig. 2. – Left pane: Charmed hadrons yields in PbPb collision at 5.02TeV. Coalescence plus fragmentation results shown by orange band while SHM results shown by blue open circles [21]. The band corresponds to the yields obtained with realistic distribution for the lower limit and the one obtained with thermal distribution for the upper limit. Right panel:  $dN/dy$  at mid-rapidity of single and multi-charmed hadrons as a function of the size of the systems. Different colors are for different species. Open symbols are for SHM calculation and full symbols are results obtained within coalescence plus fragmentation.

#### 4. – Multi-charmed hadrons and systems size scan

In the left panel of Fig.2 are shown the yields for single and multi-charmed hadrons in  $PbPb$  collisions for 0 – 10% centrality at mid-rapidity within coalescence plus fragmentation compared with the results for SHM considering an enhanced set of charmed baryons with respect to the ones listed by the PDG, as suggested in [35, 31, 21]. The orange band in the plot, corresponds to the yields obtained with realistic distribution for the lower limit and the one obtained with thermal distribution for the upper limit. For multi-charmed baryons  $\Xi_{cc}$ ,  $\Omega_{cc}$  and  $\Omega_{ccc}$  the coalescence plus fragmentation approach shows a large sensitivity to the underlying charm distribution function. In fact, assuming a thermalized charm distribution the model predicts an enhancement of the yields w.r.t. the realistic distribution as shown by the upper and lower limit in the band. This behaviour is due to the fact that in a thermal distribution there is a larger number of charms in a small momentum region making easier the recombination mechanism respect to a more realistic distribution. This property produces an enhancement in the final total yields, and therefore the yields of  $\Xi_{cc}$ ,  $\Omega_{cc}$  and  $\Omega_{ccc}$  result more sensitive to the charm distribution function with respect to the single-charmed hadrons because of their quark content. In the right panel of Fig.2 it is shown the single and multi-charmed hadrons production in different collision systems like  $Pb + Pb$ ,  $Kr + Kr$ ,  $Ar + Ar$  and  $O + O$  collision systems. For these systems the initial  $p_T$  distribution used is the one from FONLL calculations that evolves in a QGP medium described by a relativistic Boltzmann approach, for details of the calculation see Ref.[22]. From large to small collision systems the lifetime of the fireball decreases and consequently also the time that a charm quark spent in the QGP. Therefore, in smaller collision systems, the final transverse momentum spectrum of charm quarks are flatter than the one for example in  $Pb + Pb$  collisions, see Ref.[22]. In the right panel of Fig.2 is shown the  $dN/dy$  obtained by coalescence plus fragmentation for each species (different bands), as a function of the size of the system

$A^{1/3}$  in comparison with SHM results (open symbols). The upper limit of the band corresponds to a fully thermalized charm distribution while the lower limit is the result obtained using the charm distribution as obtained by solving the Boltzmann transport approach. The comparison with SHM shows that the  $dN/dy$ , have a similar but still different scaling with the decrease of the system size.

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