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Theoretical overview of heavy-flavor hadronization

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Experimental observations on the heavy hadron production has shown baryon over meson ratios that were unexpected both in AA and pp collisions. In AA collision the Λ_c/D^0 ratio has a value close to one, and in pp collision the ratio between charm baryons Λ_c, Ξ_c^0 and Ω_c^0 respect to D^0 meson is larger than the one measured in e^+e^-, ep collisions. The assumption of the simple fragmentation as hadronization process in these collisions is not sufficient to describe these evidences. We will show a brief recap of some theoretical efforts that has been made to catch the features of this collision stage.

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1. Introduction

Experiments at Large Hadron Collider (LHC) and at Relativistic Heavy-Ion Collider (RHIC) that have studied Ultra-relativistic heavy ion collision have shown indication of a new state of matter composed of deconfined quark and gluons that interact via the strong force, called Quark-Gluon Plasma (QGP).Charm and bottom quarks are used as probes that experience all the QGP evolution, because of their large mass and their early formation time. A lot of works have studied the effects of the interaction between the heavy quarks and the bulk particles [1–10]. In both heavy-ion and proton-proton collision the experimental data have shown baryon/meson ratio in the heavy flavor sector similar to the one observed for light and strange hadrons, that deviates significantly from the one observed in elementary collisions like e^+e^-, $e^\pm p$. [11]. These results represent, at the moment, a challenge for the heavy-quark hadronization theoretical understanding. In fact, at the energy of $\sqrt{s} = 5TeV$ and $13TeV$ at LHC, in the low p_T region, the Λ_c/D^0 ratio has been measured with a value of about 0.5 . Furthermore the ratio of other charmed baryons such as Ξ_c and Ω_c with the D^0 have been measured by ALICE collaboration showing an unexpected behavior in pp collision [12].

1.1 Heavy quark theoretical models

In the following are described some of the models that describe the evolution and hadronization of heavy quarks in the QGP: In [13] is presented a recombination model based on 4-momentum conservation that takes into account the space-momentum correlations between HQ and a bulk which follows an hydrodynamic expansion to describe AA collisions. The effect found with the presence of correlations is the enhancement of the production via recombination, especially in the region near the surface of the QGP fireball. In this model the states considered for the baryon consists in an enlarged set w.r.t. the Particle Data Group, justified by Quark model prediction, and from results able to reproduce the Λ_c/D^0 ratio in pp collision with a SHM from the same authors[14]. In [3] the evolution of HQ is performed using a Langevin equation that includes both quasi-elastic scattering and the gluon radiation induced by the medium presence. The bulk properties come from hydrodynamic simulations. The hadronization via recombination plus fragmentation is followed by an ultrarelativistic quantum molecular dynamics hadron cascade in order to take into account the hadron interactions. This model has underlined the relevance of both radiative and collisional energy loss, shadowing, hybrid hadronization and hadronic rescattering to get a good description of R_{AA} and v_2. In [15] has been evaluated the effect that comes from the inclusion of s and p-wave hadronic states, the influence of radial flow and momentum distribution change from RHIC energies to LHC ones. Suggesting also a change of the charmed hadrons size in the medium. An hadronization based on the formation of color-singlet clusters has been performed in [16]. The heavy quark recombination happens in presence of a reservoir of light particle, with a local color neutralization inside QGP fluid cells. Baryons formation takes into account the presence of di-quarks as effective degrees of freedom when the temperature approaches the QCD crossover. The presence of di-quarks leads to a production enhancement for baryons in agreement with recent measurements. The color neutralization leads to a space momentum correlation that affects the final hadron flow and momentum distribution. Finally, heavy hadrons have been incorporated in Statistical Hadronization Models [17] that give good description of light hadrons yields. Charm quark are assumed thermalized, i.e. with thermal distribution, and their number is fixed by the experimentally measured open charm cross section. In this framework also hadron transverse momentum distributions are computed with blast-wave modelling and the inclusion of resonance decay and relative kinematics.

2. Catania coalescence plus Fragmentation hadronization model

We study the heavy hadrons production using for the hadronization process a coalescence plus fragmentation model, that has been able to reproduce the enhancement of the baryon over meson ratio [18–24]. The hadron production can be evaluated solving the coalescence integral which is based on the Wigner formalism, described by the following formula:

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

where $d\sigma_i$ is 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 is the Wigner function and describes the distribution of quarks, in space and momentum, within an hadron; in our case we use a Gaussian distribution in relative space and momentum. We can assume that the hadrons can be treated as harmonic oscillator and their Wigner function width σ_r can be related to the frequency ω by $\sigma = 1/\sqrt{\mu\omega}$ where $\mu = (m_1 m_2)/(m_1 + m_2)$ 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 $\sigma_p = 0.283$ GeV; for Λ_c^+ the mean square charge radius is $\langle r^2 \rangle_{ch} = 0.15\, fm^2$ with the related widths $\sigma_{p_1} = 0.251$ GeV and $\sigma_{p_2} = 0.424$ GeV. We evaluate, via the coalescence integral, the probability for a charm at a given momentum to recombine, then we assign a fragmentation probability as $P_{frag}(p_T) = 1 - P_{coal}(p_T)$. We normalize the Wigner function in order to have, in the limit $p \to 0$, that all the charm quarks hadronize via coalescence, because in the zero momentum limit a charm cannot fragment into an hadron that has a lower momentum. The final hadron fragmentation momentum spectra, is evaluated taking into account the fragmentation function, in this case we use the Peterson fragmentation function parametrized as $D_{had}(z, Q^2) \propto 1/\left[z\left[1 - \frac{1}{z} - \frac{\epsilon_c}{1-z}\right]^2\right]$ [25]. The relative quantity of hadrons formed from charm quarks fragmentation is determined by the fragmentation fractions evaluated in elementary collision [11]. The bulk is modeled as a fireball consisting of gluons and u, d, s quarks and anti-quarks thermalized at a temperature of $T_C = 165$ MeV. The proper time at which the fireball hadronization has been considered is $\tau = 8.\, fm/c$ for LHC in 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. As estimated in hydrodinamic simulations [26], we use for LHC pp collisions at $\sqrt{s_{NN}} = 5.02\, TeV$ a fireball lifetime parameter that is $\tau = 2.5$ 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. Light partons at low transverse momentum, $p_T < 2$ GeV are considered as a thermal distribution, instead for $p_T > 2.5$ GeV, we consider minijets distribution that have been quenched trhough the medium. The distributions for heavy quarks in heavy ion collisions are obtained by solving the relativistic Boltzmann equation [4] that can reproduce satisfactorily the R_{AA} and v_2 for D mesons. In $p + p$ collisions, the charm quark spectrum have been taken according to Fixed Order + Next-to-Leading Log (FONLL) distribution [27]

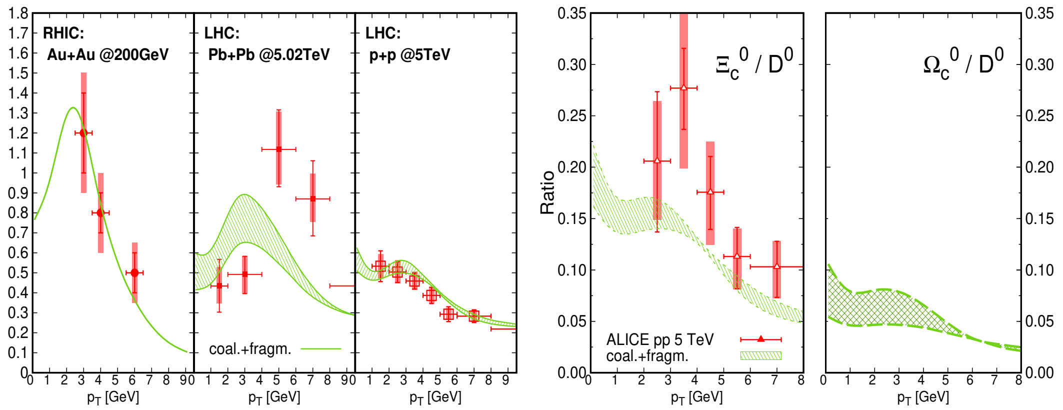

Figure 1: (Left Figure)Λ_c^+ to D^0 ratio as a function of p_T and at mid-rapidity for (left panel) $Au + Au$ collisions at $\sqrt{s} = 200$ GeV [28] for (middle panel) $Pb + Pb$ collisions at $\sqrt{s} = 5.02$ TeV [30] and for (right panel) pp collisions at $\sqrt{s} = 5.02$ TeV [31].
(Right Figure) Ratios at mid-rapidity in pp collisions at $\sqrt{s} = 5.02$ TeV for $\Xi_c^{0,+}/D^0$ (left) and Ω_c/D^0 (right) data from [12]

3. Results

The left and middle panel in Fig.1(Left Figure) the comparison between RHIC and LHC for the Λ_c^+/D^0 ratio is shown. We can see that the ratio becomes smaller with the increase in energy and going from AA to pp collision, this can be explained with the fact that flatter the charm quark distribution smaller the production ratio between coalescence and fragmentation. So the final ratio is a weighted average between the coalescence ratio and the fragmentation ratio that is about 0.1 [22]. We have evalated this ratio also in pp collisions at mid-rapidity at $\sqrt{s} = 5.02\,TeV$, assuming the formation of a QGP medium; comparing our results with experimental data coming from pp collisions at LHC [31]. Both experimental data and our results 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. In Fig.1[Right Figure], 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 Ξ_c/D^0 ratio in comparison with recent data from ALICE collaboration [12], where we have included the contribution from the main existing Ξ_c resonance states. In the right panel we show the Ω_c^0/D^0 ratio having considered the contribution that comes from both coalescence and fragmentation. In both cases we obtain a ratio that is enhanced by the presence of the recombination process. The bands in all these ratios come from the uncertainty of the Wigner function widths, in particular we have considered variations of 20% for the particles radius involved in the ratio, and alternatively shrinking and enlarging it we have obtained the maximum and minimum values plotted in these figures.

References

[1] He M, Fries R J and Rapp R 2013 *Phys. Rev. Lett.* **110** 112301

[2] Uphoff J, Fochler O, Xu Z and Greiner C 2012 *Phys. Lett.* **B717** 430–435

[3] Cao S, Qin G Y and Bass S A 2015 *Phys. Rev.* **C92** 024907

[4] Scardina F, Das S K, Minissale V, Plumari S and Greco V 2017 *Phys. Rev.* **C96** 044905

[5] S. K. Das, M. Ruggieri, F. Scardina, S. Plumari and V. Greco, J. Phys. G **44** (2017) no.9, 095102

[6] Das S K, Plumari S, Chatterjee S, Alam J, Scardina F and Greco V 2017 *Phys. Lett.* **B768** 260–264

[7] Das S K, Scardina F, Plumari S and Greco V 2015 *Phys. Lett.* **B747** 260–264

[8] Das S K, Torres-Rincon J M, Tolos L, Minissale V, Scardina F and Greco V 2016 *Phys. Rev.* **D94** 114039

[9] S. Plumari, G. Coci, V. Minissale, S. K. Das, Y. Sun and V. Greco, Phys. Lett. B **805** (2020), 135460

[10] M. L. Sambataro, Y. Sun, V. Minissale, S. Plumari and V. Greco, Eur. Phys. J. C **82** (2022) no.9, 833

[11] Lisovyi M, Verbytskyi A and Zenaiev O 2016 *Eur. Phys. J.* **C76** 397

[12] S. Acharya *et al.* [ALICE], JHEP **10** (2021), 159

[13] M. He and R. Rapp, Phys. Rev. Lett. **124** (2020) no.4, 042301

[14] He M and Rapp R 2019 *Phys. Lett.* **B795** 117–121

[15] S. Cao, K. J. Sun, S. Q. Li, S. Y. F. Liu, W. J. Xing, G. Y. Qin and C. M. Ko, Phys. Lett. B **807** (2020), 135561

[16] A. Beraudo, A. De Pace, M. Monteno, M. Nardi and F. Prino, Eur. Phys. J. C **82** (2022) no.7, 607

[17] A. Andronic, P. Braun-Munzinger, M. K. Köhler, A. Mazeliauskas, K. Redlich, J. Stachel and V. Vislavicius, JHEP **07** (2021), 035

[18] Fries R J, Muller B, Nonaka C and Bass S A 2003 *Phys. Rev. Lett.* **90** 202303

[19] Greco V, Ko C and Levai P 2003 *Phys.Rev.* **C68** 034904

[20] Minissale V, Scardina F and Greco V 2015 *Phys. Rev.* **C92** 054904

[21] Oh Y, Ko C M, Lee S H and Yasui S 2009 *Phys. Rev.* **C79** 044905

[22] Plumari S, Minissale V, Das S K, Coci G and Greco V 2018 *Eur. Phys. J.* **C78** 348

[23] S. Cho, K. J. Sun, C. M. Ko, S. H. Lee and Y. Oh, Phys. Rev. C **101** (2020) no.2, 024909

[24] V. Minissale, S. Plumari and V. Greco, Phys. Lett. B **821** (2021), 136622

[25] Peterson C, Schlatter D, Schmitt I and Zerwas P M 1983 *Phys. Rev.* **D27** 105

[26] R. D. Weller and P. Romatschke, Phys. Lett. B **774** (2017), 351-356

[27] M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason and G. Ridolfi, JHEP **10** (2012), 137

[28] J. Adam *et al.* [STAR], Phys. Rev. Lett. **124** (2020) no.17, 172301

[29] S. Acharya *et al.* [ALICE], Phys. Lett. B **793** (2019), 212-223

[30] S. Acharya *et al.* [ALICE], Phys. Lett. B **839** (2023), 137796

[31] S. Acharya *et al.* [ALICE], Phys. Rev. C **104** (2021) no.5, 054905