Heavy hadrons production by coalescence in pp and AA collisions at RHIC and LHC

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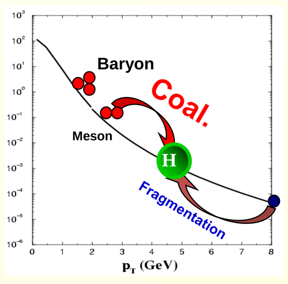
We study with a coalescence model the p_T spectra of charmed hadrons D^0, Λ_c and the respective baryon to meson ratio at RHIC and LHC in a range of transverse momentum up to 10 GeV, including both the contribution from decays of heavy hadron resonances and the fragmentation of heavy quarks do not undergo the coalescence process. The p_T dependence of the heavy baryon/meson ratios is found to be sensitive to the masses of quarks, (in particular we found that the Λ_c/D^0 can reach values of about 1-1.5 at $p_T \sim 3\ GeV$) with a quite weak dependence in transverse momentum respect to light hadrons. We also make comparisons with others coalescence models and with predictions from thermal models. In the same framework we finally evaluate the baryon to meson ratios in pp collisions assuming, as suggested in recent works, that at the present LHC energies there can be the formation of QGP matter also in this type of collisions. Applying our model we find a considerable decrease for the peak value and a slightly different behaviour in the p_T dependence.

COALESCENCE INTEGRAL



Statistical factor colour-spin-isospin

Parton Distribution function

Hadron Wigner function

$$\frac{dN_{Hadron}}{d^2p_T dy} = g_H \int \prod_{i=1}^{n} p_i \cdot d\sigma_i \frac{d^3p_i}{(2\pi)^3 E_i} f_{q_i}(x_i, p_i) f_W(x_1, \ldots, x_n; p_1, \ldots, p_n)\, \delta\left(p_T - \sum_i p_{iT}\right)$$

charm distribution function from parton simulations solving Boltzmann transport equation (R_{AA} and v_2 see below).

i=2 → mesons ; i=3 → baryons

Fireball Parameters

Constraints from Experiment

RHIC → LHC

$dE_T/dy \sim$ 740 GeV → 2100 GeV

$dN_{ch}/dy \approx$ 670 → 1600

$T_c \sim$ 165 MeV

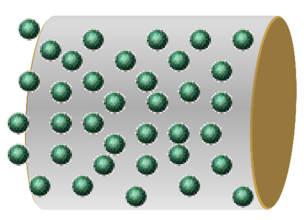
Lifetime and Volume implied

τ ~ 4.5 fm/c → 7.8 fm/c

β_0 = 0.37 → 0.63

V ~ 1100 fm³ → 2500 fm³

In agreement with HBT



LIGHT QUARK

- Thermal Distribution (p_T< 2 GeV)

$$\frac{dN_q}{d^2r_T d^2p_T} = \frac{g_q \tau m_T}{(2\pi)^3} \exp\left(-\frac{\gamma_T(m_T - p_T \cdot \beta_T)}{T}\right)$$

Collective flow $\beta_T = \beta_0 \frac{r}{R}$

- Minijet Distribution (p_T> 2 GeV)

HEAVY QUARK (initial state)

Fixed-Order plus Next-to-Leading-Log (FONLL)

M. Cacciari, P. Nason, R. Vogt, PRL 95 (2005) 122001

$$f_M(x_1, x_2; x_1, p_2) = A_W \exp\left(-\frac{x_{r1}^2}{\sigma_r^2} - p_{r1}^2\sigma_r^2\right)$$

A_W is a normalization constant fixed to guarantee that in the limit $p_T \to 0$ we have all the charm hadronizing. While σ_r is the covariant width parameter, 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 linked to the size of the hadron and in particular to the root mean square charge radius of the meson by:

$$\langle r^2 \rangle_{ch} = \frac{3}{2}\frac{Q_1 m_2^2 + Q_2 m_1^2}{(m_1 + m_2)^2}\sigma_r^2$$

$\langle r^2\rangle_{ch}^{D^0} = 0.184\ fm^2$

$\sigma_p^{D^0} = \sigma_r^{-1\,D^0} = 0.283$ GeV

$\langle r^2\rangle_{ch}^{\Lambda_c} = 0.15\ fm^2$

$\sigma_{p1}^{\Lambda_c} = 0.18$ GeV

$\sigma_{p2}^{\Lambda_c} = 0.342$ GeV

Introduction

The bulk properties of the matter created in the Quark Gluon Plasma are governed by the light quarks and gluons while heavy quarks like charm or bottom quarks are useful probes of the QGP properties. In their final state the charm quarks appear as constituent of charmed hadrons mainly D mesons and Λ_c, Σ_c baryons. The experimental advances in the study not only of heavy mesons like D mesons but also of Λ_c baryons are important in order to have a new insight in understanding the hadronization mechanism in the QGP. Recent experimental results from STAR collaboration have shown a $\Lambda_c/D^0 \simeq 1.3 \pm 0.5$ for $3<p_T<6$GeV which is a very large enhancement compared to the value predicted by the charm hadron fragmentation ratio or by the PYTHIA for p+p collisions. The idea of the coalescence model comes from the fact that comoving partons in the quark-gluon plasma combine their transverse momentum to produce a final state meson or baryon with higher transverse momentum. In the heavy quark sector, coalescence leads to a modification of the relative abundance of the different heavy hadron species produced. In particular this can manifest in a baryon-to-meson enhancement for charmed hadrons.

Heavy Hadron spectrum

In our calculations we take into account main hadronic channels, including the ground states and the first excited states for D and Λ_c

MESONS

- D^+ (I=1/2,J=0)
- D^0 (I=1/2,J=0)
- D_s^+ (I=0,J=0)

Resonances

- D^{*+} (I=1/2,J=1) → $D^0\pi^+$ B.R. 68%
  → $D^+ X$ B.R. 32%
- D^{*0} (I=1/2,J=1) → $D^0\pi^0$ B.R. 62%
  → $D^0\gamma$ B.R. 38%
- D_s^{*+} (I=0,J=1) → $D_s^+ X$ B.R. 100%
- D_{s0}^{*+} (I=0,J=0) → $D_s^+ X$ B.R. 100%

Statistical factor

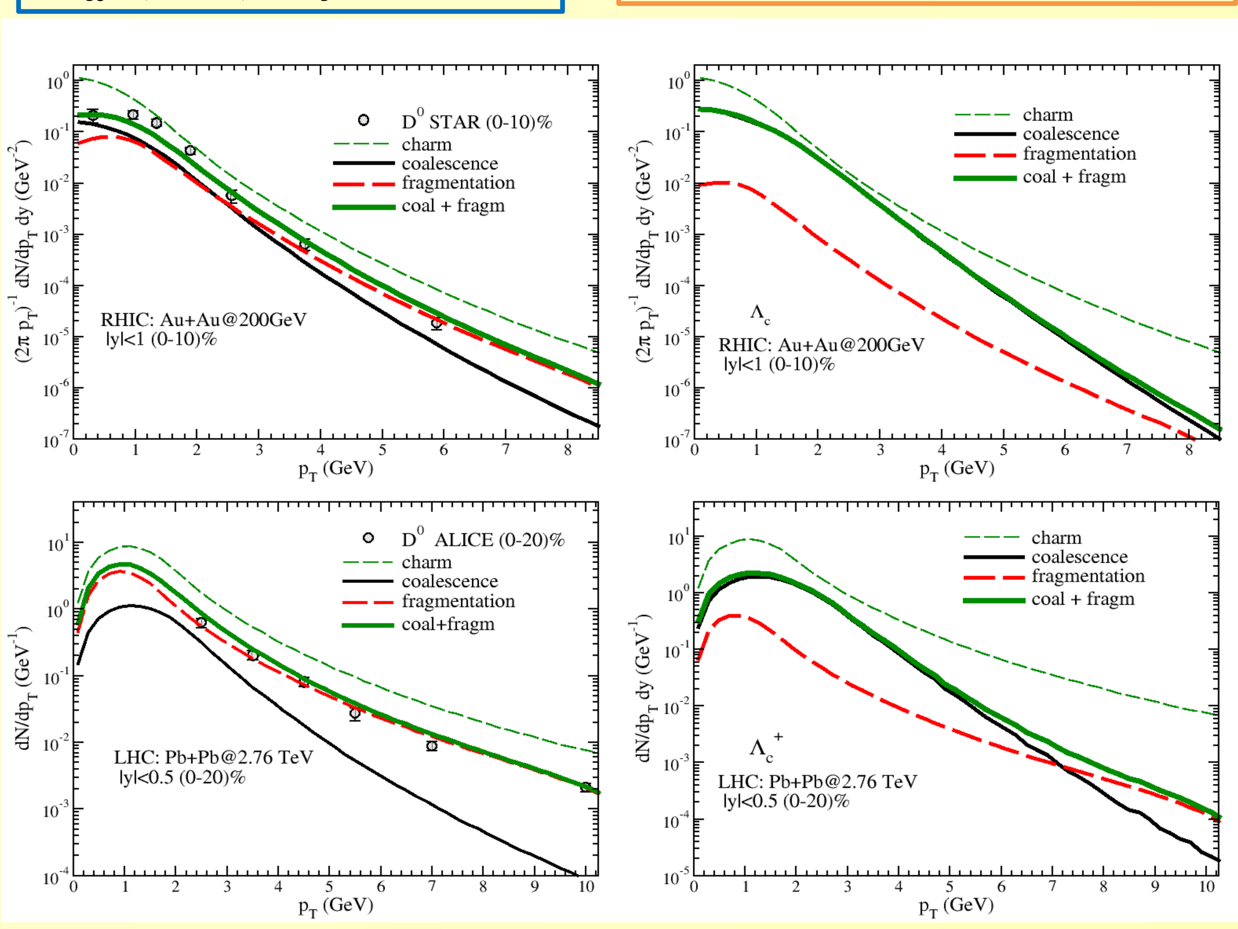
$$\frac{[(2J+1)(2I+1)]_{H^*}}{[(2J+1)(2I+1)]_H}\left(\frac{m_{H^*}}{m_H}\right)^{3/2} e^{-(E_{H^*}-E_H)/T}$$

BARYONS

- Λ_c^+ (I=0, J=1/2)

Resonances

- Λ_c^+(2595) (I=0,J=1/2) → Λ_c^+ B.R. 100%
- Λ_c^+(2625) (I=0,J=3/2) → Λ_c^+ B.R. 100%
- Σ_c^+(2455) (I=1,J=1/2) → $\Lambda_c^+\pi$ B.R. 100%
- Σ_c^+(2520) (I=1,J=3/2) → $\Lambda_c^+\pi$ B.R. 100%



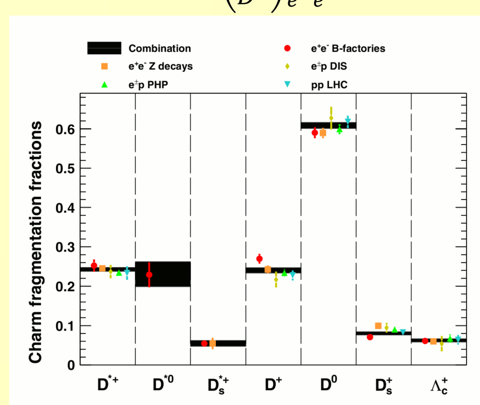
At RHIC coalescence and fragmentation for D^0 are comparable, at LHC the fragmentation becomes dominant. The same trend also for Λ_c, but the fragmentation fraction of charm into Λ_c is so small that coalescence is the dominant mechanism of hadronization.

References

1. S. Plumari, V. Minissale, S. K. Das, G. Coci, V. Greco, Eur.Phys.J. C78 (2018) no.4, 348
2. Y. Oh, C.M. Ko, S.H. Lee, S. Yasui, Phys. Rev. C79,044905 (2009)
3. F. Scardina, S.K. Das, V. Minissale, S. Plumari, V. Greco, Phys.Rev. C96 (2017) no.4, 044905

Heavy Baryon to Meson Ratios

<u>Fragmentation fraction</u> for charm quarks into hadrons → $\left(\frac{\Lambda_c^+}{D^0}\right)_{e^+e^-} \simeq 0.1$



M. Lisovyi, et al. EPJ C76 (2016) no.7, 397

We use the Peterson fragmentation function

C. Peterson, D. Schalatter, I. Schmitt, P.M. Zerwas **PRD 27 (1983) 105**

$$D_{f\to h}(z) \propto \frac{1}{z\left[1 - \frac{1}{z} - \frac{\epsilon}{1-z}\right]^2}$$

The parameter ε for D meson hadronization fixed by pp collisions data. For baryons we fix it in accordance with e⁺+e⁻ collisions as done in *<u>S.K. Das et al, PRD94 (2016) no.11, 114039.</u>*

Measurement in $e^\pm p$, pp and e^+e^- are in agreement within uncertainties: fragmentation at most independent of the specific production process

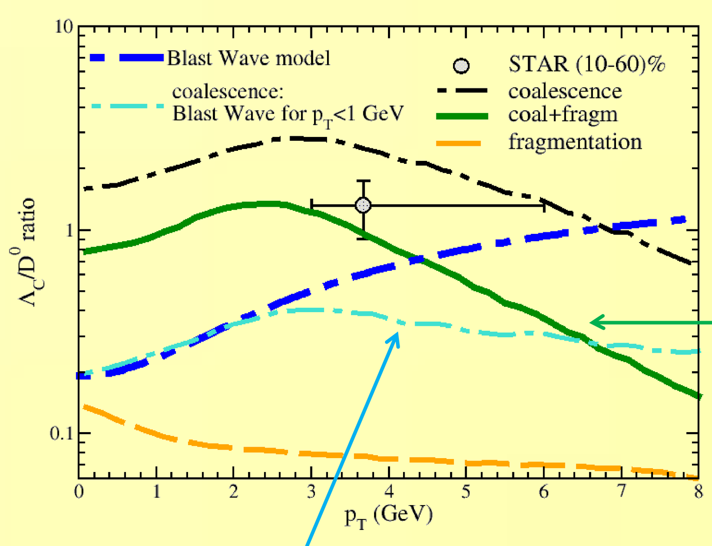
Ratio from an **<u>approximate analytical evaluation of coalescence integral</u>** (S. Plumari, V. Minissale, et al., **Eur.Phys.J. C78 (2018) no.4, 348**) :

$$\left.\frac{N_B}{N_M}\right|_{p_T\cong 0} \cong \frac{g_B}{g_M}\left(\frac{M_B}{M_M}\right) e^{-(M_B-M_M)/T} A_W \rho_q \sigma_{r2}^2\, \xi_{r2}^2\, \frac{\mu_2}{m_q}$$

Therefore, the Baryon-to-meson ratio shows a first term similar to the one of the thermal model and a second term that take into account for microscopic details of the hadronization mechanism that depends on the reduced mass μ_2. This means that the baryon-to-meson ratio increase with the increasing of the reduced mass of the baryon μ_2. In other words at low momenta coalescence predict a mass ordering for the baryon-to-meson ratio.

Comparison with thermal model

•Compared to light baryon/meson ratio the Λ_c/D^0 ratio has a larger width (flatter)



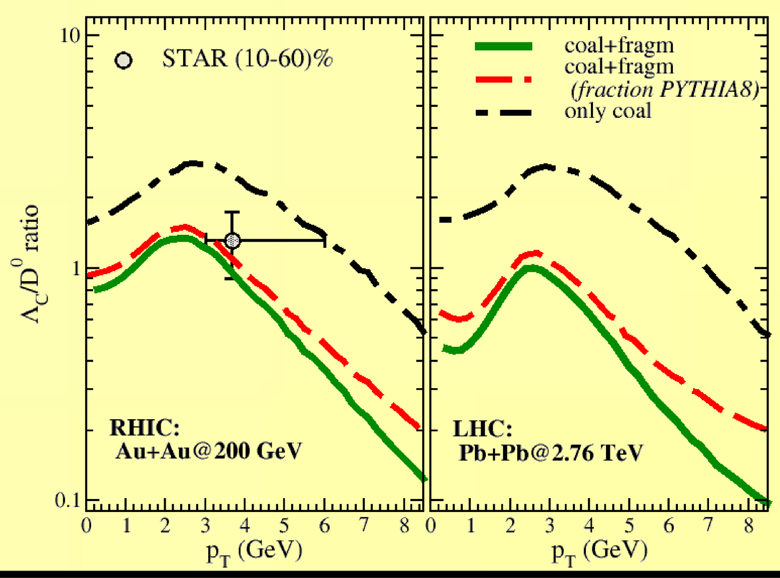
Coal with wave function width σ_p of D^0 and Λ_c changed to have Λ_c/D^0=thermal ratio at $p_T \to 0$

Evolution from RHIC to LHC

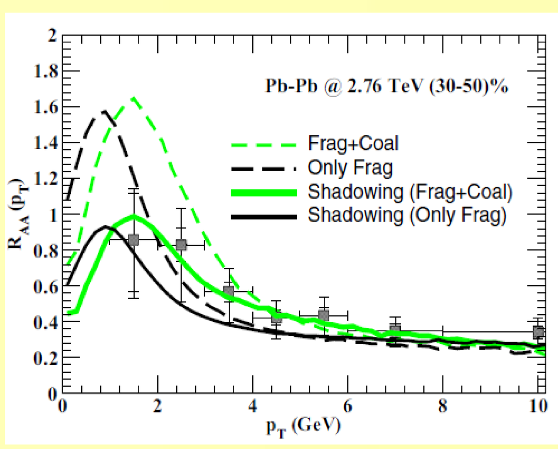
Coalescence predict similar baryon/meson ratio of about 1 for both energies. Fragmentation is established from the experimental measured fragmentation fraction into final hadrons channels, and it remains the same changing the collision energy, the ratio from fragmentation fraction is ~ 0.09 .

Even if the only coalescence ratio and the only fragmentation ratio remain similar at RHIC and LHC, the **combined ratio is different** because the <u>coalescence over fragmentation ratio at LHC is smaller than at RHIC</u>.

Therefore at LHC the larger contribution in particle production from fragmentation leads to a final ratio that is smaller than at RHIC.

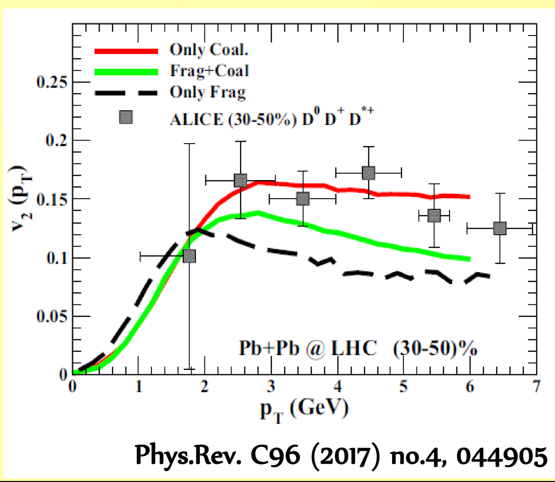


R_{AA} and v_2



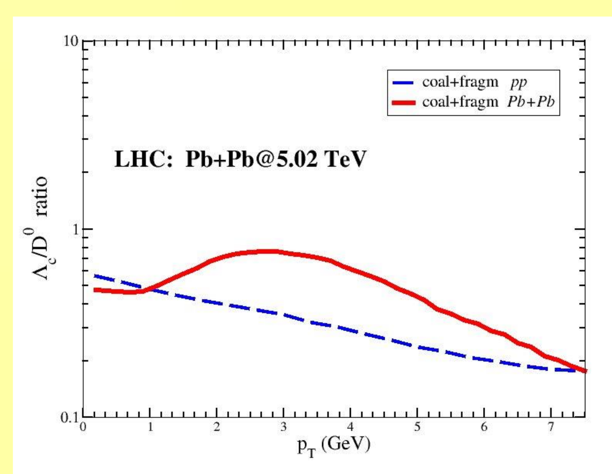
Charm distribution function from parton simulations solving Boltzmann transport equation that give good description of both R_{AA} and $v_2(p_T)$ from RHIC to LHC energies

Heavy quark hadronization by means of a hybrid model of fragmentation plus coalescence help to increase both the R_{AA} and v_2 close to the data,



Phys.Rev. C96 (2017) no.4, 044905

Prediction: coalescence in *pp*



Calculation for LHC@5.02 TeV:

- further decrease of Λ_c/D^0 ratio in *Pb+Pb* and broadening of the peak momentum dependence
- Disappearance of the peak in *pp*, but still different with respect to only fragmentation