Hadronization of heavy quark from pp to AA at TeV scale

Vincenzo Minissale

Dipartimento di Fisica e Astronomia "Ettore Majorana"
Università degli studi di Catania

INFN/LNS

***In collaboration with*: S. Plumari, V.Greco**

DIPARTIMENTO DI FISICA E ASTRONOMIA "ETTORE MAJORANA"

UNIVERSITÀ degli STUDI di CATANIA

INFN

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Outline

Hadronization:

- **Fragmentation**
- **Coalescence model**
- **SHM**

Heavy hadrons in AA collisions:

- **Λ_c , D spectra and ratio: RHIC and LHC**

Heavy hadrons in small systems (pp @ 5.02 TeV):

- **Λ_c/D^0**
- **Ξ_c/D^0 , Ω_c/D^0**

Quark Gluon Plasma

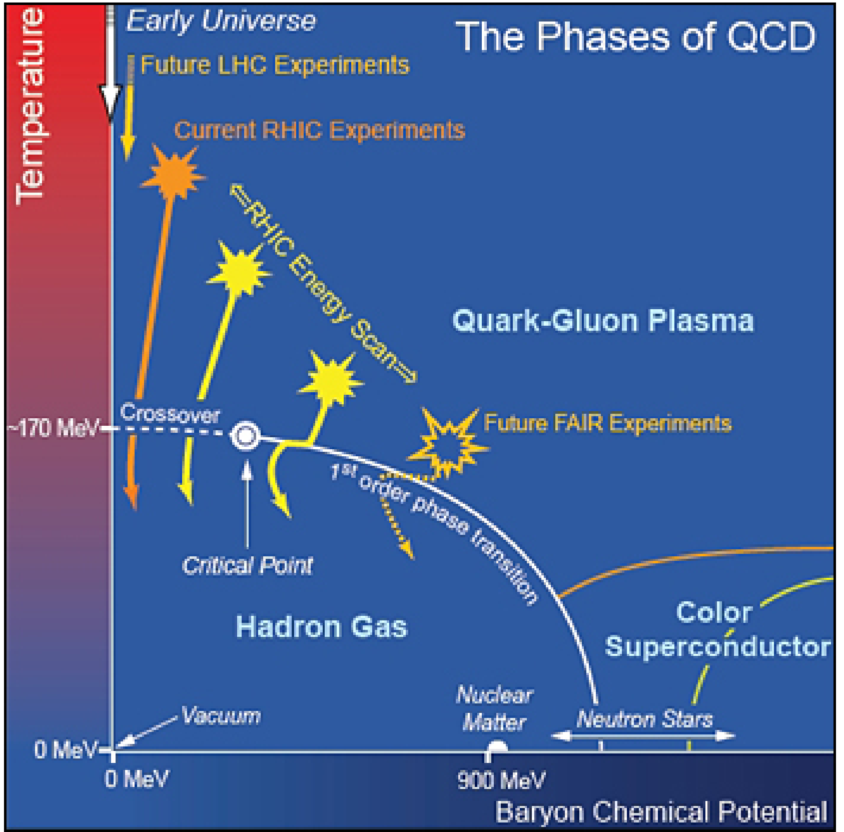
- Nuclear matter: Critical Energy and Temperature in the transition between confined and deconfined phase

$$\epsilon_c \approx 0.7\, GeV/fm^3$$
$$T_c \simeq 165\, MeV \approx 10^{12}\, K$$

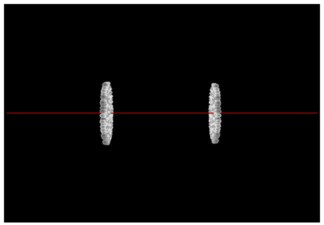
- If $T>T_c$ colour charges are deconfined in a Quark Gluon Plasma (QGP)

- Different value of T and ρ for deconfinement

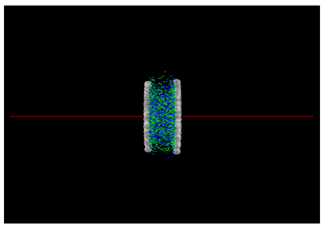
  → Phase Diagram



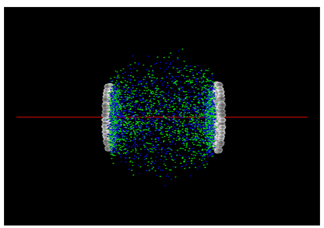
Ultra-Relativistic Heavy-Ion Collisions



Initial Stage

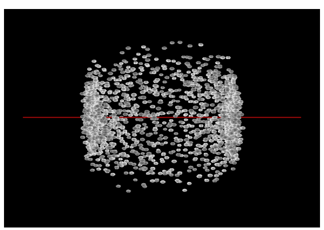


Pre-equilibrium stage



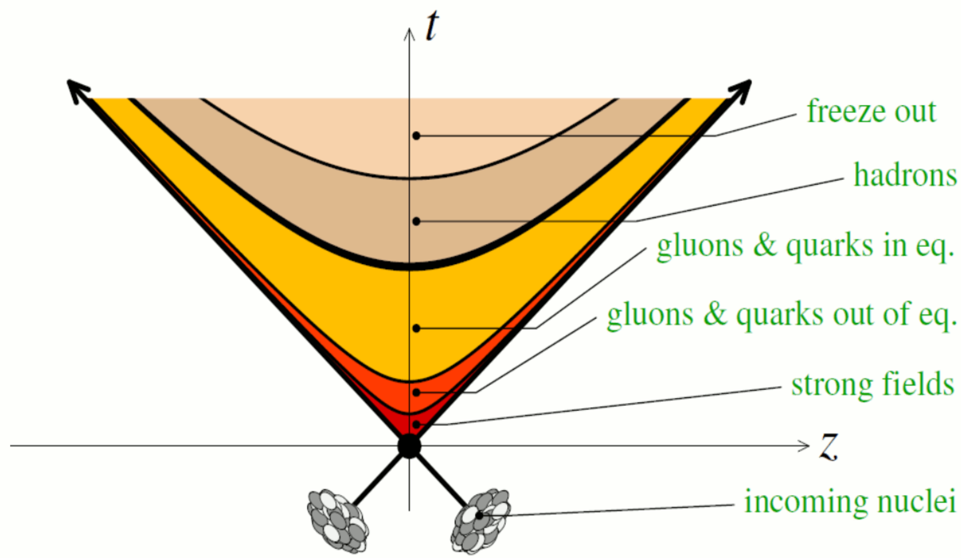
Expansion

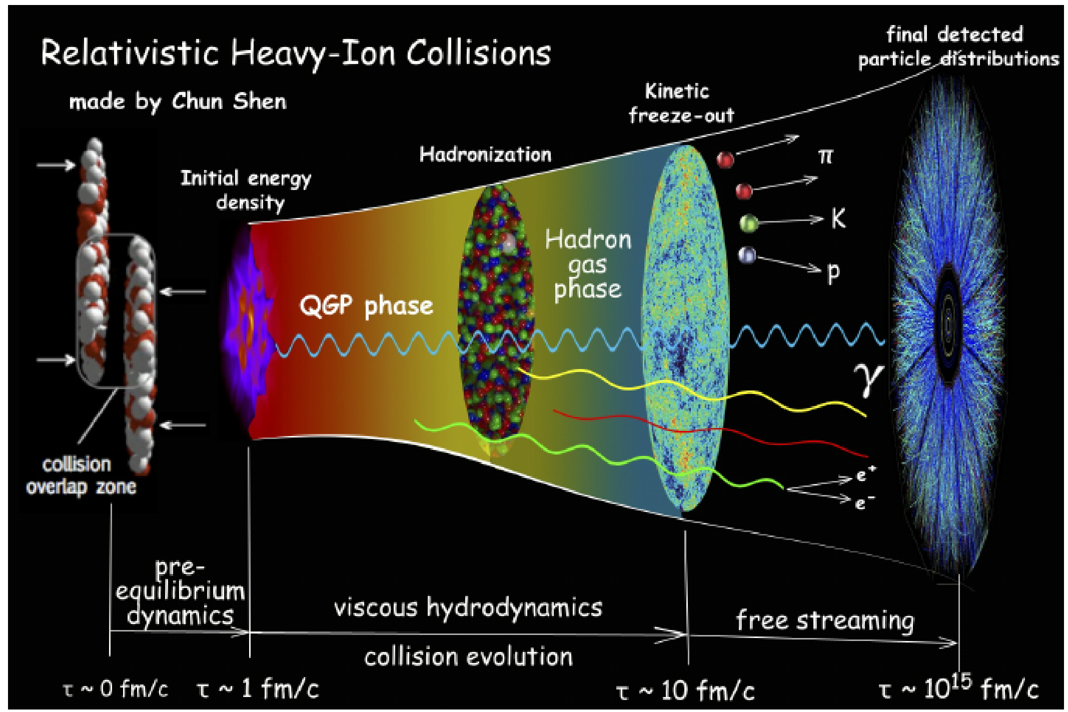
QGP



Hadronization

Chemical and kinetic freeze-out



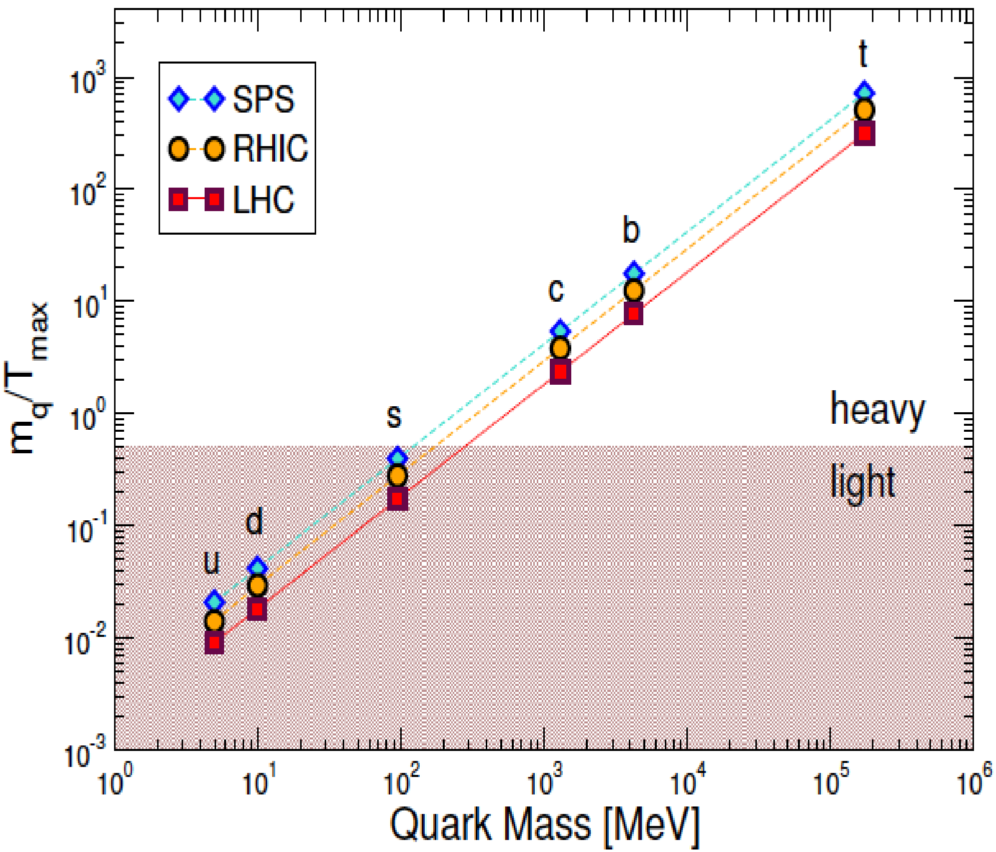


Specific of Heavy Quarks

- $m_{c,b} >> \Lambda_{QCD}$
  produced by pQCD process (out of equilibrium)
- $m_{c,b} >> T_0$
  negligible thermal production
- $\tau_0 << \tau_{QGP}$

HQs experience the full QGP evolution

Carry informations about initial stages, more than light quarks



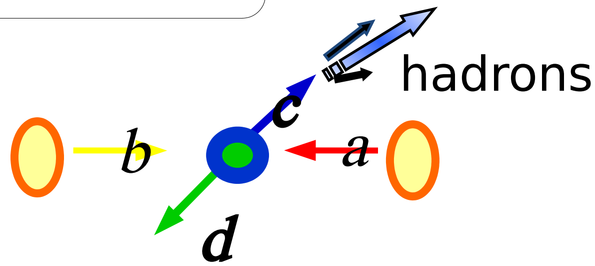
Heavy flavour Hadronization

Microscopic

Fragmentation:

production from hard-scattering processes (PDF+pQCD).
Fragmentation functions: data parametrization, assumed "universal"

$$\sigma_{pp\to h} = PDF(x_a, Q^2)\, PDF(x_b, Q^2) \otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to h}(z, Q^2)$$

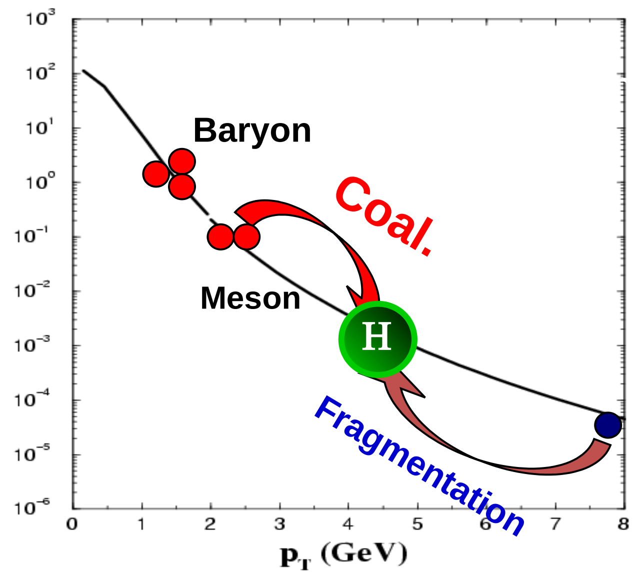


<u>Parton shower:</u> String fragmentation(Lund model – PYTHIA)
+colour reconnection(interaction from different scattering)
Cluster decay (HERWIG)

Coalescence: recombination of partons in QGP close in phase space

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

Have described first AA observations in light sector for the enhanced baryon/meson ratio and elliptic flow splitting



Macroscopic

Statistical hadronization:

Equilibrium + hadron-resonance gas + freeze-out temperature.
Production depends on hadron masses and degeneracy, and on system properties.

pQCD Charm production + total yield from charm cross section (not Temp.)
charm hadrons according to thermal weights

Catania Model: Coalescence + Fragmentation

Statistical factor colour-spin-isospin

Parton Distribution function

Hadron Wigner function

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

LIGHT

Thermal+flow for **u,d,s** (p_T < 3 GeV)

$$\frac{dN_{q,\bar{q}}}{d^2 p_T} \sim \exp\left(-\frac{\gamma_T - p_T \cdot \beta_T \mp \mu_q}{T}\right)$$

$$\beta(r) = \frac{r}{R} \beta_{max}$$

$$V = \pi R^2 \tau \cosh(y_z), R(\tau_f) = R_0 (1 + \beta_{max} \tau_f)$$

PbPb@5ATeV(0-10%): $\tau_f = 8.4 \frac{fm}{c} \rightarrow V_{|y|<0.5} = 4500\, fm^3$

+quenched minijets for u,d,s (p_T > 3 GeV)

CHARM

In <u>AA collisions</u> charm distribution from the studies of R_{AA} and v_2 of **D-meson** to determine the Space Diffusion coefficient:

parton simulations solving relativistic Boltzmann transport equation

In <u>pp collisions</u> the charm distribution are the FONLL distribution

<u>Coalescence simulation in a fireball with radial flow for light quarks → dimension set by experimental constraints</u>

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Wigner function – Wave function

$$\Phi_M^W(\mathbf{r}, \mathbf{q}) = \int d^3 r' \, e^{-i\mathbf{q}\cdot\mathbf{r}'} \phi_M\left(\mathbf{r} + \frac{\mathbf{r}'}{2}\right) \phi_M^*\left(\mathbf{r} - \frac{\mathbf{r}'}{2}\right)$$

$\phi_M(\mathbf{r})$ *meson wave function*

Assuming gaussian wave function

$$f_H(\ldots) = \prod_{i=1}^{N_q - 1} A_W \exp\left(-\frac{x_{ri}^2}{\sigma_{ri}^2} - p_{ri}^2 \sigma_{ri}^2\right)$$

only one width coming from $\phi_M(\mathbf{r})$, constraint $\sigma_r \sigma_p = 1$

Wigner function **width** fixed by root-mean-square charge radius from **quark model**

C.-W. Hwang, EPJ C23, 585 (2002)
C. Albertus et al., NPA 740, 333 (2004)

$$\langle r^2 \rangle_{ch} = \frac{3}{2} \frac{m_2^2 Q_1 + m_1^2 Q_2}{(m_1 + m_2)^2} \sigma_{r1}^2 + \frac{3}{2} \frac{m_3^2 (Q_1 + Q_2) + (m_1 + m_2)^2 Q_3}{(m_1 + m_2 + m_3)^2} \sigma_{r2}^2$$

$$\sigma_{ri} = 1/\sqrt{(\mu_i \, \omega)} \qquad \mu_1 = \frac{m_1 m_2}{m_1 + m_2} \qquad \mu_2 = \frac{(m_1 + m_2) m_3}{m_1 + m_2 + m_3}$$

Meson	$\langle r^2 \rangle_{ch}$	σ_{p1}	σ_{p2}
$D^+ = [c\bar{d}]$	0.184	0.282	—
$D_s^+ = [\bar{s}c]$	0.083	0.404	—
Baryon	$\langle r^2 \rangle_{ch}$	σ_{p1}	σ_{p2}
$\Lambda_c^+ = [udc]$	0.15	0.251	0.424
$\Xi_c^+ = [usc]$	0.2	0.242	0.406
$\Omega_c^0 = [ssc]$	-0.12	0.337	0.53

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$\phi_M(\boldsymbol{r})$ *meson wave function*

- Normalization of $f_H(\ldots)$ requiring that $P_{coal}=1$ at $p=0$
- The charm that does not coalesce undergo fragmentation

Assuming gaussian wave function

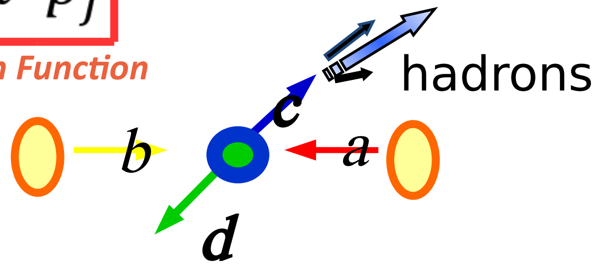
$$f_H(\ldots) = \prod_{i=1}^{N_q - 1} A_W \exp\left(-\frac{x_{ri}^2}{\sigma_{ri}^2} - p_{ri}^2 \sigma_{ri}^2\right)$$

only one width coming from $\phi_M(\mathbf{r})$, constraint $\sigma_r \sigma_p = 1$

Catania Model: Coalescence + Fragmentation

$$\frac{dN_h}{d^2p_h} = \sum_f \int dz \boxed{\frac{dN_f}{d^2p_f}} D_{f\to h}(z)$$

Parton Distribution Function



The distribution function is evaluated at the Fixed-Order plus Next-to-Leading-Log (FONLL)

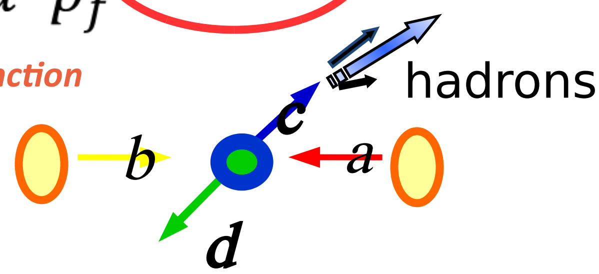
M. Cacciari, P. Nason, R. Vogt, PRL 95 (2005) 122001

<u>In AA: bulk+charm evolution with Relativistic Transport Boltzmann Equation</u>

Catania Model: Coalescence + Fragmentation

$$\frac{dN_h}{d^2p_h} = \sum_f \int dz \frac{dN_f}{d^2p_f} D_{f\to h}(z)$$

Fragmentation function



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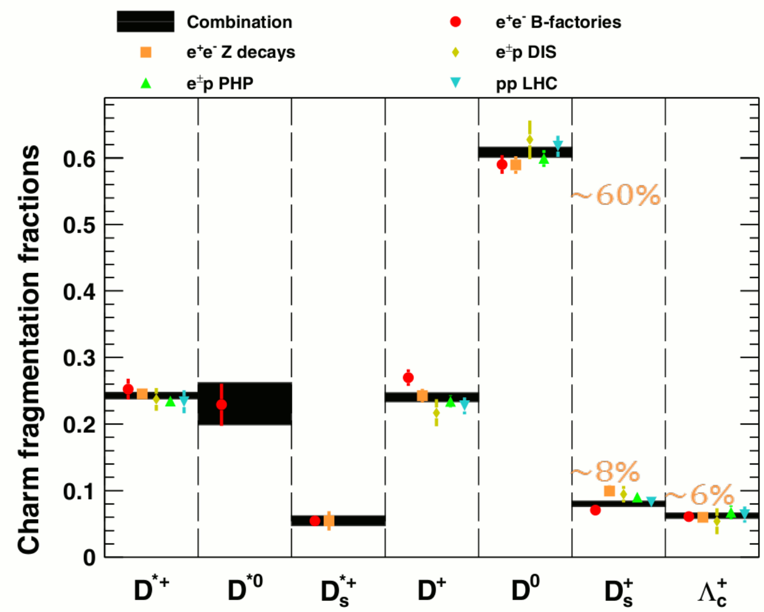


M. Lisovyi, et al. EPJ C76 (2016) no.7, 397

We use the Peterson fragmentation function
C. Peterson, D. Schalatter, I. Schmitt, P.M. Zerwas PRD **27** (1983) 105

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

Sligthly modified to reproduce tail of the Λ_c/D^0

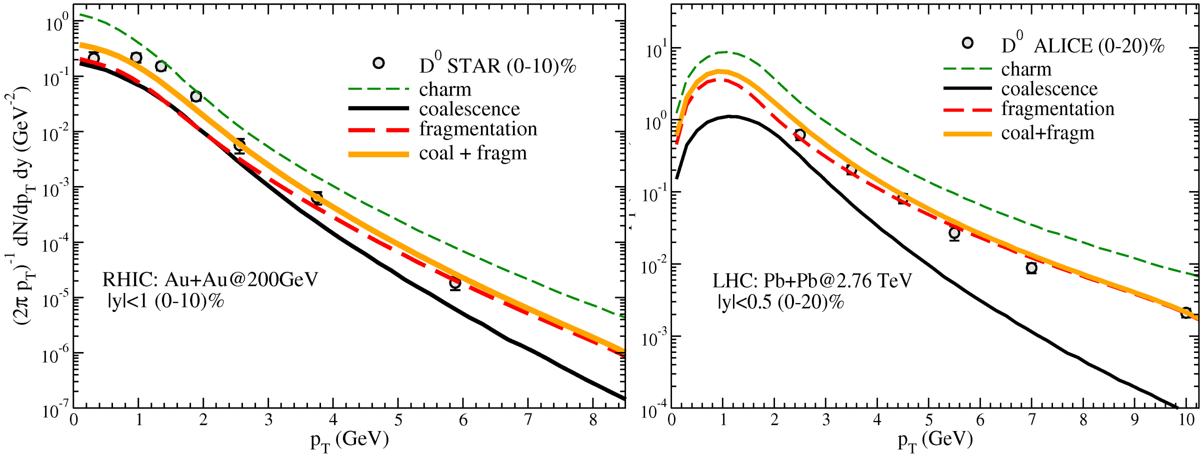
Charm Fragmentation Fraction (c→h)
Measurement in *$e^{\pm}p$, e^+e^- and old pp data*

$$\left(\frac{\Lambda_c^+}{D^0}\right)_{\substack{e^+e^-\\ pp}} \simeq 0.1 \qquad \left(\frac{D_s^+}{D^0}\right)_{\substack{e^+e^-\\ pp}} \simeq 0.13$$

AA @ RHIC & LHC

wave function widths σ_p of baryon and mesons are the same at RHIC and LHC!

Data from ALICE Coll. JHEP 1209 (2012) 112



Coalescence lower at LHC than at RHIC → main contribution from Fragmentation

$\boxed{D^0}$

S. Plumari, V. Minissale et al., Eur. Phys. J. ***C78*** *no. 4, (2018) 348*

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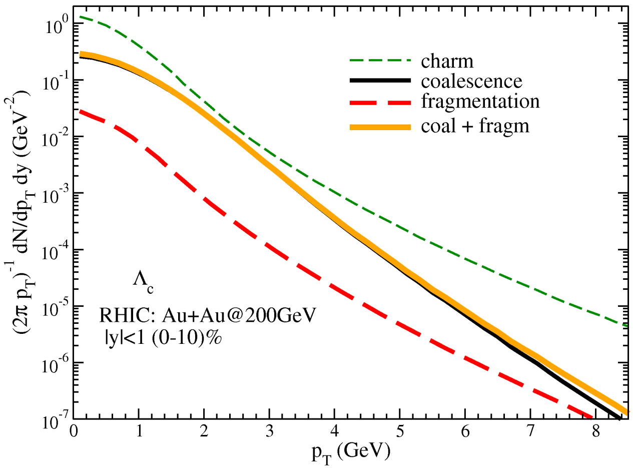

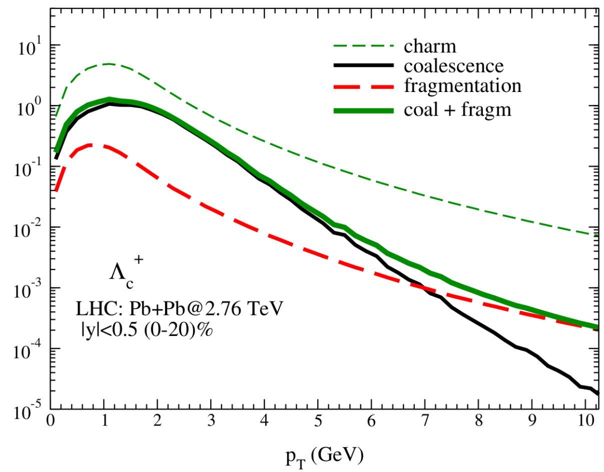

Coalescence lower at LHC than at RHIC → main contribution from Coalescence

$\boxed{\Lambda_c}$

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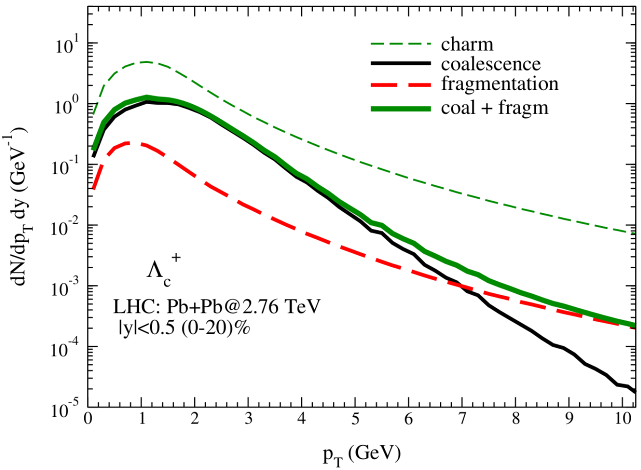

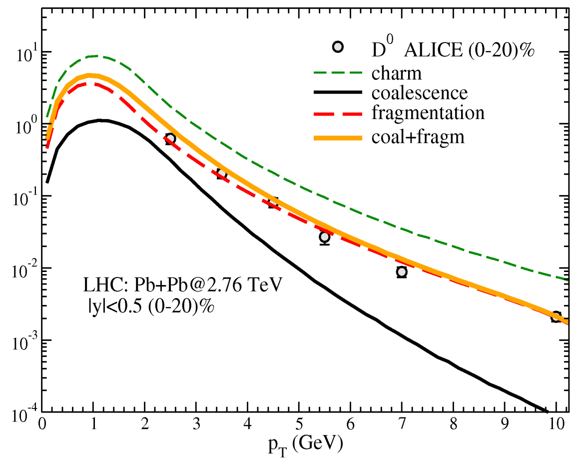

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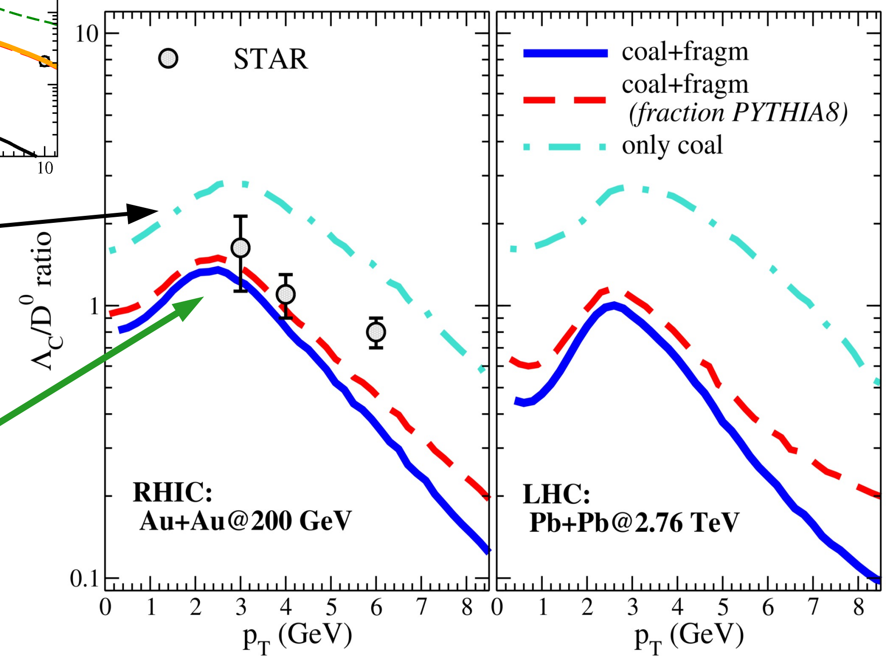


Only Coalescence ratio is similar at both energies.

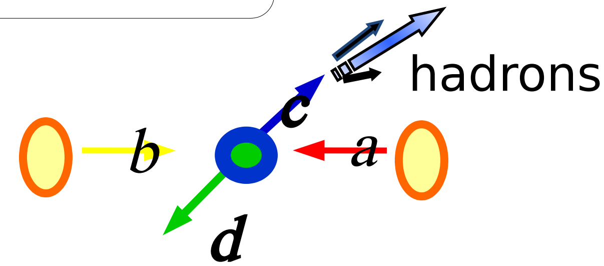
Fragmentation ~ 0.1 at both energies.

the **combined ratio is different** because the coalescence over fragmentation ratio at LHC is smaller than at RHIC

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

S. Plumari, V. Minissale et al., Eur. Phys. J. ***C78*** *no. 4, (2018) 348*

Heavy flavour Hadronization



Fragmentation: production from hard-scattering processes (PDF+pQCD).
Fragmentation functions: data parametrization, assumed "universal"

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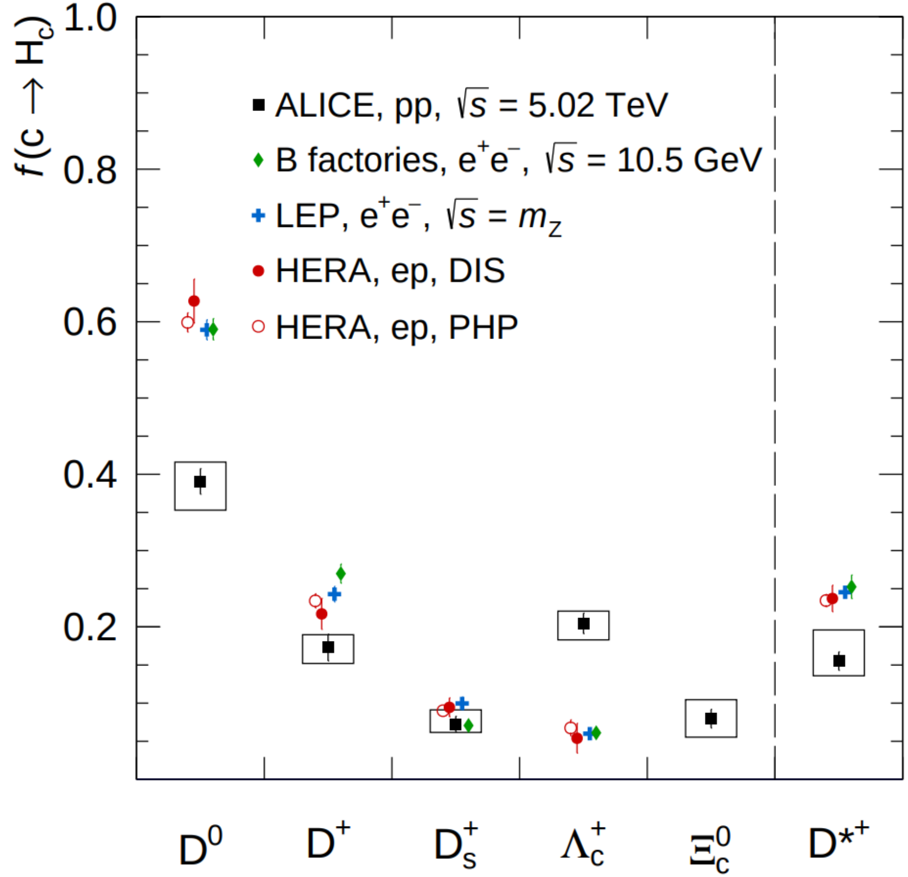
ALICE, arXiv:2105.06335

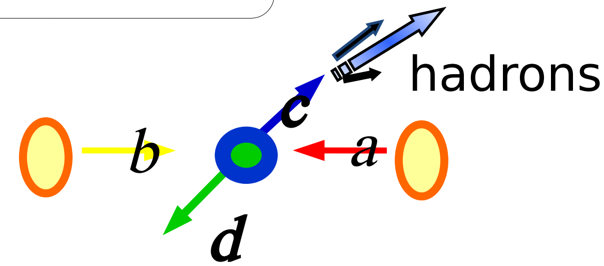


Things get more complicated after experimental evidence in pp@5TeV:

Fragmentation fractions (c→h) depends on <u>collision system</u>...*and QGP presence*?

No more Universality?

Heavy flavour Hadronization



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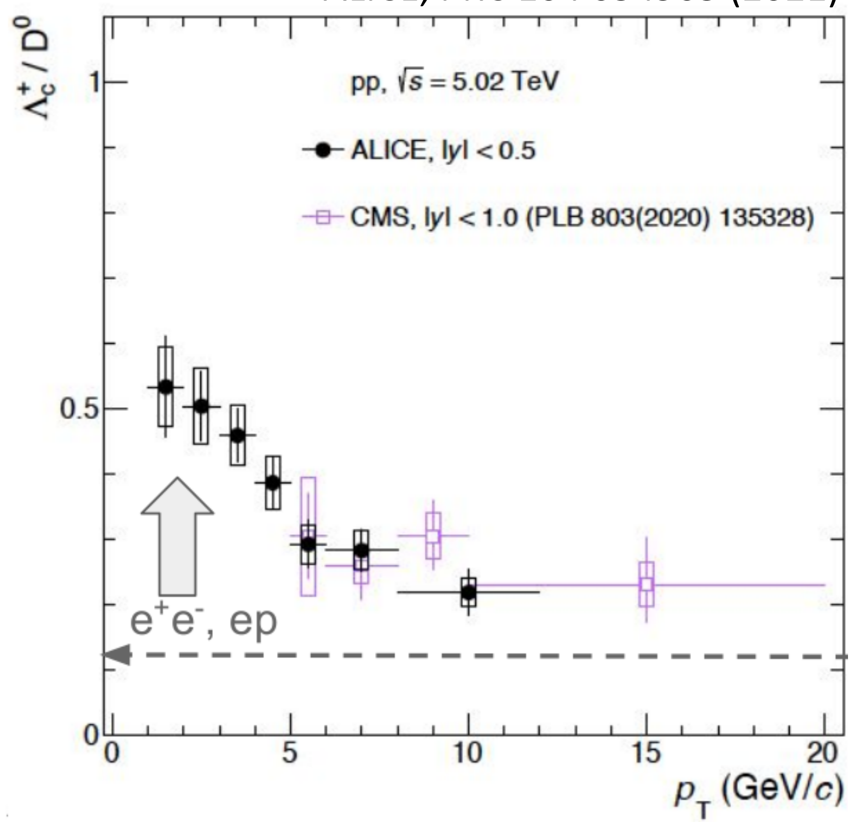
ALICE, PRL 127 202301 (2021)
ALICE, PRC 104 054905 (2021)



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Fragmentation fractions (c→h) depends on collision system...*and QGP presence*?

No more Universality?

Baryon/meson ratio is underestimated, and no p_T dependence

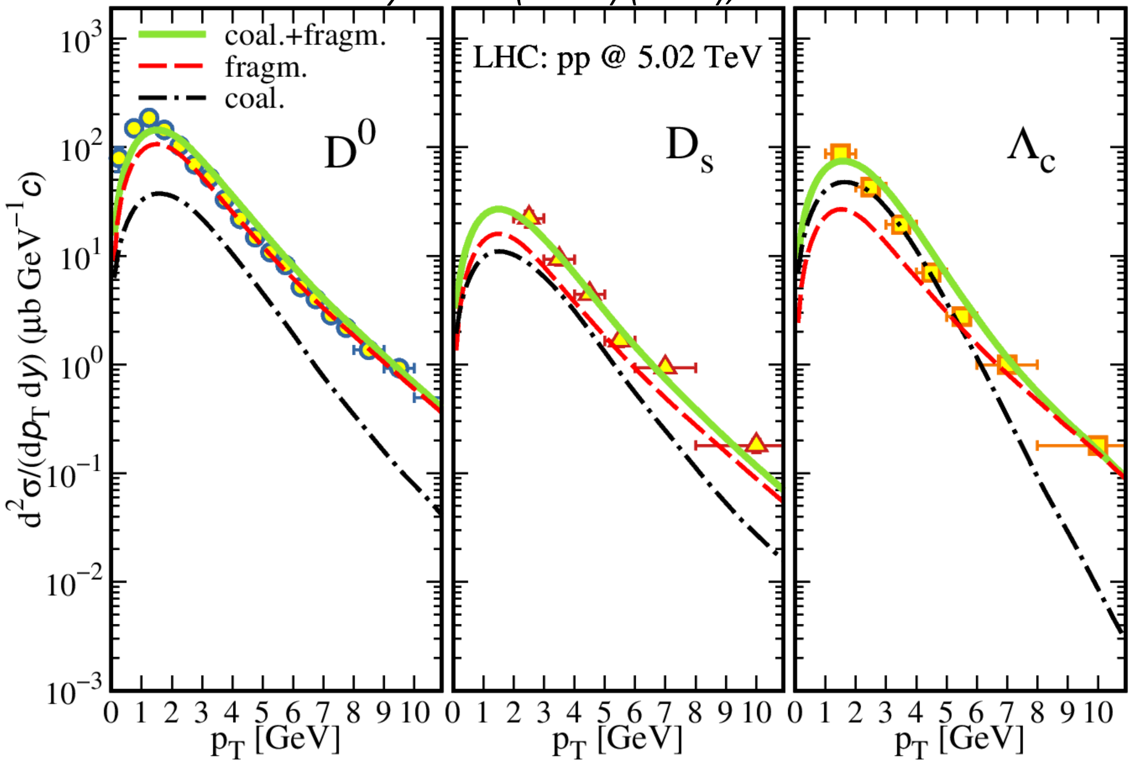
Small systems: Coalescence in pp?

Common consensus of possible presence of QGP in smaller system.

What if:

- **Assuming QGP formation also in pp?**
- **What coalescence+fragmentation predicts in this case?**

Data from:
S. Acharya et al. (ALICE), Eur. Phys. J. C 79, 388 (2019)
S. Acharya et al. (ALICE) (2020), 2011.06078 - 2011.06079



V. Minissale, S. Plumari, V. Greco, Physics Letters B 821 (2021) 136622

If we assume in p+p @ 5 TeV a medium similar to the one simulated in hydro:

p+p @ 5 TeV

- τ_{pp}=2 fm/c
- β_0=0.4
- R=2.5 fm
- V~30 fm^3

LIGHT

- Thermal Distribution (p_T< 2 GeV)

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

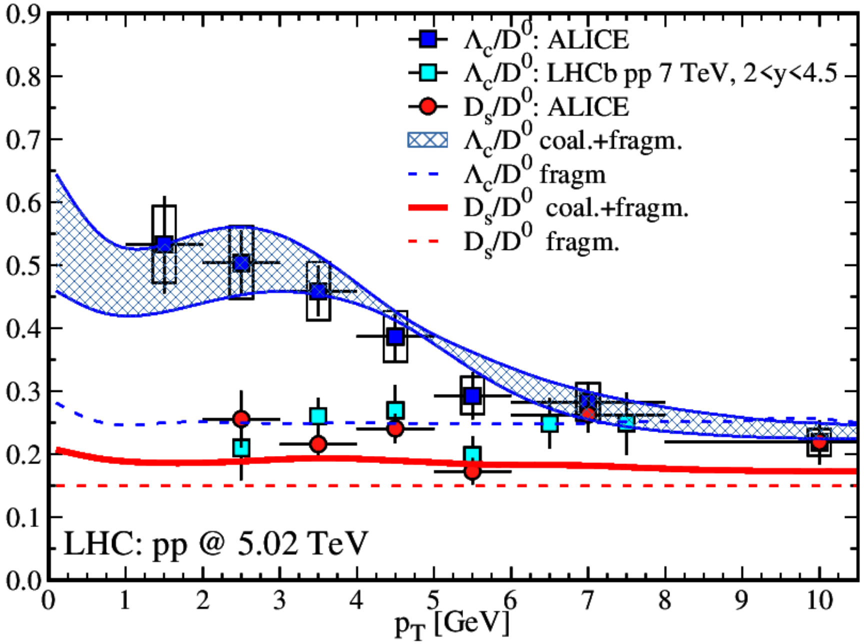
- Minijet Distribution (p_T> 2 GeV)
  NO QUENCHING

CHARM

FONLL Distribution

wave function widths σ_p of baryon and mesons kept the same from AA to pp

Small systems: Coalescence in pp?



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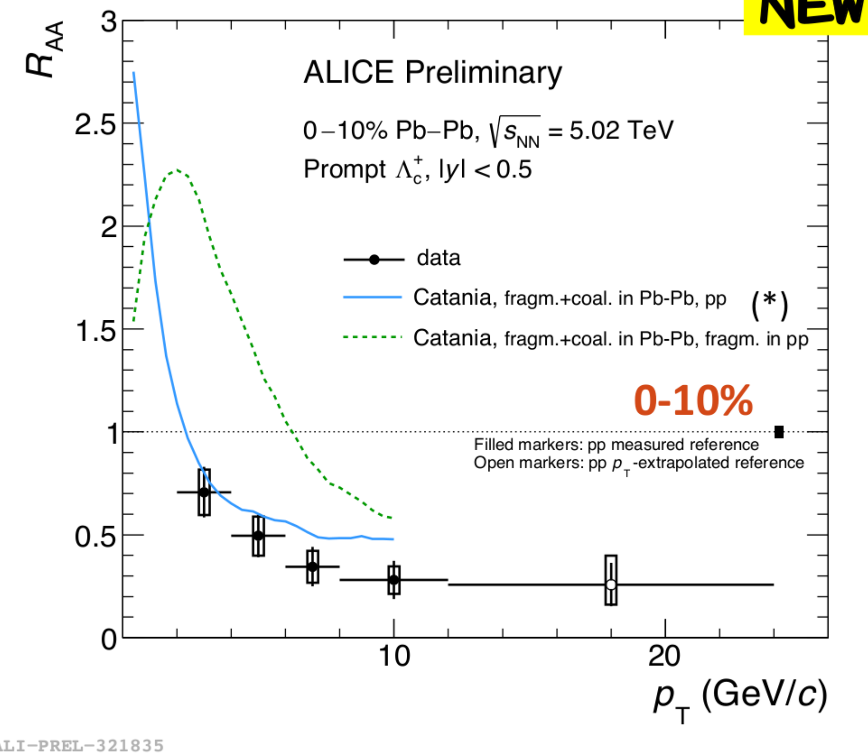
Reduction of rise-and-fall behaviour in Λ_c / D^0 ratio:

-Confronting with AA: Coal. contribution smaller w.r.t. Fragm.

-FONLL distribution flatter w/o evolution trough QGP

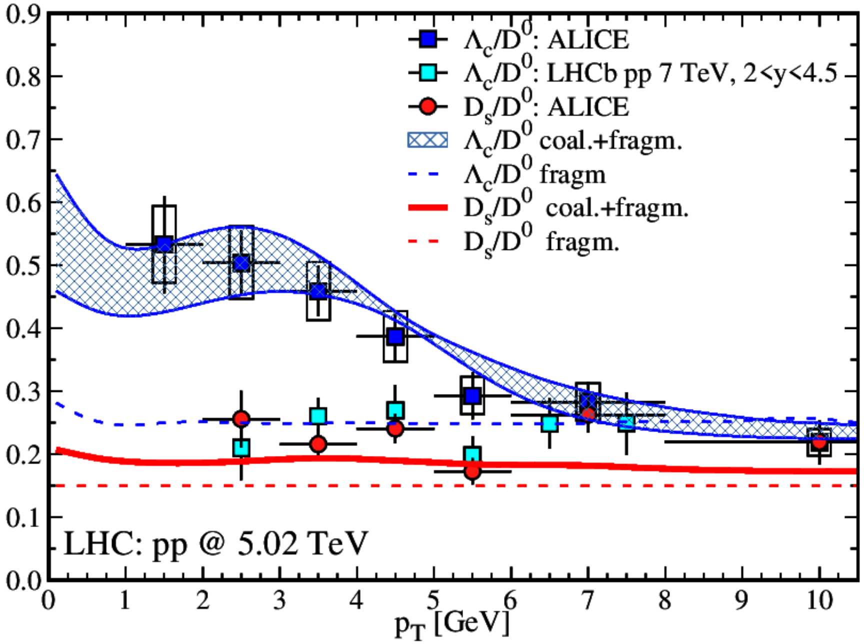
-Volume size effect

NEW



The increase of Λ_c production in pp has big effect on R_{AA} of Λ_c $\rightarrow$ coal.+fragm. has different behaviour especially at low momenta.

Small systems: Coalescence in pp?



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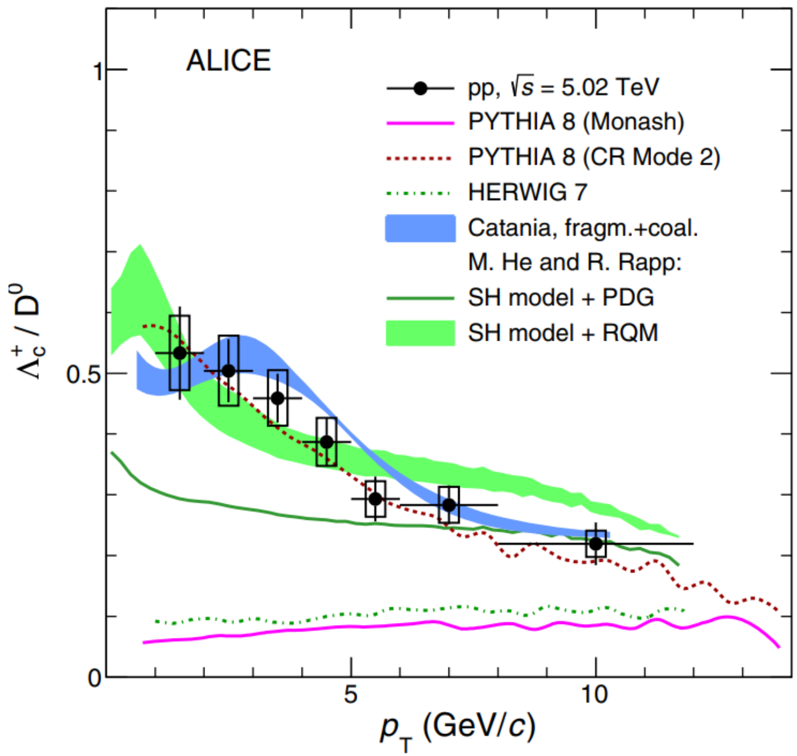
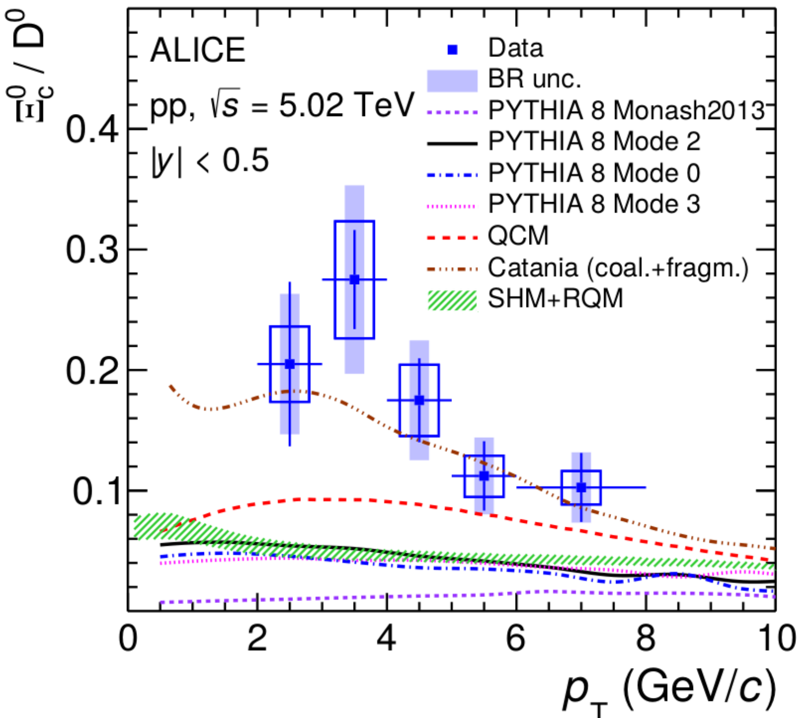


<u>Other models</u>

PYTHIA8+Colour Reconnection *JHEP 1508 (2015) 003:* including "interactions" among partons from different partonic scatterings

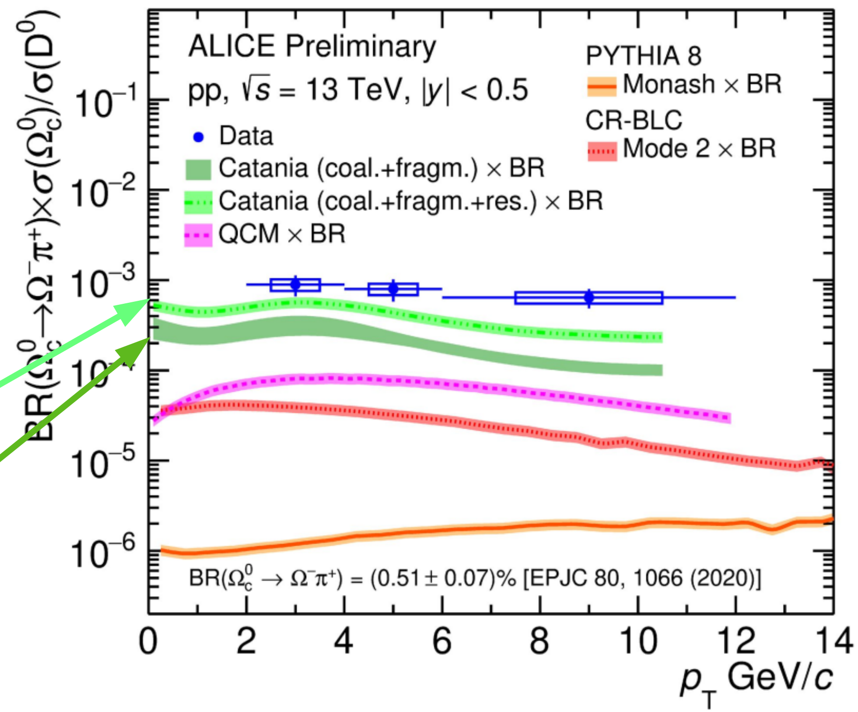
Statistical Hadronization Model with augmented set of baryonic states respect PDG *[He,Rapp, PLB 795 117-121 (2019)]*

Small systems: Coalescence in pp?



New measurements of heavy hadrons at ALICE:

- Ξ_c/D^0 ratio, same order of Λ_c/D^0: coalescence gives enhancement
- very large Ω_c/D^0 ratio, our model does not get the big enhancement



Assuming additional PDG resonances with J=3/2 and decay to Ω_c additional to $\Omega_c^0(2770)$

$$\Omega_c^0(3000), \Omega_c^0(3005), \Omega_c^0(3065), \Omega_c^0(3090), \Omega_c^0(3120)$$

supply an idea of how these states may affect the ratio

Error band correspond to <r^2> uncertainty in quark model

ALICE Collaboration, JHEP 10 (2021) 159
V. Minissale, S. Plumari, V. Greco, Physics Letters B 821 (2021) 136622

Conclusions

- ***Good agreement with experimental data of hadrons spectra in AA collisions from RHIC to LHC***
- ***Extension to pp: description of D mesons and Λ_c spectra***
- ***Coalescence plus fragmentation gives peculiar enhancement in baryon/ meson ratio for all heavy hadrons Λ_c, Ξ_c, Ω_c***
- ***Outlook: multicharm hadrons production***

Backup Slides

Hadronization: Coalescence

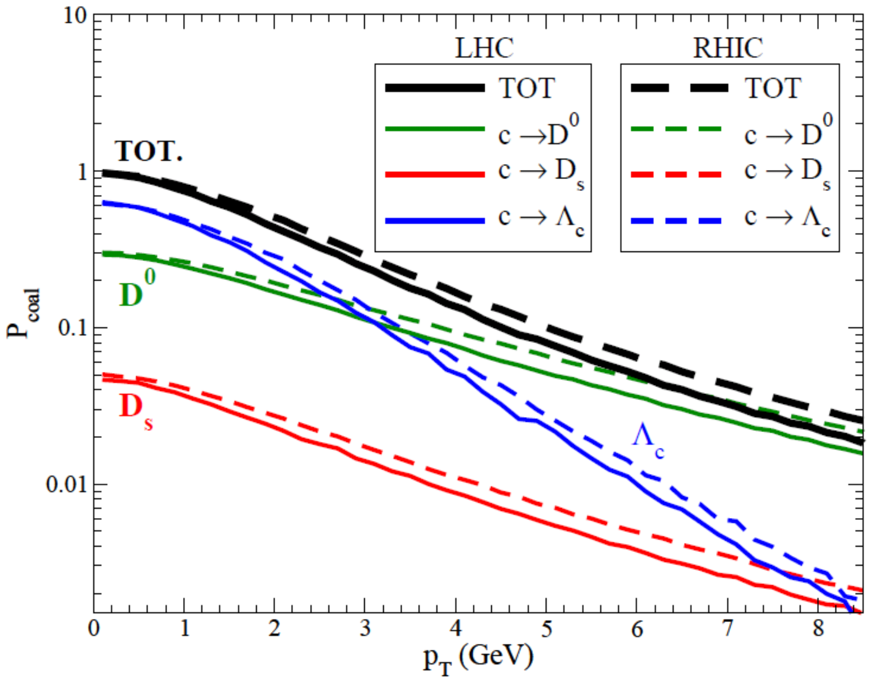
Statistical factor colour-spin-isospin

Parton Distribution function

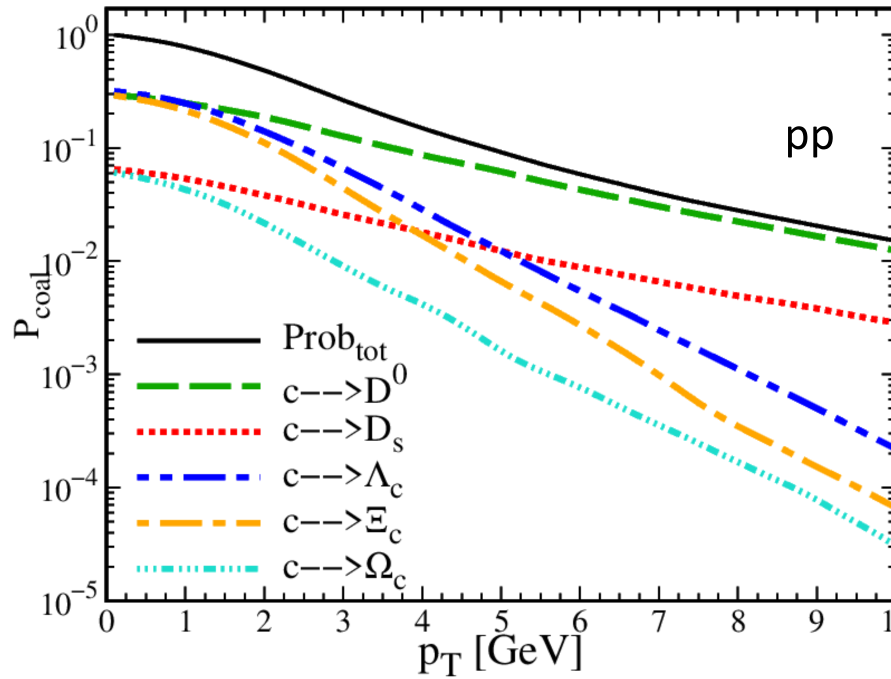
Hadron Wigner function

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

- Normalization in $f_W(\ldots)$ requiring that $P_{coal}=1$ at $p=0$
- The charm that does not coalesce undergo fragmentation



S. Plumari, V. Minissale et al., Eur. Phys. J. **C78** no. 4, (2018) 348



V. Minissale, S. Plumari, V. Greco, arXiv:2012.12001

Heavy flavour: Resonance decay

Meson	Mass(MeV)	I (J)	Decay modes	B.R.
$D^+ = \bar{d}c$	1869	$\frac{1}{2}\,(0)$		
$D^0 = \bar{u}c$	1865	$\frac{1}{2}\,(0)$		
$D_s^+ = \bar{s}c$	2011	$0\,(0)$		
Resonances				
D^{*+}	2010	$\frac{1}{2}\,(1)$	$D^0\pi^+$; D^+X	68%,32%
D^{*0}	2007	$\frac{1}{2}\,(1)$	$D^0\pi^0$; $D^0\gamma$	62%,38%
D_s^{*+}	2112	$0\,(1)$	D_s^+X	100%
Baryon				
$\Lambda_c^+ = udc$	2286	$0\,(\frac{1}{2})$		
$\Xi_c^+ = usc$	2467	$\frac{1}{2}\,(\frac{1}{2})$		
$\Xi_c^0 = dsc$	2470	$\frac{1}{2}\,(\frac{1}{2})$		
$\Omega_c^0 = ssc$	2695	$0\,(\frac{1}{2})$		
Resonances				
Λ_c^+	2595	$0\,(\frac{1}{2})$	$\Lambda_c^+\pi^+\pi^-$	100%
Λ_c^+	2625	$0\,(\frac{3}{2})$	$\Lambda_c^+\pi^+\pi^-$	100%
Σ_c^+	2455	$1\,(\frac{1}{2})$	$\Lambda_c^+\pi$	100%
Σ_c^+	2520	$1\,(\frac{3}{2})$	$\Lambda_c^+\pi$	100%
$\Xi_c^{\prime +,0}$	2578	$\frac{1}{2}\,(\frac{1}{2})$	$\Xi_c^{+,0}\gamma$	100%
Ξ_c^+	2645	$\frac{1}{2}\,(\frac{3}{2})$	$\Xi_c^+\pi^-$,	100%
Ξ_c^+	2790	$\frac{1}{2}\,(\frac{1}{2})$	$\Xi_c^{\prime}\pi$,	100%
Ξ_c^+	2815	$\frac{1}{2}\,(\frac{3}{2})$	$\Xi_c^{\prime}\pi$,	100%
Ω_c^0	2770	$0\,(\frac{3}{2})$	$\Omega_c^0\gamma$,	100%

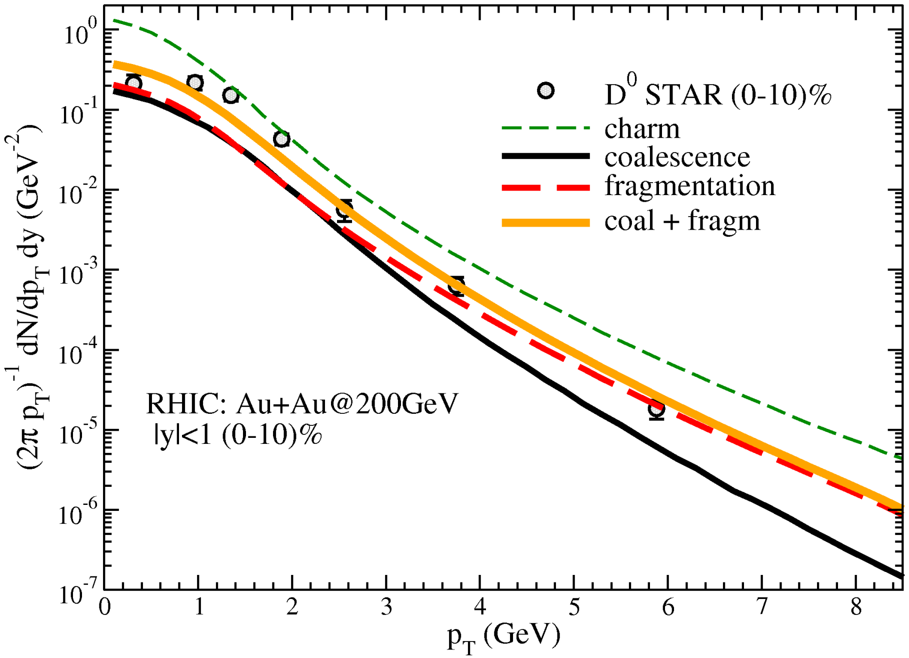
In our calculations we take into account hadronic channels including the ground states + first excited states

Statistical factor suppression for resonances

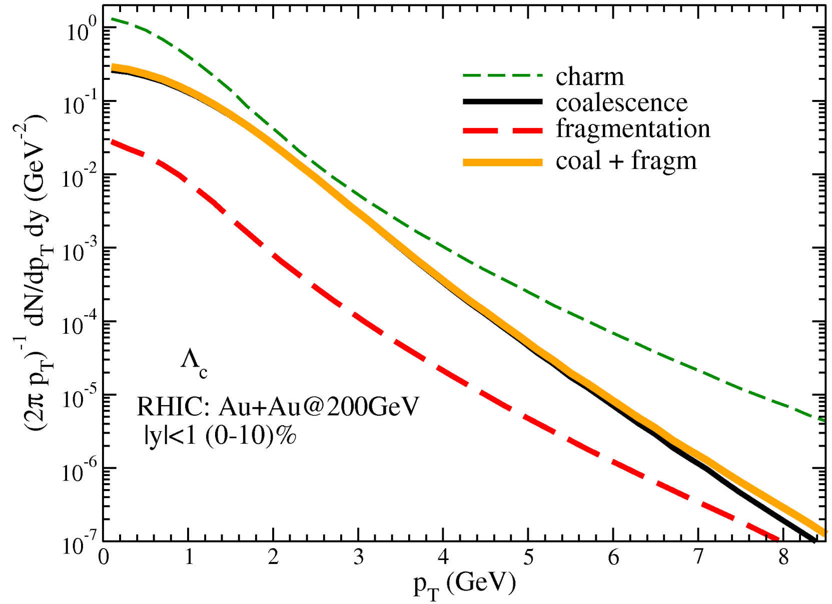
$$\frac{[(2J+1)(2I+1)]_{H^*}}{[(2J+1)(2I+1)]_H}\left(\frac{m_{H^*}}{m_H}\right)^{3/2} e^{-(m_{H^*}-m_H)/T}$$

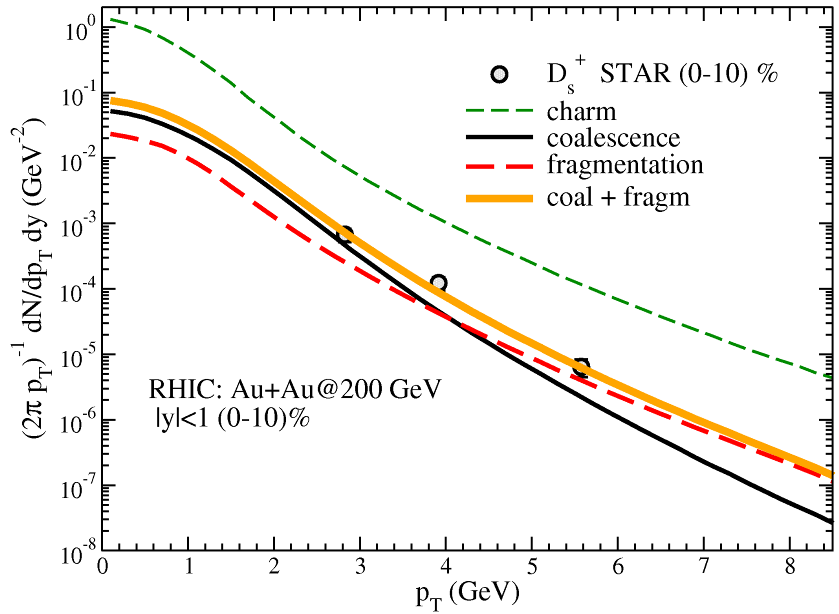
RHIC: results

*S. Plumari, V. Minissale et al., Eur. Phys. J. **C78** no. 4, (2018) 348*



Data from STAR Coll. PRL **113** (2014) no.14, 142301

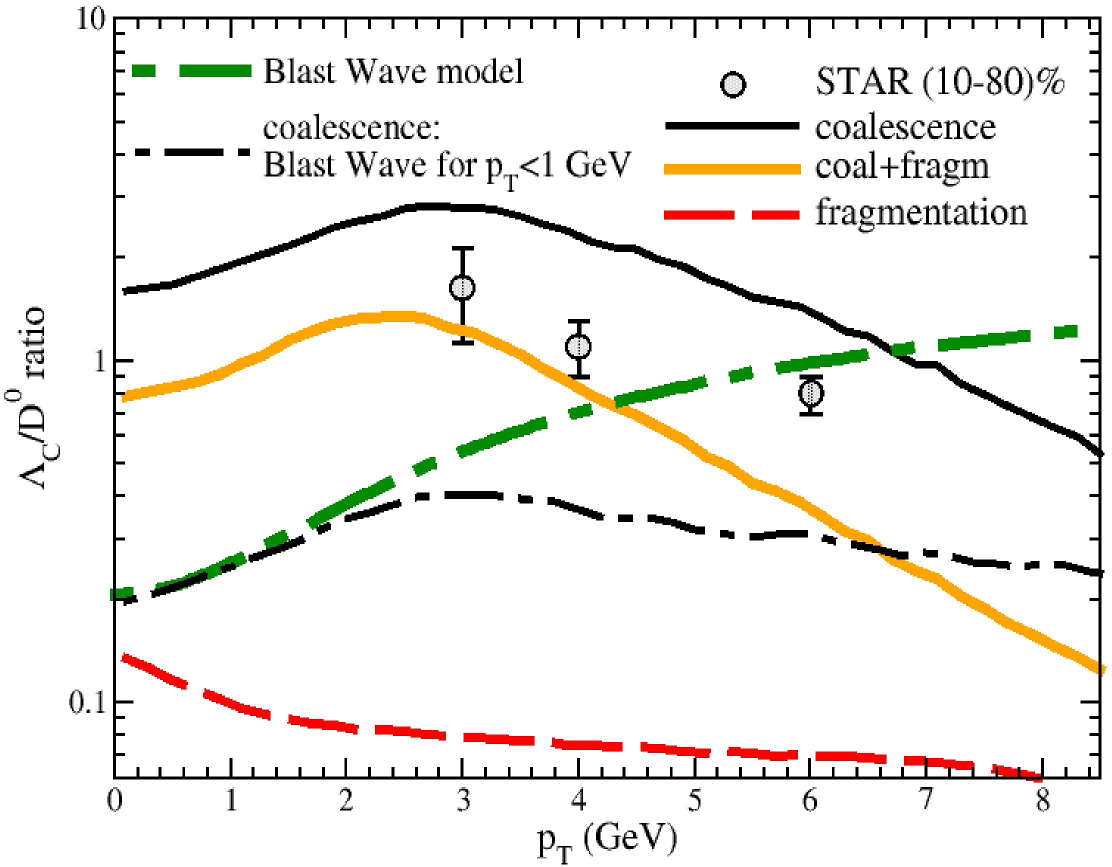




- For D^0 coalescence and fragmentation comparable at 2 GeV
- fragmentation fraction for D^+_s are small and less than about 8% of produced total heavy hadrons
- Λ_c^+ fragmentation is even more smaller, coalescence gives the dominant contribution

RHIC: Baryon/meson

STAR, Phys.Rev.Lett. 124 (2020) 17, 172301



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

More flatter → should coalescence extend to higher pt? Indication also in light sector

V. Minissale, F. Scardina, V. Greco **PRC 92**,054904 (2015)
Cho, Sun, Ko et al.,**PRC 101 (2020)** 2, 024909

Needed data at low p_T

S. Plumari, V. Minissale et al., Eur. Phys. J. ***C78*** *no. 4, (2018) 348*

Elliptic Flow – Quark Number Scaling

Fourier expansion of the azimuthal distribution

$$f(\varphi, p_T) = 1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos n\varphi$$

momentum anisotropy in the transverse plane

n=2 Elliptic flow

coalescence brings to

$$\begin{aligned} v_{2,M}(p_T) &\approx 2v_{2,q}(p_T/2) \\ v_{2,B}(p_T) &\approx 3v_{2,q}(p_T/3) \end{aligned}$$

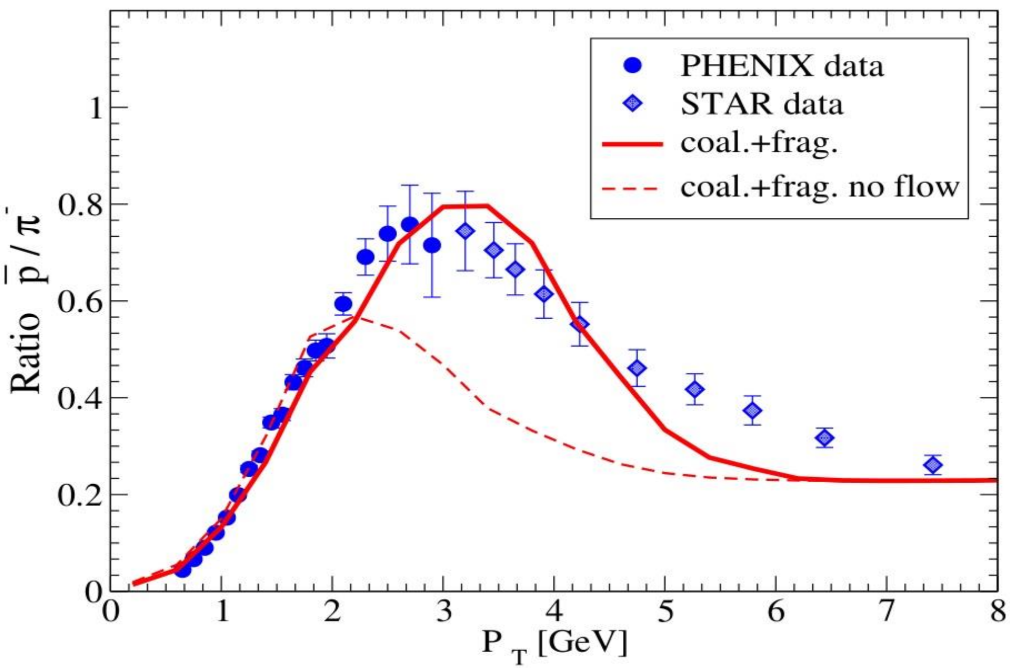
Partonic elliptic flow

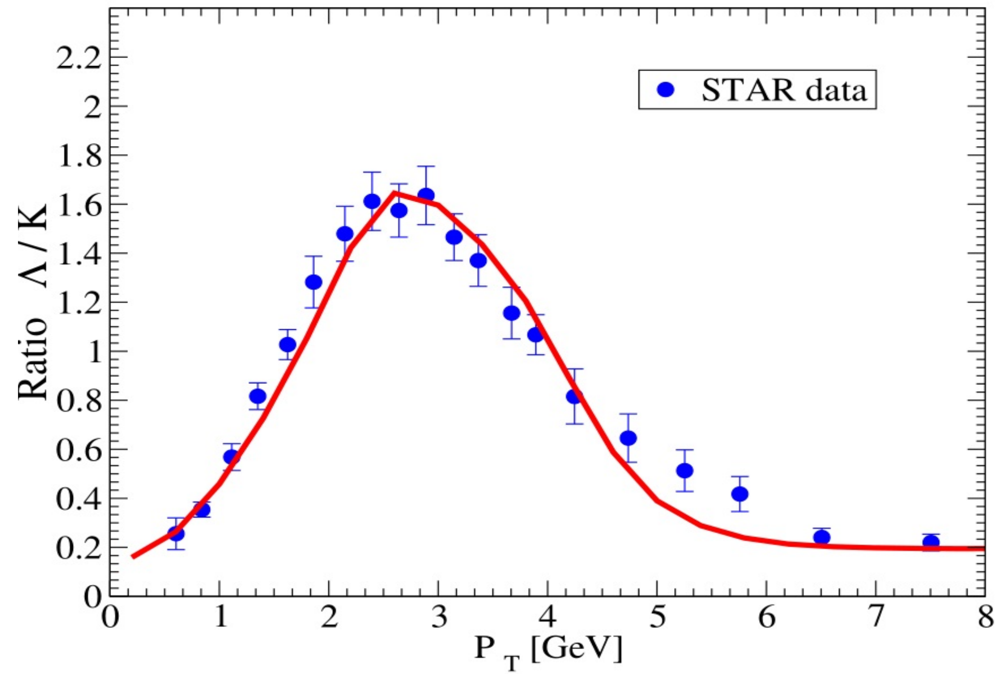
Hadronic elliptic flow

Assumption

- one dimensional
- Dirac delta for Wigner function
- isotropic radial flow
- not including resonance effect

Baryon to meson ratio at RHIC





- coalescence naturally predict a baryon/meson enhancement in the region $p_T \simeq 2\text{–}4GeV$ with respect to *pp* collisions
- Lack of baryon yield in the region $p_T \simeq$ 5–7GeV

Relativistic Boltzmann transport at finite η/s

Bulk evolution

$$\underbrace{p^{\mu}\,\partial_{\mu} f_{q,g}(x,p)}_{\text{free-streaming}} + \underbrace{M(x)\,\partial^{x}_{\mu} M(x)\,\partial^{\mu}_{p} f_{q,g}(x,p)}_{\substack{\text{field interaction}\\ \varepsilon-3p\neq 0}} = \underbrace{C_{22}\left[f_{q,g}\right]}_{\substack{\text{collisions}\\ \eta\neq 0}}$$

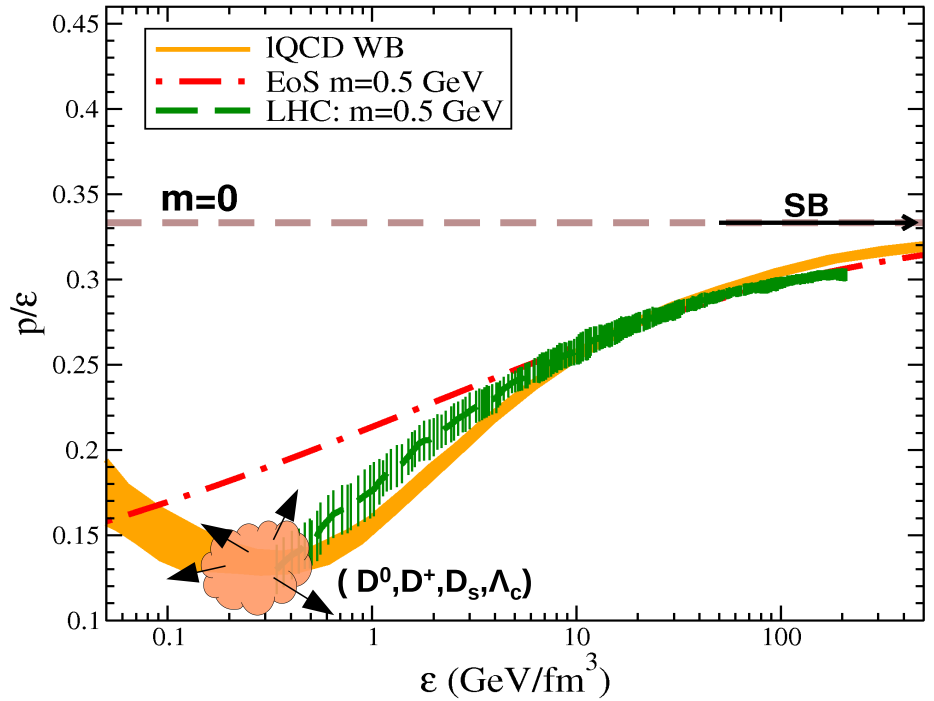
Heavy quark evolution

$$p^{\mu}\partial_{\mu} f_{Q}(x,p) = C[f_q, f_g, f_Q]$$

·**Describes the evolution of the one body distribution function f(x,p)**

·**It is valid to study the evolution of both bulk and Heavy quarks**

·**Possible to include f(x,p) out of equilibrium**



S. Plumari et al.,J.Phys.Conf.Ser. 981 012017 (2018).