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INFN LNS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

Coalescence plus fragmentation approach for the hadronization mechanism of heavy hadrons from AA to pp collisions

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INFN/LNS

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

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):

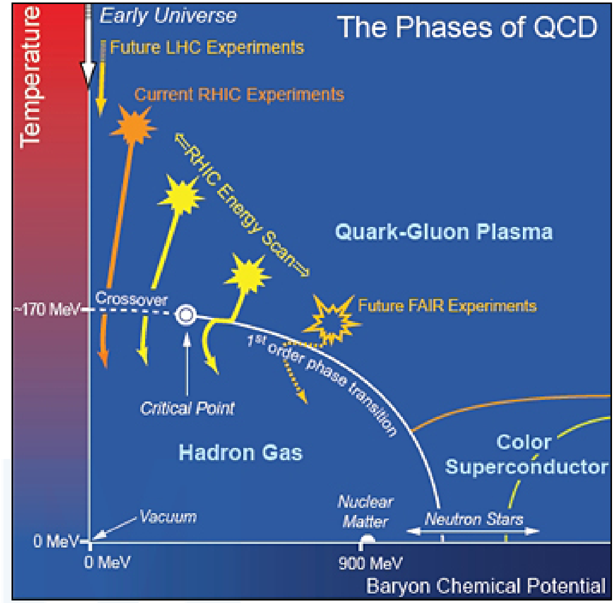
- Λ_c/D^0
- Ξ_c/D^0 , Ω_c/D^0

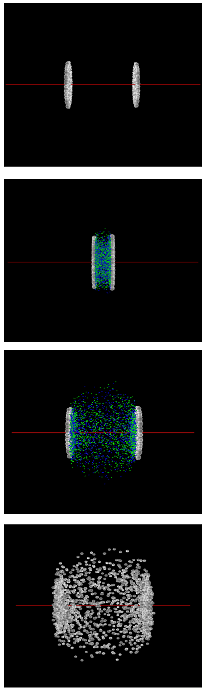
Quark Gluon Plasma in Ultra-Relativistic Heavy-Ion Collisions

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

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

- If $T>T_c$ colour charges are deconfined in a Quark Gluon Plasma (QGP)
- Different value of T and ρ for deconfinement → Phase Diagram





Initial Stage

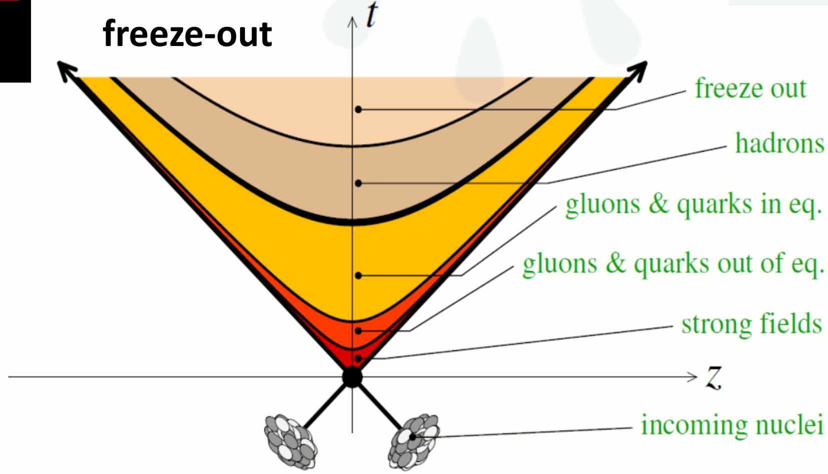
Pre-equilibrium stage

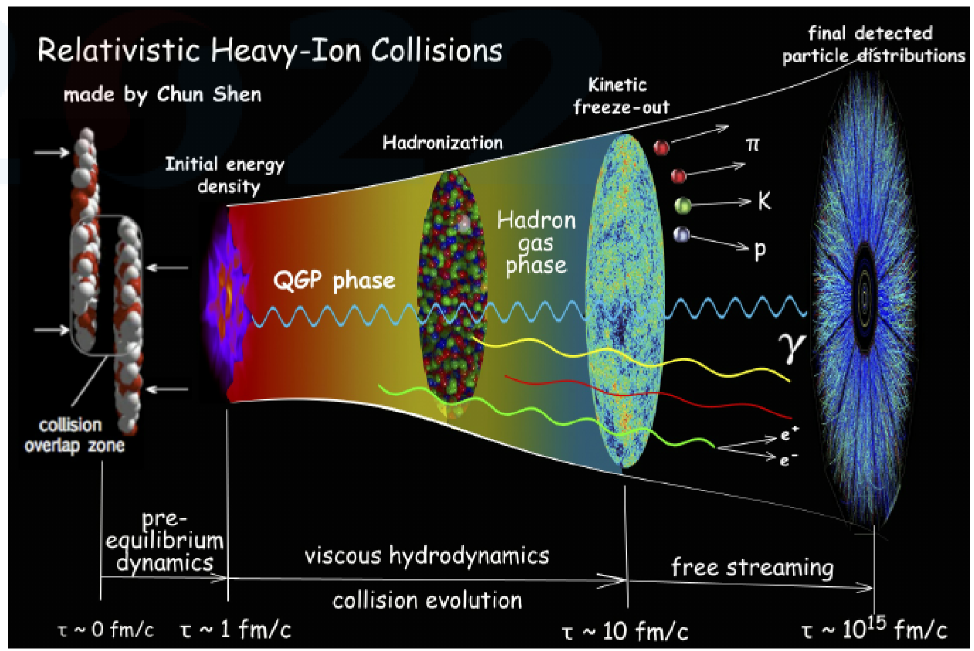
Expansion

QGP

Hadronization

Chemical and kinetic freeze-out





Specific of Heavy Quarks

- $m_{c,b} >> \Lambda_{QCD}$

produced by pQCD process (out of equilibrium)

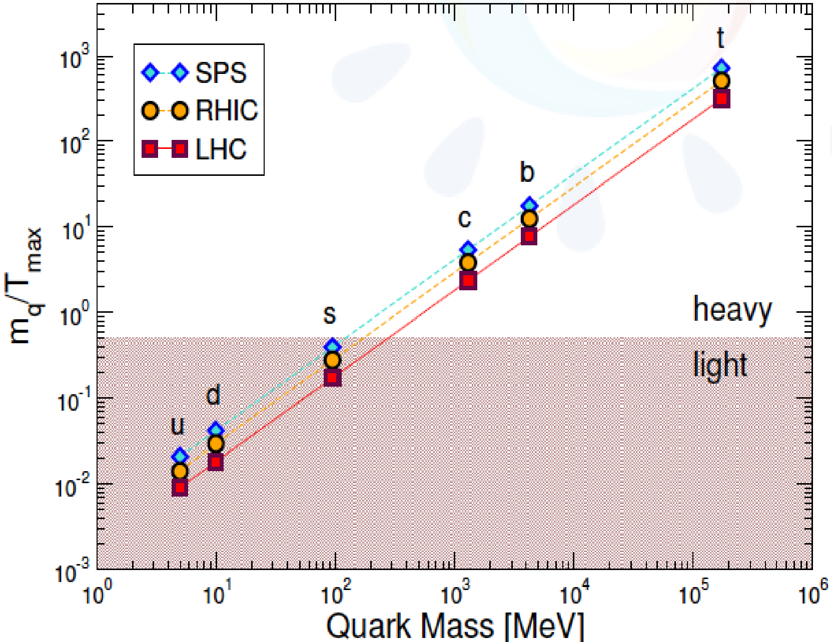
- $m_{c,b} >> T_0$

negligible thermal production

- $\tau_0 << \tau_{QGP}$
- $\tau_{therm.} \approx \tau_{QGP} >> \tau_{g,q}$

HQs experience the full QGP evolution

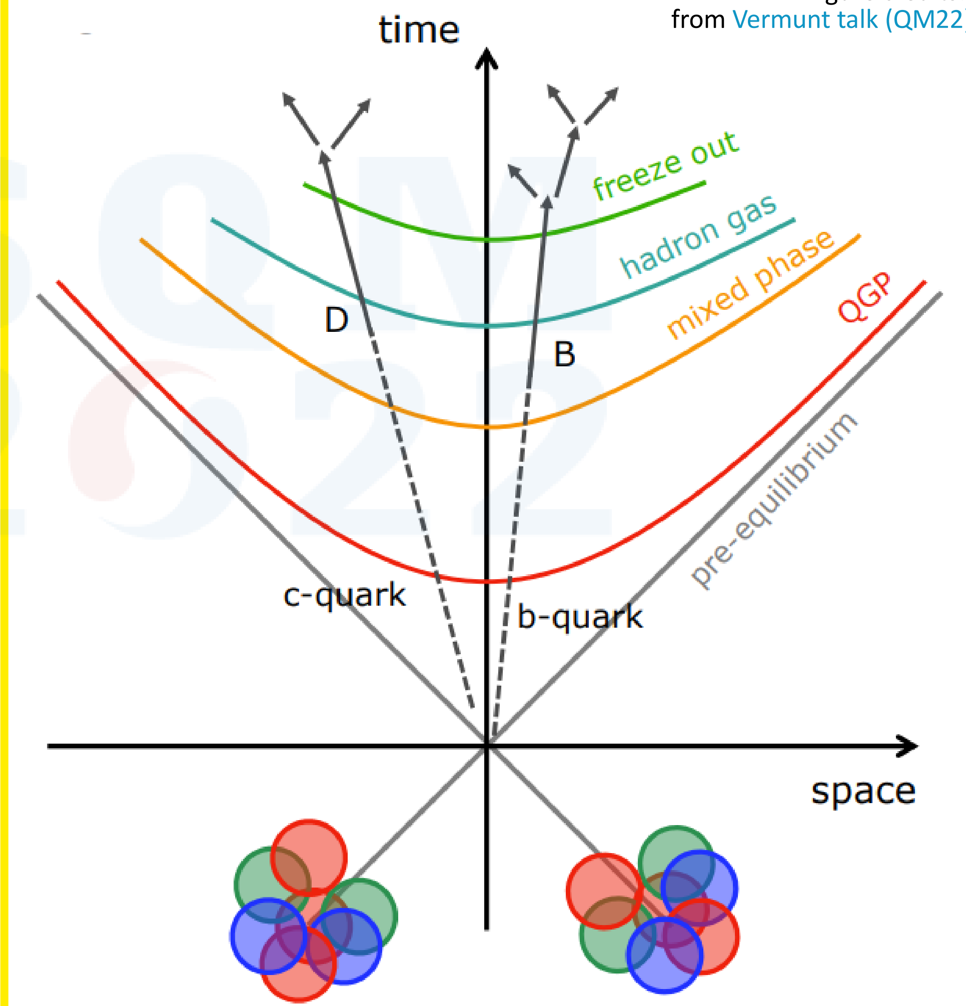
Carry informations about initial stages, more than light quarks



Recent reviews:

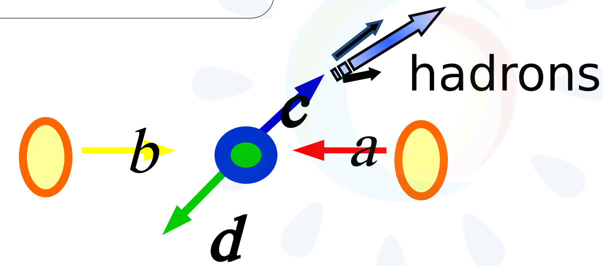
1) X.Dong, V. Greco Prog. Part. Nucl. Phys. 104 (2019)
2) A.Andronic Eur.Phys.J.C 76 (2016) 3, 107
3) F.Prino, R.Rapp, J.Phys.G 43 (2016) 9, 093002

Figure credits: from Vermunt talk (QM22)



Heavy flavour Hadronization

Microscopic



Fragmentation:

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

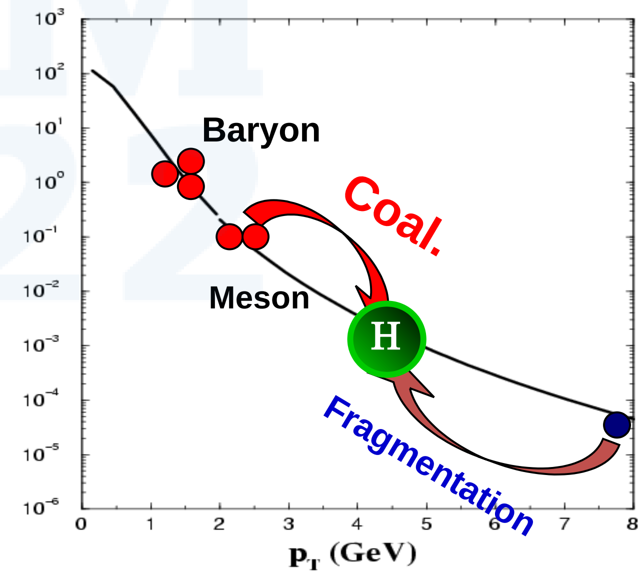
$$\sigma_{pp\to h} = PDF(x_a, Q^2)\, PDF(x_b, Q^2) \otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to h}(z, Q^2)$$

Parton shower: 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



Statistical hadronization:

Macroscopic

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

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

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 AA collisions 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 pp collisions the charm distribution are the FONLL distribution

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

Catania Model: Coalescence + Fragmentation

Statistical factor colour-spin-isospin · **Parton Distribution function** · **Hadron Wigner function**

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

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

Catania Model: Coalescence + Fragmentation

Statistical factor colour-spin-isospin

Parton Distribution function

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

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

Assuming gaussian wave function

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

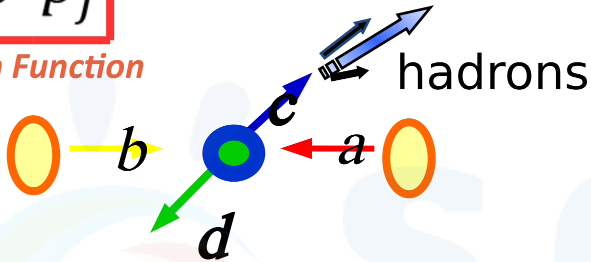
only one width coming from $\phi_M(\mathbf{r})$, constraint $\sigma_r \sigma_p = 1$

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

Catania Model: Coalescence + Fragmentation

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

Parton Distribution Function

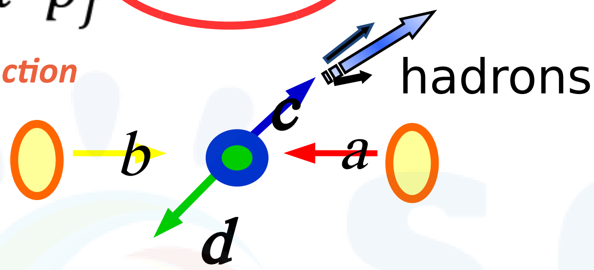


The distribution function is evaluated at the Fixed-Order plus Next-to-Leading-Log (FONLL)
M. Cacciari, P. Nason, R. Vogt, PRL 95 (2005) 122001
In AA: bulk+charm evolution with Relativistic Transport Boltzmann Equation

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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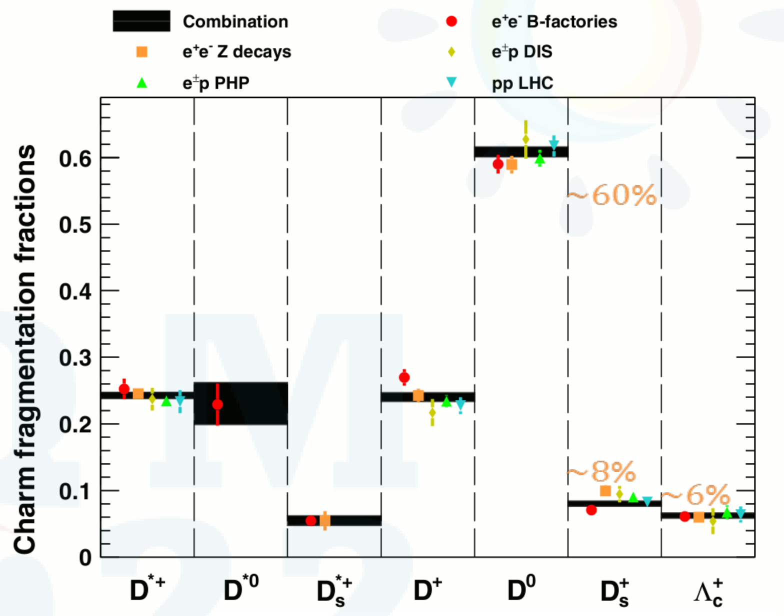


M. Lisovyi, et al. EPJ C76 (2016) no.7, 397

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

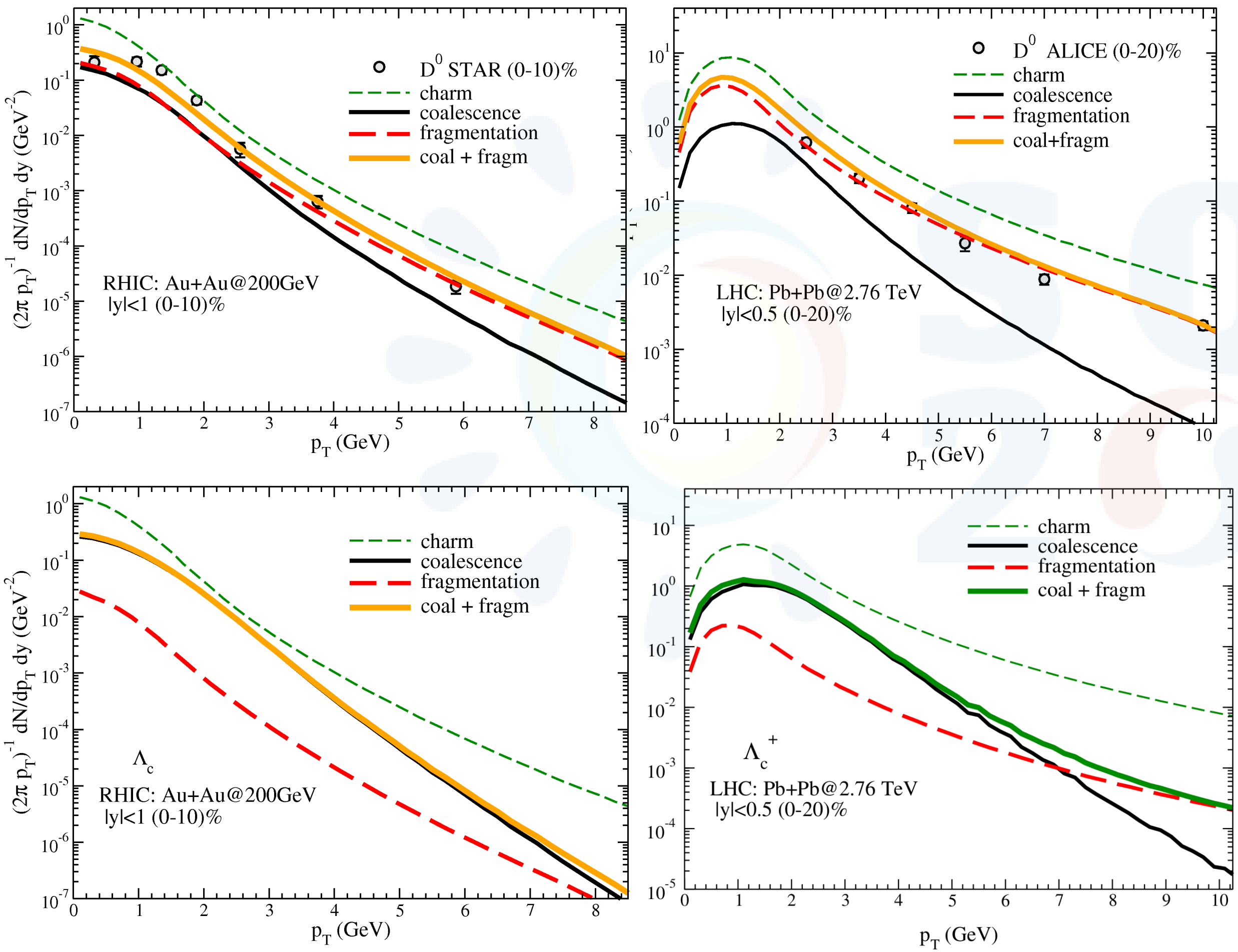
Charm Fragmentation Fraction (c→h)
Measurement in $e^{\pm} p$, $e^+ e^-$ *and old pp data*

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

AA @ RHIC & LHC

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

Data from: STAR Coll. PRL 113, 142301 (2014), ALICE Coll. JHEP 09 (2012) 112



D^0

Coalescence lower at LHC than at RHIC

main contribution: Fragmentation

Λ_c

Coalescence lower at LHC than at RHIC

main contribution:Coalescence

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

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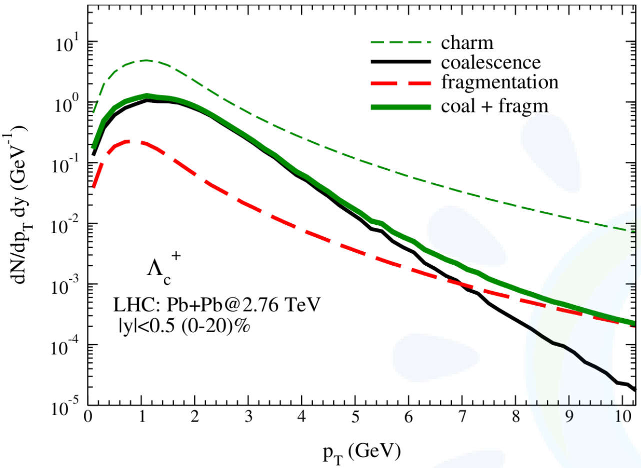
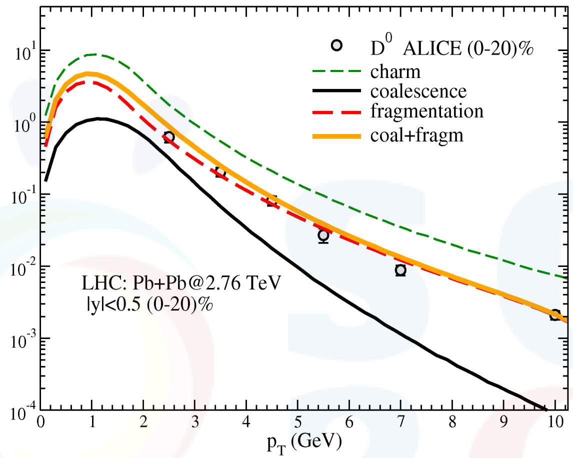
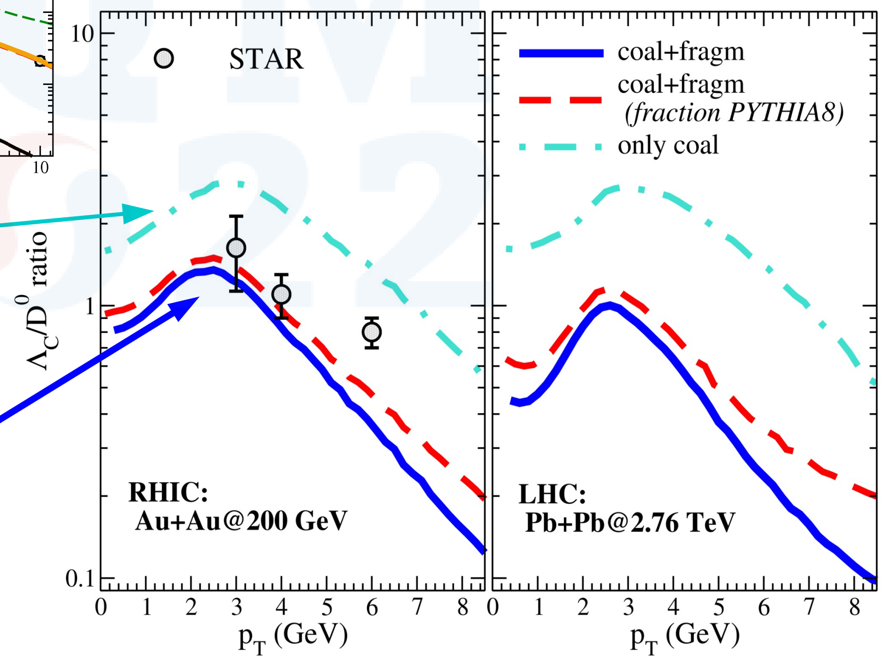




Coalescence lower at LHC than at RHIC



Only Coalescence ratio is similar at both energies.

Fragmentation ~ 0.1 at both energies.

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.

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

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

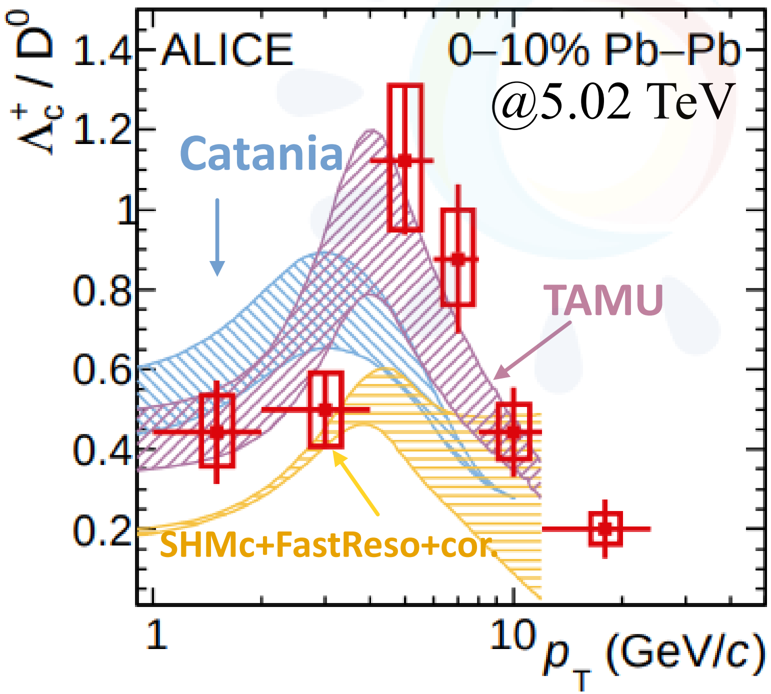
AA @ RHIC & LHC

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

Results for 0-10% in PbPb @5.02TeV:

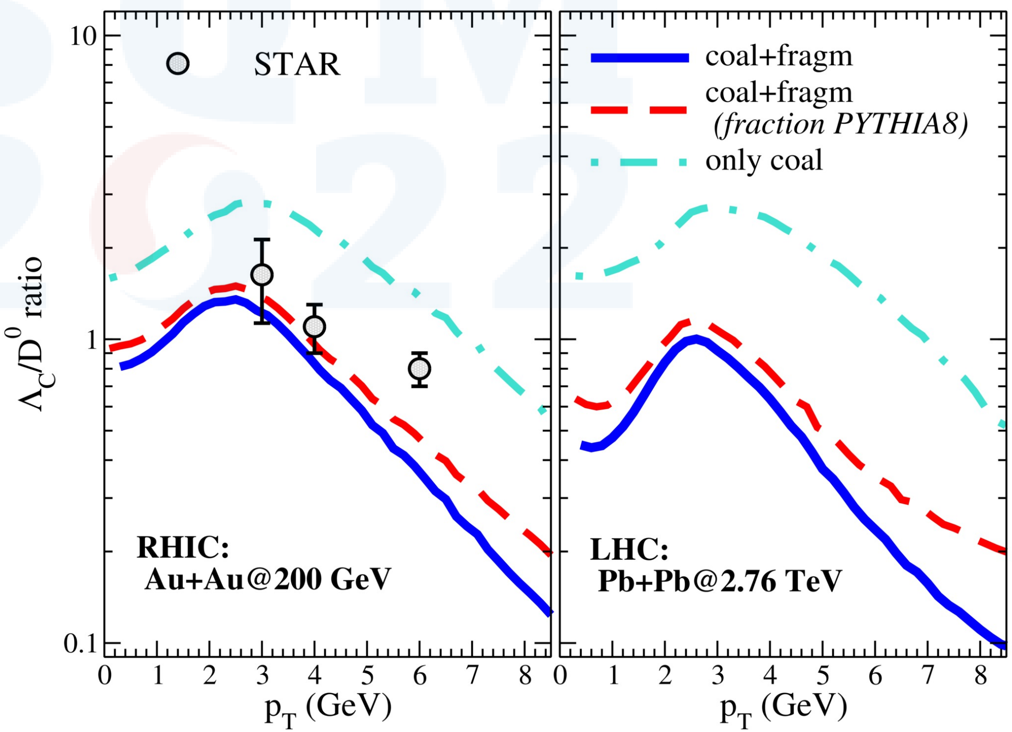
Consistent with the trend shown at RHIC and LHC @2.76TeV

Available data at low p_T → differences recombination vs SHM



ALICE Coll. arXiv:2112.08156v1

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



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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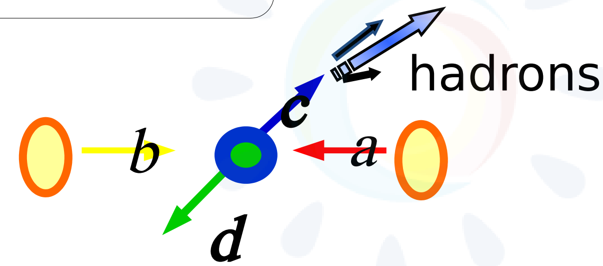
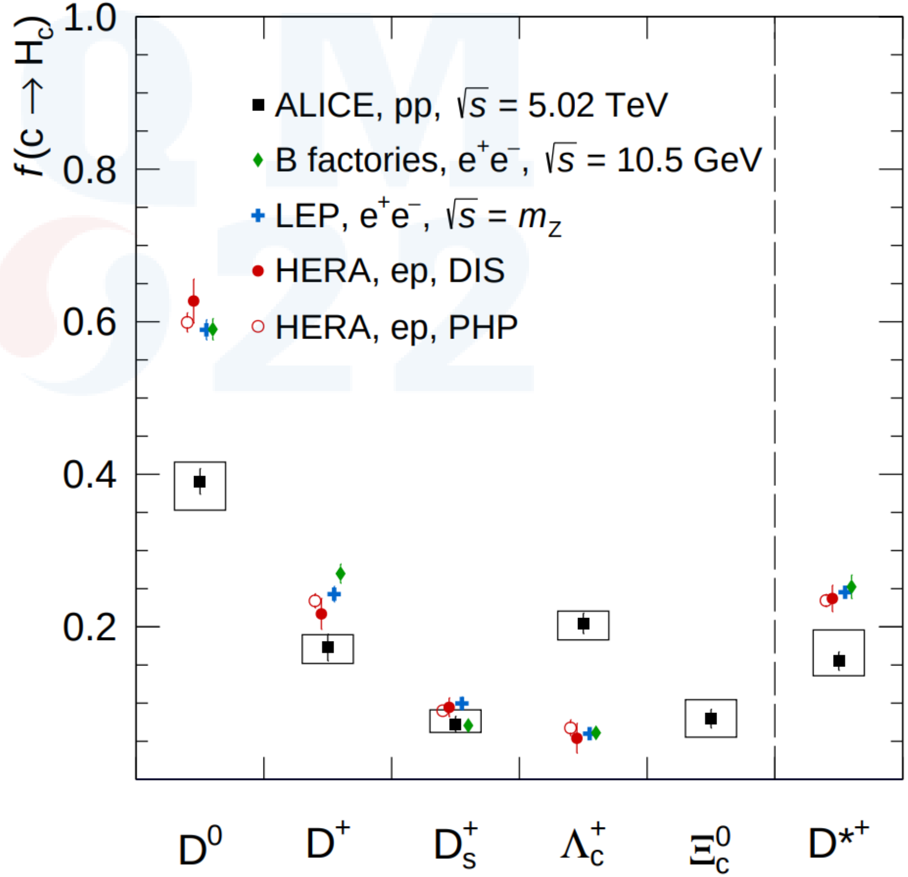


ALICE,Phys.Rev.D 105 (2022) 1, L011103

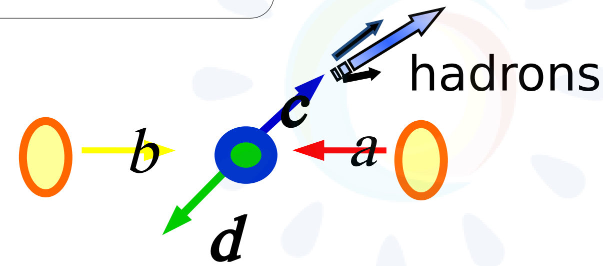


Things get more complicated after experimental evidence in pp@5TeV:

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

No more Universality?

Heavy flavour Hadronization



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

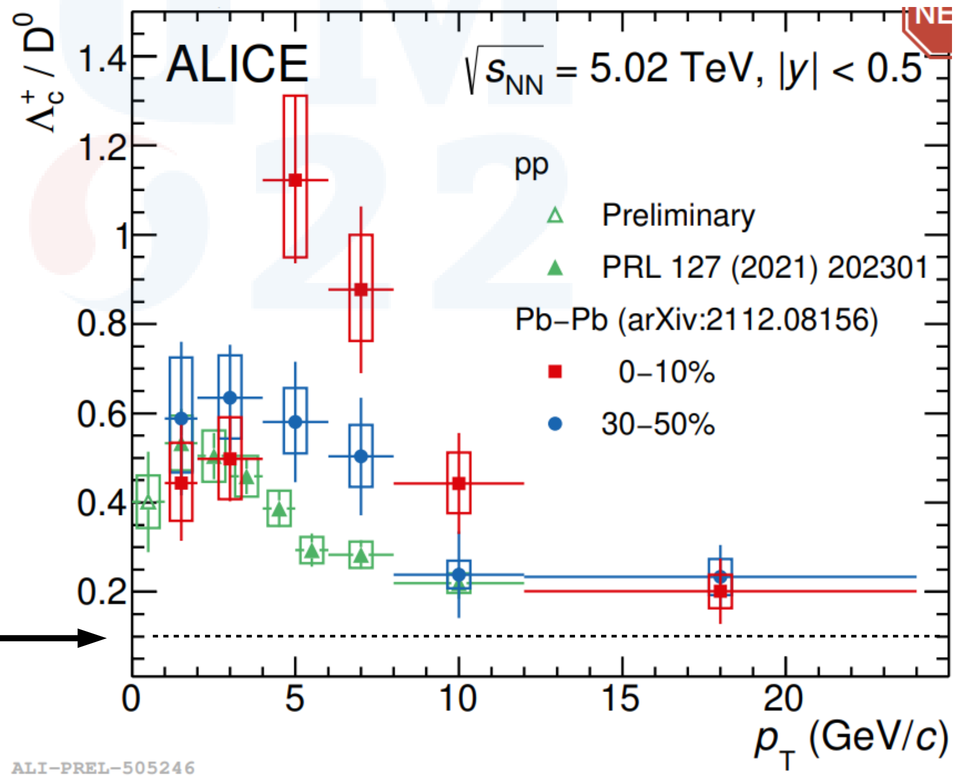
Things get more complicated after experimental evidence in pp@5TeV:

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

No more Universality?

<u>Baryon/meson ratio is underestimated, and no p_T dependence</u>

$$\left(\frac{\Lambda_c^+}{D^0}\right)_{e^+e^-} \simeq 0.1$$

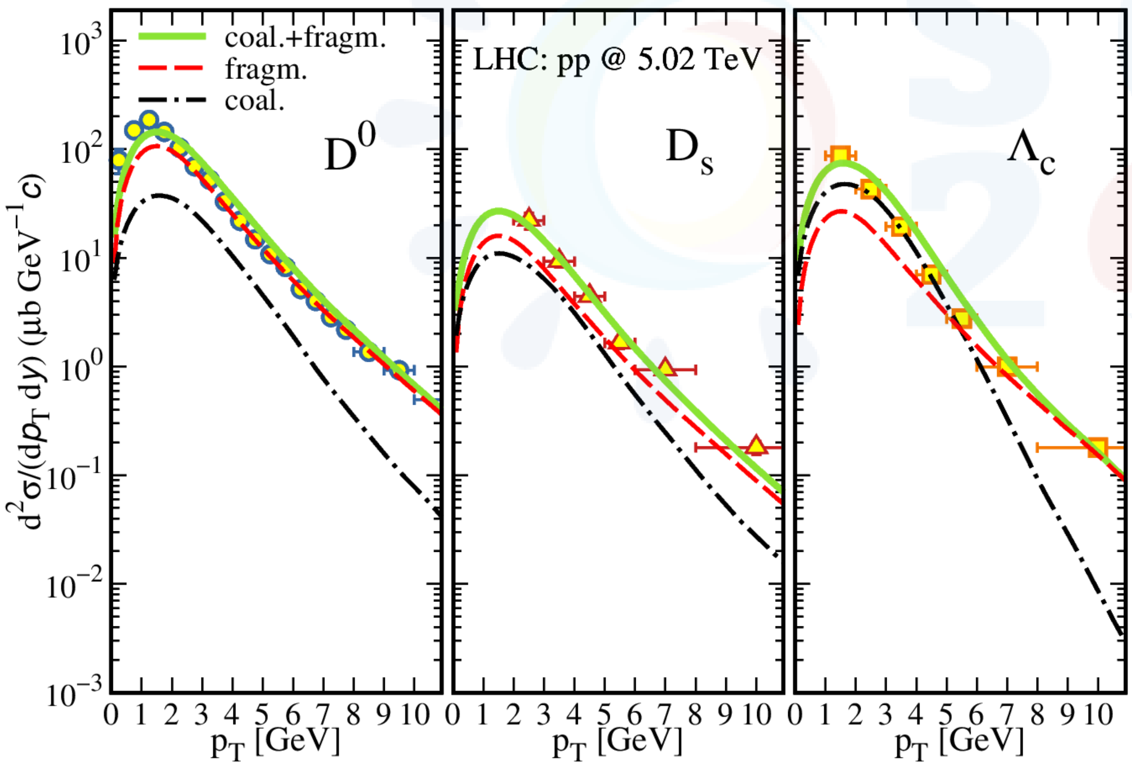


Small systems: Coalescence in pp?

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)
ALICE Coll., Phys.Rev.Lett. 127 (2021) 20, 202301 - Phys.Rev.C 104 (2021) 5, 054905



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

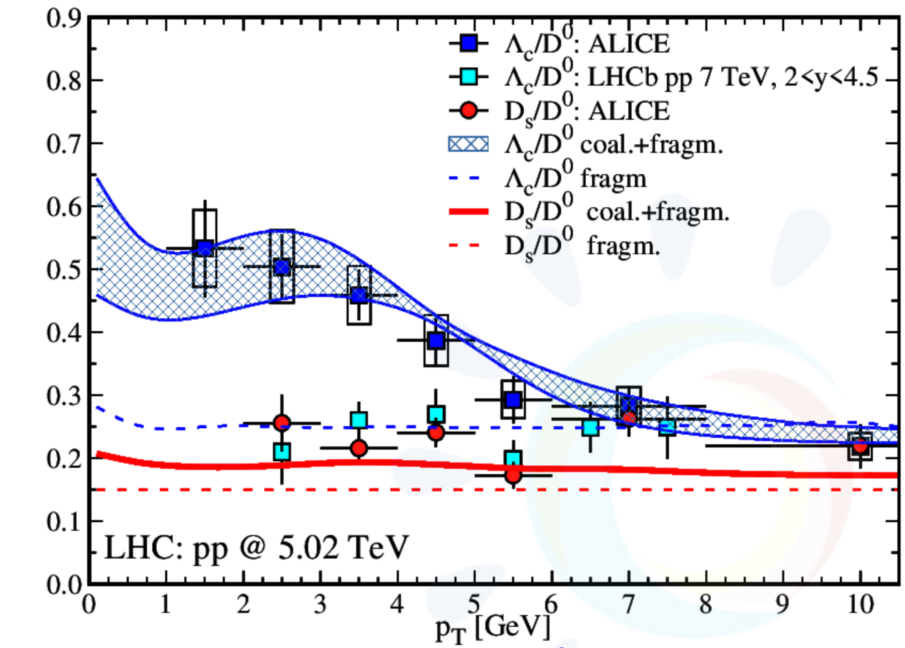
FONLL Distribution

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

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

Small systems: Coalescence in pp?

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



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

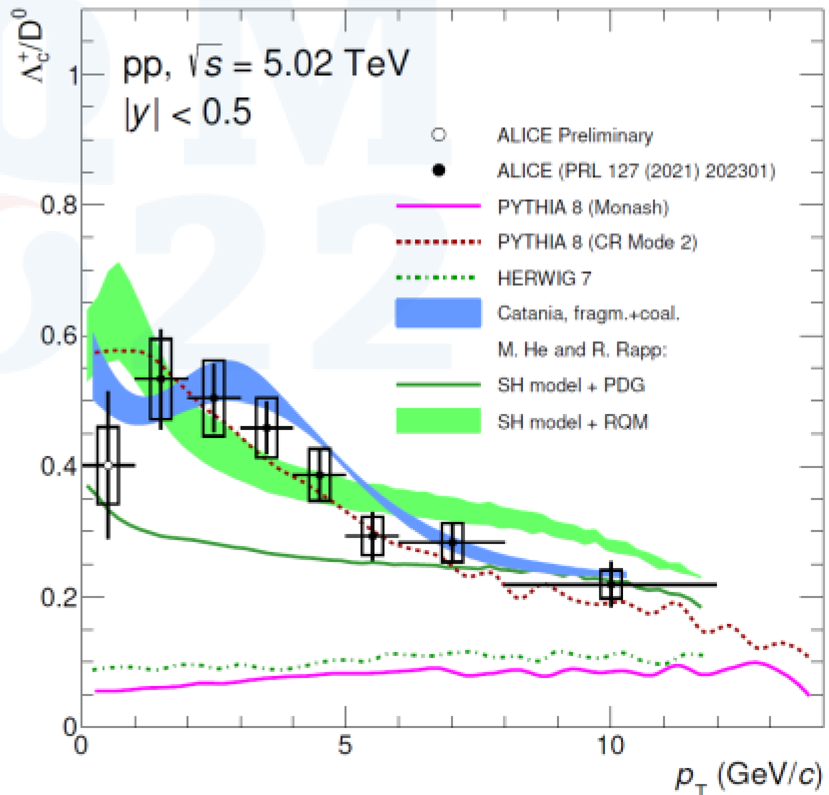
Reduction of rise-and-fall behaviour in Λ_c / D^0 ratio:

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

-FONLL distribution flatter w/o evolution trough QGP

-Volume size effect

The increase of Λ_c production in pp have effect on R_{AA} of Λ_c



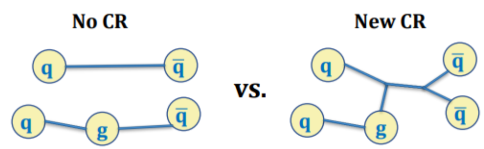
ALICE, Phys.Rev.Lett. 127 (2021) 20, 202301

Other models:

He-Rapp, Phys.Lett.B 795 (2019) 117-121: Increase≈2 to Λ_c production: SHM with resonance not present in PDG

PYTHIA8 + color reconnection

CR with SU(3) weights and string length minimization



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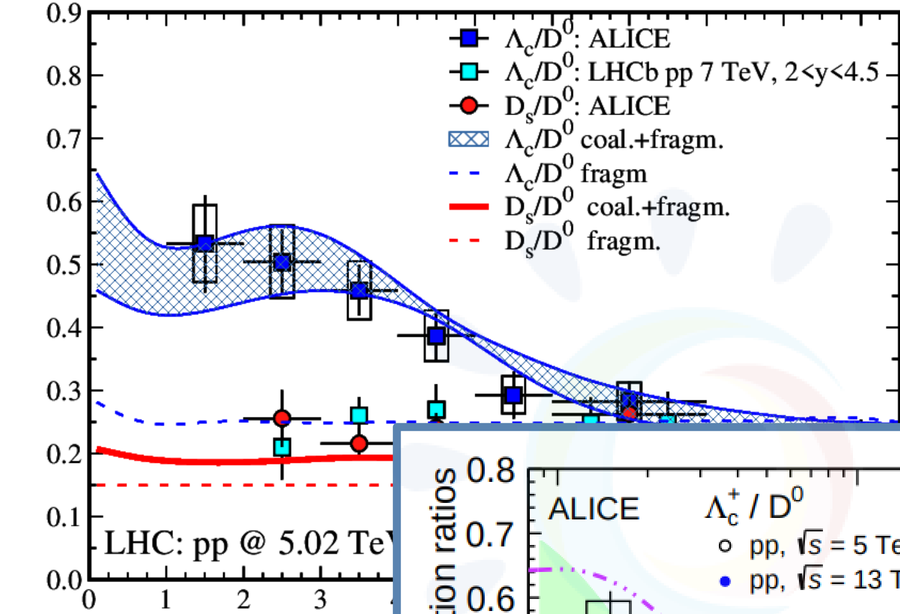

Error band correspo

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

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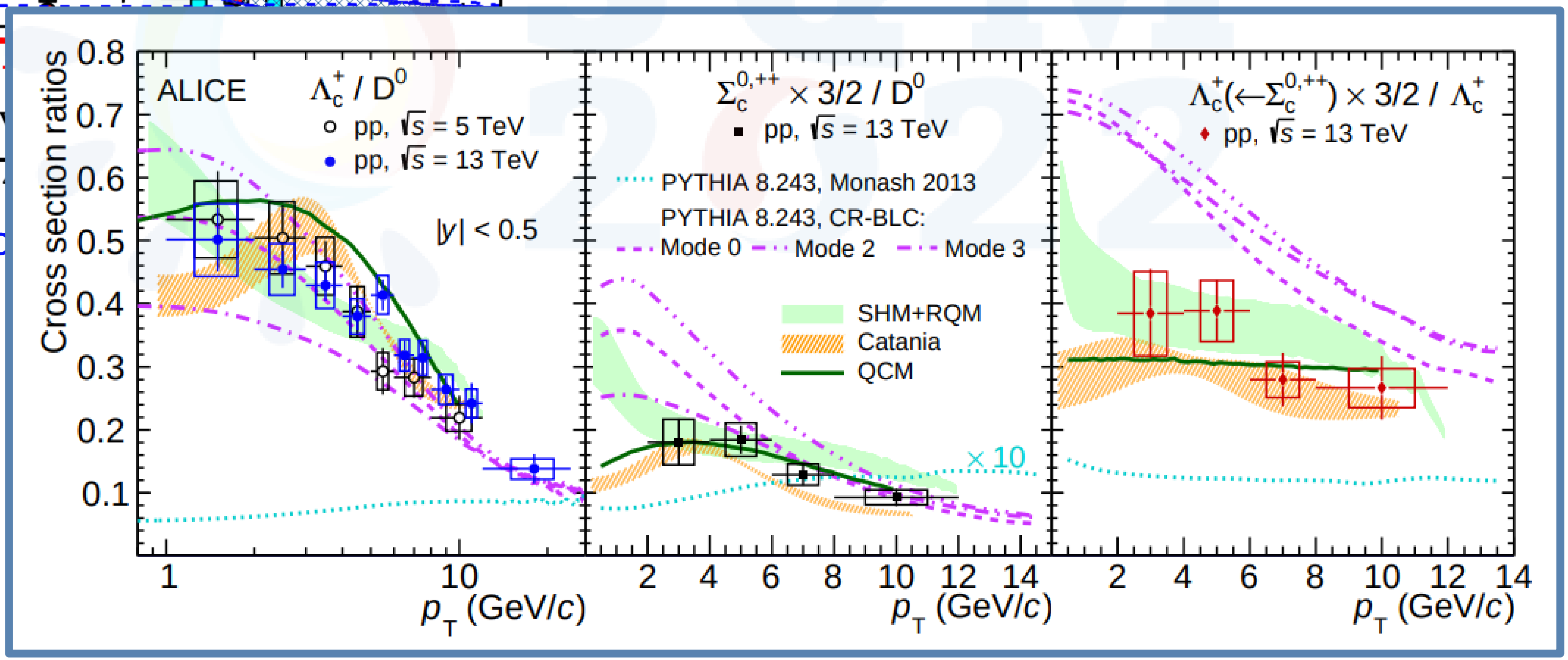

ALICE Coll., Physical Review Letters 128, 012001 (2022)

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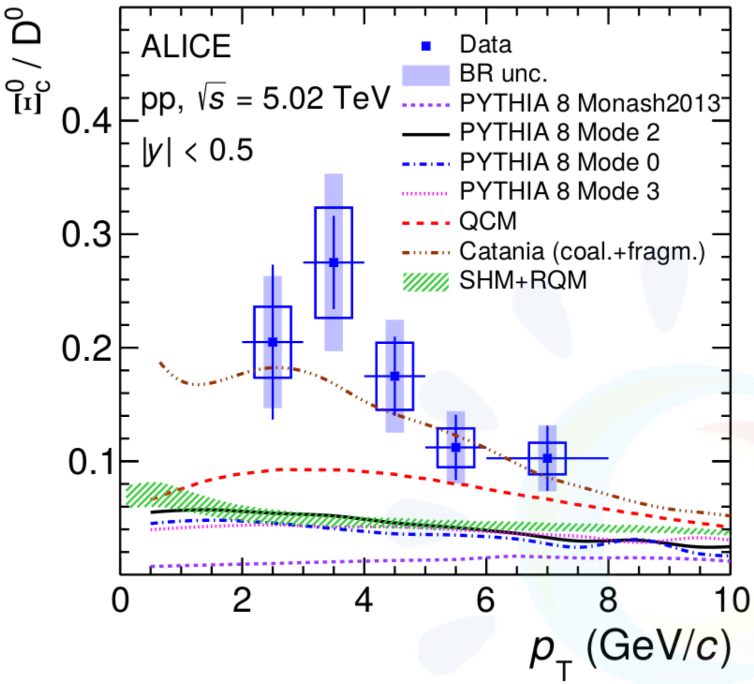
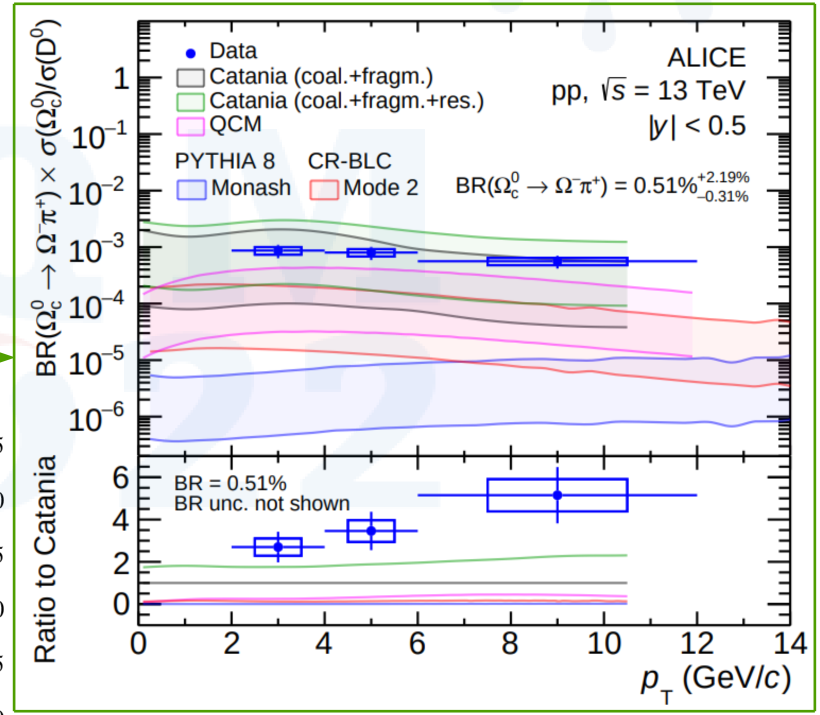


New measurements of heavy hadrons at ALICE:

- 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

Uncertainties bands coming from the Branching Ratio error



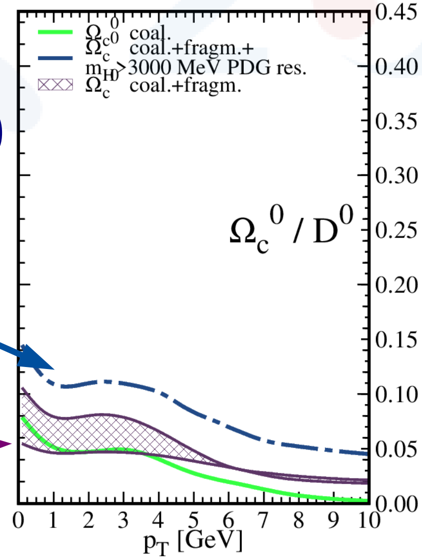
ALICE Coll. JHEP 10 (2021) 159
ALICE Coll. arXiv:2205.13993

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

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

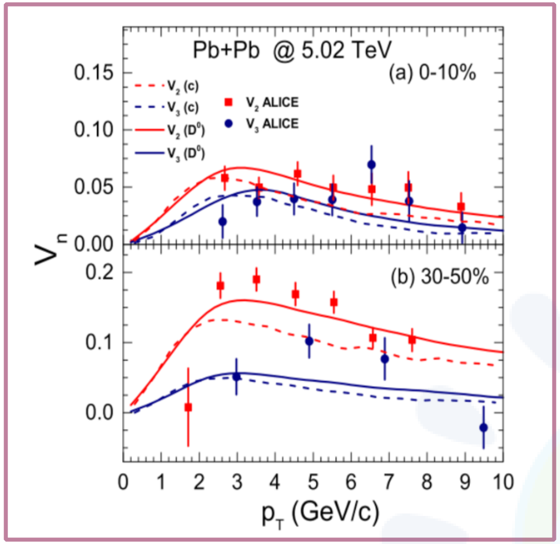
supply an idea of how these states may affect the ratio

Error band correspond to <r² > uncertainty in quark model



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

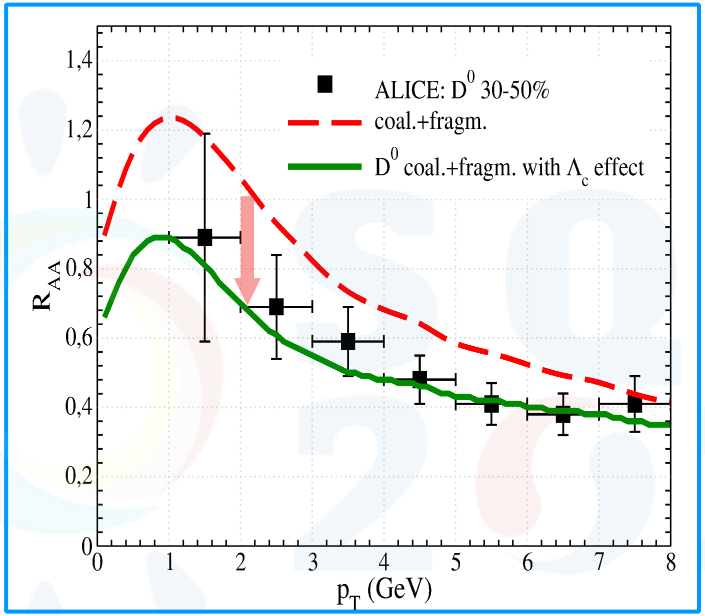
Implications, developments and outlooks:

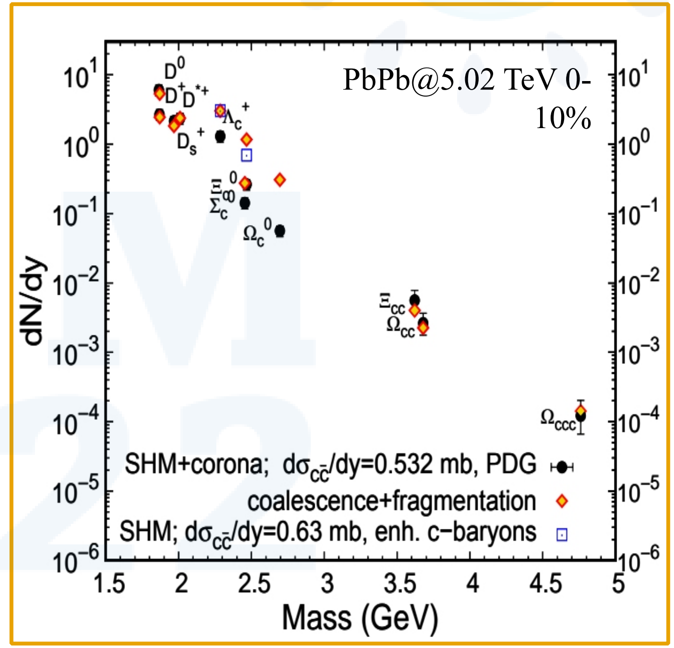


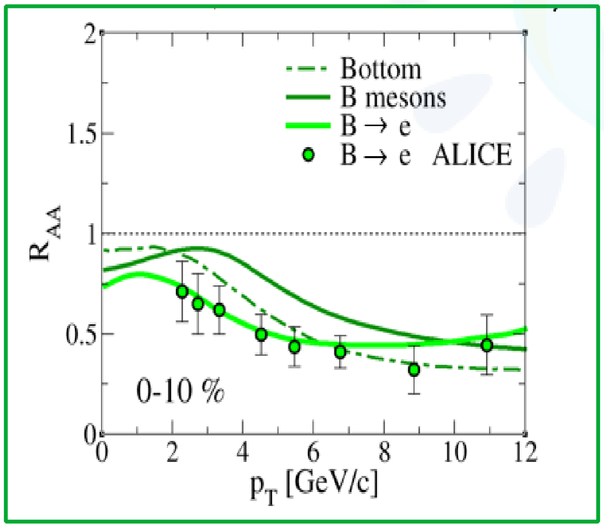
Coalescence give an enhancement to the $v_n(p_T)$ of final hadrons compared to the charm $v_n(p_T)$.

Sambataro,Sun,Minissale,Plumari,Greco, arxiv:2206.03160

MULTICHARM







The large Λ_c production has effects on the R_{AA} of D^0, because of the charm conservation

Yields of multicharm hadrons similar to SHM in PbPb, possible effects with system size and on the distribution vs p_T are under investigation.

A baryon like Ω_{ccc} formed only by heavy quarks can give insights on the baryon wave function and the potential $V_{cc}(r,T)$ between quarks.

Enhancement for single charmed baryons as seen in pp collisions.

Electrons from semileptonic B meson decay with a coal + fragm model for B meson production

Sambataro, Minissale et al.(in preparation)

Minissale, Plumari, Greco (in preparation)

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

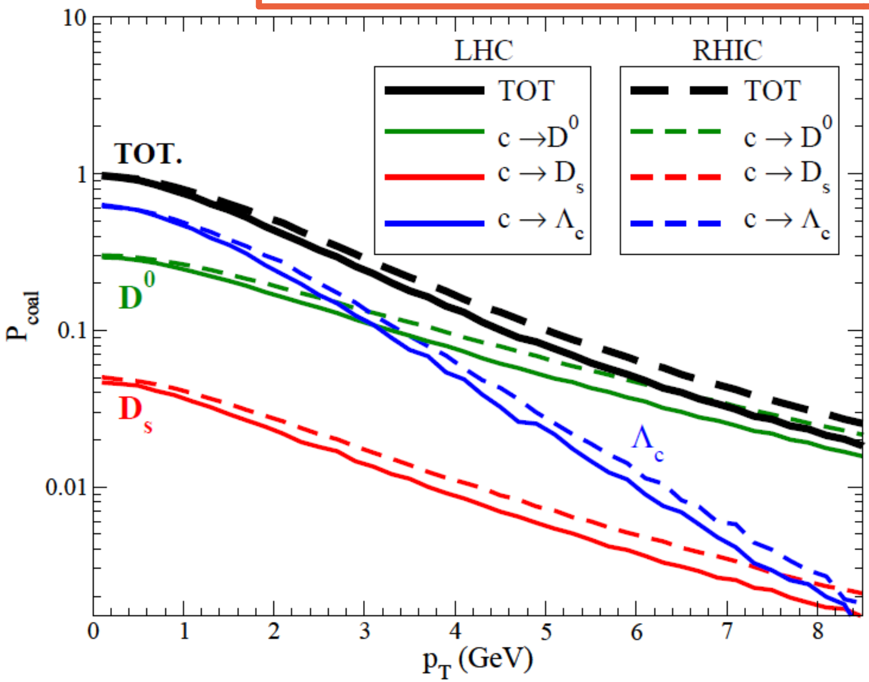
Statistical factor colour-spin-isospin

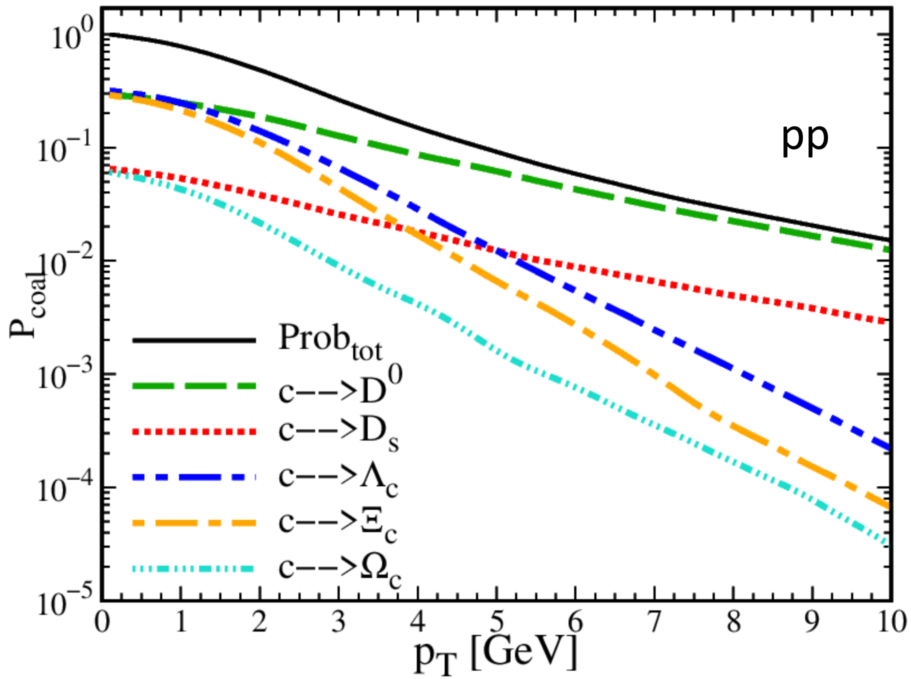
Parton Distribution function

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%

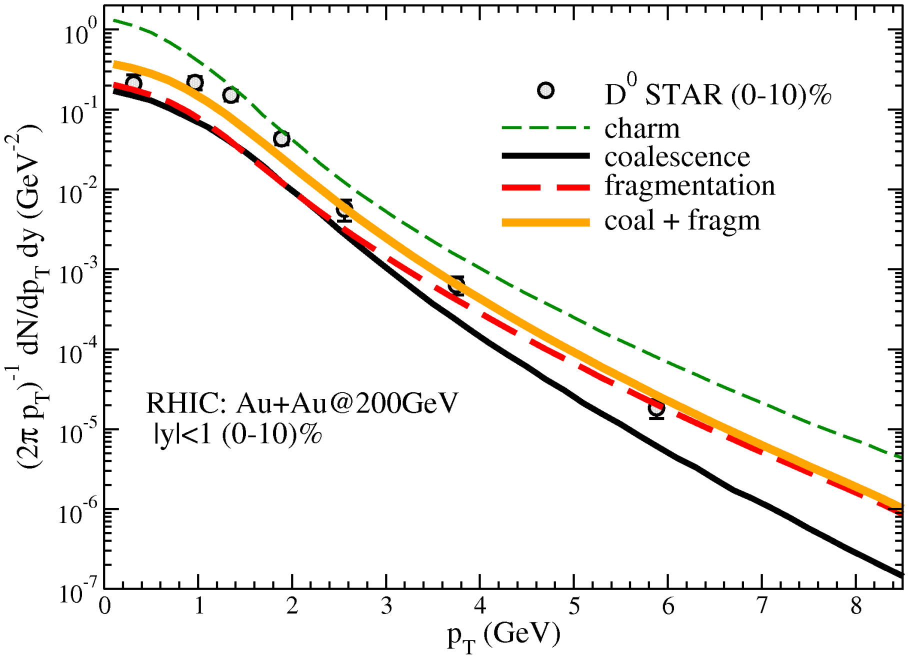
In our calculations we take into account hadronic channels including the ground states + first excited states

Statistical factor suppression for resonances

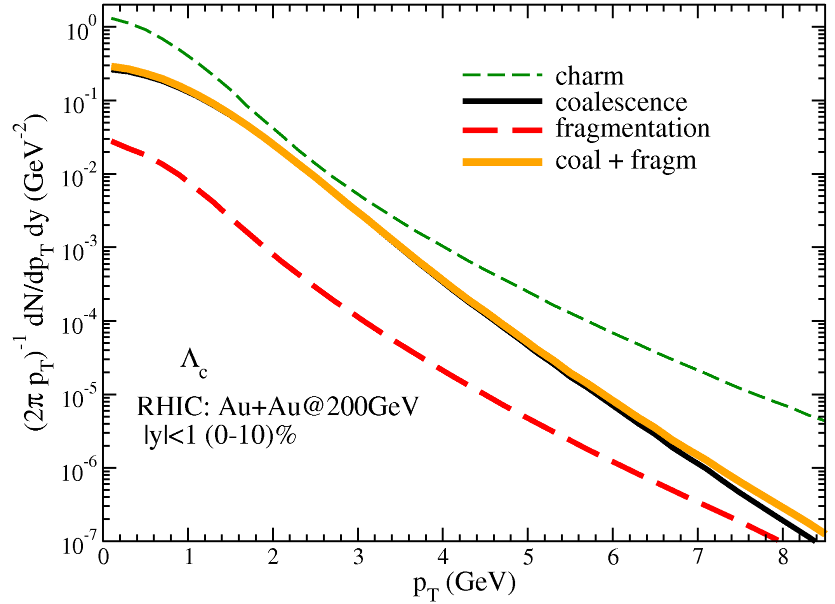
$$\frac{[(2J+1)(2I+1)]_{H^*}}{[(2J+1)(2I+1)]_{H}}\left(\frac{m_{H^*}}{m_H}\right)^{3/2} e^{-(m_{H^*}-m_H)/T}$$

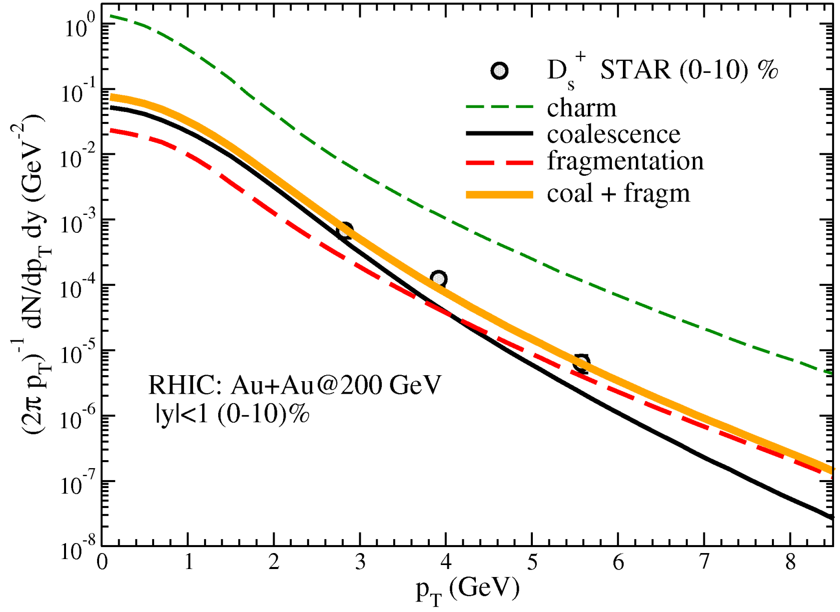
RHIC: results

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



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

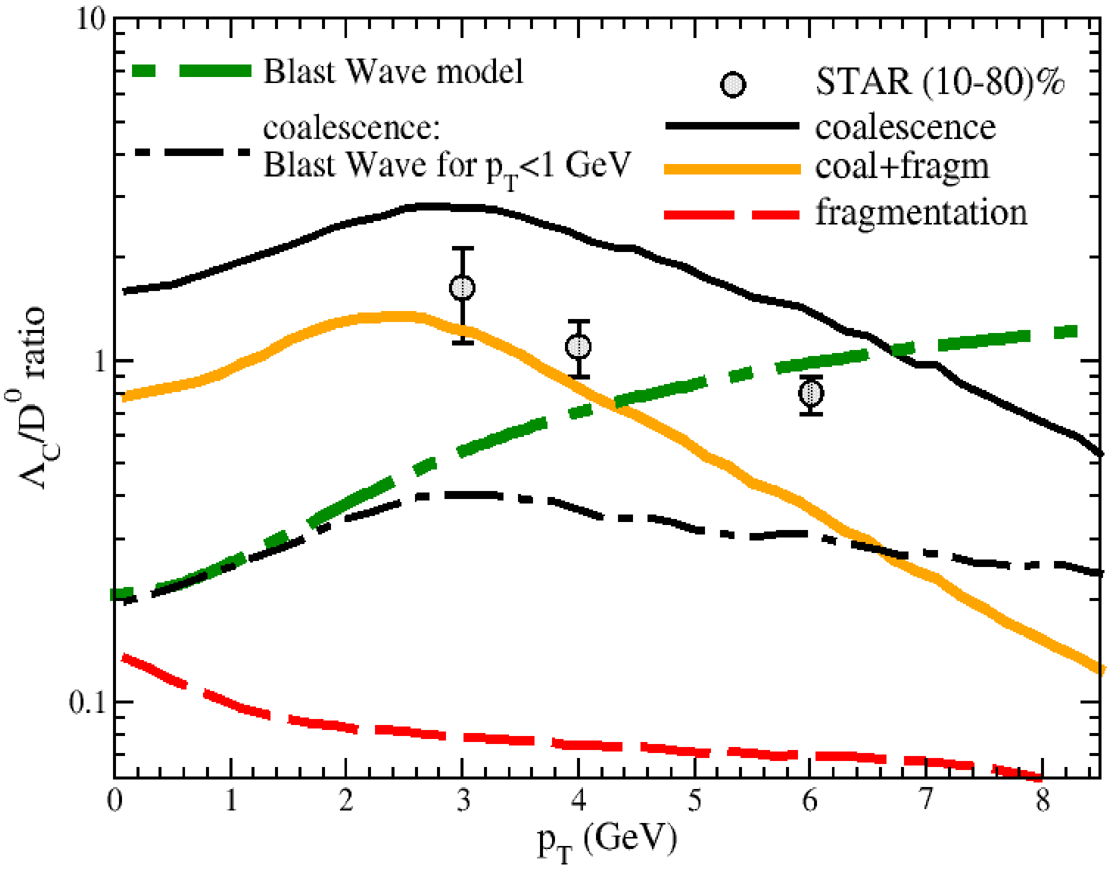




- For D^0 coalescence and fragmentation comparable at 2 GeV
- fragmentation fraction for D^+_s are small and less than about 8% of produced total heavy hadrons
- Λ_c^+ fragmentation is even more smaller, coalescence gives the dominant contribution

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

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

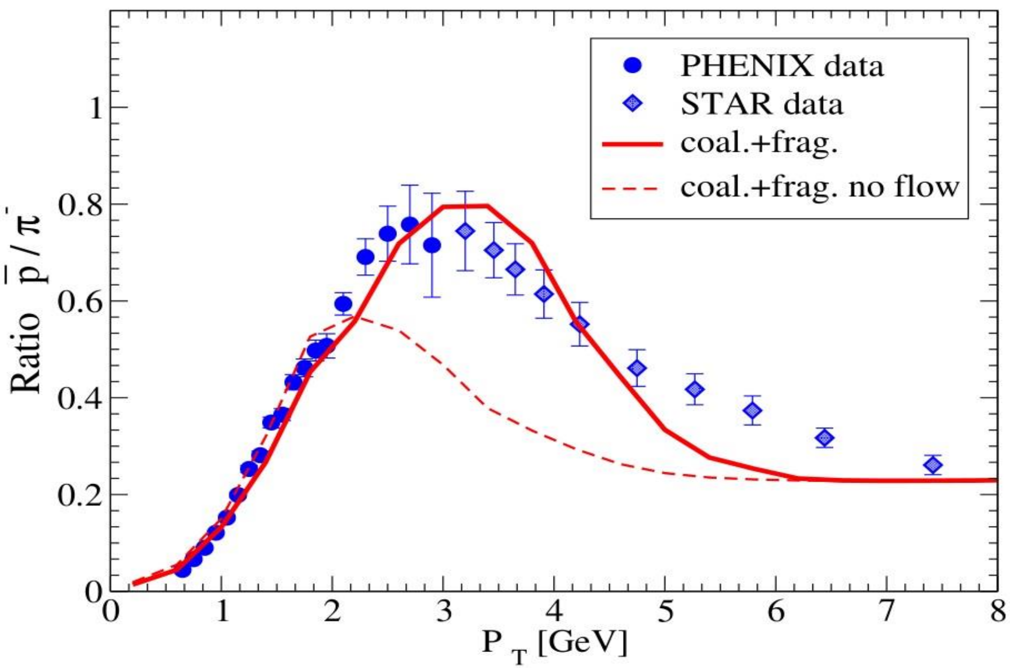
Partonic elliptic flow

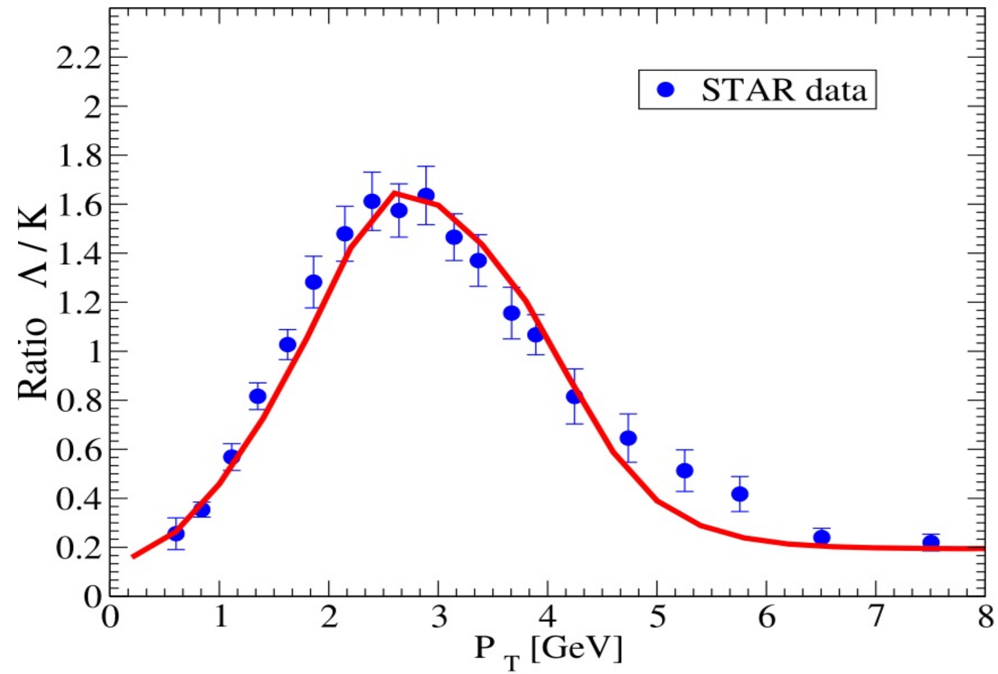
Hadronic elliptic flow

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 $p_T \simeq 2\text{–}4 GeV$ with respect to *pp* collisions
- Lack of baryon yield in the region $p_T \simeq$ 5–7GeV

Relativistic Boltzmann transport at finite η/s

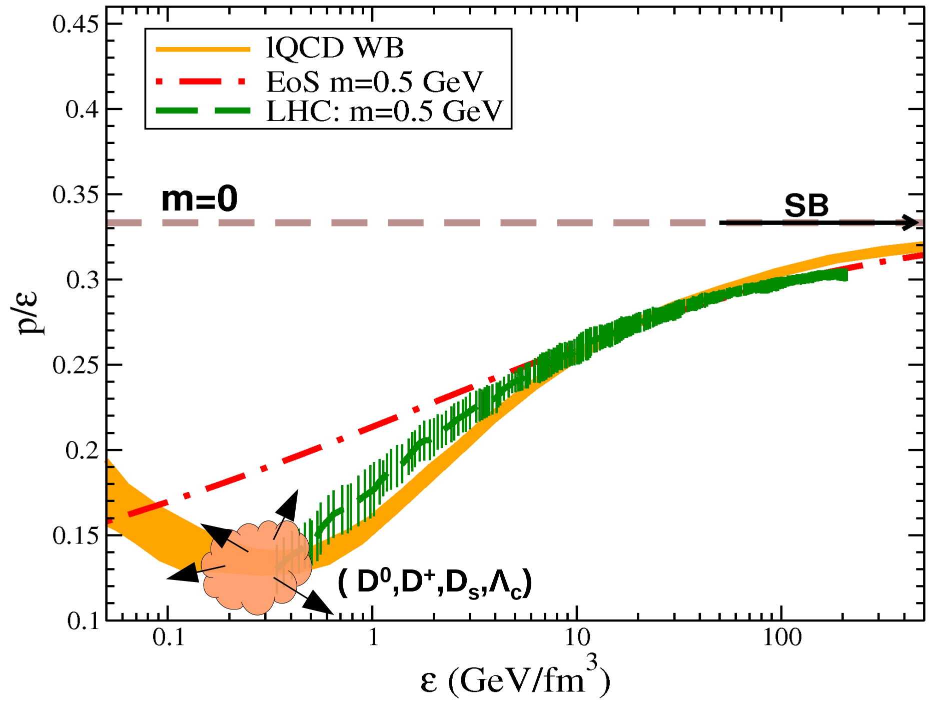
Bulk evolution

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

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).