Recombination of heavy quarks for meson and baryon production in a large range of collisions systems

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Outline

Hadronization:

- Coalescence model
- Fragmentation

Heavy hadrons in AA collisions:

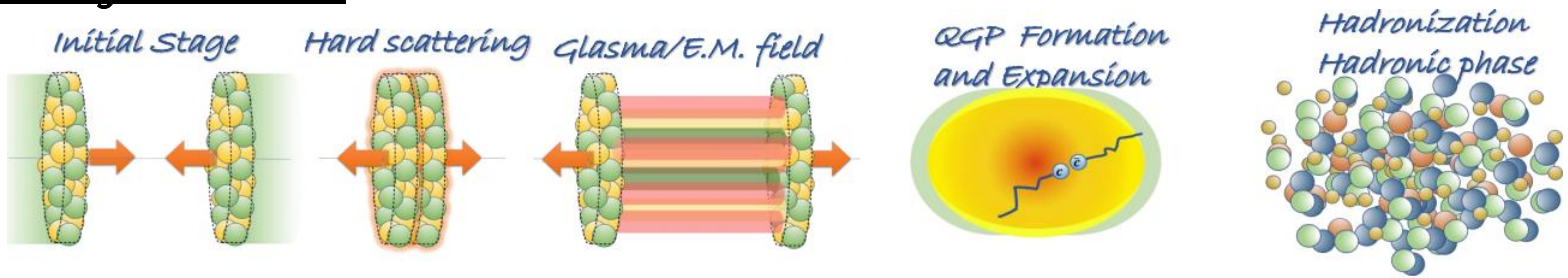
- Λ_c , D spectra and ratio: RHIC and LHC
  S. Plumari, et al. Eur. Phys. J. C 78, no.4, 348 (2018)
- Multicharm production
  V. Minissale, et al., Eur. Phys. J. C 84, no.3, 228 (2024)

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

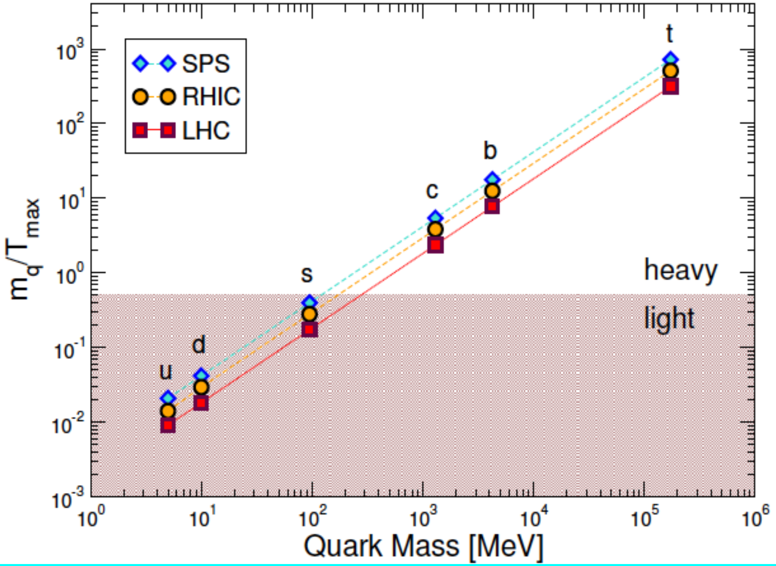
- Λ_c/D^0 , Ξ_c/D^0, Ω_c/D^0 *V. Minissale, et al., Phys. Lett. B 821, 136622 (2021)*
- Λ_b/B^0, Ξ_b/B^0 , Ω_b/B^0 *V. Minissale et al, Phys. Lett. B 860 (2025) 139190*

Specific of Heavy Quarks

Figure credits:
Plumari talk (QM25)



- $m_{c,b} \gg \Lambda_{QCD}$ produced by pQCD process (out of equilibrium)
- $m_{c,b} \gg T_0$ negligible thermal production
- $\tau_0 \ll \tau_{QGP}$ HQs experience the full QGP evolution
- $\tau_{therm} \approx \tau_{QGP} \gg \tau_{g,q}$ carry informations about initial stages, more than light quarks



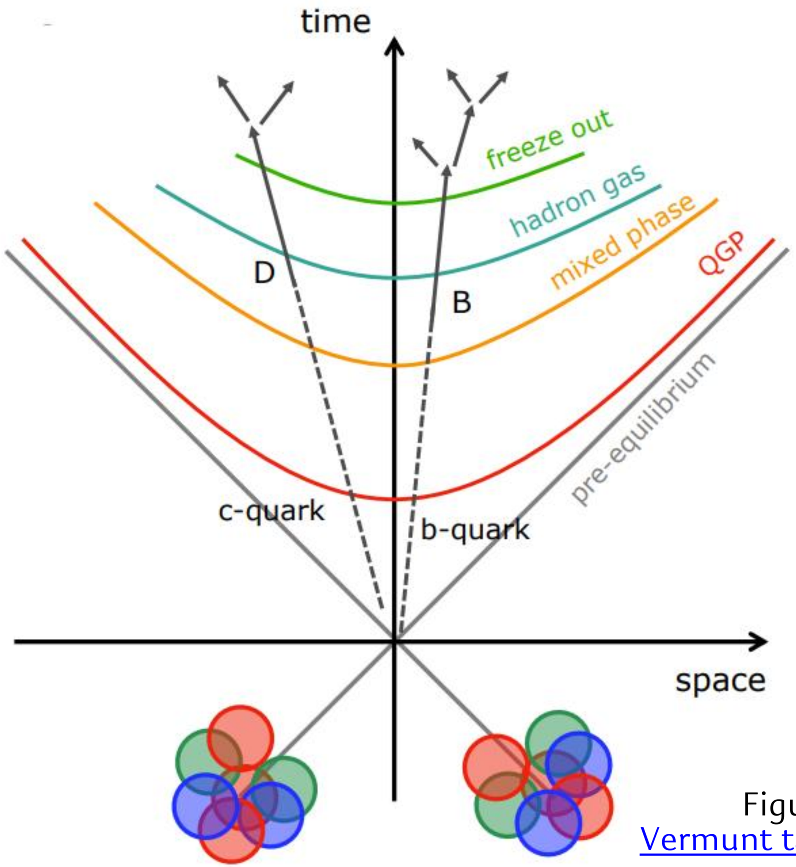
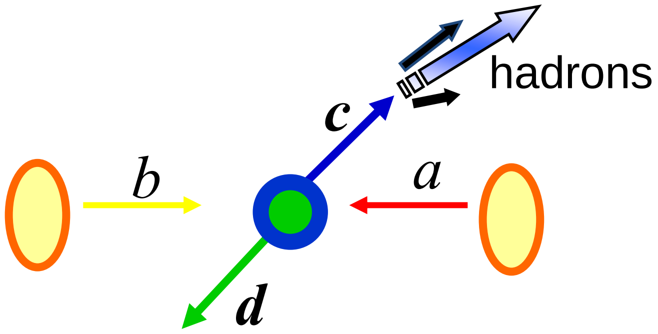


Figure credits:
Vermunt talk (QM22)

Heavy flavour Hadronization



Fragmentation:

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

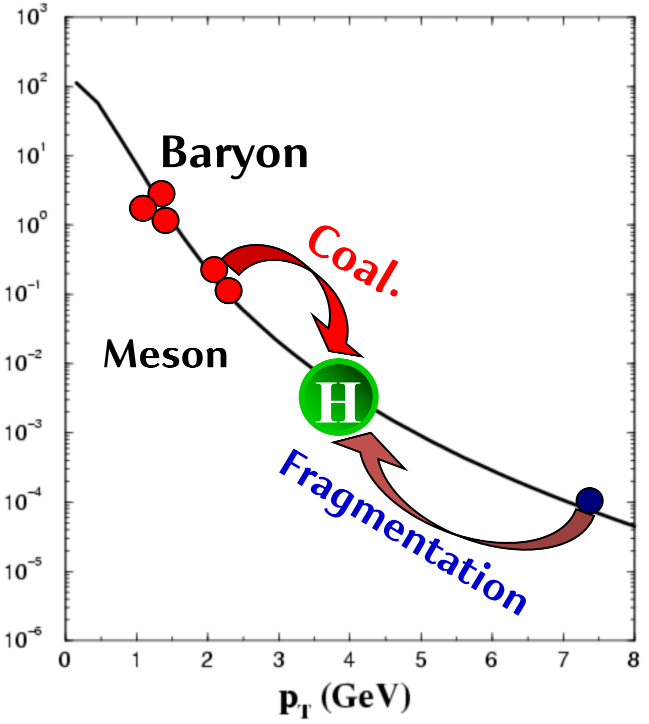
$$\sigma_{pp\to h} = PDF(x_a, Q^2)PDF(x_b, Q^2)\otimes\sigma_{ab\to q\bar{q}}\otimes D_{q\to h}(z, Q^2)$$

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

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

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



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

Comparison between hadronization mechanisms (HF Collaboration) in Phys.Rev.C 109 (2024) 5, 054912

Catania Model: Coalescence + Fragmentation

Statistical factor colour-spin-isospin — *Parton Distribution function* — *Hadron Wigner function* $C_H = \mathcal{N} f_H$

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

Wigner function – Wave function

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

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

Assuming gaussian wave function

$$f_H(\ldots) = \prod_{i=1}^{N_q-1} 8\exp\left(\frac{-x_{ri}^2}{\sigma_{ri}^2} - p_{ri}^2\sigma_{ri}^2\right)$$

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

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

$\sigma_{ri} = 1/\sqrt{\mu_i\omega}$

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

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

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

Meson	$\langle r^2\rangle_{ch}$	σ_{p1}	Baryon	$\langle r^2\rangle_{ch}$	σ_{p1}	σ_{p2}
$B^-[b\bar{u}]$	-0.378	0.302	$\Lambda_b^0[udb]$	0.13	0.264	0.5
$\bar{B}^0[b\bar{d}]$	0.187	0.303	$\Xi_b^0[usb]$	0.16	0.279	0.527
$\bar{B}_s^0[b\bar{s}]$	0.119	0.374	$\Xi_b^-[dsb]$	-0.21	0.295	0.557
$B_c^-[b\bar{c}]$	-0.043	0.74	$\Omega_b^-[ssb]$	-0.18	0.318	0.592

Catania Model: Coalescence + Fragmentation

Statistical factor colour-spin-isospin

Parton Distribution function

Hadron Wigner function $C_H = \mathcal{N} f_H$

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

Wigner function – Wave function

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)

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

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

Assuming gaussian wave function

$$f_H(\ldots) = \prod_{i=1}^{N_q-1} 8 \exp\left(\frac{-x_{ri}^2}{\sigma_{ri}^2} - p_{ri}^2\sigma_{ri}^2\right)$$

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

Normalization $\mathcal{N}$ of $C_H(\ldots)$ requiring that $P_{coal}=1$ at $p_T=0$

The charm that does not coalesce undergo fragmentation

Catania Model: Coalescence + Fragmentation

Statistical factor colour-spin-isospin

Parton Distribution function

Hadron Wigner function $C_H = \mathcal{N} f_H$

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

LIGHT

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

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

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

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

PbPb@5TeV(0-10%): $\tau_f = 8{,}5\frac{fm}{c} \rightarrow V_{|y|<0{,}5} = 4500\, fm^3$

+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:

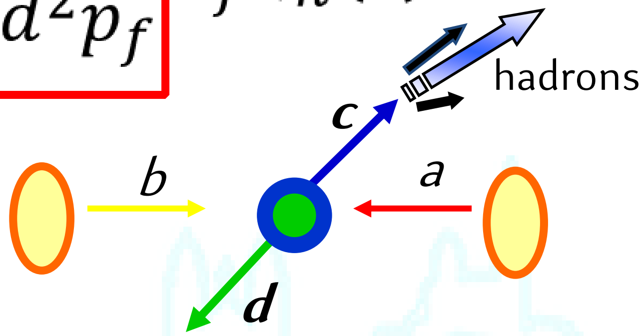
parton simulations solving relativistic Boltzmann transport equation

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

Catania Model: Coalescence + Fragmentation

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

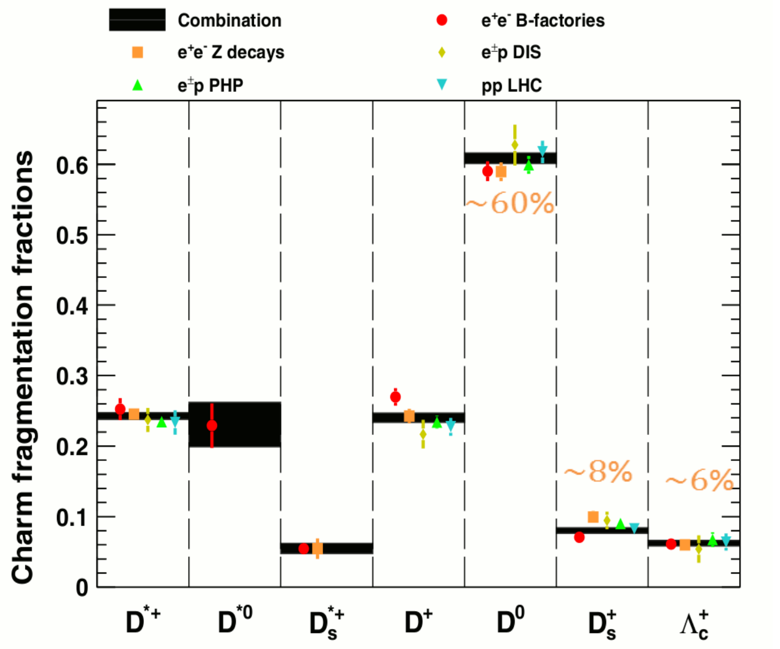
Parton Distribution Function



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



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± p, e+ e- and old pp data*

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

AA @ RHIC & LHC

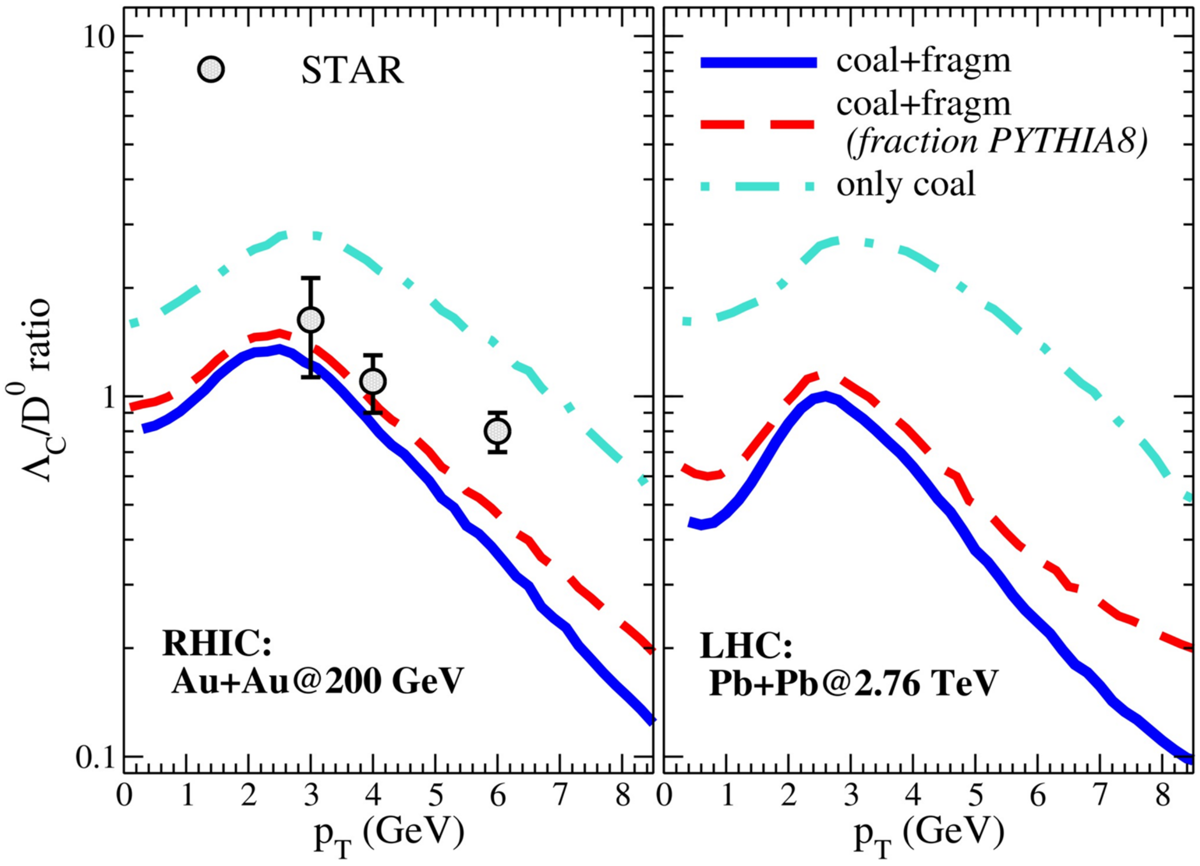
wave function widths σ_p of baryon and mesons are the same at RHIC and LHC!

Results for 0-10% in PbPb @5.02TeV, consistent with the trend shown at RHIC and LHC @2.76TeV

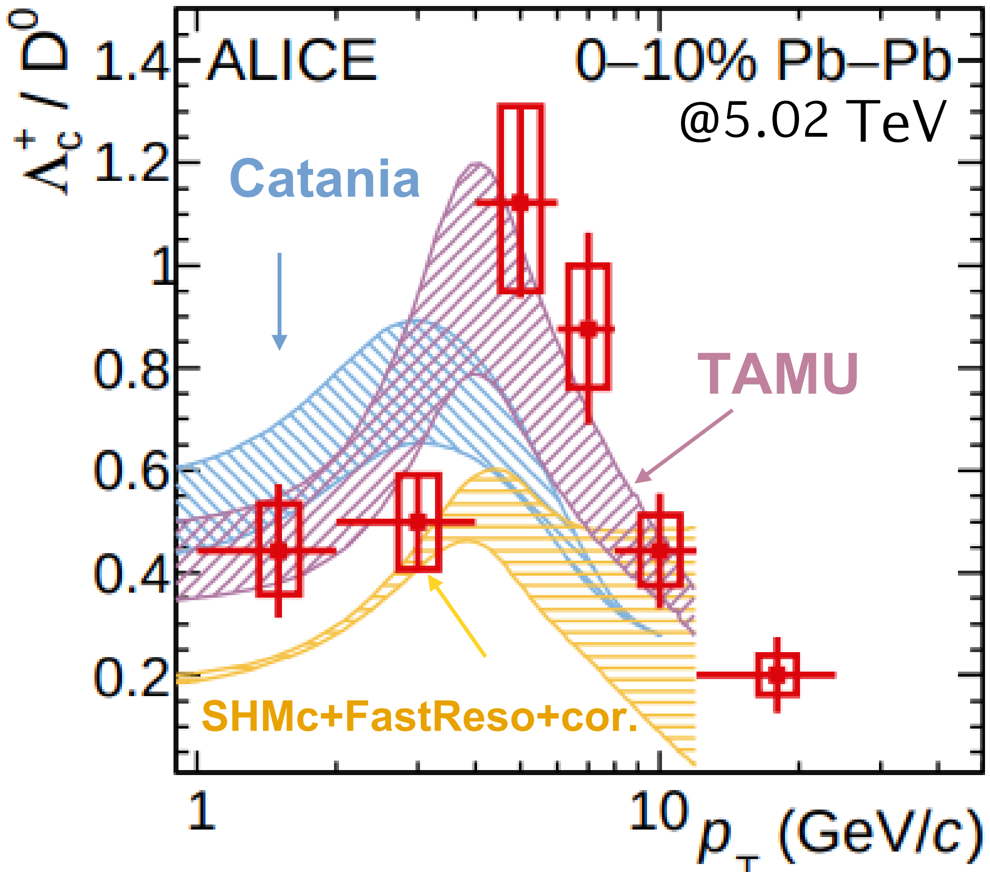
Λ_c production is dominated by coalescence contribution → enhancement in $\Lambda_c/D^0 \sim 1$

Available data at low p_T → differences recombination vs SHM

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

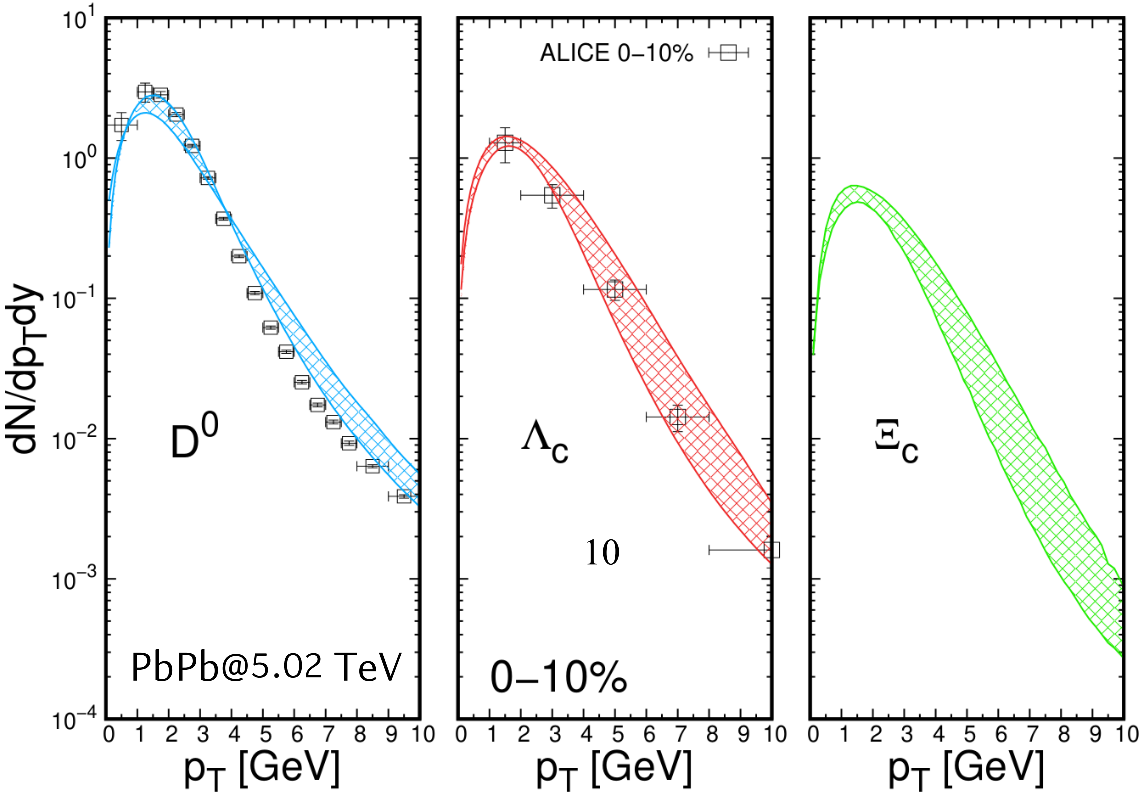


ALICE Coll. Phys. Lett. B 839 (2023) 137796



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

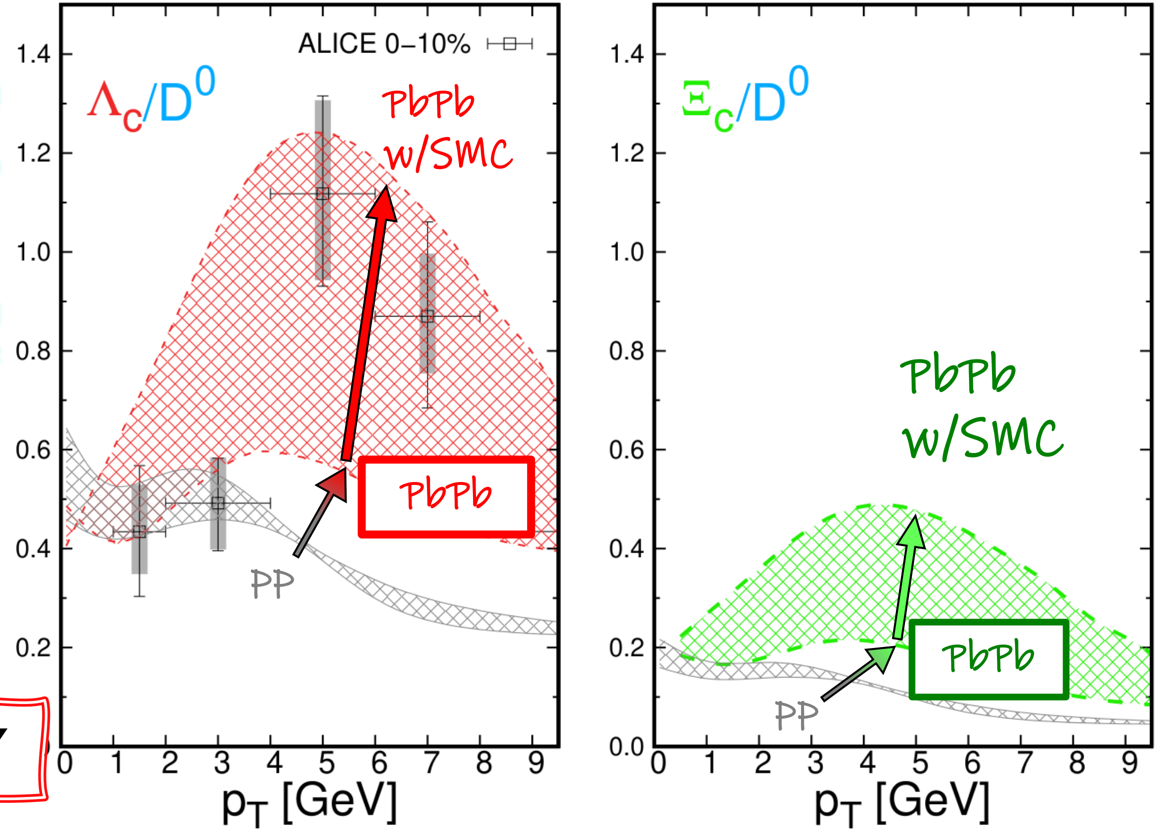
Space-Momentum-Correlations effect on D^0, Λ_c and Ξ_c



Further increase in the baryon over meson ratio.

SMC favour the recombination of quarks with a larger effect on baryons w.r.t. mesons.

In these preliminary calculation we show a case with large correlation between charm and the bulk

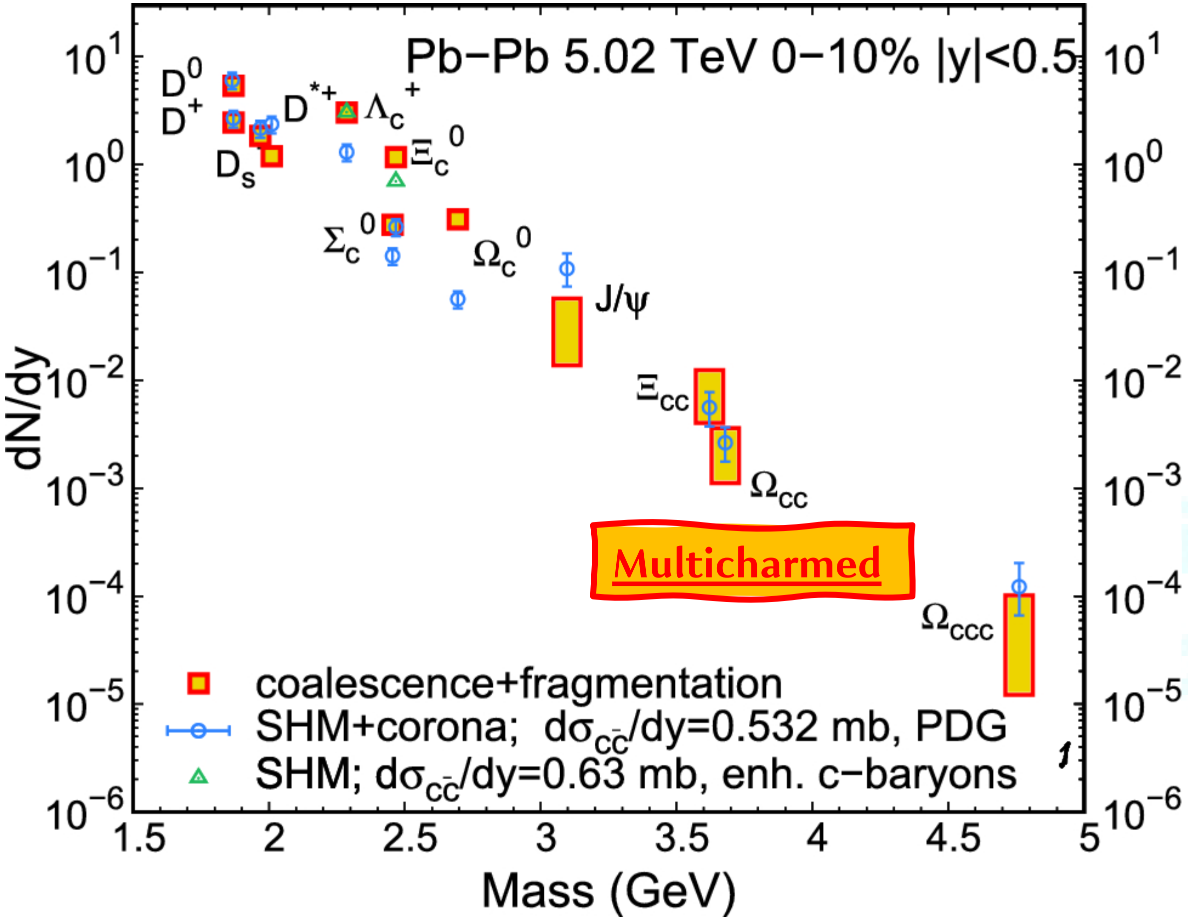


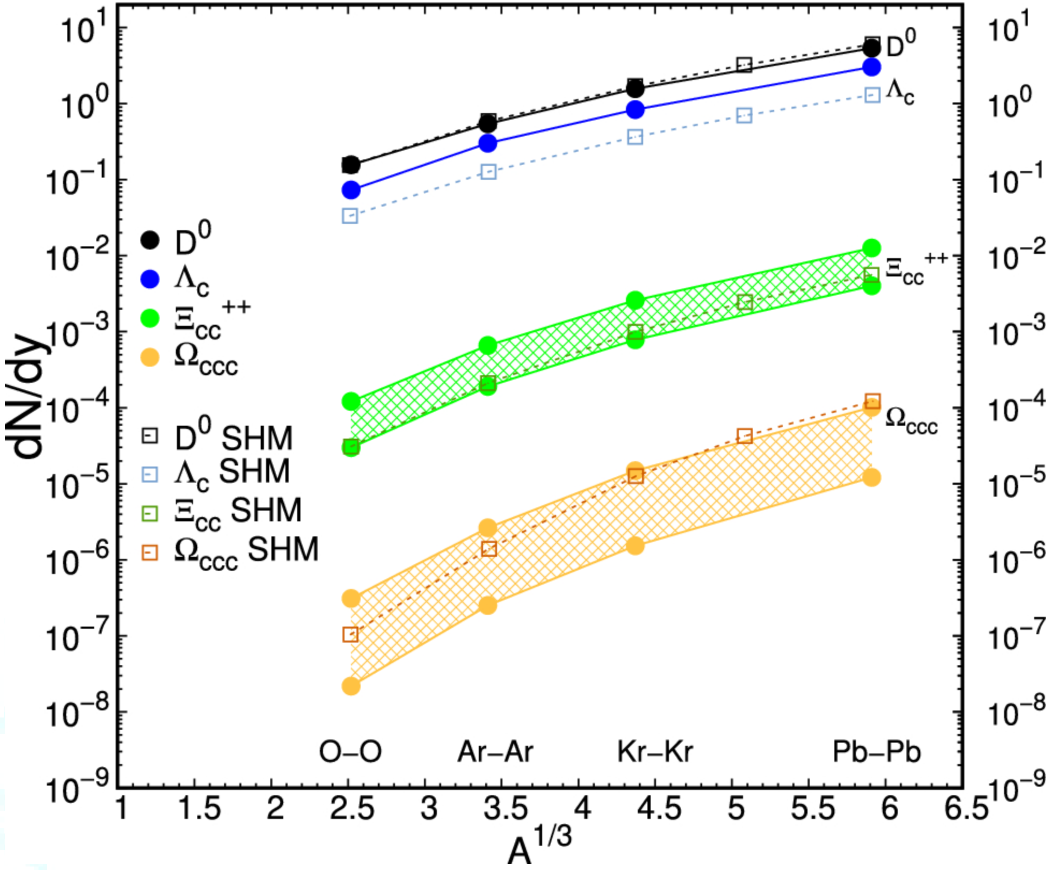
The Space-Momentum Correlation (SMC) between charm and light quarks enhances the particle production via coalescence in the intermediate and high momentum region. (The bands are given by the presence or the absence of SMC)

PRELIMINARY

Multicharm hadrons in AA

V. Minissale, S. Plumari, Y. Sun and V. Greco, *Eur. Phys. J. C 84, no.3, 228 (2024)*





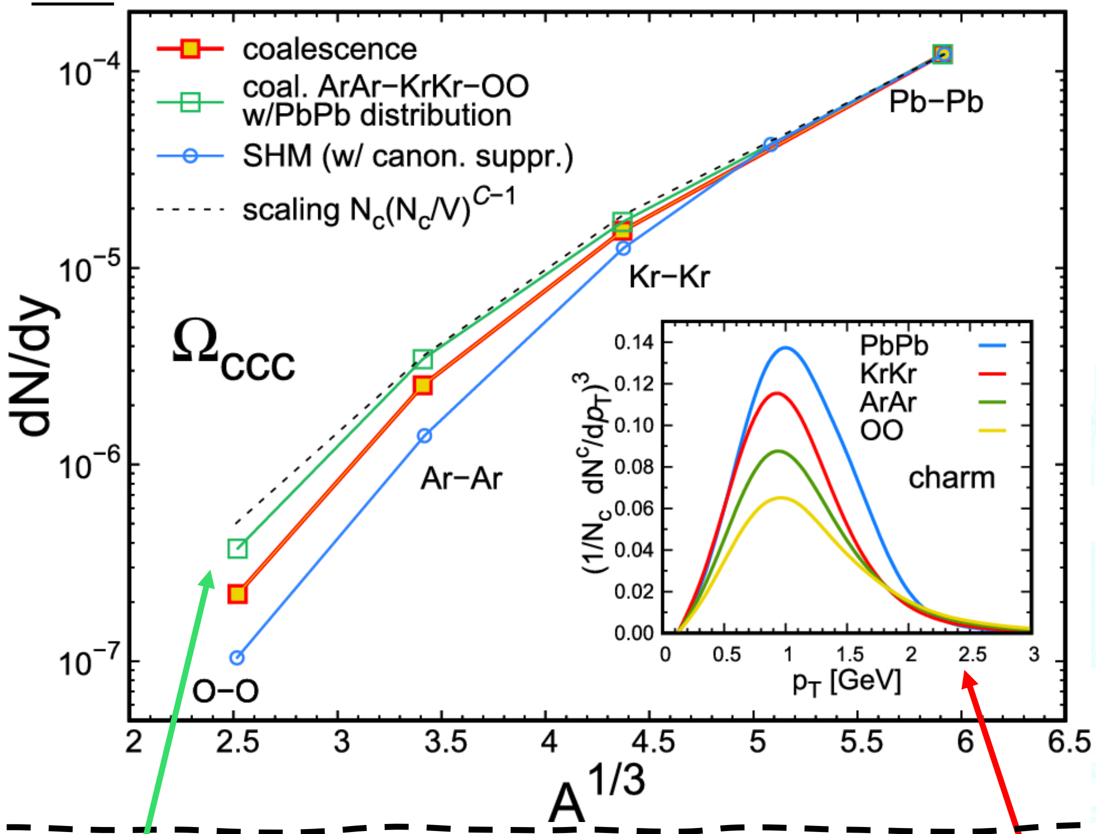
	OO	ArAr	KrKr	PbPb
$R_0(fm)$	2.76	3.75	4.9	6.5
$R_{max}(fm)$	5.2	7.65	10.1	14.1
$\tau(fm)$	4	5	6.2	8
β_{max}	0.55	0.6	0.64	0.7
$V_{\lvert y\rvert<0.5}(fm^3)$	345	920	2000	5000

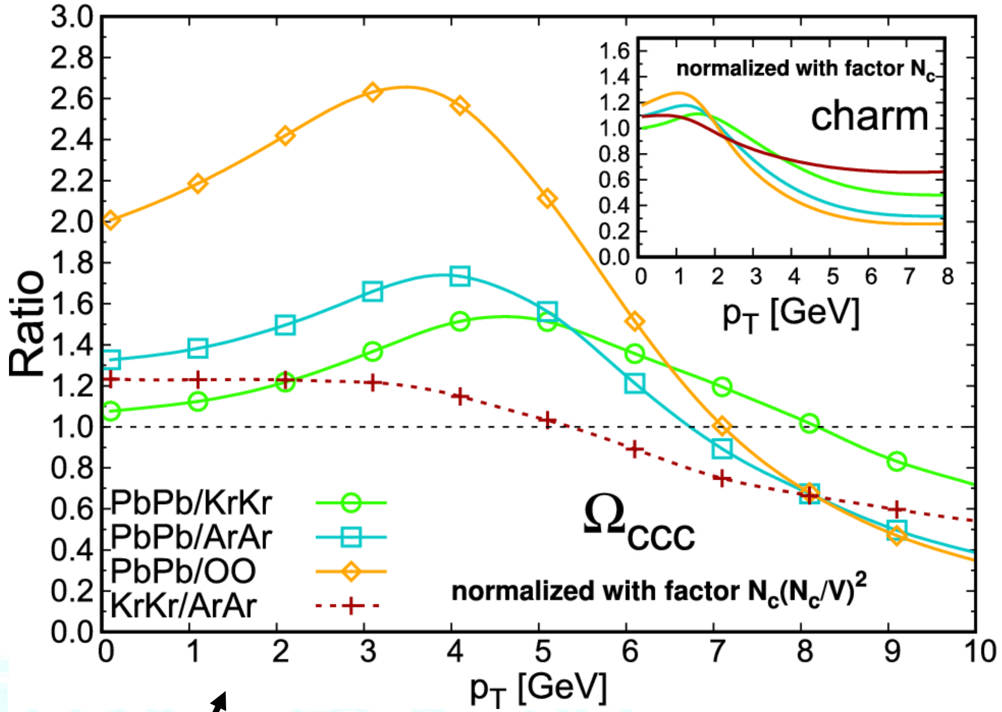
→ We employ same volume in SHM A. Andronic et al., JHEP 07 (2021) 035

→ upper limit: charm thermal distribution

→ lower limit: PbPb distribution with widths rescaled as standard Harm. Oscill. (ω from Ω_c)

Ω_{ccc} in PbPb/KrKr/ArAr/OO

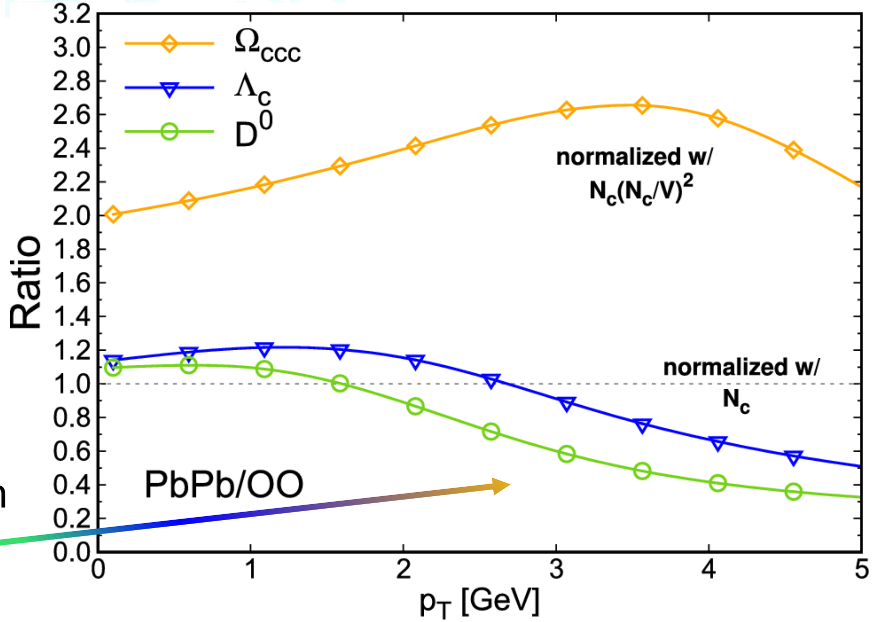




Follow the $V\left(\frac{N_c}{V}\right)^{C} = N_c\left(\frac{N_c}{V}\right)^{C-1}$ *scaling at fixed distribution*

Ω_{ccc} reduced following approx. the c^3 distr. (inset)

- Ω_{ccc} ratio in diff. systems as meter of non-equilibrium.
- Features of charm spectra at low p_T to hadron high momentum region
- More sensitive to system change w.r.t. D^0 Λ_c (fragm. Effect)

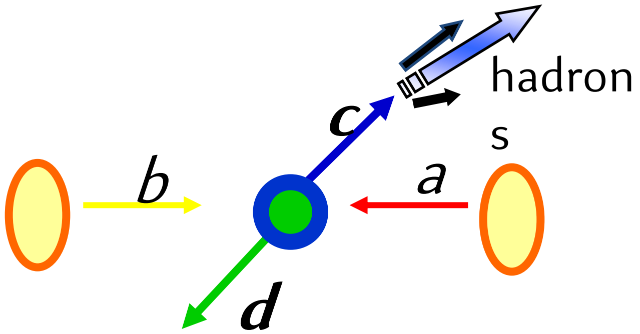


V. Minissale, S. Plumari, Y. Sun and V. Greco, *Eur. Phys. J. C 84, no.3, 228 (2024)*

Heavy flavour Hadronization

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

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



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

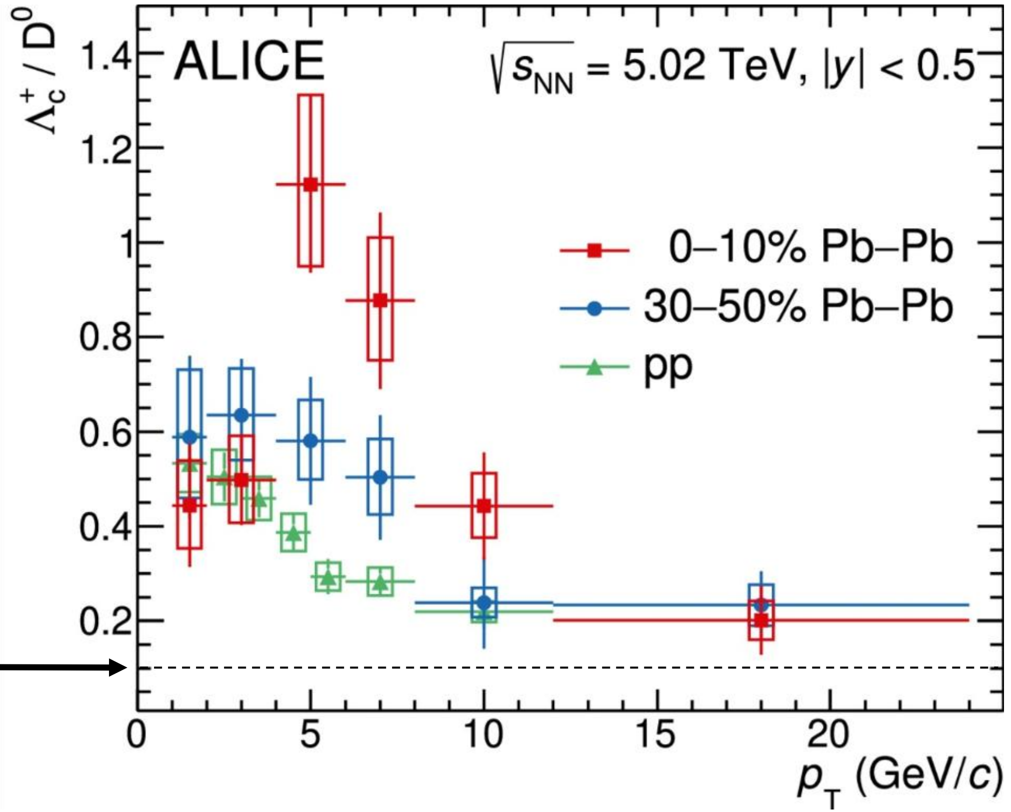
Fragmentation fractions (c→h) depends on collision system…*and QGP presence*?

No more Universality?

Baryon/meson ratio is underestimated, and no p_T dependence

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

ALICE, PRC 107 (2023) 064901
ALICE, PLB 839 (2023) 137796



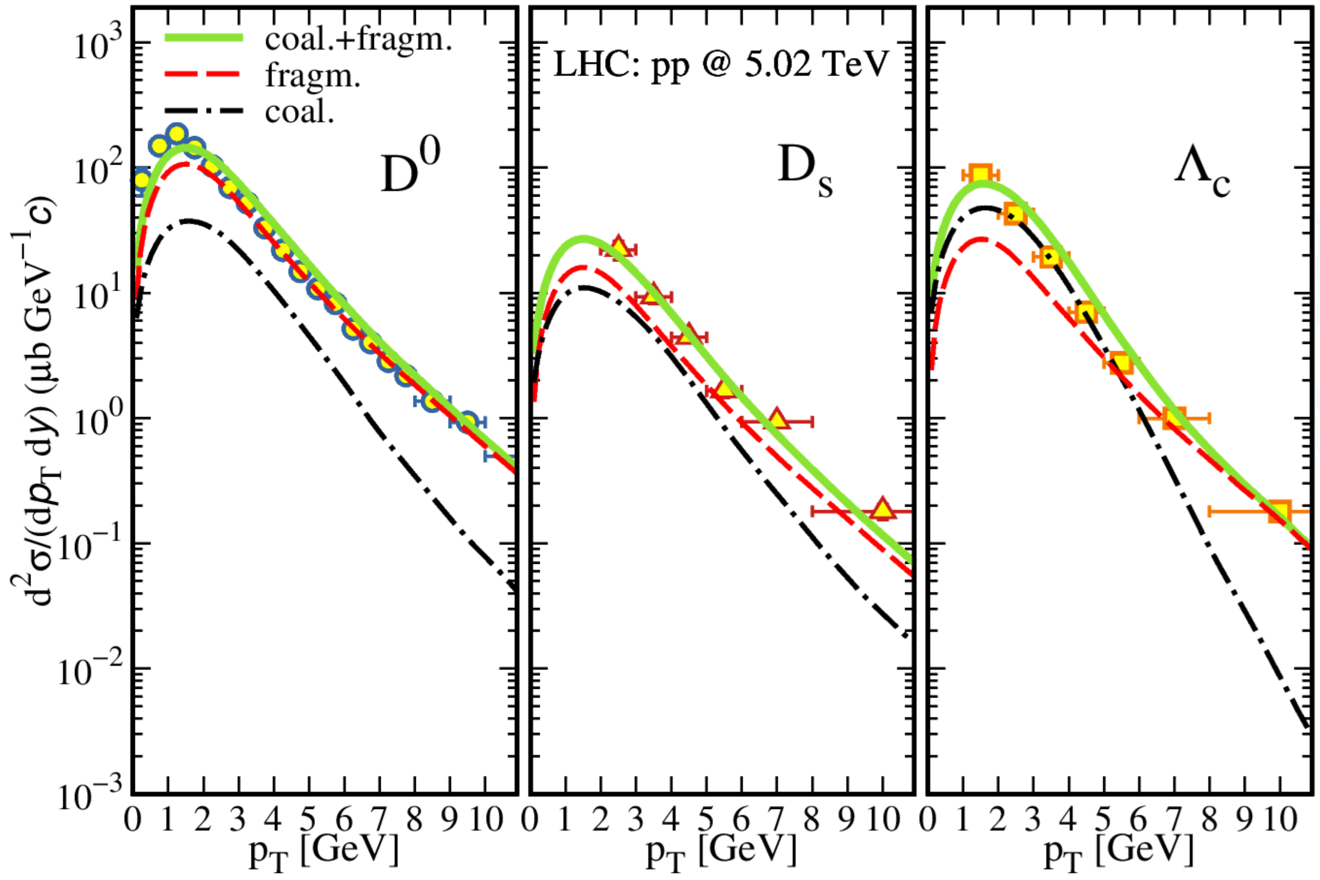
Small systems: Coalescence in pp?

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



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)

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

- Minijet Distribution (p_T> 2 GeV)
  NO QUENCHING

CHARM

FONLL Distribution

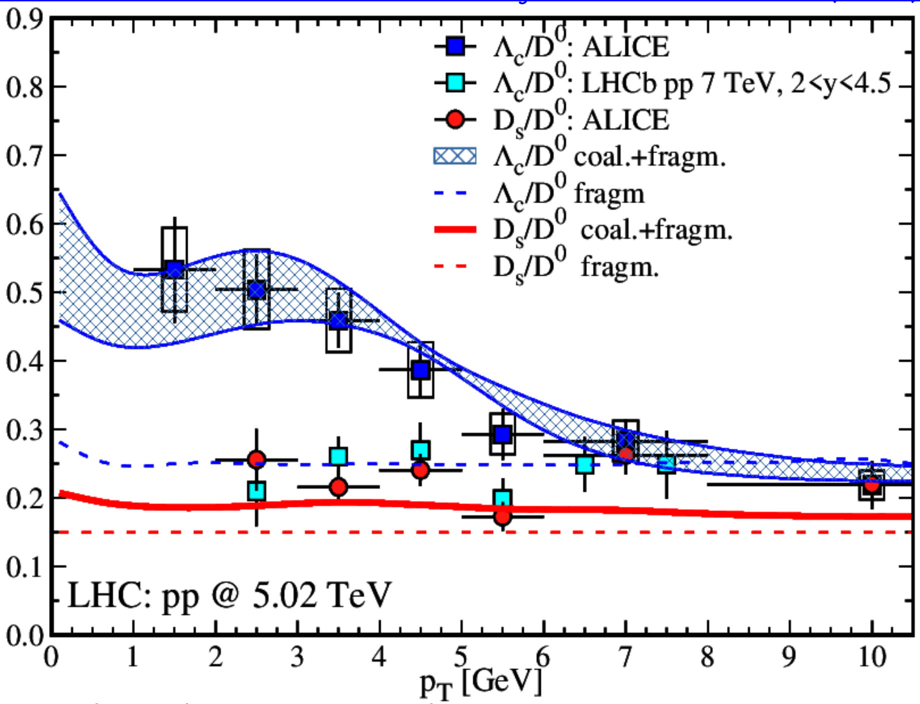
wave fuction widths σ_p of baryon and mesons kept the same from AA to pp

Small systems: Coalescence in pp?

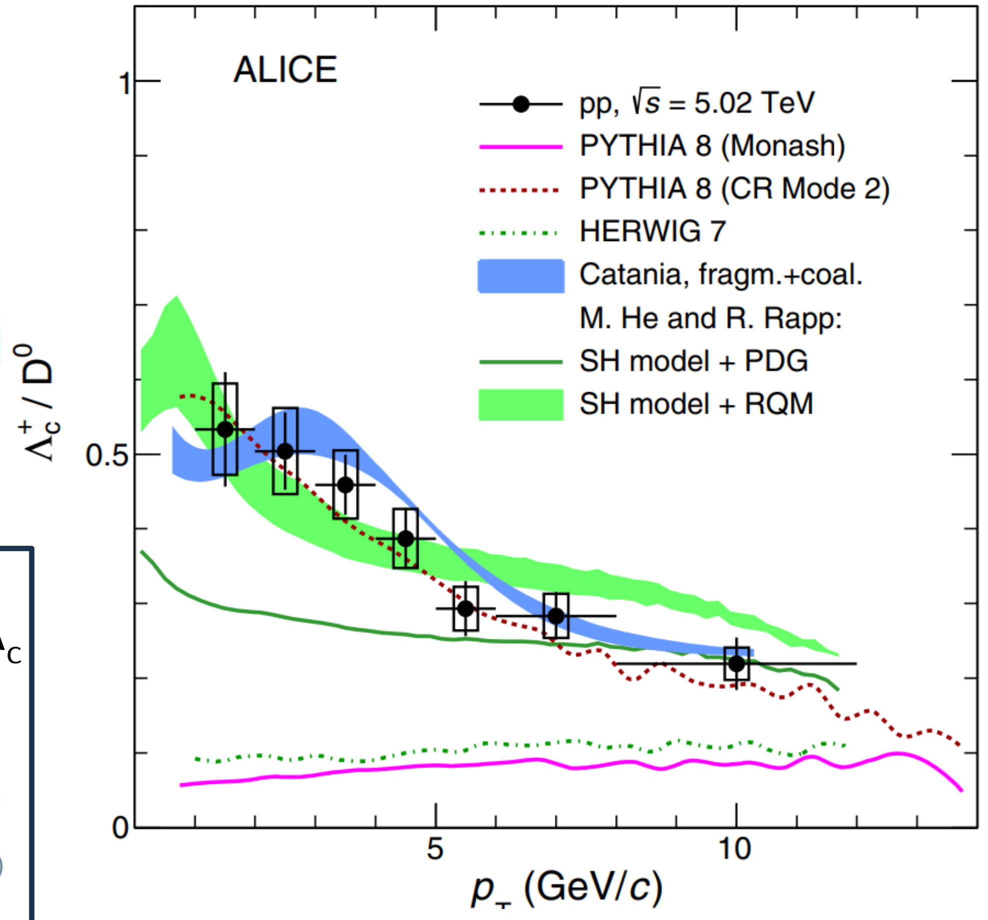
V. Minissale, S. Plumari, V. Greco, Physics Letters B 821 (2021) 136622

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



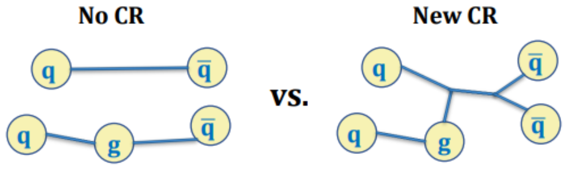
Error band correspond to <r²> uncertainty in quark model



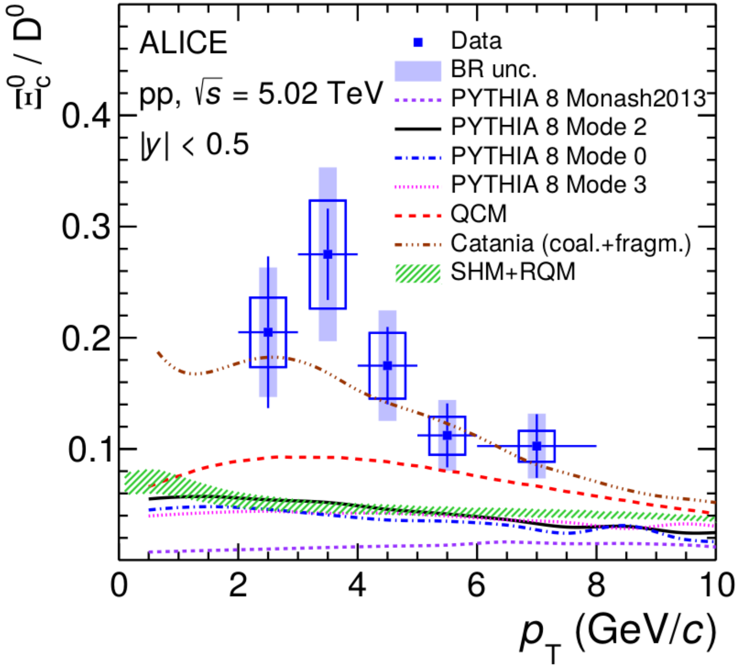
ALICE,Phys.Rev.Lett. 127 (2021) 20, 202301

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



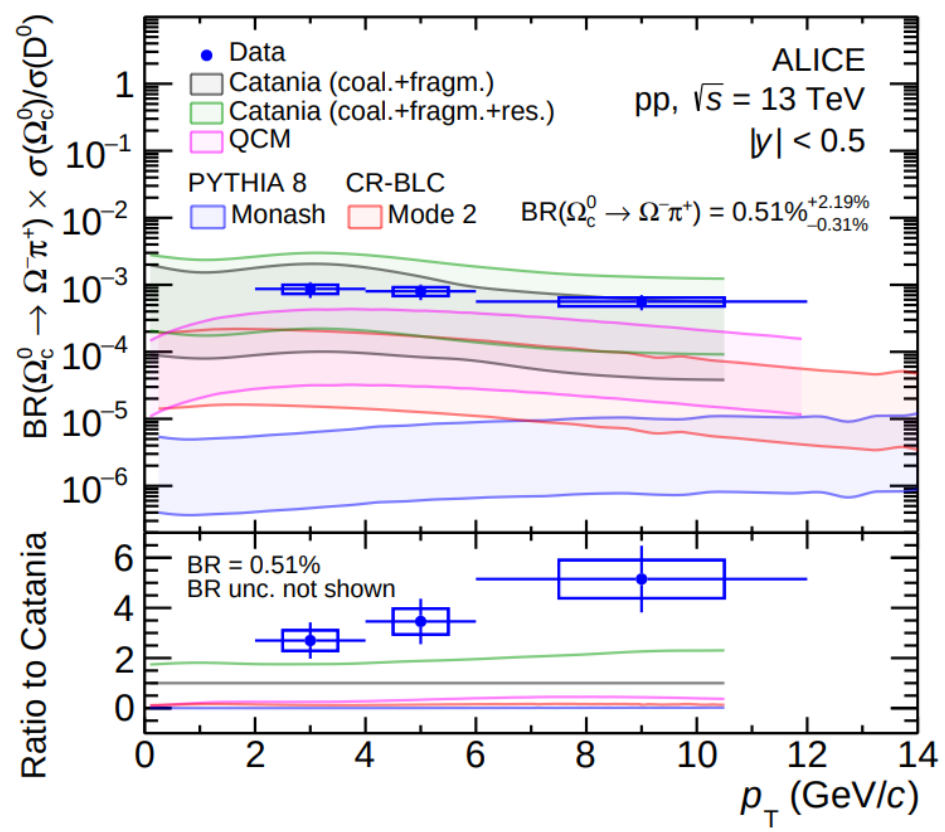
Small systems: Coalescence in pp?



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

Uncertainties bands coming from the Branching Ratio error

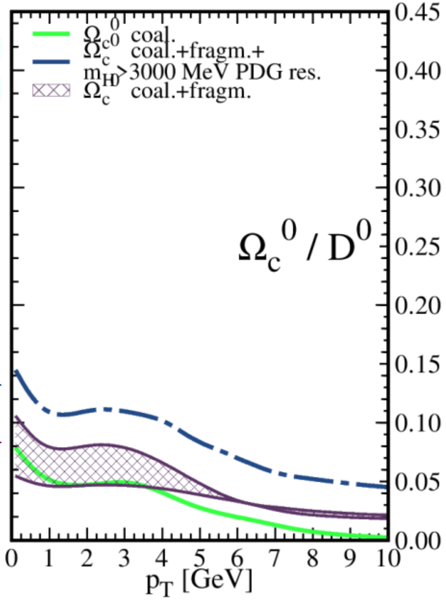


Assuming additional PDG resonances with J=3/2 and decay to Ω_c additional to $\Omega_c^0(2770)$

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

supply an idea of how these states may affect the ratio

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



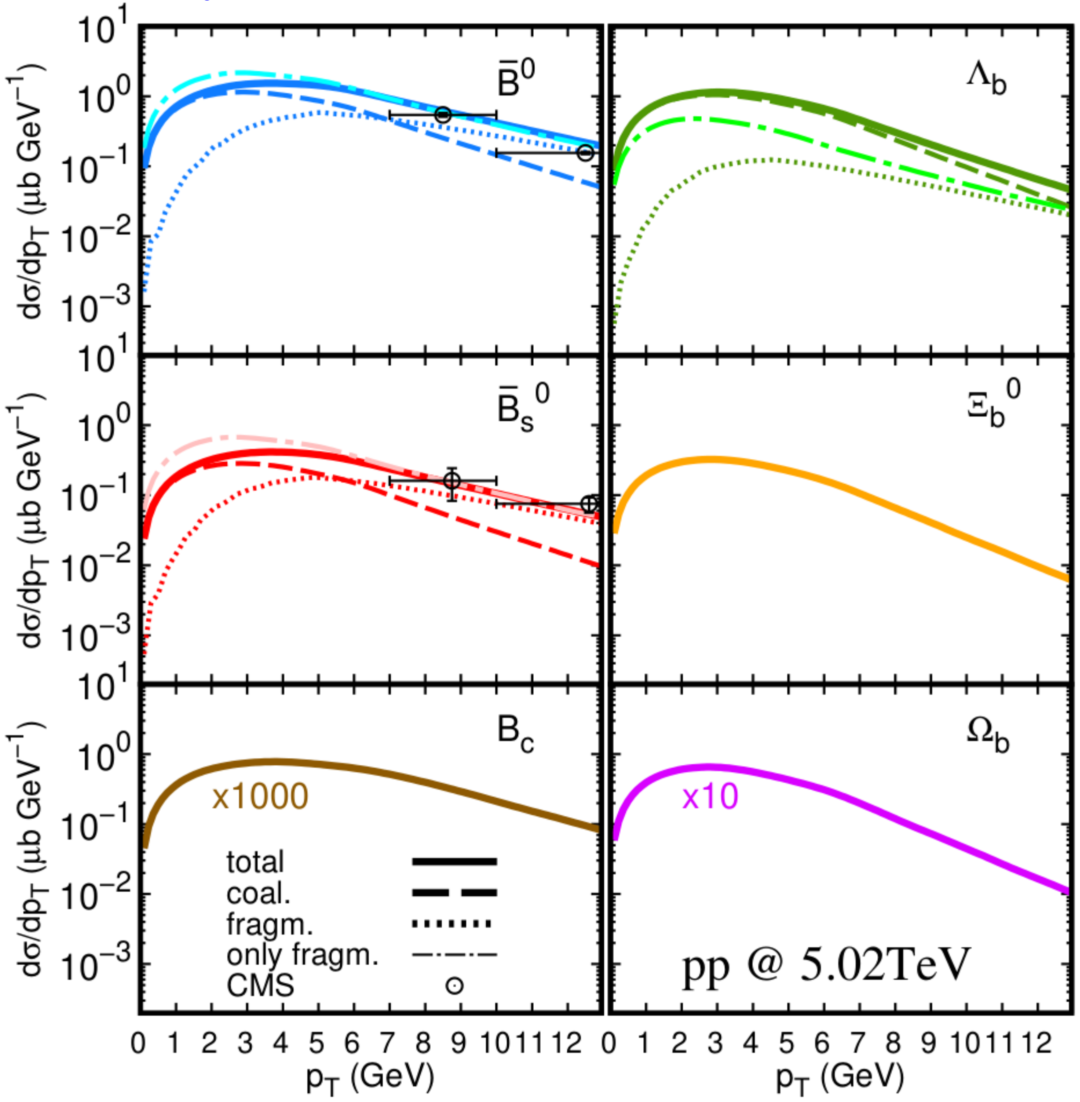
ALICE Coll. JHEP 10 (2021) 159

ALICE Coll. PLB 846(2023) 137625

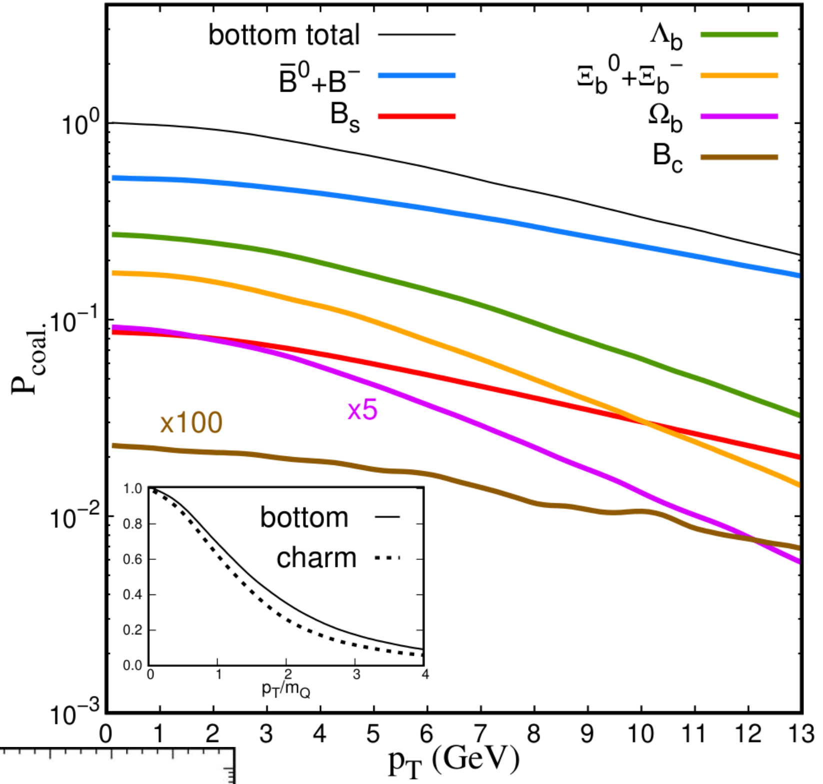
V. Minissale, S. Plumari, V. Greco, Physics Letters B 821 (2021) 136622

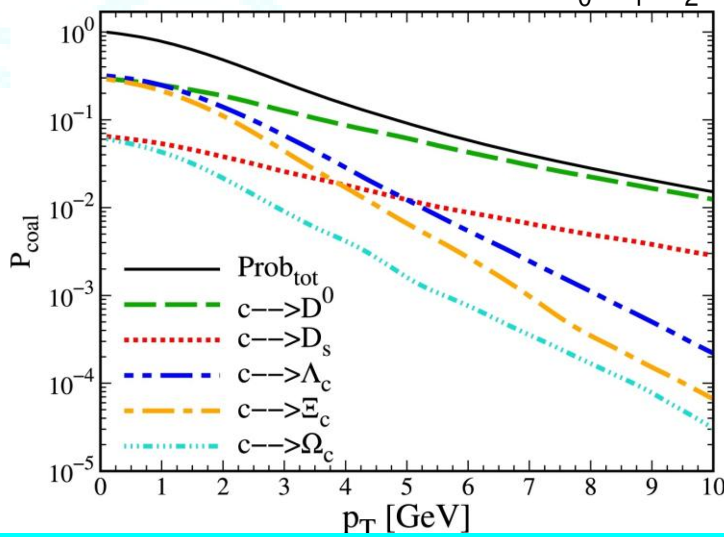
Small systems: Coalescence in pp for bottom hadrons?

Data from:
A. M. Sirunyan et al. (CMS), PRL 119, 152301 (2017).



- Bottom P_{coal} is flatter than charm → Coal. big impact on bottom hadron production in a wider p_T region
- B meson at p_T < 5 GeV mainly from Coal
- Λ_b mainly from Coal. for p_T < 10 GeV





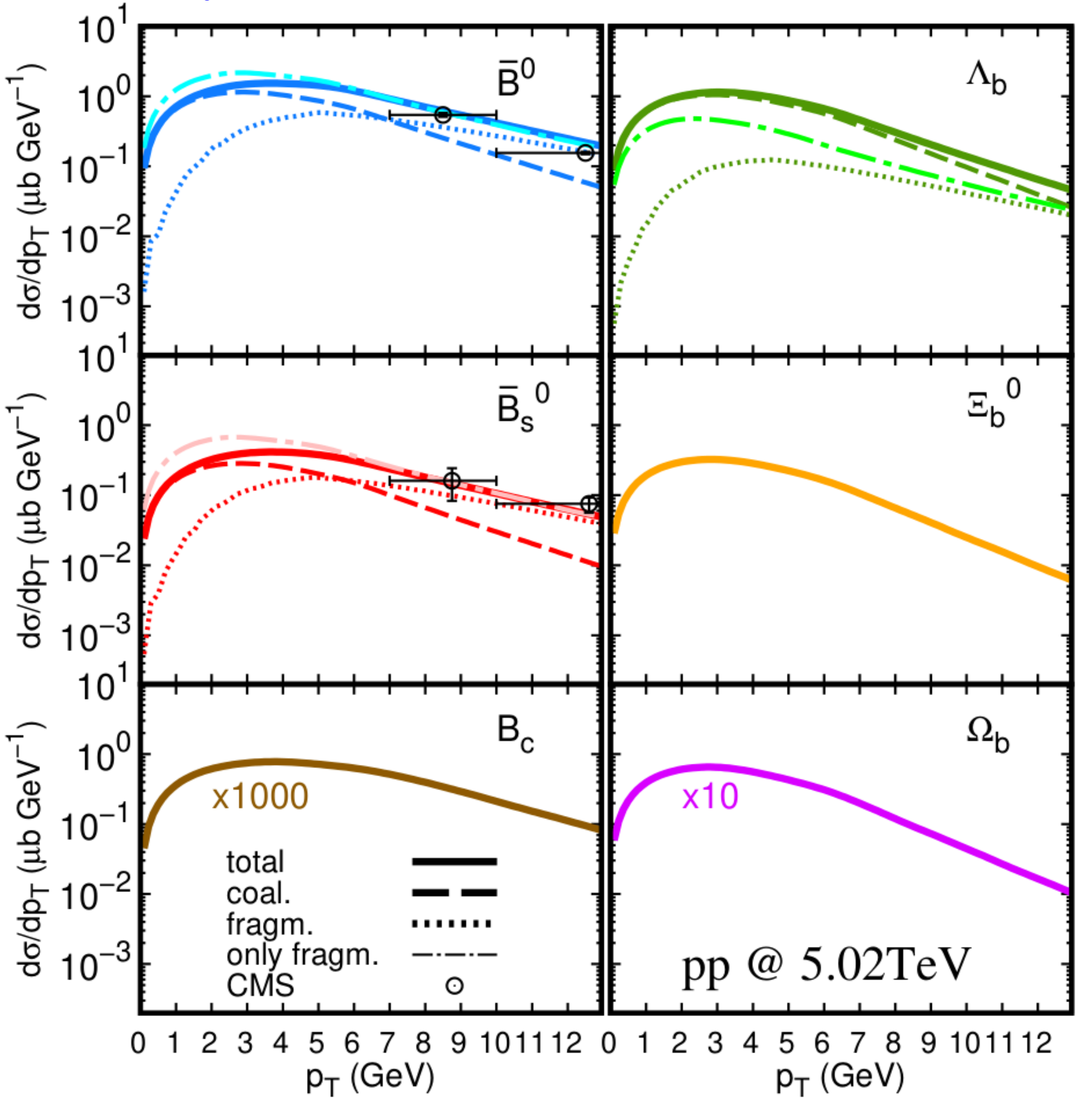
- Similar probabilities when p_T is scaled with m_Q

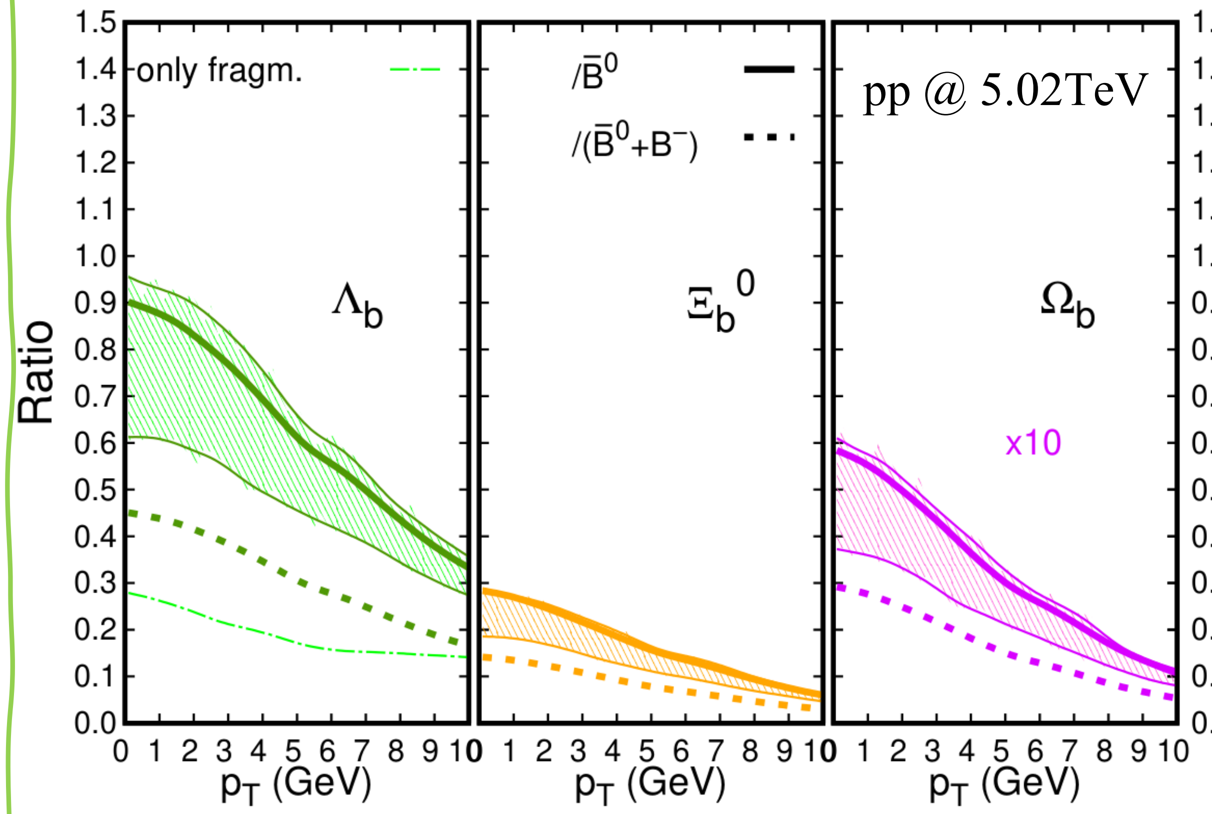
V. Minissale et al, Phys.Lett.B 860 (2025) 139190

 Kartvelishvili fragm. function Phys.Lett.B 78 (1978) 615-617

Small systems: Coalescence in pp for bottom hadron?

Data from:
A. M. Sirunyan et al. (CMS), PRL 119, 152301 (2017).



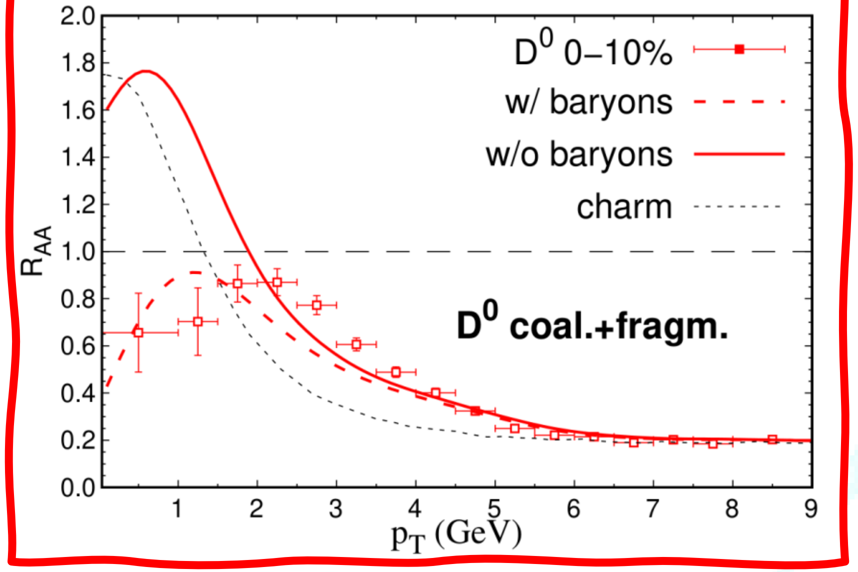


Error band correspond to <r^2> uncertainty in quark model
Coal gives enhancement of Baryon/meson ratio

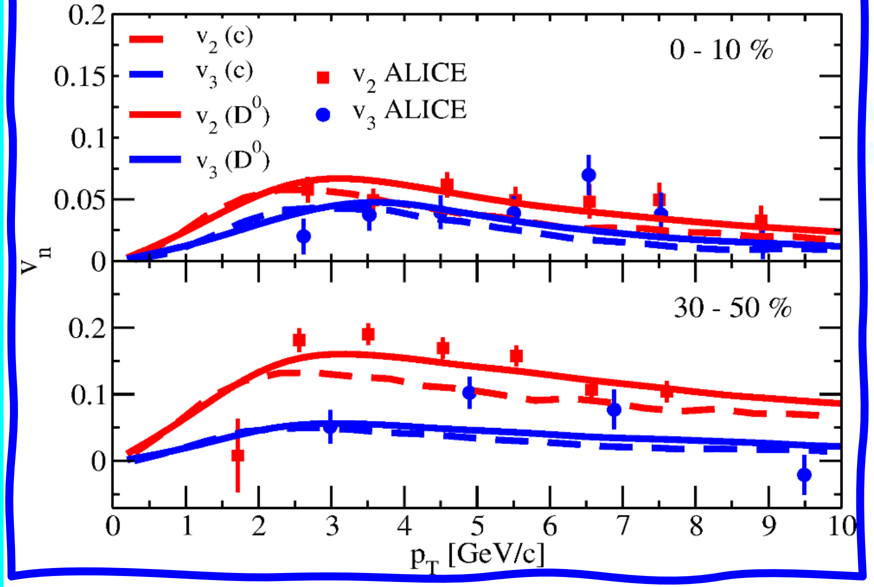
V. Minissale et al, Phys.Lett.B 860 (2025) 139190

 Kartvelishvili fragm. function Phys.Lett.B 78 (1978) 615-617

Implications and developments:



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

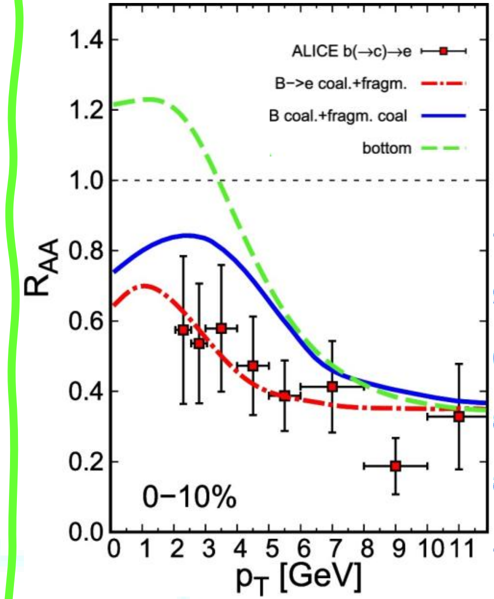


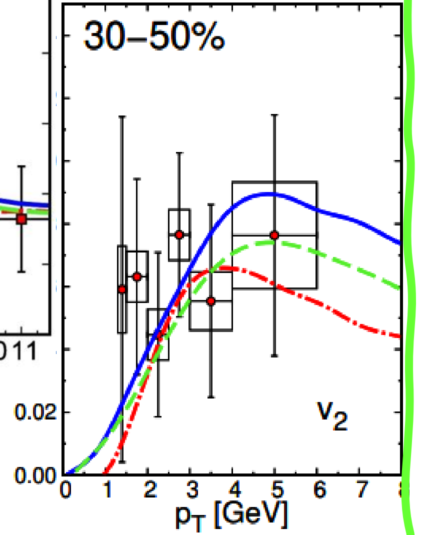
Coalescence give an enhancement to the $v_n(p_T)$ of final hadrons compared to the charm $v_n(p_T)$.

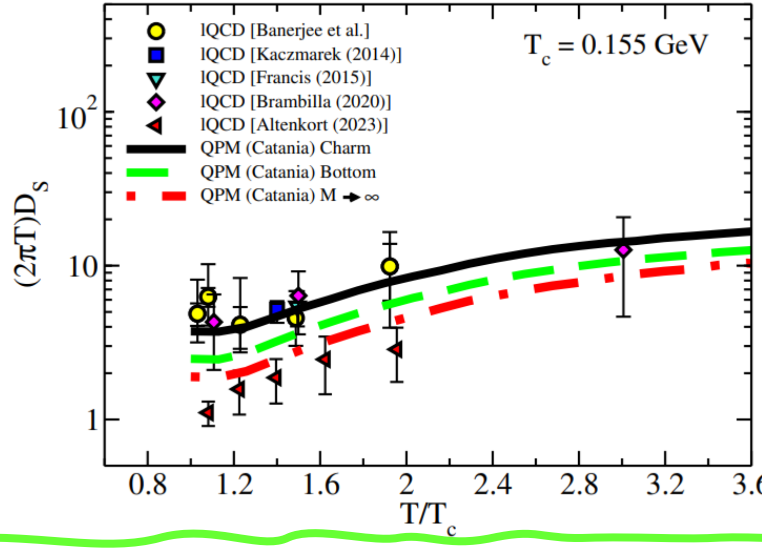
Sambataro,Sun,Minissale,Plumari, Greco,Eur.Phys.J.C 82 (2022) 9, 833

- Electrons from semileptonic B meson decay with coal + fragm model
- D_s diffusion coeff. estimate

Sambataro,Minissale,Plumari, Greco *Phys.Lett.B* 849 (2024) 138480







Conclusions

- **Charm hadronization in AA:**

✓ Coalescence+fragmentation gives enhancement of Λ_c production at intermediate momentum region: $\Lambda_c/D^0 \sim 1$ for $p_T \sim 3\ GeV$

✓ *Multicharm hadrons:* - role of non-equilibrium distribution function
- in accord with SHM predictions

- ***In p+p assuming a medium:***

Charm:

✓ Coal.+fragm. good description of heavy baryon/meson ratio (closer to Λ_c/D^0 , Ξ_c/D^0, Ω_c/D^0 data)

Bottom:

✓ B,B_s good agreement with exp. data.

✓ Coal.+fragm. Enhancement of Λ_b

✓ Predictions for Λ_b/B^0 , Ξ_b/B^0, Ω_b/B^0

Backup Slides

Relativistic Boltzmann transport at finite η/s

Bulk evolution

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

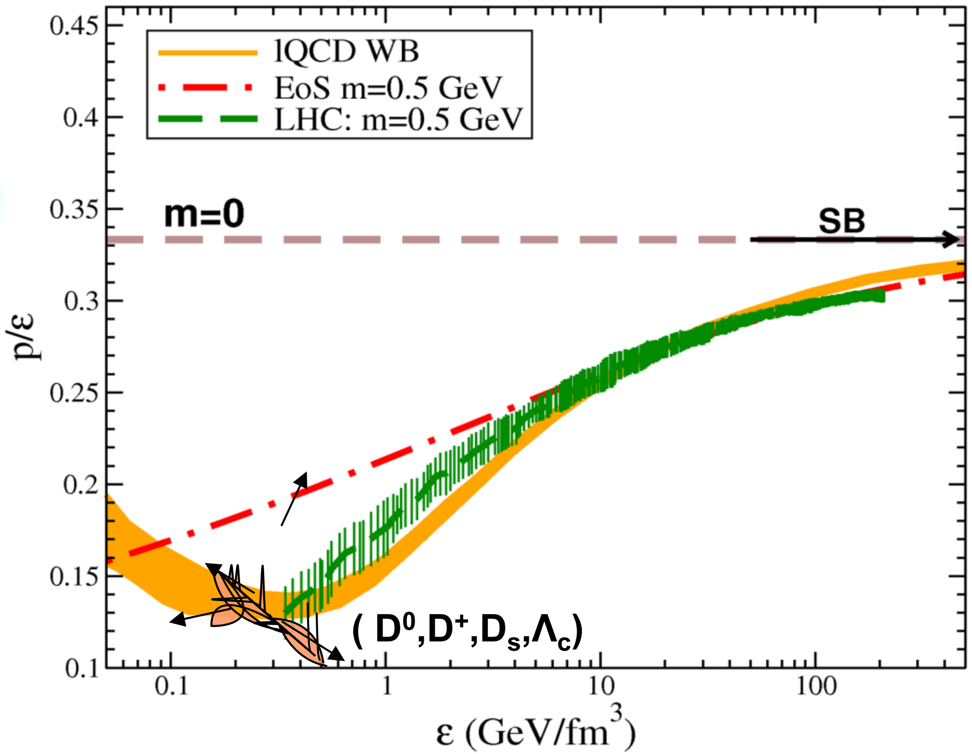
Heavy quark evolution

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

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

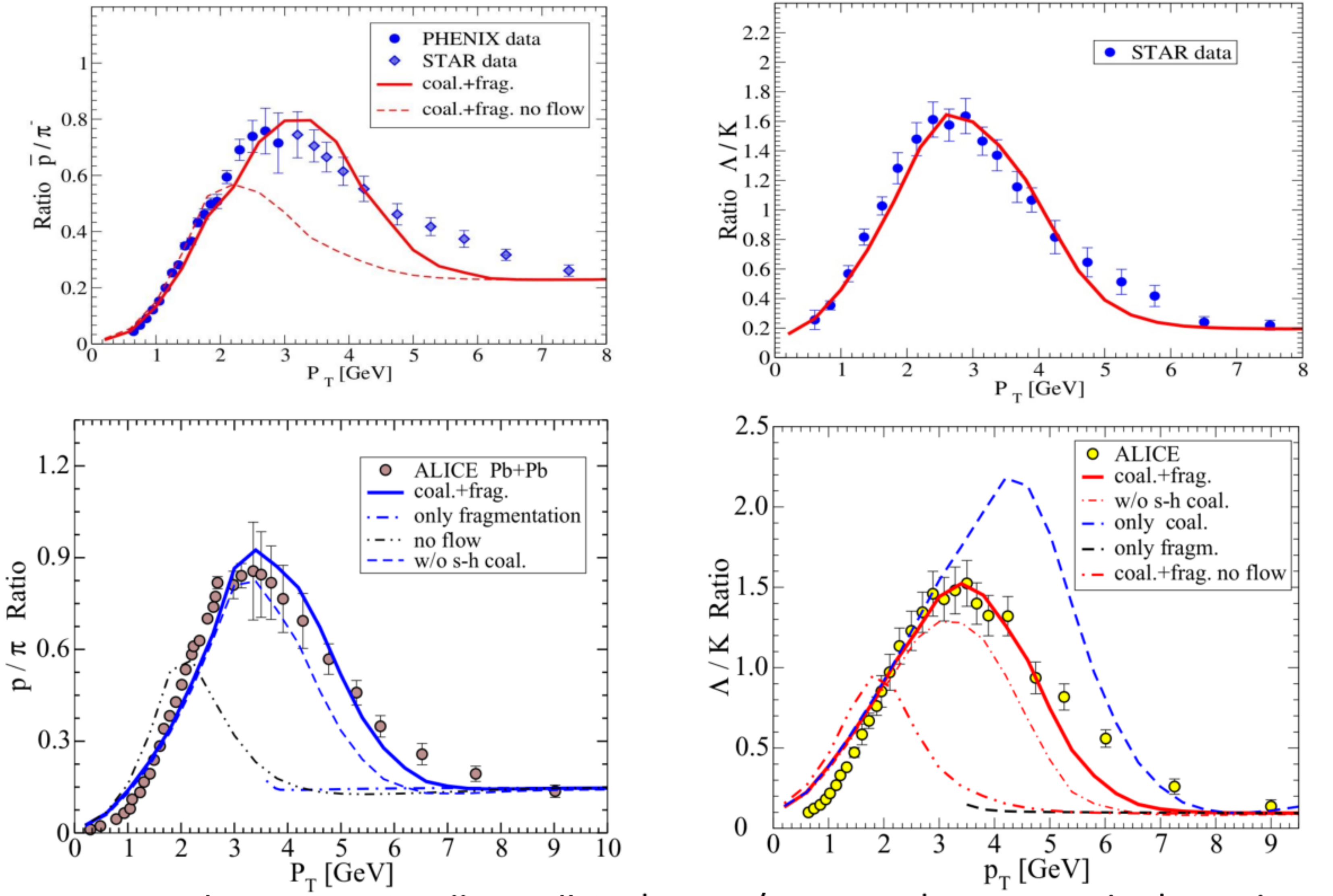
Possible to include f(x,p) out of equilibrium



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

Baryon to meson ratio at RHIC & LHC

Minissale, Scardina, Greco, Phys.Rev. C 92 (2015) 5,054904



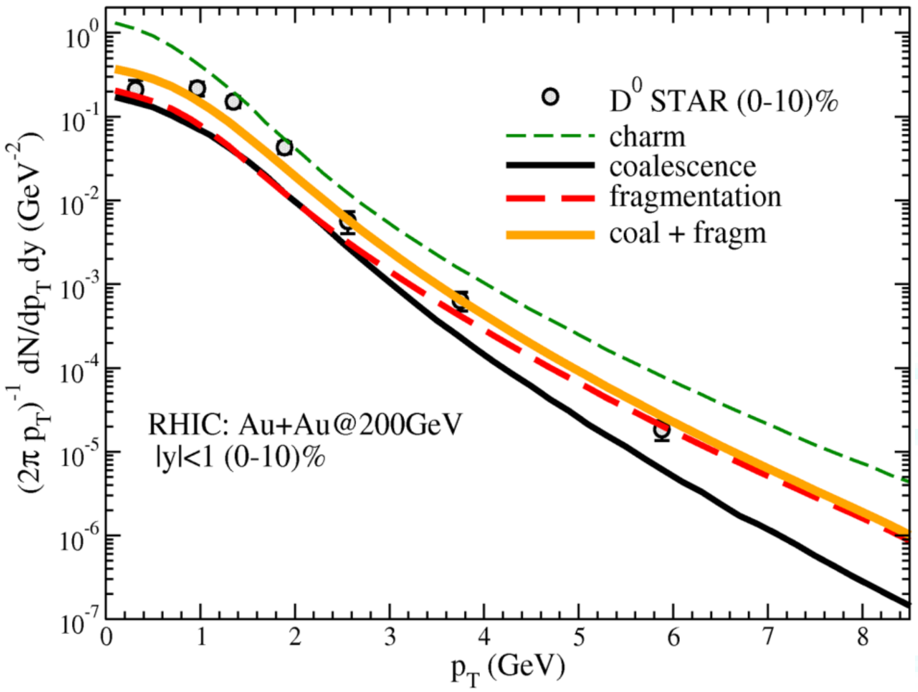
RHIC

LHC

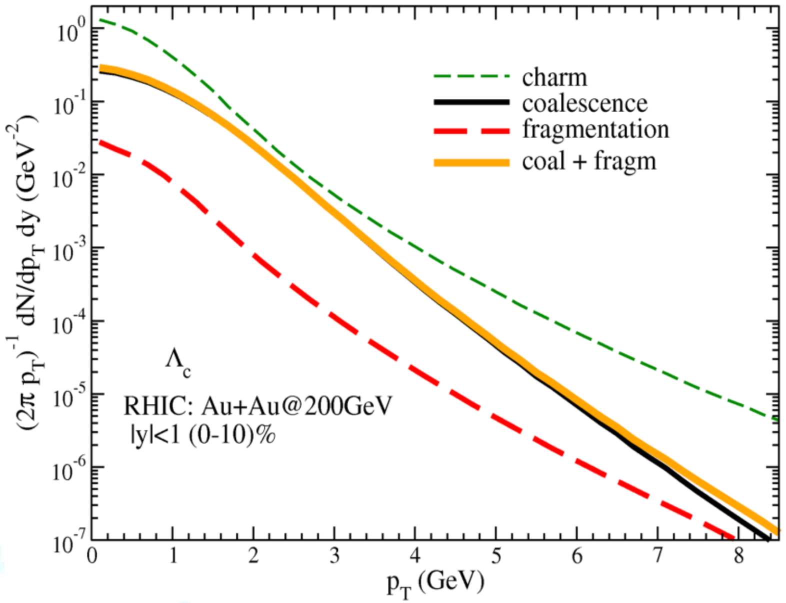
- coalescence naturally predict a baryon/meson enhancement in the region $p_T \simeq$ 2−4*GeV* with respect to *pp* collisions
- Lack of baryon yield in the region $p_T \simeq$ 5−7GeV

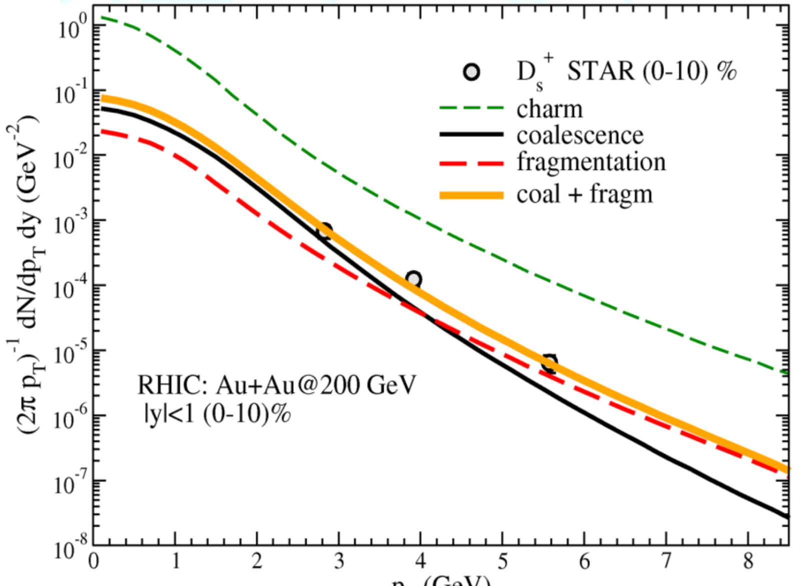
RHIC: results

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



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

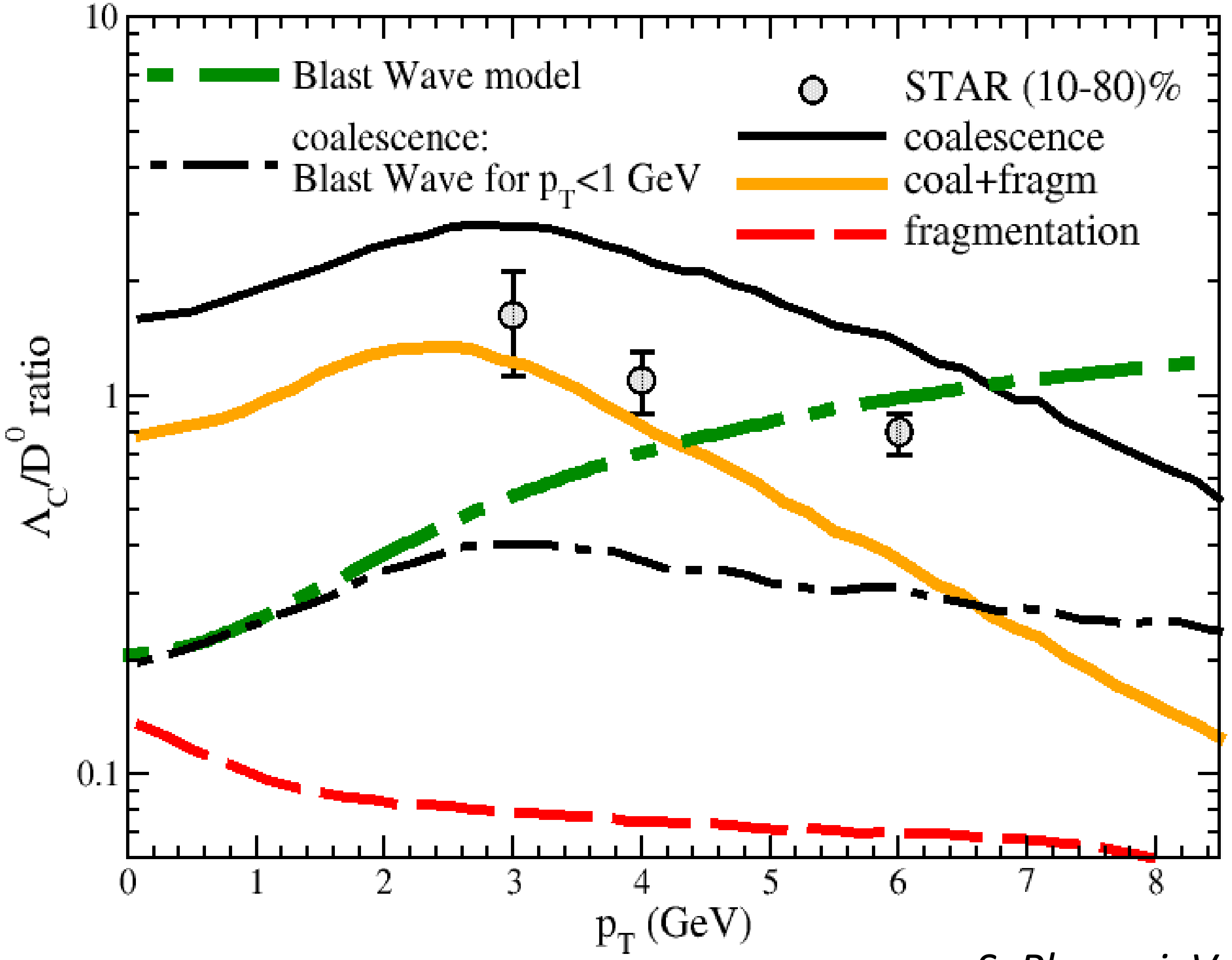




- For D^0 coalescence and fragmentation comparable at 2 GeV
- fragmentation fraction for D^+_s are small and less than about 8% of produced total heavy hadrons
- Λ_c^+ fragmentation is even more smaller, coalescence gives the dominant contribution

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*

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

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

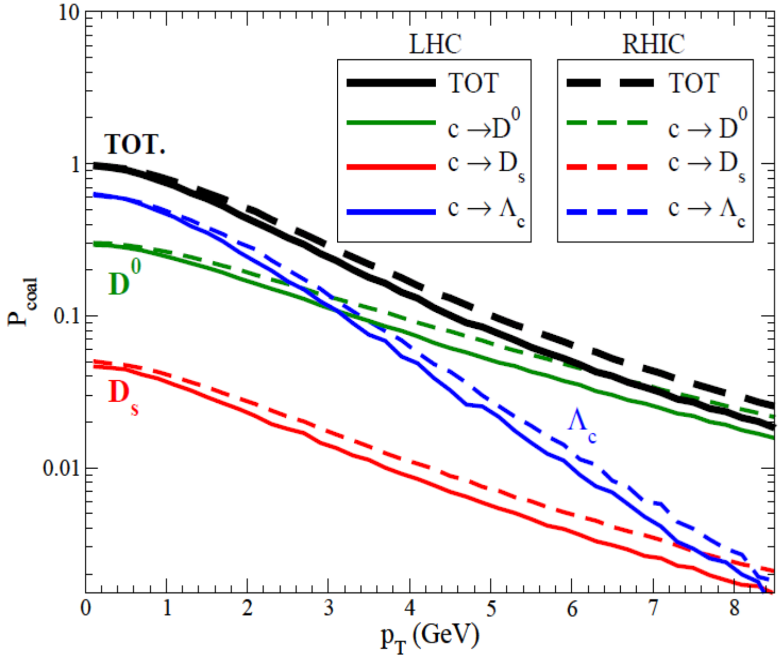
Catania Model: Coalescence + Fragmentation

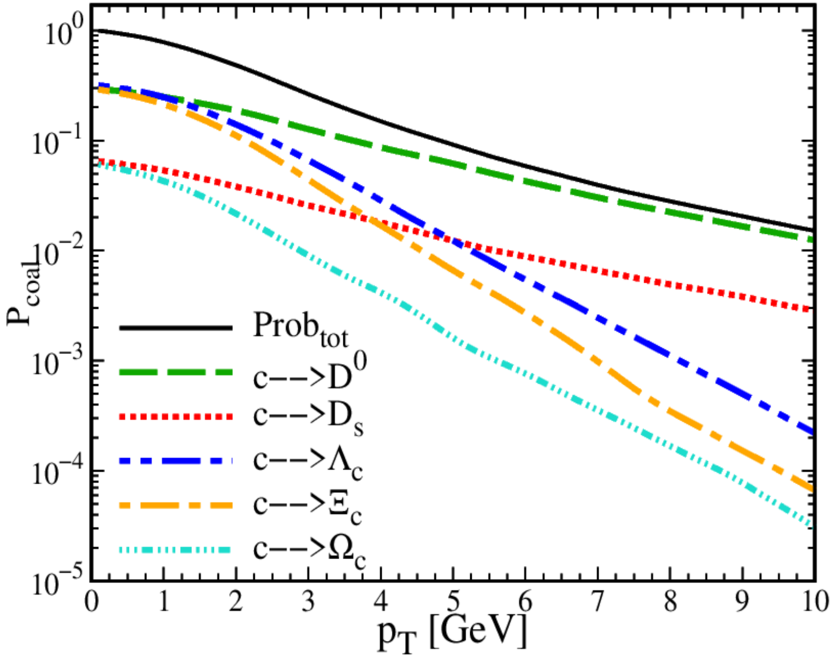
Statistical factor colour-spin-isospin — *Parton Distribution function* — *Hadron Wigner function* — $C_H = \mathcal{N} f_H$

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

Normalization $\mathcal{N}$ of $C_H(\ldots)$ requiring that $P_{coal}=1$ at $p=0$

The charm that does not coalesce undergo fragmentation

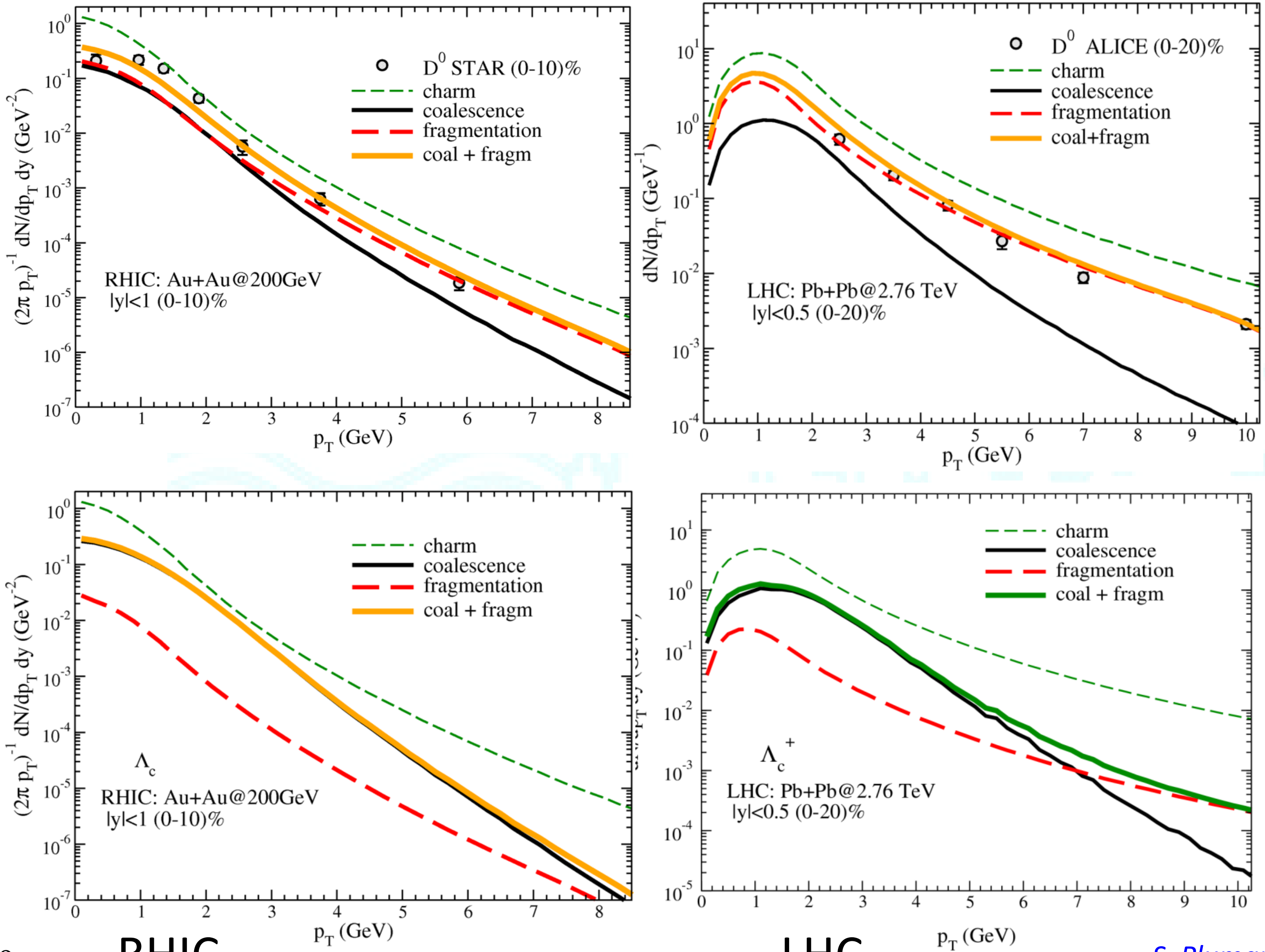




AA @ RHIC & LHC

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



RHIC LHC

D^0

Coalescence lower at LHC than at RHIC

main contribution: Fragmentation

Λ_c

Coalescence lower at LHC than at RHIC

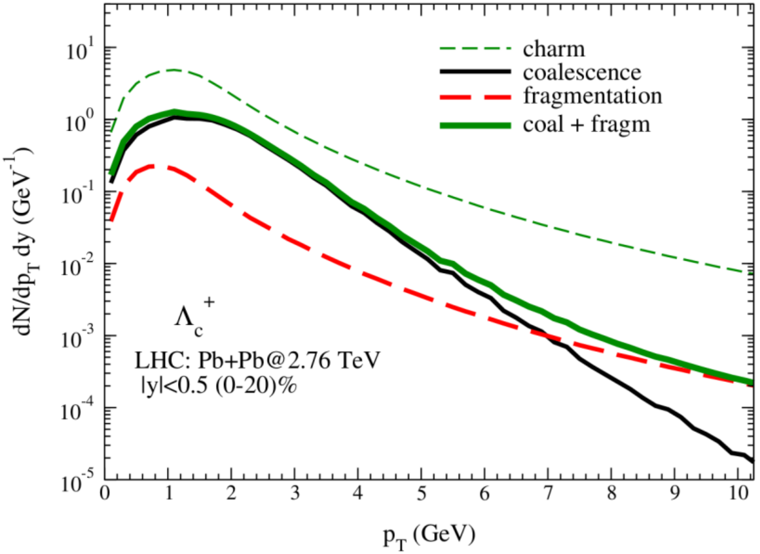
main contribution: Coalescence

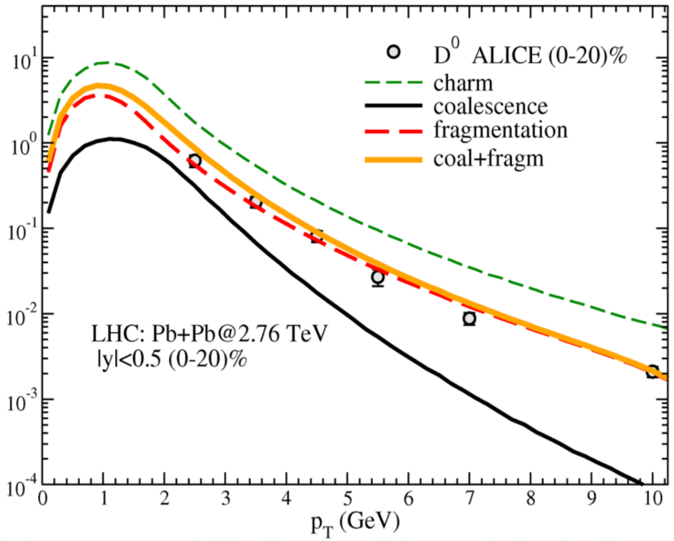
S. Plumari, V. Minissale et al., Eur. Phys. J. C78 no. 4, (2018) 348

AA @ RHIC & LHC

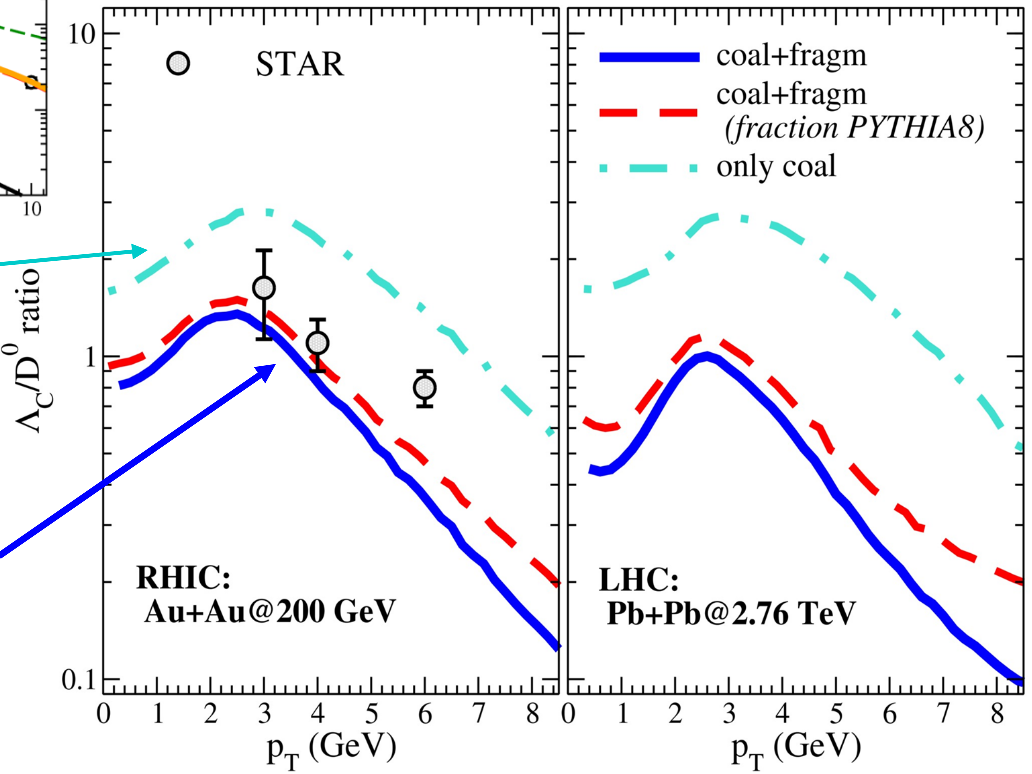
wave function widths σ_p of baryon and mesons are the same at RHIC and LHC!

Data from [ALICE Coll. JHEP 09 (2012) 112]





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 coalescence over fragmentation ratio at LHC is smaller than at RHIC

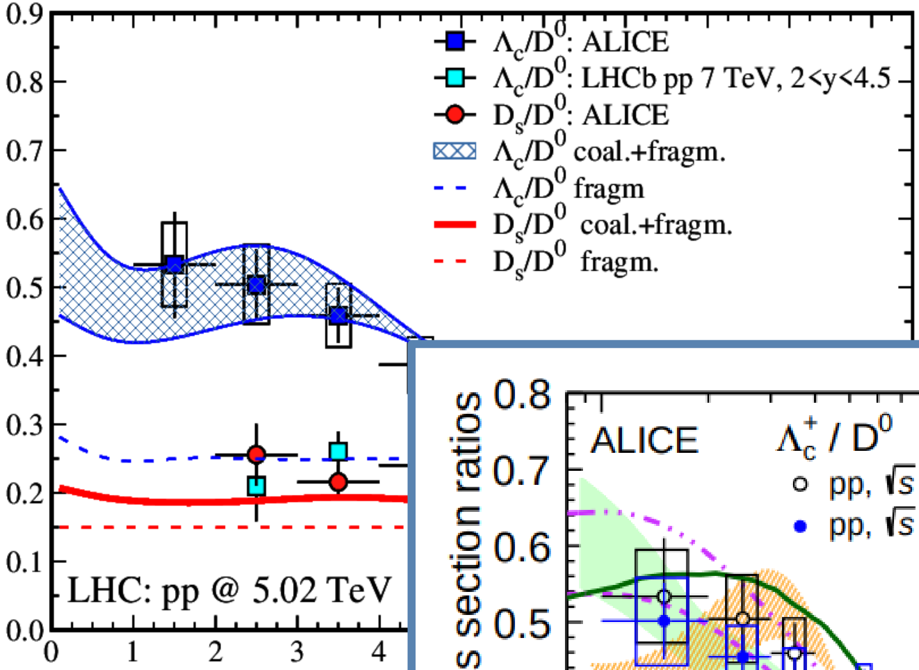
Therefore at LHC the larger contribution in particle production from fragmentation leads to a final ratio that is smaller than at RHIC.

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

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

Small systems: Coalescence in pp?

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



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

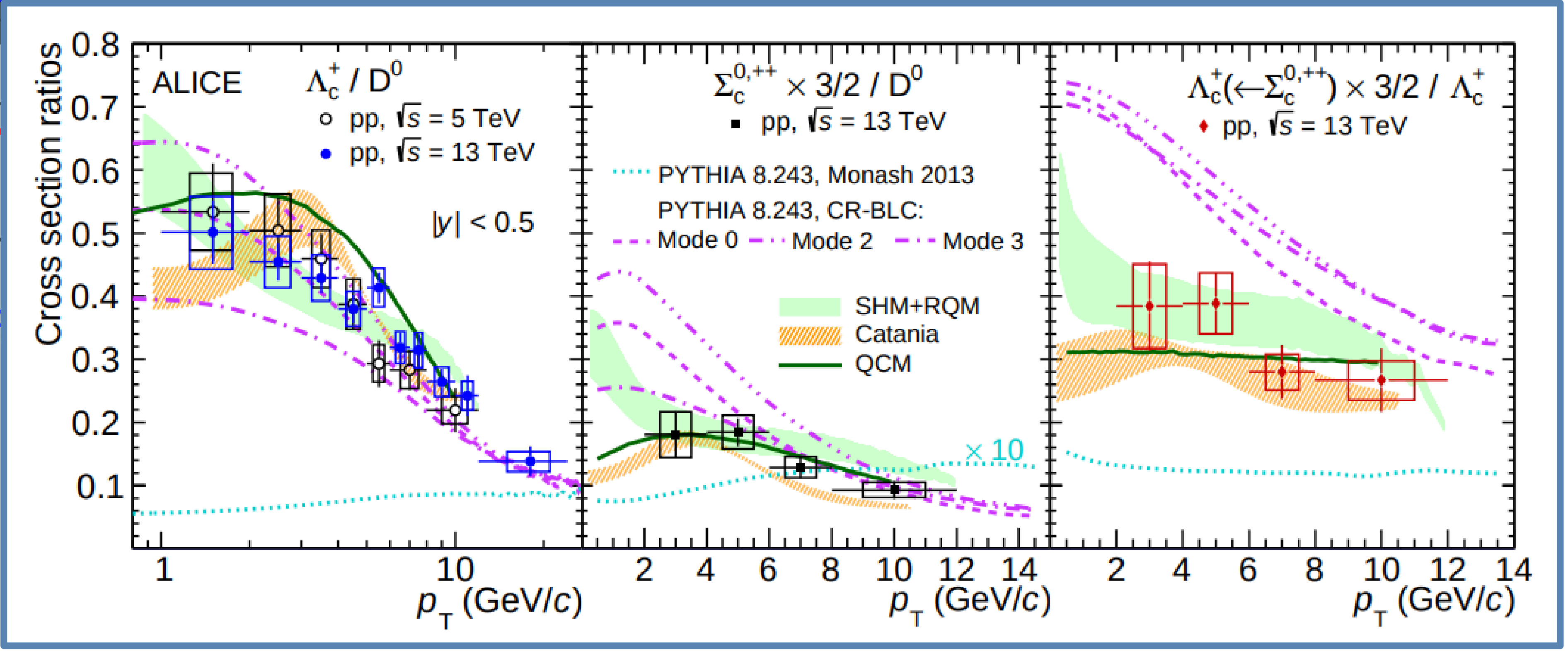
-Confronting with AA: Coal. contribution smaller w.r.t. Fragm.

-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

Error band correspond to



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

Multicharm production Pb-Pb, Kr-Kr, Ar-Ar, O-O

V. Minissale, S. Plumari, Y. Sun and V. Greco, *Eur. Phys. J. C 84, no.3, 228 (2024)*

Baryon			
$\Xi_{cc}^{+,++} = dcc, ucc$	3621	$\frac{1}{2}\,(\frac{1}{2})$	
$\Omega_{scc}^{+} = scc$	3679	$0\,(\frac{1}{2})$	
$\Omega_{ccc}^{++} = ccc$	4761	$0\,(\frac{3}{2})$	
Resonances			
Ξ_{cc}^{*}	3648	$\frac{1}{2}\,(\frac{3}{2})$	$1.71 \times g.s$
Ω_{scc}^{*}	3765	$0\,(\frac{3}{2})$	$1.23 \times g.s$

like S.Cho and S.H. Lee, PRC101 (2020)
from R.A. Briceno et al., PRD 86(2012)

Strengths of the approach:

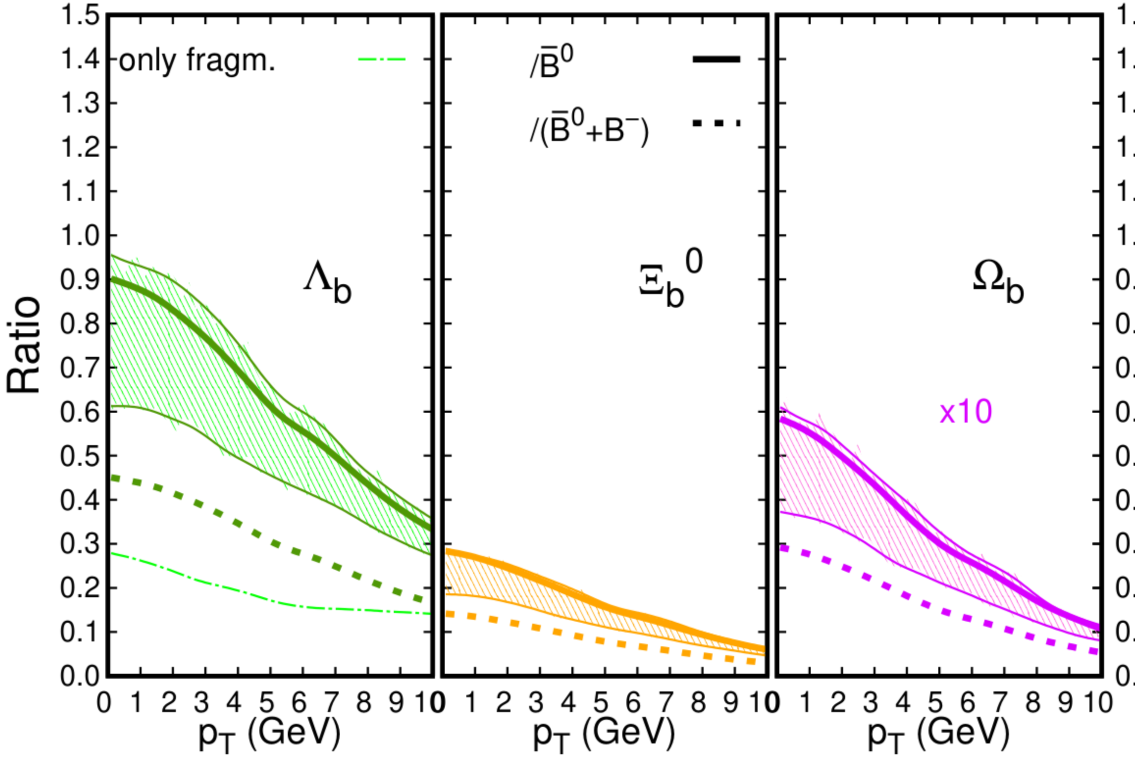
- Does not rely on distribution in equilibrium for charm
  → useful for small AA down to pp collisions and at p_T> 3-4 GeV

- Provide a p_T dependence of spectra and their ratios vs p_T

Widths from harmonic oscillator rescaling and from<r> of Tsingua approach

	$\sigma_{p_1}(GeV)$	$\sigma_{p_2}(GeV)$	$\sigma_{r_1}(fm)$	$\sigma_{r_2}(fm)$
Ξ_c	0.262	0.438	0.751	0.450
Ω_c	0.345	0.557	0.572	0.354
Ξ_{cc}^{ω}	0.317	0.573	0.622	0.344
$\Omega_{ccc}^{\sigma_r\sigma_p=3/2}$	0.522	0.522	0.566	0.566

Small systems: Coalescence in pp for bottom hadron?



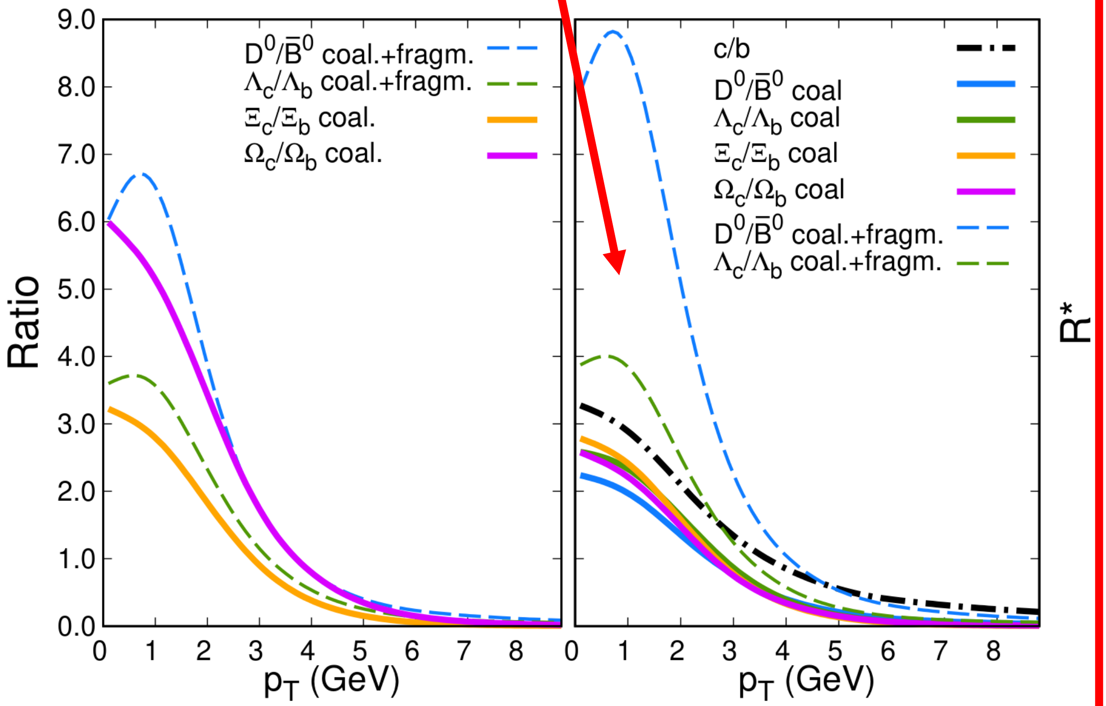
Error band correspond to $\langle r^2 \rangle$ uncertainty in quark model

Coal gives enhancement of Baryon/meson ratio

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

$$\mathcal{F}_{\mathrm{H}}^{\mathrm{c,b}} = 1 + \sum_{Res} g_{H^*}^{c,b}$$

$$R^*_{H_{c,b}} = \left(\frac{\mathcal{F}_{\mathrm{H}}^{\mathrm{c}}}{\mathcal{F}_{\mathrm{H}}^{\mathrm{b}}}\right)^{-1} \frac{d\sigma^{H_c}/dp_T}{d\sigma^{H_b}/dp_T}$$



D/B, Λ_c/Λ_b, Ξ_c/Ξ_b, Ω_c/Ω_b provide information about hadronization and f(c)/f(b)

Scaling when only coal. is assumed, considering only the g.s.