Charm and Bottom hadron production with a coalescence plus fragmentation hadronization approach: AA system size scan down to pp collisions

S. Plumari

**Dipartimento di Fisica e Astronomia ‘E. Majorana’,
Università degli Studi di Catania**

INFN-LNS

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V. Minissale, M.L. Sambataro, S. K. Das, Y. Sun, V. Greco

UNIVERSITÀ degli STUDI di CATANIA

INFN
Istituto Nazionale di Fisica Nucleare

DIPARTIMENTO DI FISICA E ASTRONOMIA "ETTORE MAJORANA"

SQM2024

The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

Outline

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)

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** *(new)*

V. Minissale et al, arXiv:2405.19244 [hep-ph]

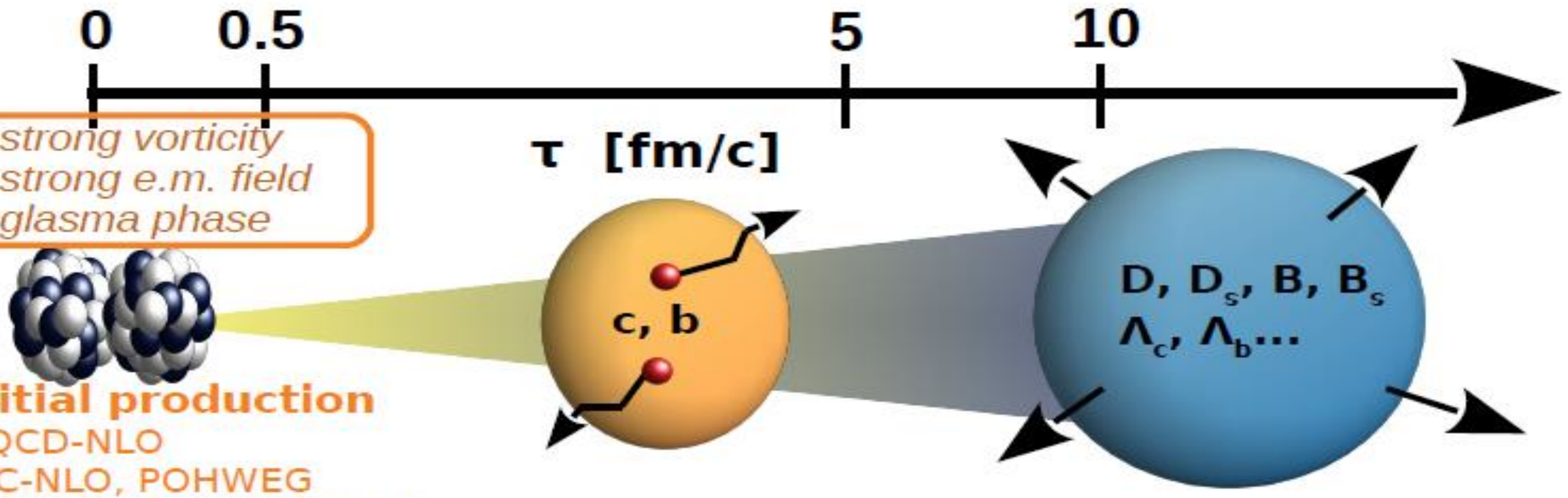
Multi-charm production PbPb vs KrKr vs ArAr vs OO: *(new)*

- comparing evolution with A-A to SHM

- looking at <r> dependence of Ω_{ccc} production

V. Minissale, et al., Eur. Phys. J. C 84, no.3, 228 (2024)

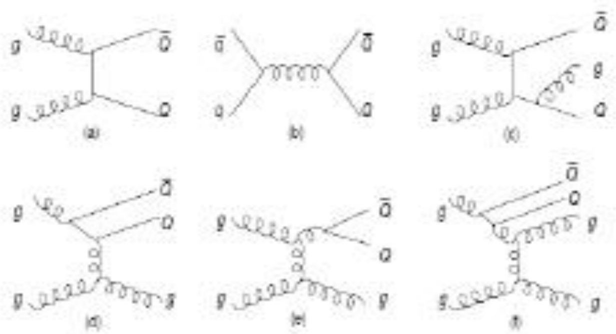
Heavy quarks in uRHIC



- *strong vorticity*
- *strong e.m. field*
- *glasma phase*

Initial production
- pQCD-NLO
- MC-NLO, POHWEG
- CNM effect[pp,pA exp.]

$$\sigma_{pp\to c\bar{c}} = \int_0^1 dx_1 dx_2 \sum_{i,j} f_i(x_1, Q^2) f_j(x_2, Q^2) \sigma_{ij\to c\bar{c}}(x_1, x_2, Q^2),$$



Dynamics in QGP
- Transport approaches: Boltzmann/Fokker-Planck
- Themalization
- Transp. Coeff. of QCD matter $D_s(T)$
- Jet Quenching

Hadronization
- SHM/coalescence and/or fragm. D, D_s, B, B_s, Λ_c, Λ_b, Ξ_c, Ω_c...
- Λ_c/D in pp,pA,AA
- R_{AA}, collective flow harmonics

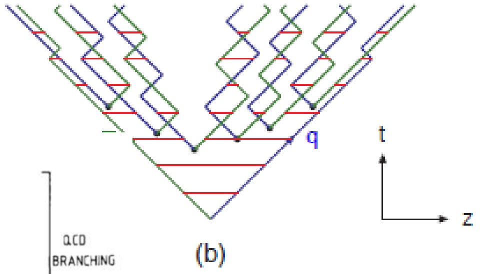
HF Hadronization schemes

- **Independent fragmentation**

$q \rightarrow \pi, K, p, \Lambda$ ..

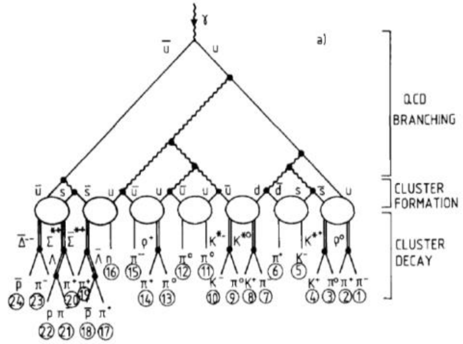
$c \rightarrow D, D_s, \Lambda_c$, ...

- **String fragmentation** (PYTHIA)



- **In medium hadronization with Cluster deca**

A. Beraudo et al., arXiv:2202.08732v1 [hep-ph]



- **Coalescence/recombination**

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

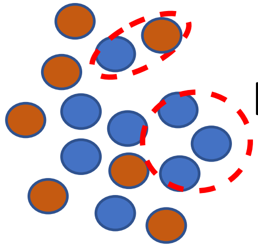
S. Cao et al. , Phys. Lett. B 807 (2020) 135561

Resonance Recombination model

L. Ravagli and R. Rapp, Phys. Lett. B 655, 126 (2007).

L. Ravagli, H. van Hees and R. Rapp, Phys. Rev. C 79, 064902 (2009).

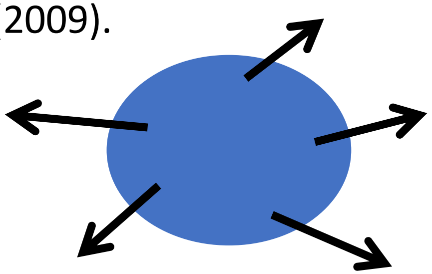
π, K, D, ...



p, Λ, Λ_c , ...

- **Statistical hadronization model (SHM)**

A. Andronic et al, JHEP 07 (2021) 035



For recent reviews see:

J. Altmann, arXiv:2405.19137 [hep-ph]

J. Zhao, et al., PRC **109**, no.5, 054912 (2024)

Relativistic Boltzmann eq. at finite η/s

Bulk evolution

For details see M.L. Sambataro [5 Jun 2024, 09:10]

$$p^{\mu}\partial_{\mu}f_q(x,p) + m(x)\partial_{\mu}^{x}m(x)\partial_{p}^{\mu}f_q(x,p) = C[f_q, f_g]$$

$$p^{\mu}\partial_{\mu}f_g(x,p) + m(x)\partial_{\mu}^{x}m(x)\partial_{p}^{\mu}f_g(x,p) = C[f_q, f_g]$$

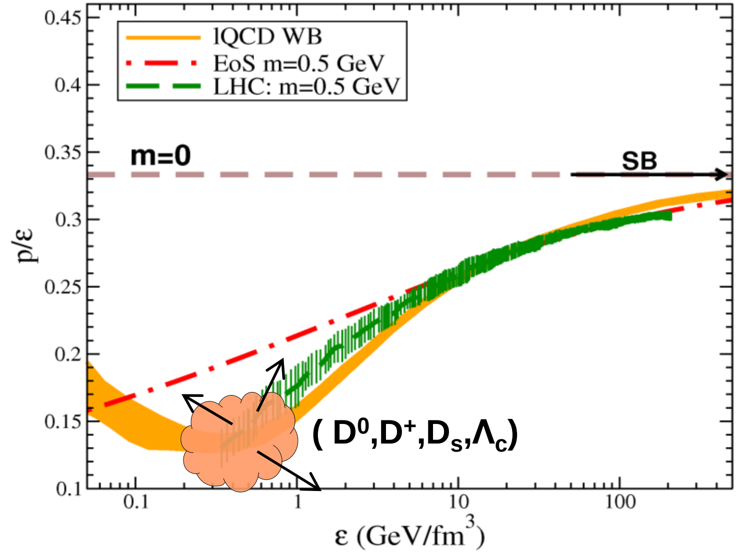
free-streaming

field interaction
ε-3p≠0

collision term
gauged to some η/s≠0

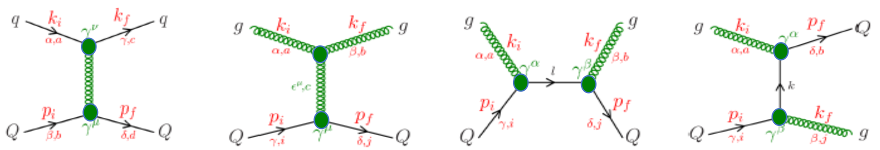
Equivalent to viscous hydro η/s≈0.1

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



HQ evolution

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



$$\mathcal{C}[f_Q] = \frac{1}{2E_1}\int\frac{d^3p_2}{2E_2(2\pi)^3}\int\frac{d^3p'_1}{2E_{1'}(2\pi)^3}$$
$$\times[f_Q(p'_1)f_{q,g}(p'_2) - f_Q(p_1)f_{q,g}(p_2)]$$
$$\times|\mathcal{M}_{(q,g)+Q}(p_1p_2 \to p'_1p'_2)|^2$$
$$\times(2\pi)^4\delta^4(p_1+p_2-p'_1-p'_2),$$

M scattering matrix by QPM model fit to lQCD EoS

More details in:

M. L. Sambataro, et al., Phys. Lett. B **849**, 138480 (2024)
M. L. Sambataro, et al., Eur. Phys. J. C **82**, no.9, 833 (2022)
L. Oliva, S. Plumari and V. Greco, JHEP **05**, 034 (2021)
S. Plumari, et al., Phys. Lett. B **805**, 135460 (2020)
Y. Sun, S. Plumari and V. Greco, Eur. Phys. J. C **80**, no.1, 16 (2020)
S. Plumari, Eur. Phys. J. C 79, no.1, **2** (2019)
F. Scardina, et al., Phys. Rev. C **96**, no.4, 044905 (2017)

Indipendent fragmentation

Spectrum of heavy quarks produced in pp-collisions can be computed up to NLO in s with available tools

Transition from quark momentum spectrum to hadron momentum, using fragmentation model:

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

q → π, K, p, Λ ..

c → D, D_s , Λ_c , ...

Fragmentation function

- **Fragmentation functions** $D_{f\to h}$ are phenomenological functions to parameterize the *non-perturbative parton-to-hadron transition* (z = fraction of the parton momentum taken by the hadron h)

- **Fragmentation functions** assumed **universal** among energy and collision systems and constrained from $e^+e^-$and ep

- Different models for FFs are currently in use in literature:

- Peterson et al., $D(z) = \frac{C}{z\left(1-\frac{1}{z}-\frac{\epsilon}{1-z}\right)^2}$

- Kartvelishvili et al., $D(z) = C z^{\alpha}(1-z)$

Coalescence approach in phase space for HQ

Statistical factor colour-spin-isospin

Parton Distribution function

Hadron Wigner function

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

Wigner function <-> Wave function

$$\Phi^W_M(\mathbf{r},\mathbf{q}) = \int d^3r' e^{-i\mathbf{q}\cdot\mathbf{r}'} \varphi_M\left(\mathbf{r}+\frac{\mathbf{r}'}{2}\right)\varphi^*_M\left(\mathbf{r}-\frac{\mathbf{r}'}{2}\right)$$

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

Assuming gaussian wave function

$$f_M(x_1, x_2; p_1, p_2) = A_W \exp\left(-\frac{x_{r1}^2}{\sigma_r^2} - p_{r1}^2\sigma_r^2\right)$$

For baryon N_q=3

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

Note: only σ_r coming from $\varphi_M(\boldsymbol{r})$ or σ_r*σ_p=1 valid for harmonic oscillator with V(r) σ_r*σ_p>1

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

$$\langle r^2\rangle_{ch} = \frac{3}{2}\frac{m_2^2Q_1 + m_1^2Q_2}{(m_1+m_2)^2}\sigma_{r1}^2 + \frac{3}{2}\frac{m_3^2(Q_1+Q_2) + (m_1+m_2)^2Q_3}{(m_1+m_2+m_3)^2}\sigma_{r2}^2 \quad (8)$$

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

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

$$\mu_1 = \frac{m_1m_2}{m_1+m_2}, \quad \mu_2 = \frac{(m_1+m_2)m_3}{m_1+m_2+m_3}.$$

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

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

Normalization f_H*(...) fixed by requiring* P_{coal}(p->0)=1 which fixes A_w , additional assumption wrt standard coalescence which does not have confinement

Coalescence approach in phase space for HQ

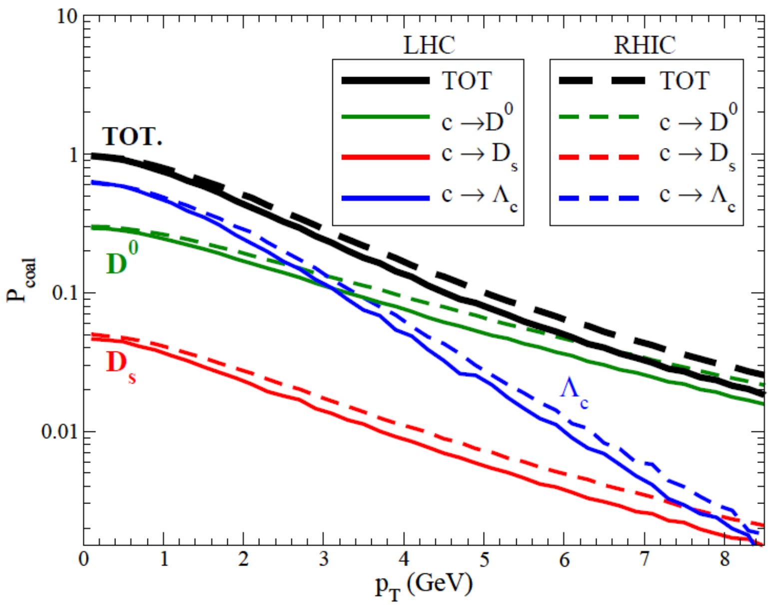
Statistical factor colour-spin-isospin

Parton Distribution function

Hadron Wigner function

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

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



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

- Normalization in $f_W(\dots)$ *fixed by requiring* $P_{coal}(p \to 0)=1$: ....others modify by hand σ_r to enforce confinement for a charm at rest in the medium

- The charm not "coalescencing" undergo fragmentation:

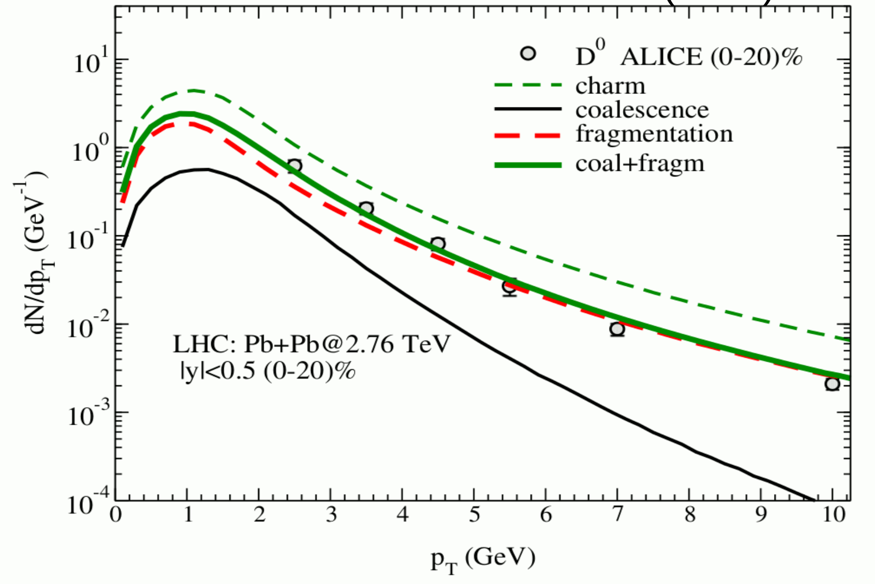
$$\frac{dN_{had}}{d^2p_T\,dy} = \sum \int dz \frac{dN_{fragm}}{d^2p_T\,dy} \frac{D_{had/c}(z, Q^2)}{z^2}$$

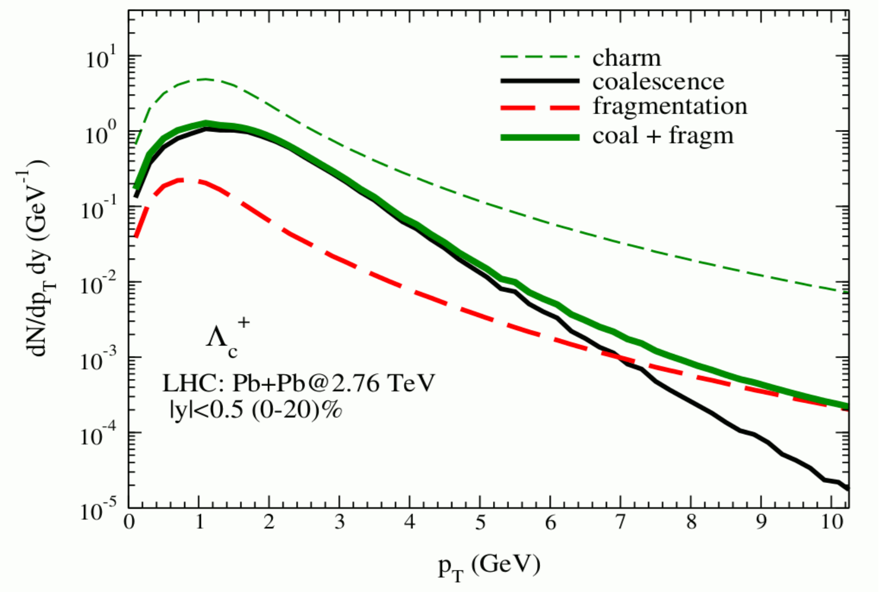
charm number conserved at each p_T,
we have employed e^+e^- FF now PYTHIA

For the discussion about $R_{AA}(p_T)$, $v_n(p_T)$, of charm and bottom hadrons
See M.L. Sambataro [5 Jun 2024, 09:10]

LHC: results

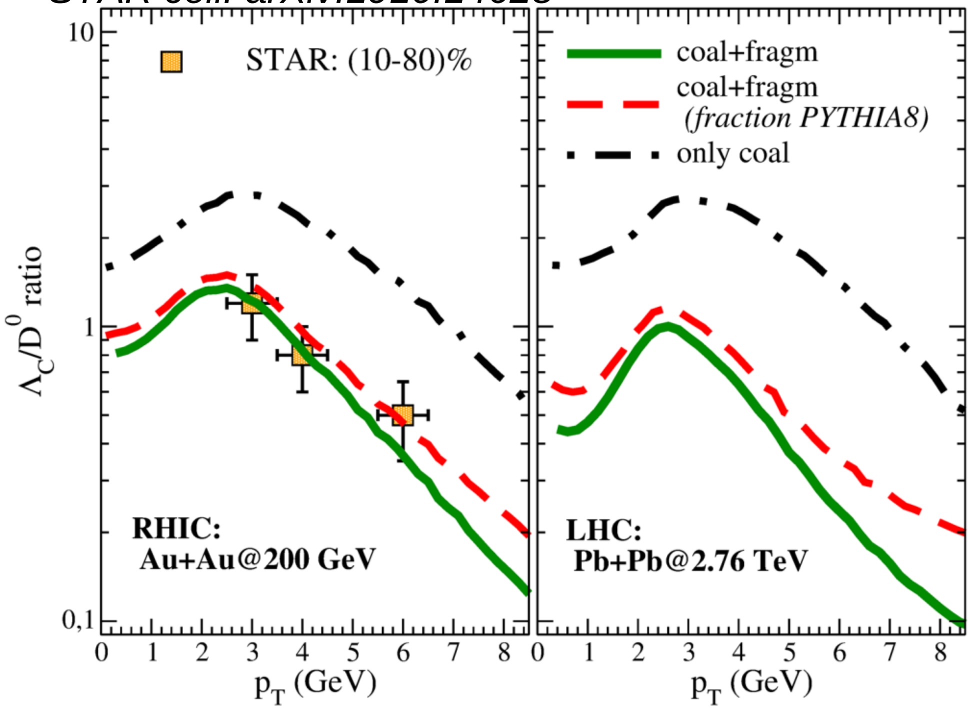
Data from ALICE Coll. JHEP 1209 (2012) 112





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

STAR coll. arXiv:1910.14628



The Λ_c/D^0 ratio is smaller at LHC energies: fragmentation play a role at intermediate p_T

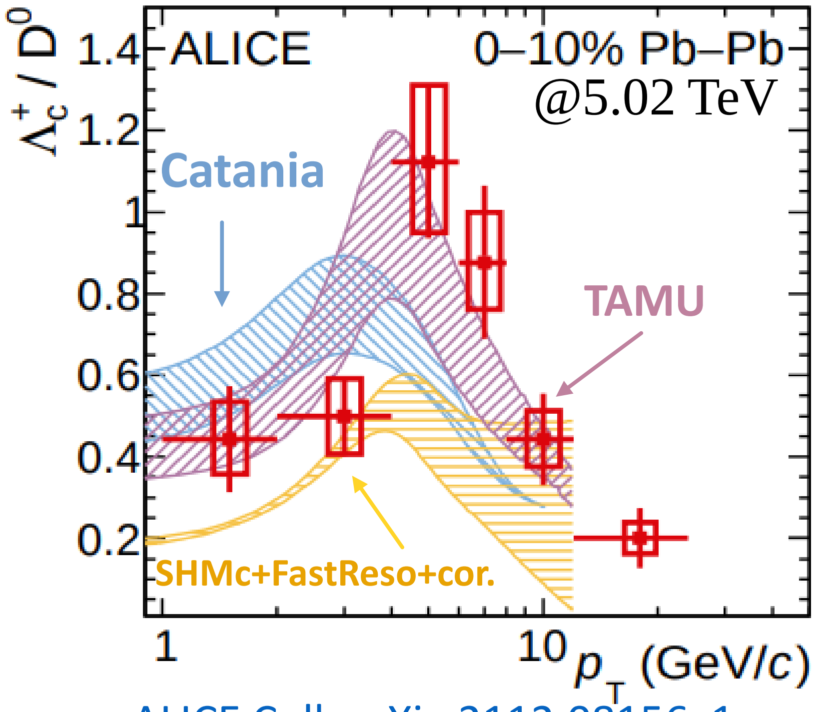
S. Plumari, et al., Eur. Phys. J. ***C78*** *no. 4, (2018) 348*

LHC: results

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

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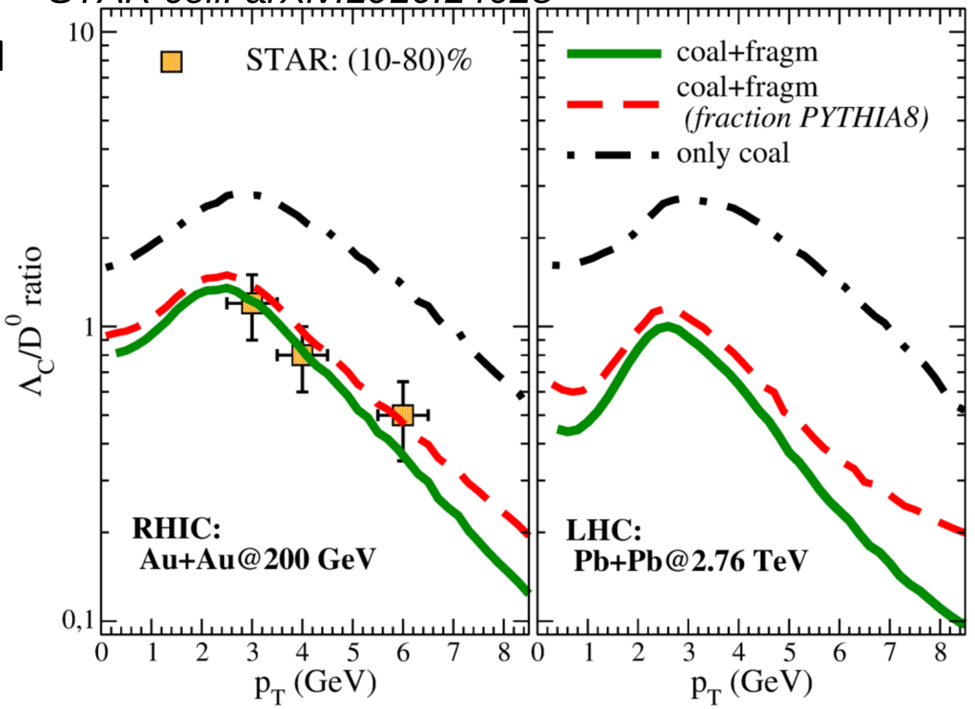

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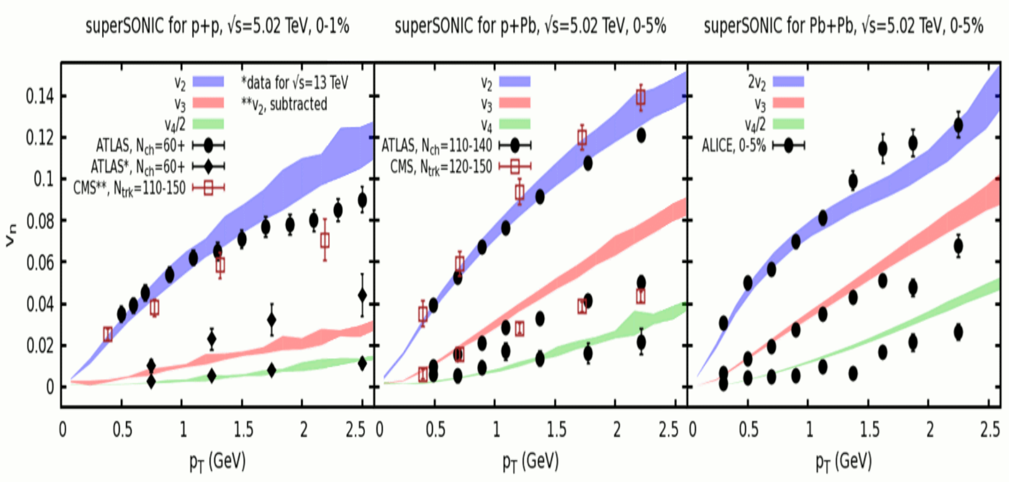
S. Plumari, et al., Eur. Phys. J. ***C78*** *no. 4, (2018) 348*

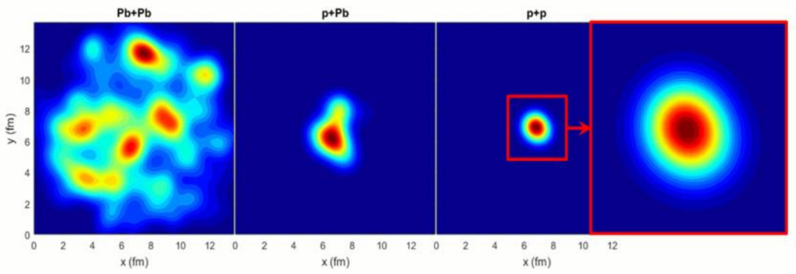
Small systems

Traditional view:

- **QGP in Pb+Pb**
- **no QGP in p+p (“baseline”)**



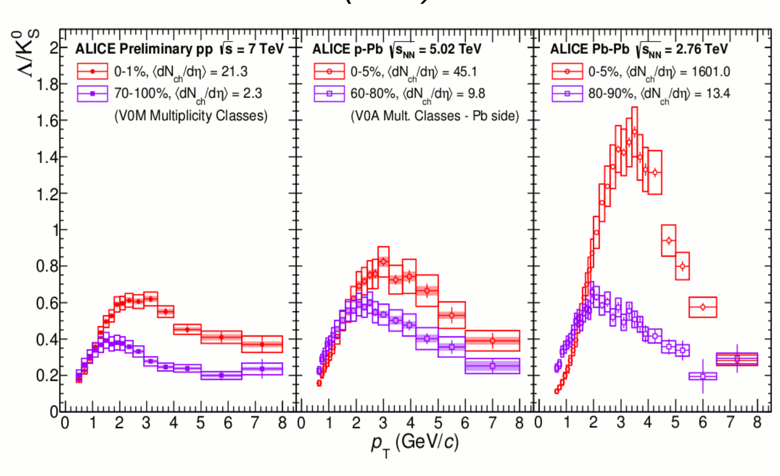
R. D. Weller, P. Romatschke PLB 774 (2017) 351-356



Objections to apply hydro in pp

- **Too few particles, cannot be collective**
- **System not in equilibrium**

ALICE Coll.,PRL 111 (2013) 222301
ALICE Coll.,J. Phys.: Conf.Ser. 509 (2014) 012091
ALICE Coll.NPA 956 (2016) 777-780.

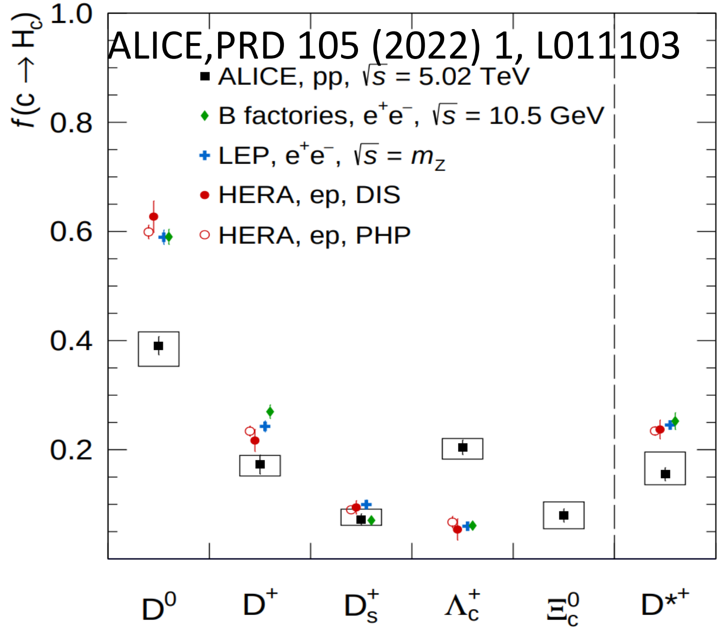


Fragmentation:

production from hard-scattering processes (PDF+pQCD).

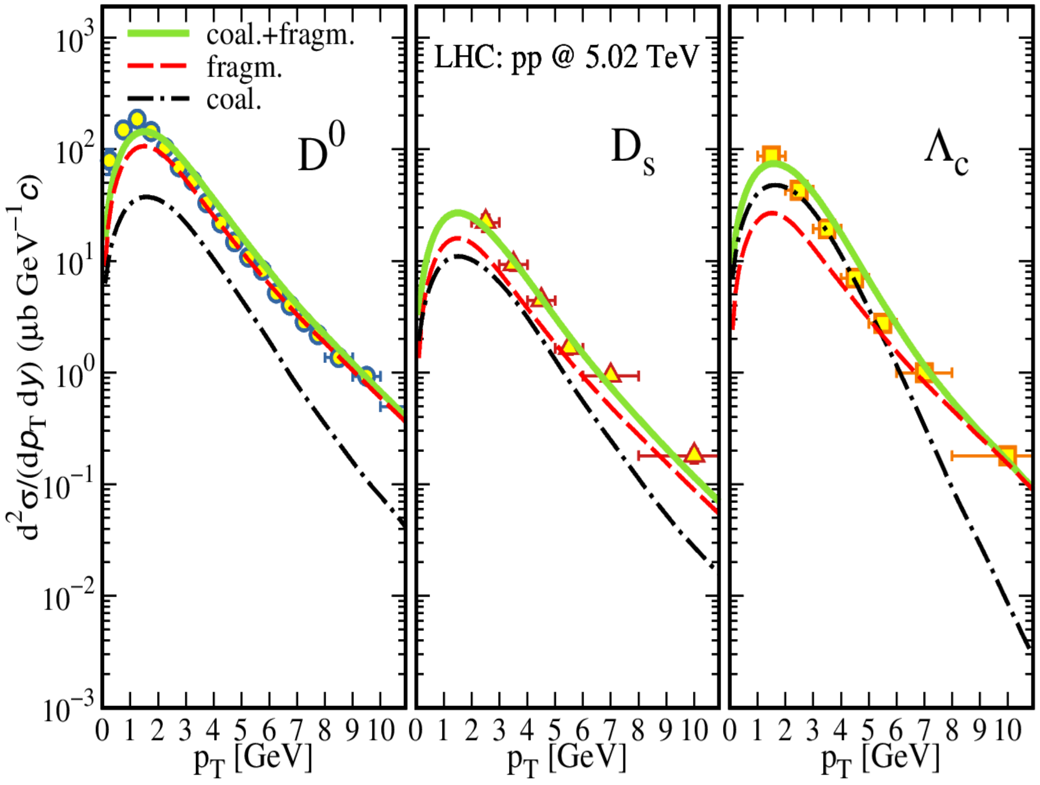
Fragmentation functions assumed “universal”

- Indication that fragmentation depends on the collision system
- Assumption of their universality not supported by the measured cross sections



Small systems: Coalescence in pp? (Charm hadrons)

Data from: ALICE coll. EPJ C79 (2019) no.5, 388
ALICE coll. Meninno Hard Probes 2018



V. Minissale et al., *Phys.Lett.B* 821 (2021) 136622

- Thermal Distribution (p_T< 2 GeV)

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

- Collective flow $\beta_T = \beta_0 \frac{r}{R}$
- Fireball radius+radial flow constraints dN_{ch}/dy and dE_T/dy
- Minijet Distribution (p_T> 2 GeV)
- NO QUENCHING

p+p @ 5 TeV

- t_{pp}=1.7 fm/c
- β_0=0.4
- R=2.5 fm
- V~30 fm^3

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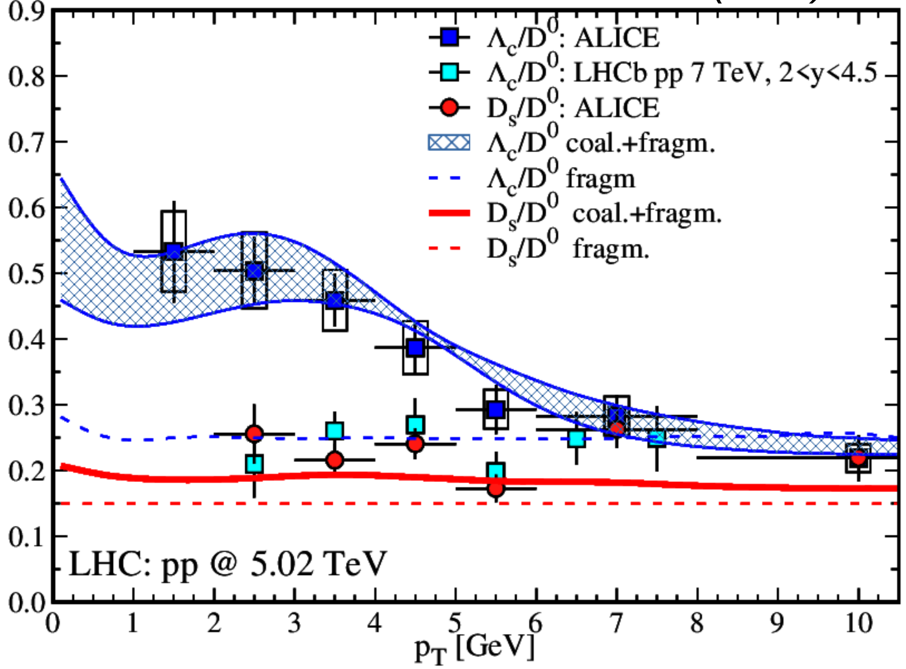
Small systems: Coalescence in pp? (Charm hadrons)

Data taken from: ALICE coll. JHEP 04 (2018) 108



V. Minissale et al., *Phys.Lett.B* 821 (2021) 136622

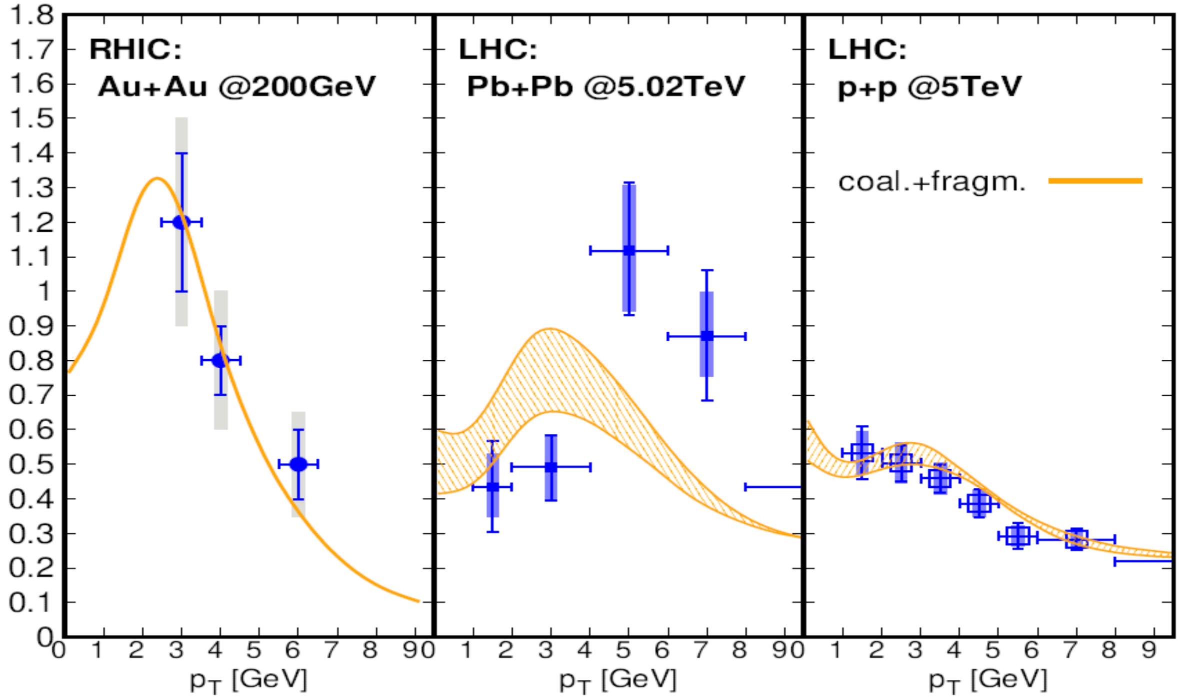
Error band correspond to <r^2> uncertainty in quark model

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



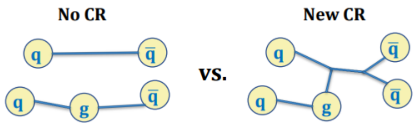
Other models:

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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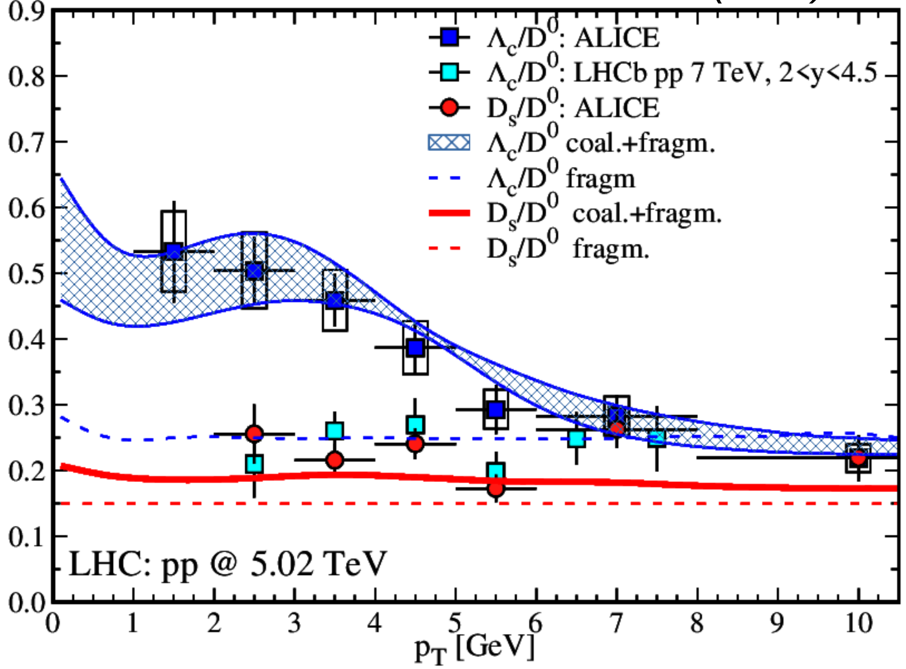

V. Minissale et al., *Phys.Lett.B* 821 (2021) 136622

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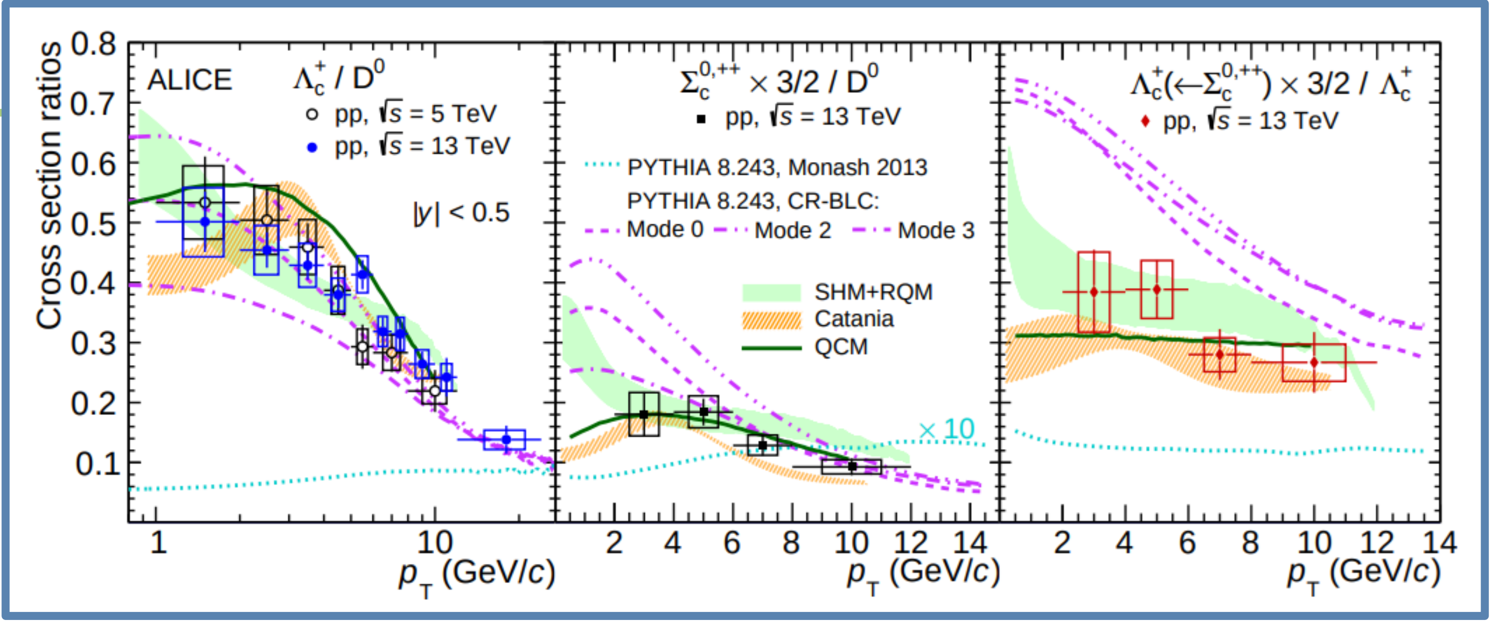
ALICE Coll., Physical Review Letters 128, 012001 (2022)



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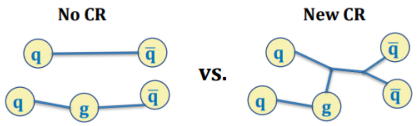
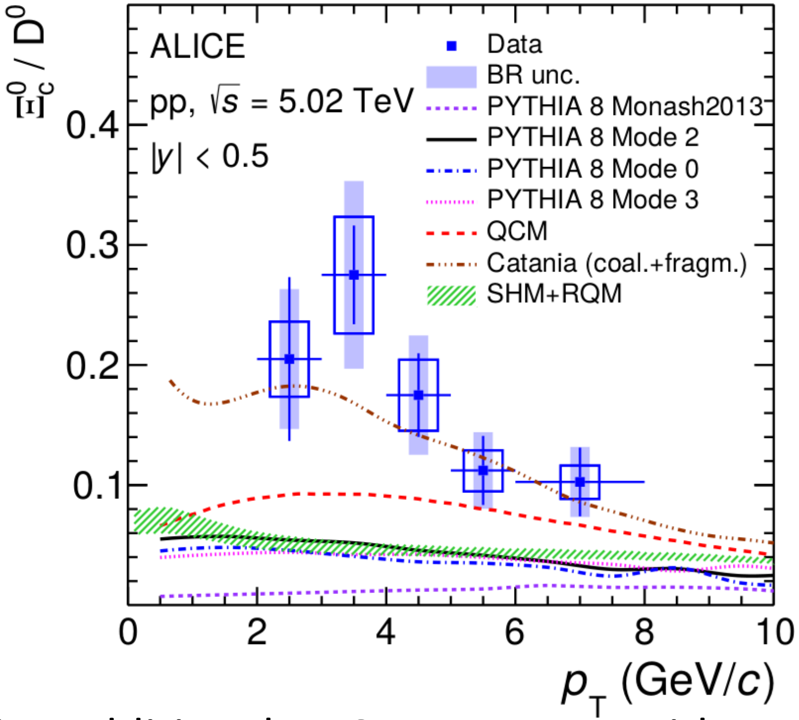


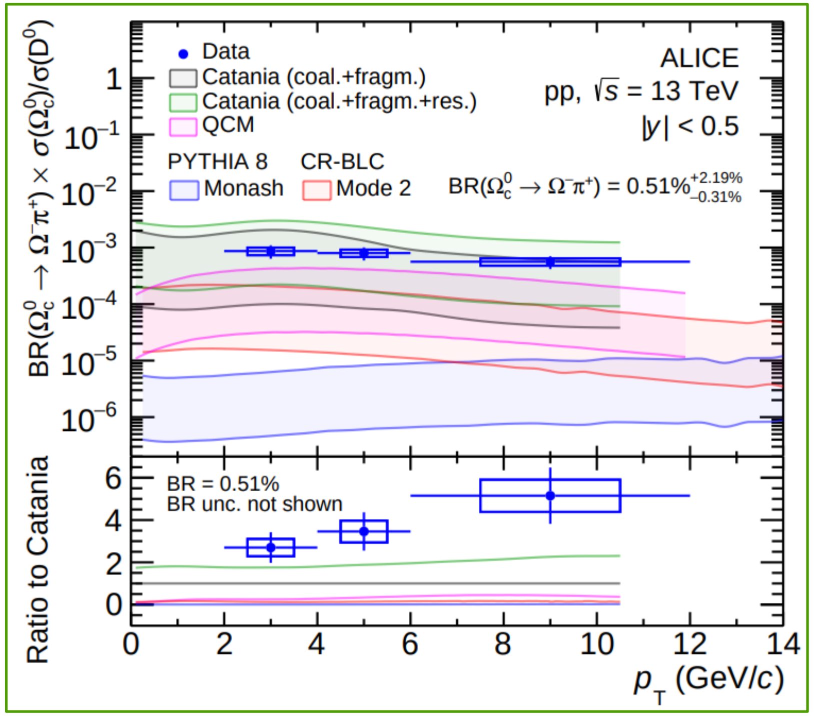
Small systems: Coalescence in pp? (Charm hadrons)



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



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

E. Santopinto et. al, EPJC 79 (2019) 12, 1012

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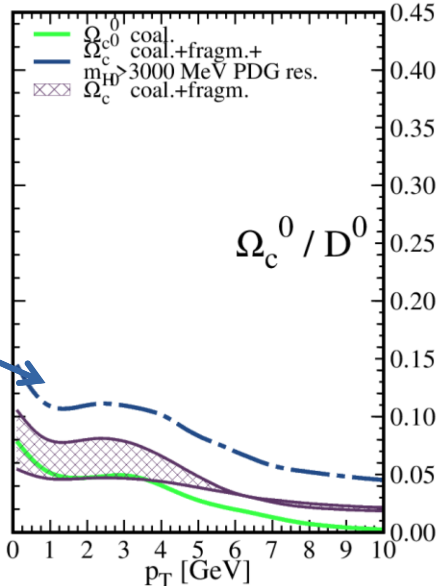


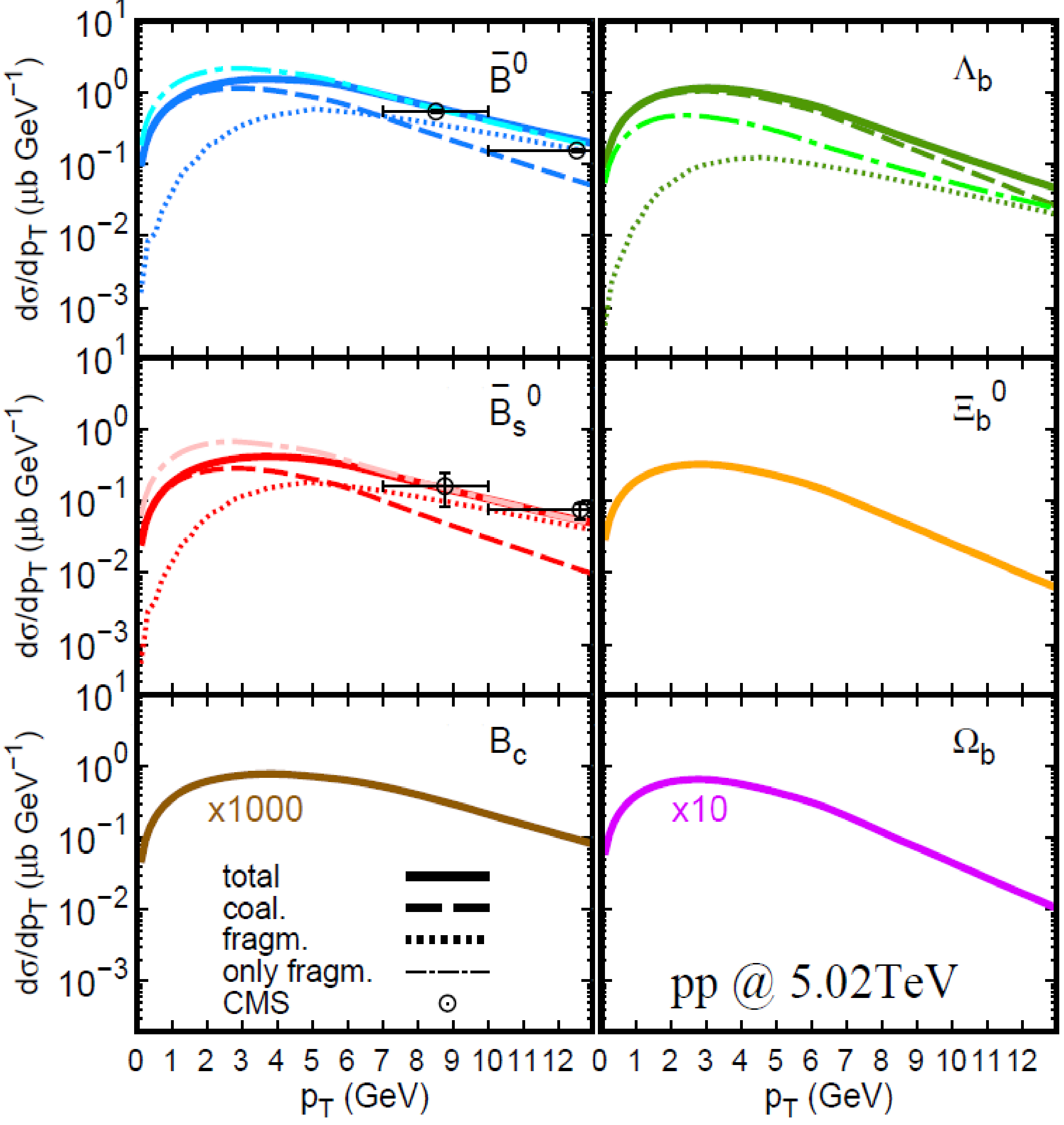
ALICE Coll. JHEP 10 (2021) 159

ALICE Coll. arXiv:2205.13993

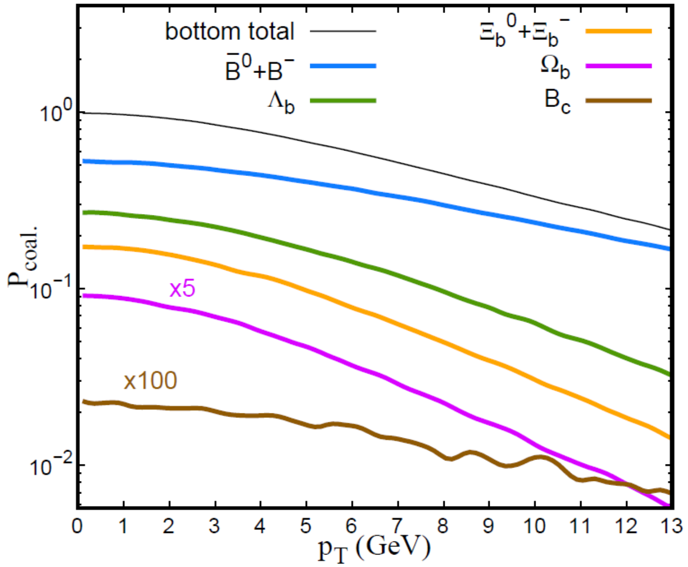
V. Minissale, S. Plumari, V. Greco, Physics Letters B 821 (2021) 136622

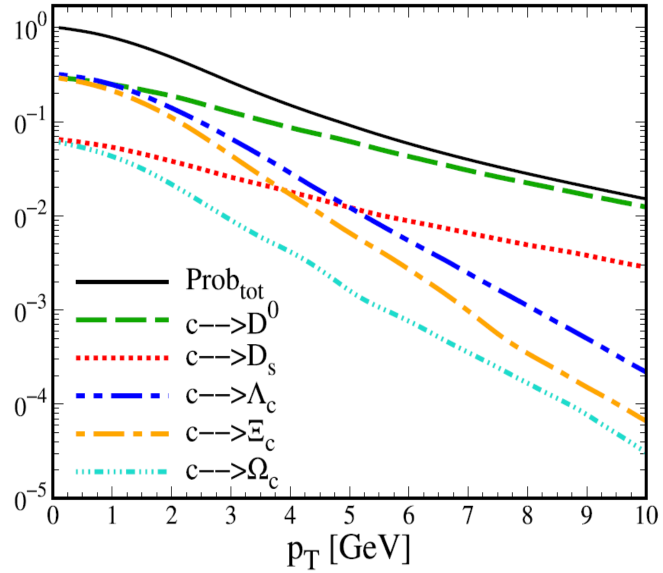
Small systems: Coalescence in pp? (Bottom hadrons)

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



V. Minissale et al. arXiv:2405.19244 [hep-ph]





- Pcoal of bottom is flatter than Pcoal of charm
  -> Coal. greater impact on bottom hadron production

- B meson production at pT < 5 GeV mainly from Coal
- Λb production mainly from Coal. for pT < 10 GeV

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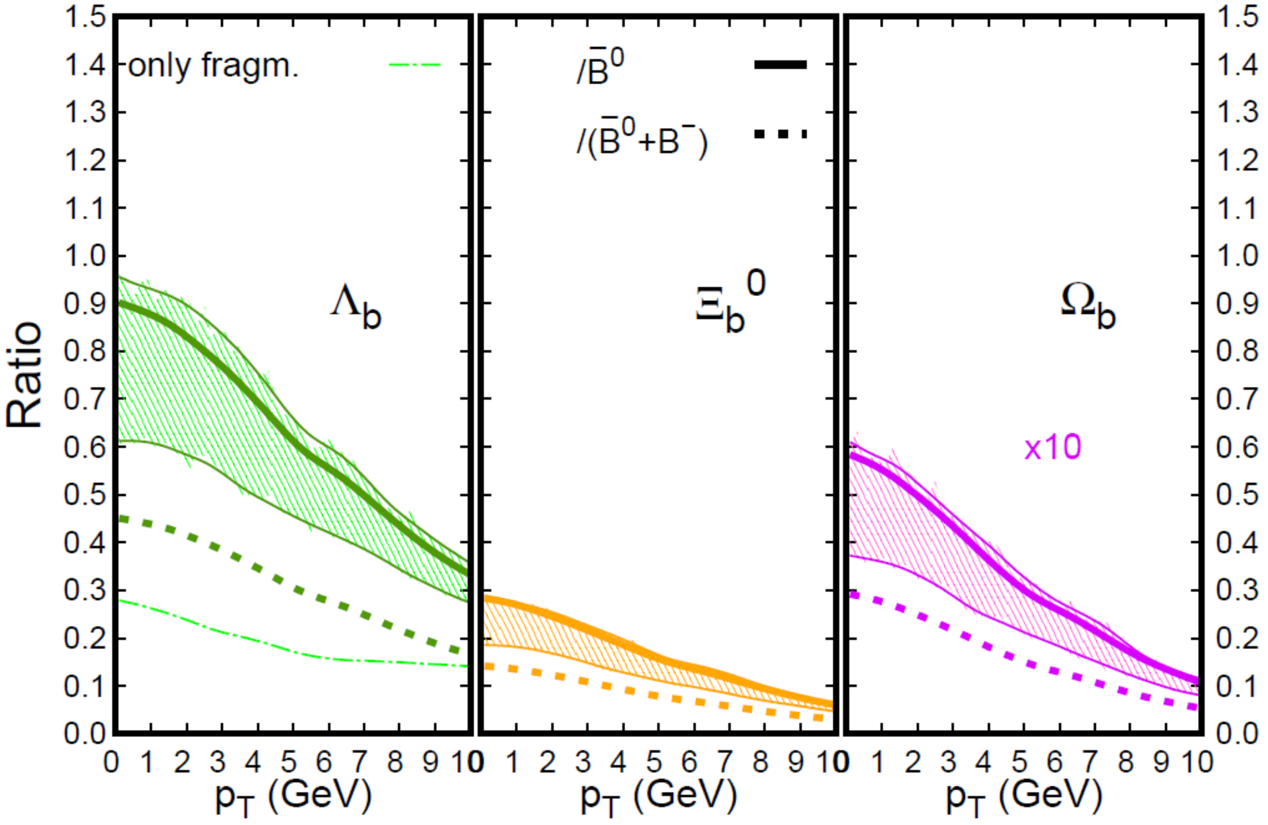
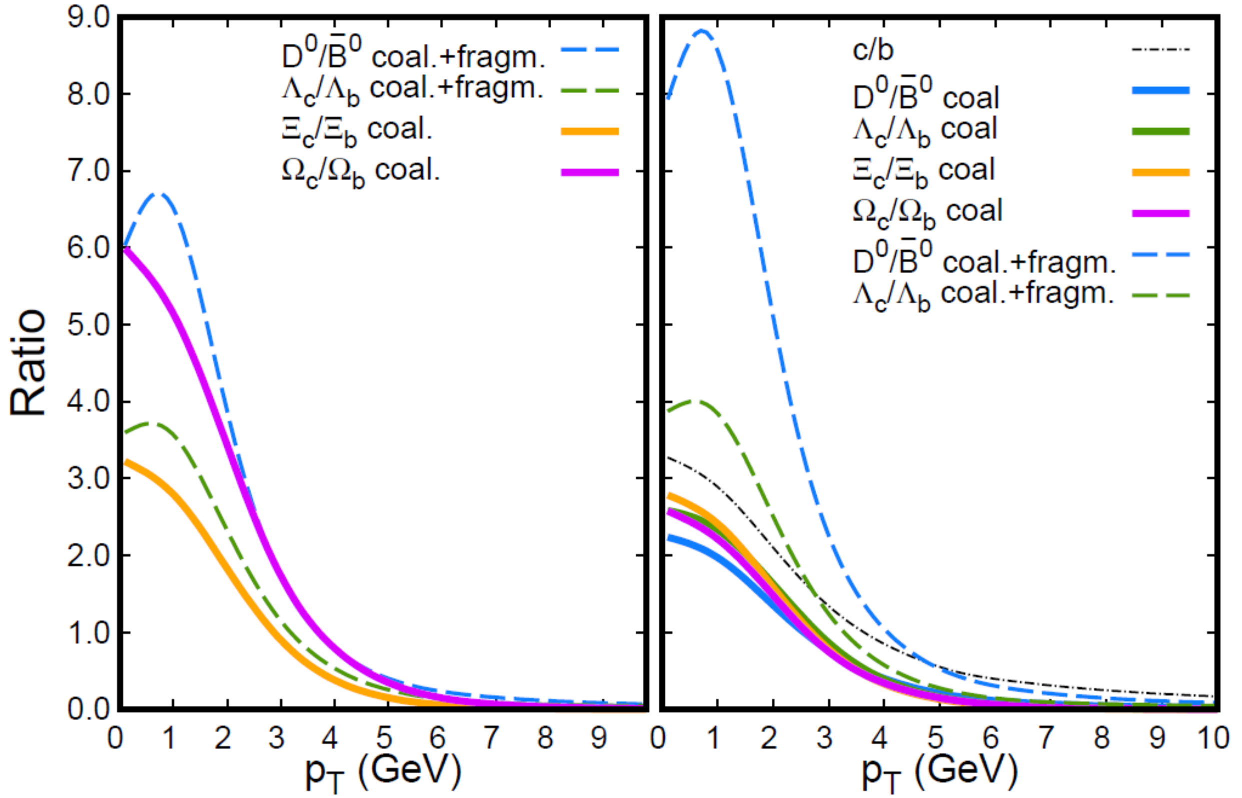


Error band correspond to <r^2> uncertainty in quark model

- D/B, Λ_c/Λ_b , Ξ_c/Ξ_b , Ω_c/Ω_b provide information about hadronization and f(c)/f(b)
- Scaling if only coal. is assumed

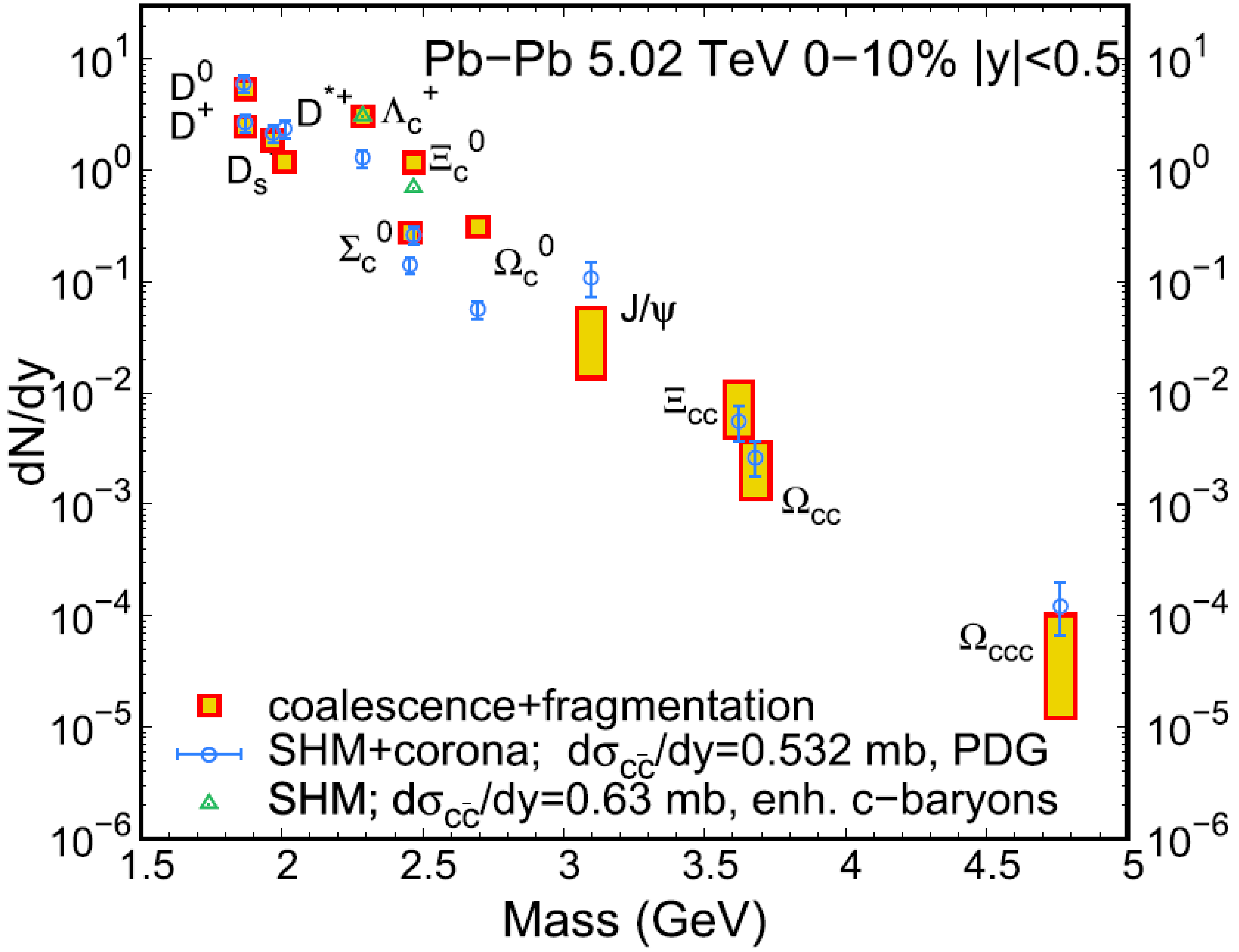


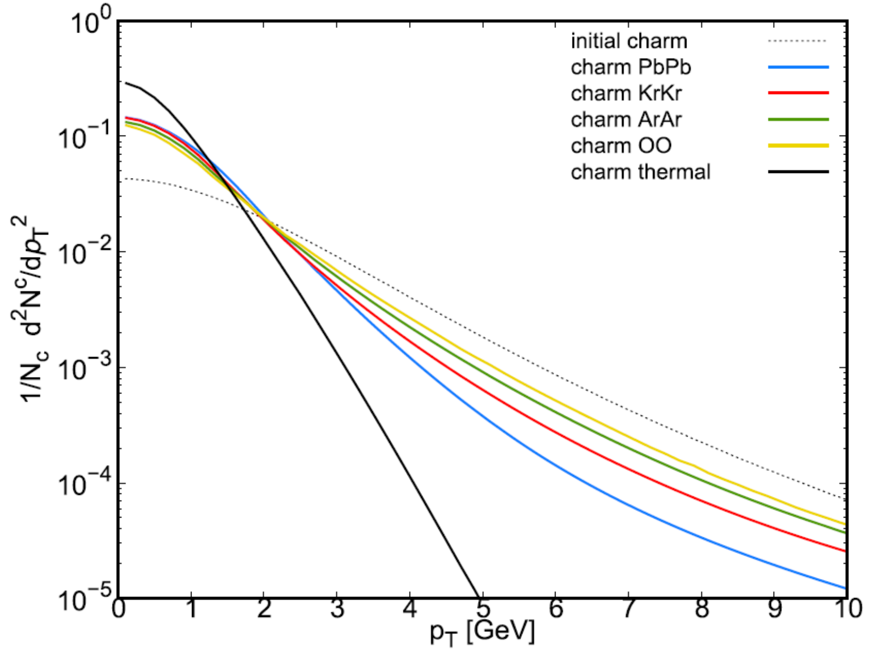
Coal gives enhancement of Baryon/meson ratio

Multi-charm in PbPb - KrKr – ArAr -OO

Yelds in PbPb: coalescence vs SHM

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





We employ same volume in SHM
A. Andronic JHEP (2021) 035

	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
τ (fm)	4	5	6.2	8
β_{max}	0.55	0.6	0.64	0.7
$V_{\|y\|<0.5}(\mathrm{fm}^3)$	345	920	2000	5000

→ upper limit: charm thermal distribution

→ lower limit: PbPb distribution with widths rescaled as standard Harm. Oscill. (ω from Ω_c^0)

$\Sigma_c^0, \Xi_c^0, \Omega_c^0$, widths from quark model

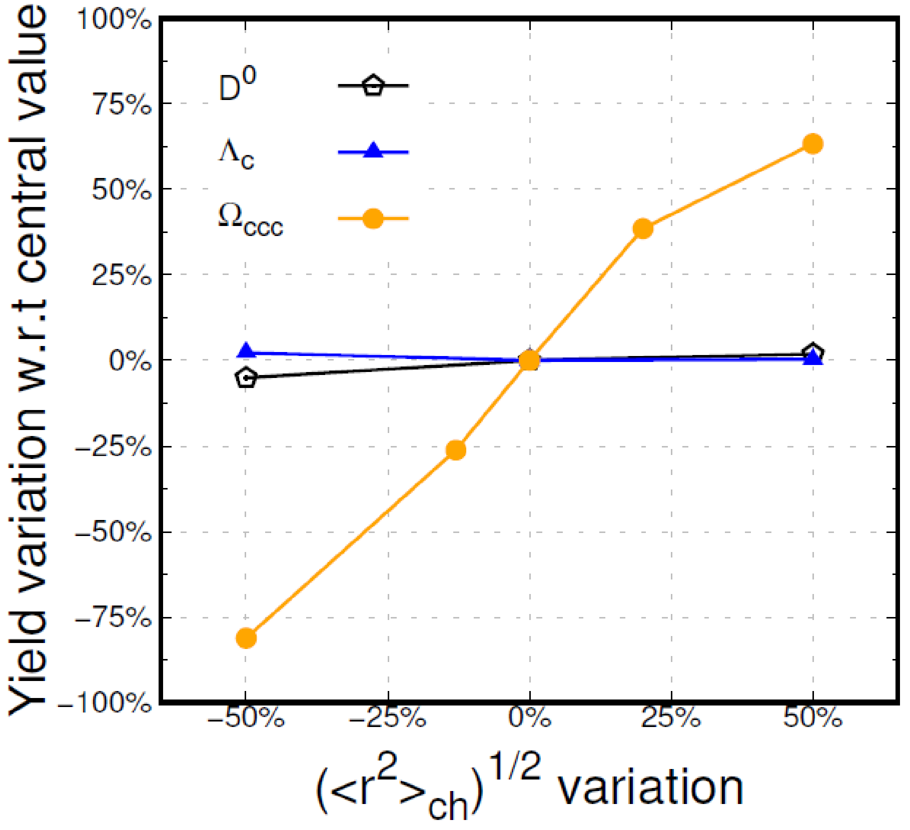
Ξ_{cc}, Ω_{cc} widths obtained rescaling with harm. oscillator

Yelds in PbPb: coalescence

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

D^0 and Λ_c determine the yield, the radius variation is compensated by the constraint on the charm hadronization

A ± 50% in the radius of Ω_{ccc} induces **a change in the yield by about 1 order of magnitude**



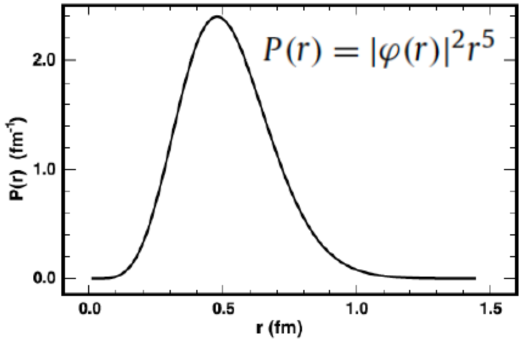
$$V(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)=\sum_{i<j}V_{cc}(\mathbf{r}_i,\mathbf{r}_j). \qquad V_{c\bar{c}}(\mathbf{r}_i,\mathbf{r}_j)=-\frac{\alpha}{|\mathbf{r}_{ij}|}+\sigma|\mathbf{r}_{ij}|,$$

Solve the 3-body problem by a 1-body in higher dimensions hyperspherical coordinates method

$$\left[\frac{1}{2m_c}\left(-\frac{d^2}{dr^2}-\frac{5}{r}\frac{d}{dr}\right)+v(r)\right]\varphi(r)=E\varphi(r)$$

$$W(\mathbf{r},\mathbf{p})=\int d^6\mathbf{y}e^{-i\mathbf{p}\cdot\mathbf{y}}\psi\left(\mathbf{r}+\frac{\mathbf{y}}{2}\right)\psi^*\left(\mathbf{r}-\frac{\mathbf{y}}{2}\right)$$

$$W(r,p,\theta)=\frac{1}{\pi^3}\int d^6\mathbf{y}e^{-ipy_1}\varphi(r_y^+)\varphi^*(r_y^-),$$

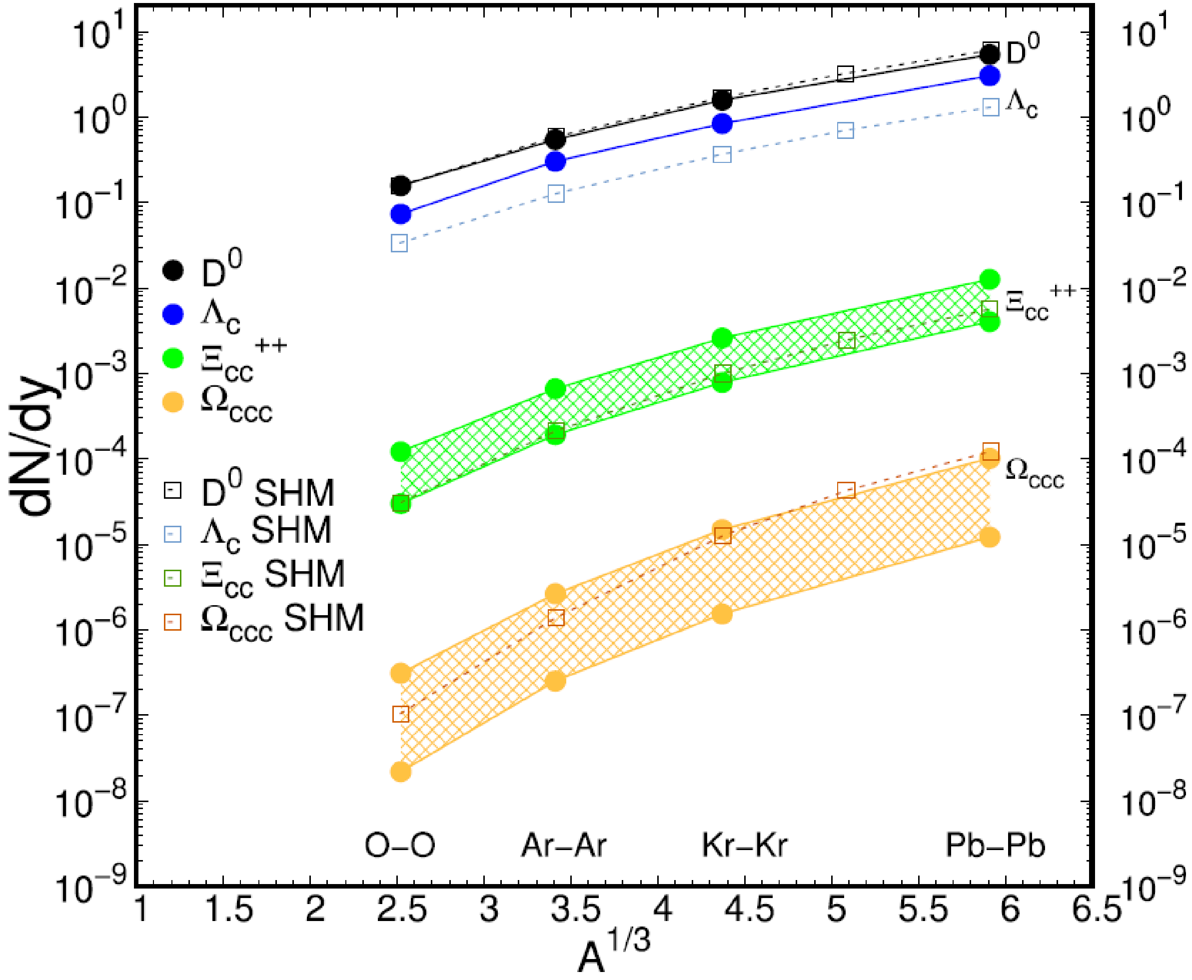


$$\frac{dN}{d^2\mathbf{P}_T d\eta}=C\int_\Sigma\frac{P^\mu d\sigma_\mu(R)}{(2\pi)^3}\int\frac{d^4r_x d^4r_y d^4p_x d^4p_y}{(2\pi)^6}\times F(\tilde{r}_1,\tilde{r}_2,\tilde{r}_3,\tilde{p}_1,\tilde{p}_2,\tilde{p}_3)W(r_x,r_y,p_x,p_y),$$

Ω_{ccc} <r>=0.5 fm & $\sigma_r \cdot \sigma_p \approx 1.5$
similar to Tsinghua PLB746 (2015)

Yelds in PbPb: coalescence vs SHM

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



$\Sigma_c^0, \Xi_c^0, \Omega_c^0$, widths from quark model

Ξ_{cc}, Ω_{cc} widths obtained rescaling with harm. oscillator

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

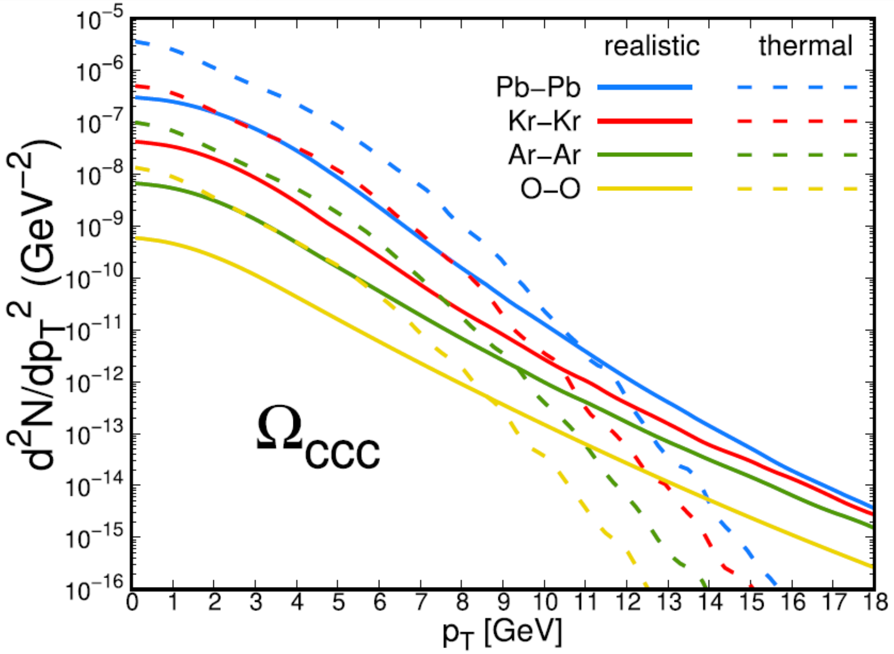
→ upper limit: charm thermal distribution

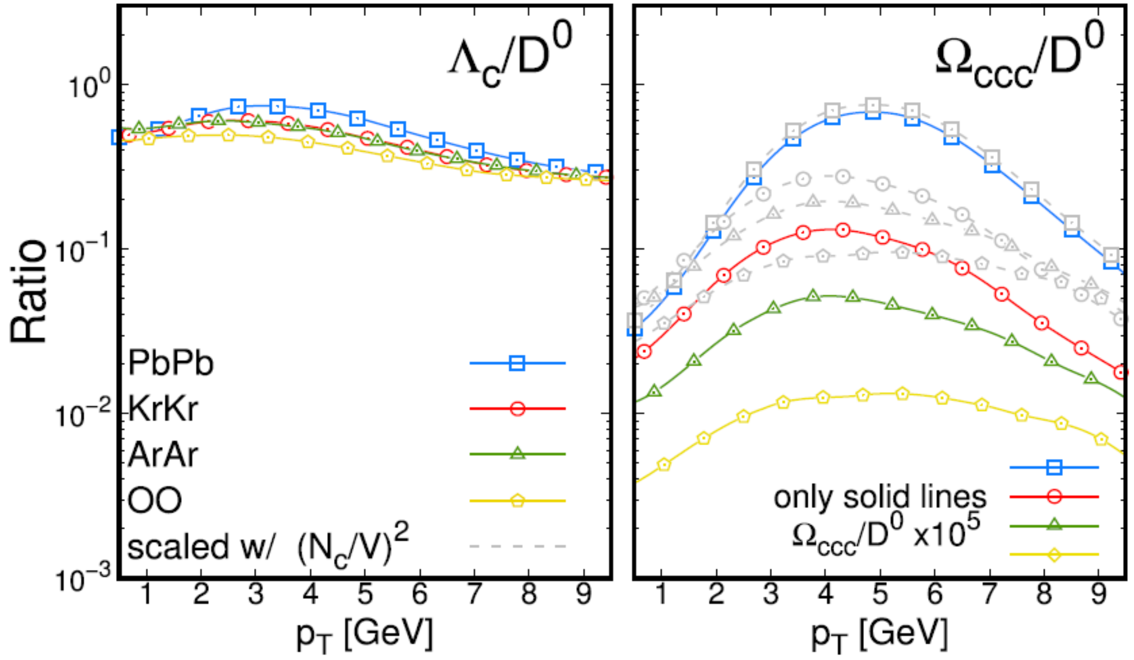
→ lower limit: PbPb distribution with widths rescaled as standard Harm. Oscill. (ω from Ω_c^0)

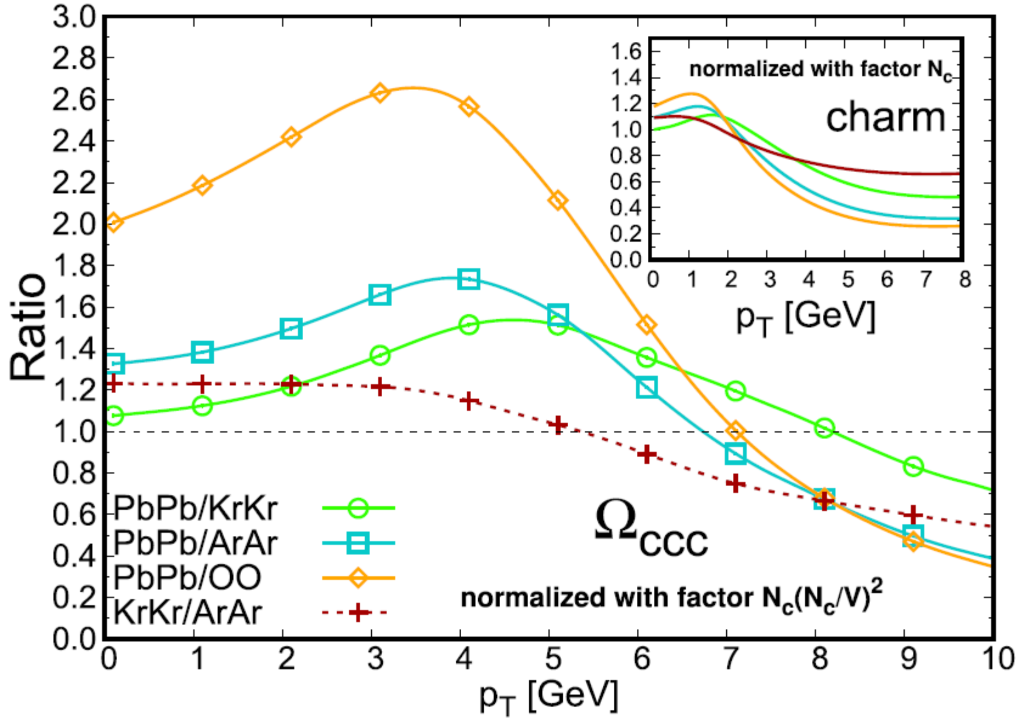
	D^0	Λ_c	$\Xi_{cc}^{+,++}$	Ω_{ccc}
OO	0.156	0.0732	$3-12.1\cdot10^{-5}$	$2.2-29.2\cdot10^{-8}$
$ArAr$	0.543	0.301	$1.9-6.6\cdot10^{-4}$	$2.5-26.3\cdot10^{-7}$
$KrKr$	1.564	0.835	$0.78-2.6\cdot10^{-3}$	$1.5-14.9\cdot10^{-6}$
$PbPb$	5.343	3.0123	$4-12.5\cdot10^{-3}$	$0.12-1.01\cdot10^{-4}$

Ratios of pT distribution Ωccc in PbPb/KrKr/ArAr/OO

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







- It can be a meter of non-equilibrium.
- Translation of features of charm spectra at low pT in to higher momentum region.
- More sensitive to multicharm Ω_{ccc}/D^0 respect to Λ_c/D^0

Conclusion

- **Charm hadronization in AA different than in e^+e^- and ep collisions**
  -Coalescence+fragmentation/Resonance Recombination Model enhancement of Λ_c production at intermediate p_T -> Λ_c/D^0 ~1 for p_T ~ 3 GeV

- ***In p+p assuming a medium:***
  - Coal.+fragm. good description of heavy baryon/meson ratio
    (closer to the data for Λ_c/D^0 , Ξ_c/D^0, Ω_c/D^0)
  - B,Bs 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
  - D/B, Λ_c/Λ_b , Ξ_c/Ξ_b provide information about hadronization and f(c)/f(b)

- The yield of multi-charm decreases slowly with A in a coalescence approach
  - role of non-equilibrium distribution function

Heavy flavour (charm): Resonance decay

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

Statistical factor

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

MESONS

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

D^0 *(I=1/2,J=0)*

D_s^+ *(I=0,J=0)*

BARYONS

Λ_c^+ *(I=0, J=1/2)*

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%*

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%*

Heavy flavour (bottom): Resonance decay

Meson	Mass	I(J)	Baryon	Mass	I(J)
$B^-[\bar{u}b]$	5280	$\frac{1}{2}\,(0)$	$\Lambda_b^0[udb]$	5620	$0\,(\frac{1}{2})$
$\bar{B^0}[\bar{d}b]$	5280	$\frac{1}{2}\,(0)$	$\Xi_b^0[usb]$	5792	$\frac{1}{2}\,(\frac{1}{2})$
$\bar{B_s^0}[\bar{s}b]$	5366	$0\,(0)$	$\Xi_b^-[dsb]$	5797	$\frac{1}{2}\,(\frac{1}{2})$
$B_c^-[\bar{c}b]$	6275	$0\,(0)$	$\Omega_b^-[ssb]$	6045	$0\,(\frac{1}{2})$

Meson Res.	Mass	I(J)	Decay	B.R.
B^*	5325	$\frac{1}{2}\,(1)$	$B\gamma$	
$B_1(5721)$	5726	$\frac{1}{2}\,(1)$	$B^*\gamma$	100%
$B_2(5747)$	5737	$\frac{1}{2}\,(2)$	$B^*\gamma$	100%
B_s^*	5415	$0\,(1)$	$B_s\gamma$	
$B_{s1}^0(5830)$	5829	$0\,(1)$	$B^{*+}K^-$	
$B_{s2}^0(5840)$	5840	$0\,(2)$	B^+K^-	
Baryon Res.				
$\Lambda_b^0(5912)$	5912	$0\,(\frac{1}{2})$	$\Lambda_b^0\pi^+\pi^-$	100%
$\Lambda_b^0(5920)$	5920	$0\,(\frac{3}{2})$	$\Lambda_b^0\pi^+\pi^-$	100%
$\Lambda_b^0(6070)$	6072	$0\,(\frac{1}{2})$	$\Lambda_b^0\pi^+\pi^-$	100%
$\Lambda_b^0(6146)$	6146	$0\,(\frac{3}{2})$	$\Lambda_b^0\pi^+\pi^-$	100%
$\Lambda_b^0(6152)$	6152	$0\,(\frac{5}{2})$	$\Lambda_b^0\pi^+\pi^-$	100%
Σ_b	5811	$1\,(\frac{1}{2})$	$\Lambda_b^0\pi$	100%
Σ_b^*	5830	$1\,(\frac{3}{2})$	$\Lambda_b^0\pi$	100%
$\Xi_b^{'-}(5935)$	5935	$(\frac{1}{2})$	$\Xi_b^0\pi^-$	100%
$\Xi_b^0(5945)$	5952	$(\frac{3}{2})$	$\Xi_b^-\pi^+$	100%
$\Xi_b^-(6100)$	5952	$(\frac{3}{2})$	$\Xi_b^-\pi^-\pi^+$	100%

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

Statistical factor

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

Multi-charm production in PbPb, KrKr, ArAr, OO

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:

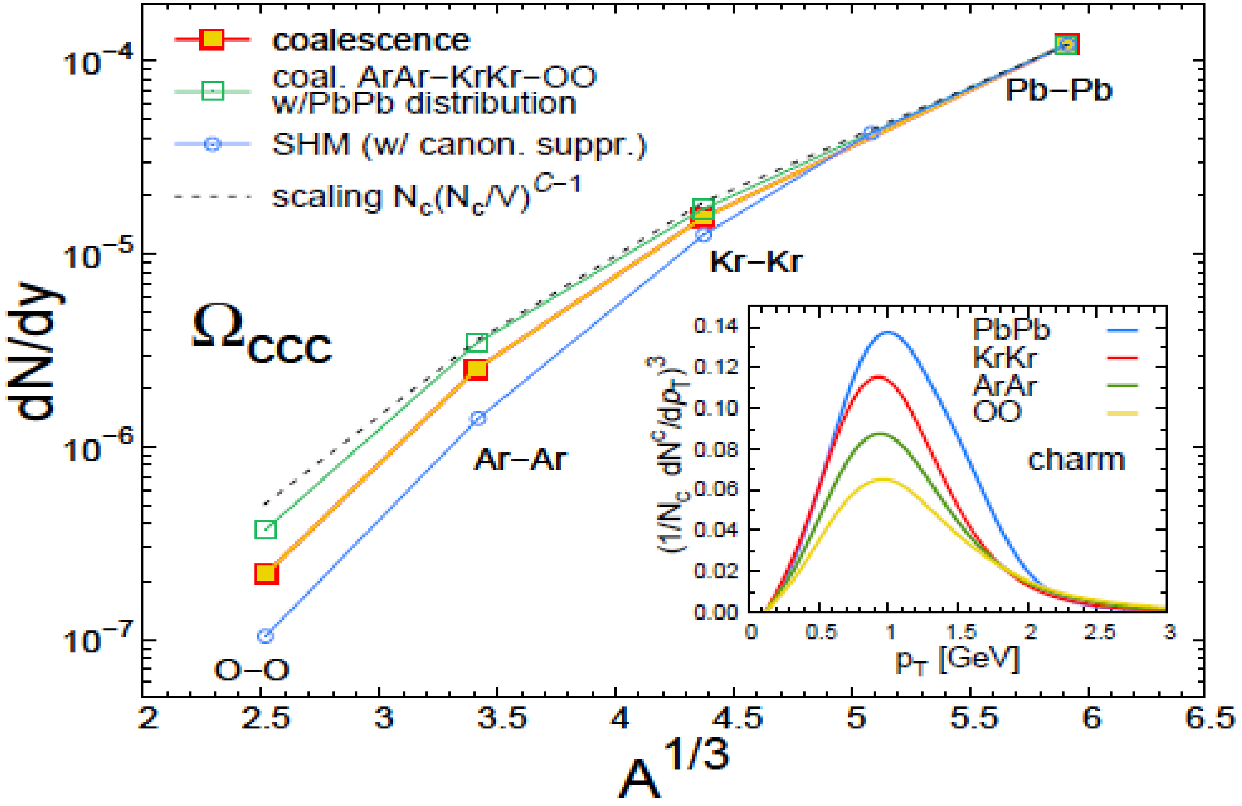
- Does not rely on distribution in equilibrium for charm
  → useful for small AA down to pp collisions and at p_T> 3-4 GeV

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

Widths from harmonic oscillator rescaling

	Ξ_c	Ω_c	$\Xi_{cc}^{(scal.\omega)}$	$\Omega_{ccc}^{(scal.\omega)}$
$\sigma_{p_1}(GeV)$	0.262	0.345	0.317	0.668
$\sigma_{p_2}(GeV)$	0.438	0.557	0.573	0.771
$\sigma_{r_1}(fm)$	0.751	0.572	0.622	0.295
$\sigma_{r_2}(fm)$	0.450	0.354	0.344	0.256
$\langle r^2\rangle_{ch}(fm^2)$	0.2	-0.12	0.363	0.09
$\langle r^2\rangle(fm^2)$	0.745	0.428	0.545	0.13
ω	$1.03e-2$	$1.5e-2$	$1.03e-2$	$1.5e-2$

Yelds scaling with A



Scaling of SHM (for A>40)

$$\frac{dN^{AA}}{dy}(h^i) = \frac{dN^{PbPb}}{dy}(h^i)\left(\frac{A}{208}\right)^{(\alpha+3)/3}\frac{f_{can}(\alpha, A)}{f_{can}(\alpha, Pb)}$$

For coalescence, in an homogeneous density background in equilibrium at fixed T, discarding flow and wave functions effects the expected scaling is:

$$V\left(\frac{N_c}{V}\right)^c = N_c\left(\frac{N_c}{V}\right)^{C-1}$$

with $N_c \propto A^{4/3}$ and $V \propto A$

→ the scaling corresponds to $\frac{dN}{dy} \propto A^{\frac{C+3}{3}}$

like in SHM w/o canonical suppression

→ If the p_T-distribution does not change we obtain the scaling expected

→ There is an effect due to different charm distributions. In Ar-Ar it reduces Ω_{ccc} by ≈ 1.3 factor, in O-O it is ≈ 1.7

→ the cube of the distribution gives an idea of this difference, but Wigner function mitigate the effect

A larger production of coalescence w.r.t. SHM for small systems:

- Lack of canonical suppression, but e-b-e fluctuations can enhance production? $\langle N^3 \rangle > \langle N \rangle^3$