Production and ratios of heavy hadrons from large to small collision systems with a coalescence plus fragmentation approach

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Outline

Hadronization:

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

Heavy hadrons in AA collisions:

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

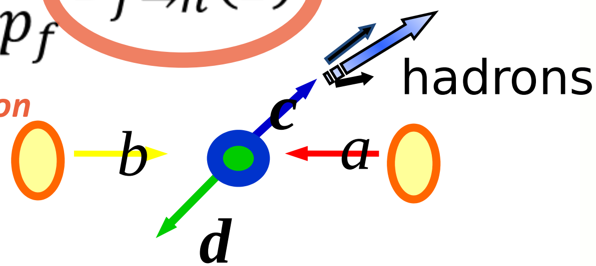
Heavy hadrons in small systems (pp @ 5.02 TeV):

- **Λ_c/D^0**
- **Ξ_c/D^0 , Ω_c/D^0**

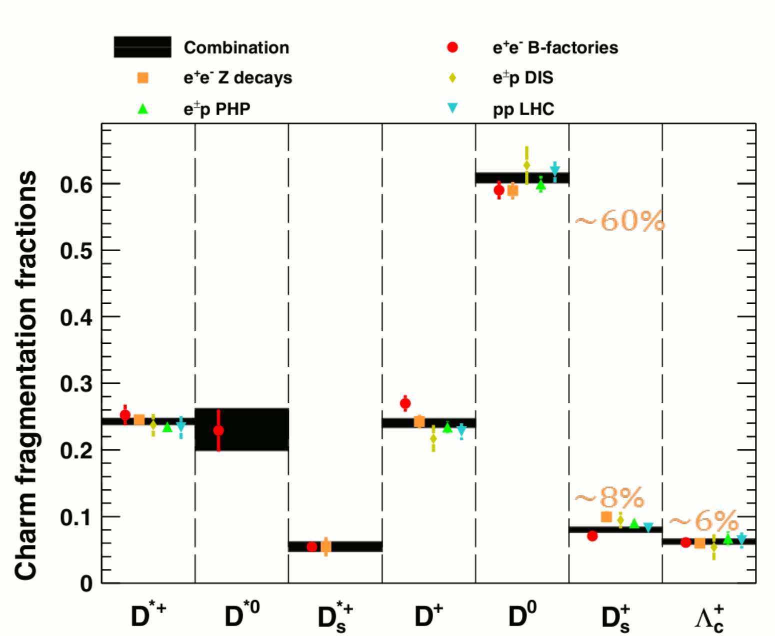
Heavy flavour Hadronization: Fragmentation

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

Fragmentation 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

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

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

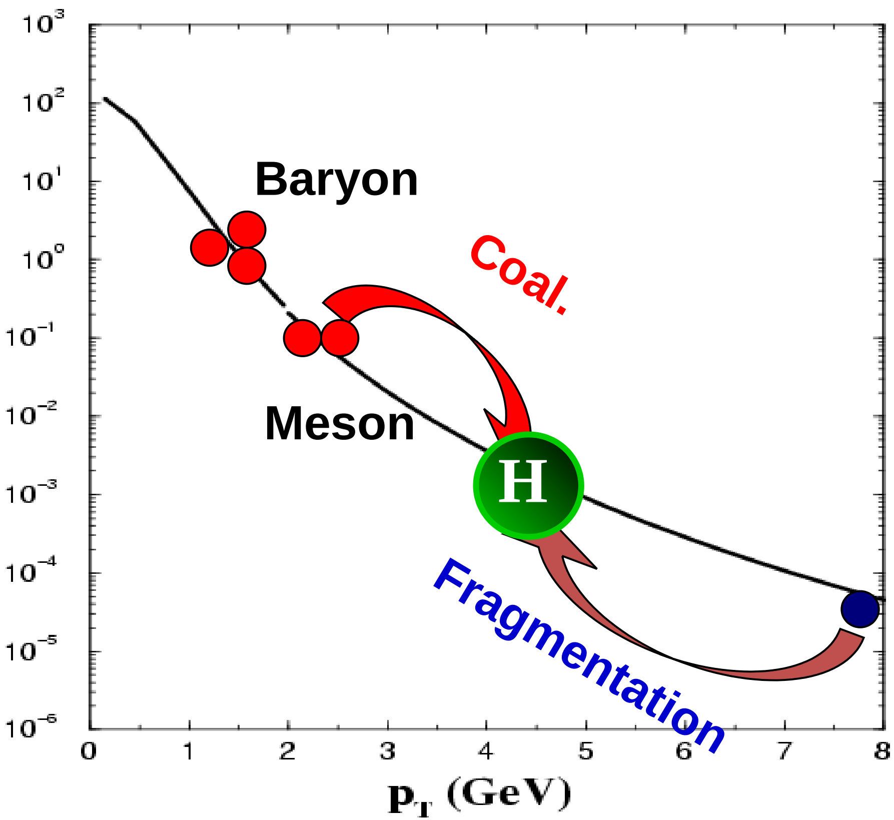
$$\left(\frac{\Lambda_c^+}{D^0}\right)_{e^+e^-,\,pp} \simeq 0.1 \qquad \left(\frac{D_s^+}{D^0}\right)_{e^+e^-,\,pp} \simeq 0.13$$

Recent update
He-Rapp, PLB795(2019): Increase≈2 to Λ_c production: SHM with resonance not present in PDG
PYTHIA8 + color reconnection

Hadronization: Coalescence

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

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



Used to describe first observations in light sector for the baryon/meson ratio and elliptic flow splitting at RHIC, more than a decade ago.

V. Greco, C.M. Ko, P. Levai PRL 90, 202302 (2003)

Hadronization: Coalescence

Statistical factor colour-spin-isospin

Parton Distribution function

Hadron Wigner function

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

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

Hadronization: Coalescence

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

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

Wigner function – Wave function

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

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

Assuming gaussian wave function

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

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)

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

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

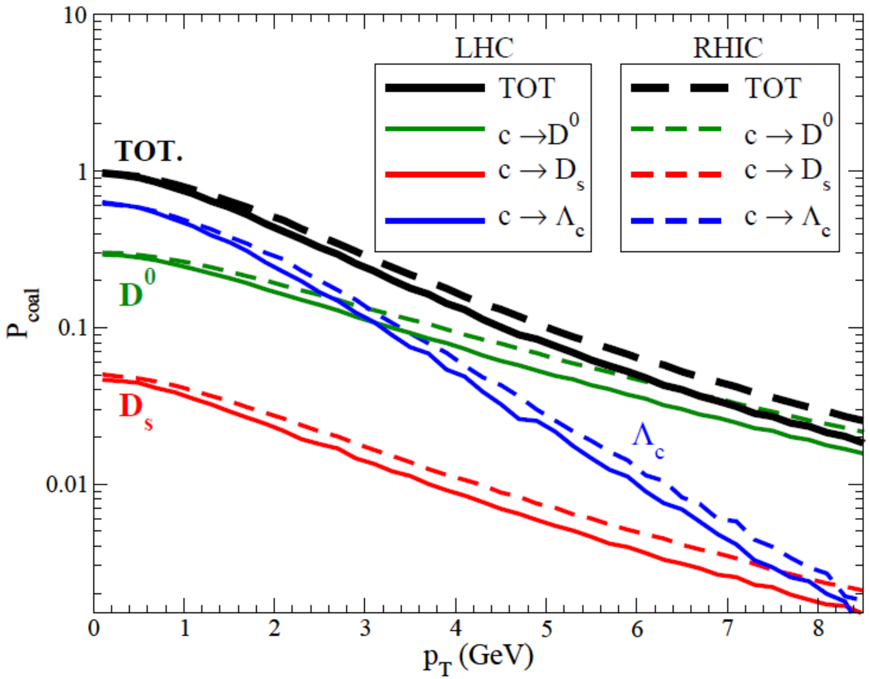
Meson	$\langle r^2 \rangle_{ch}$	σ_{p1}	σ_{p2}
$D^+ = [c\bar{d}]$	0.184	0.282	—
$D_s^+ = [\bar{s}c]$	0.083	0.404	—
Baryon	$\langle r^2 \rangle_{ch}$	σ_{p1}	σ_{p2}
$\Lambda_c^+ = [udc]$	0.15	0.251	0.424
$\Xi_c^+ = [usc]$	0.2	0.242	0.406
$\Omega_c^0 = [ssc]$	-0.12	0.337	0.53

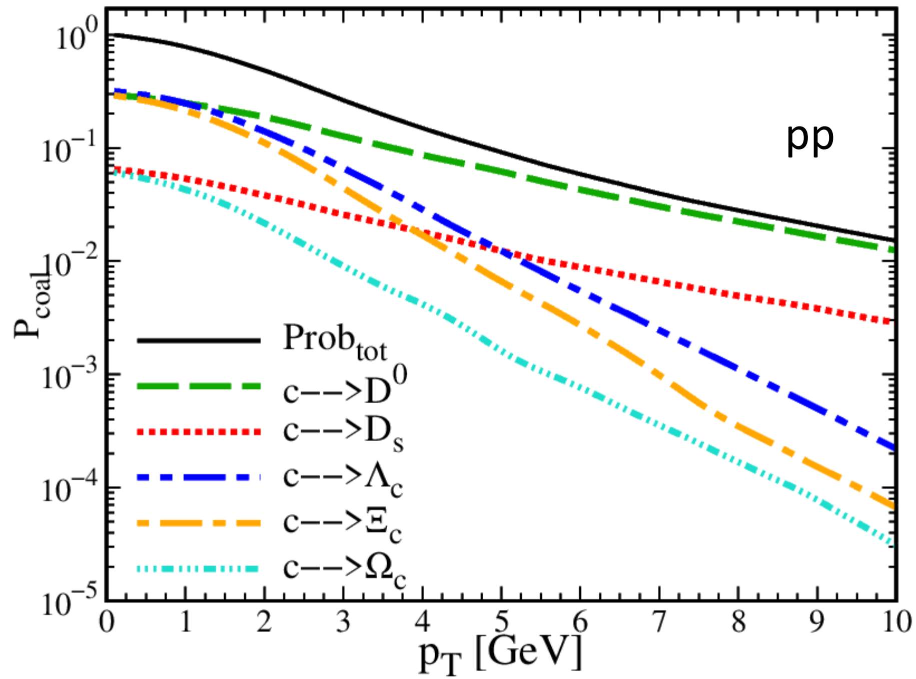
Hadronization: Coalescence

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%

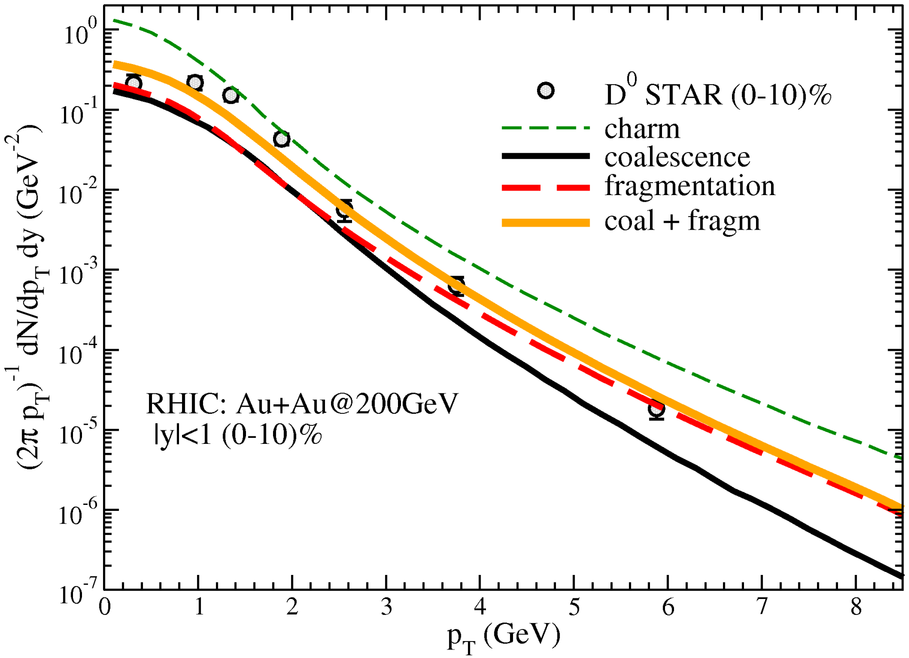
In our calculations we take into account hadronic channels including the ground states + first excited states

Statistical factor suppression for resonances

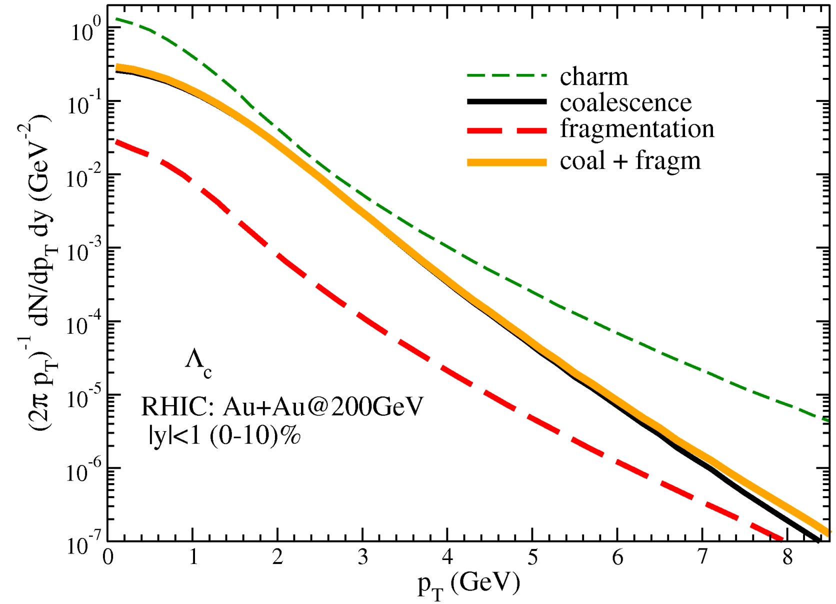
$$\frac{[(2J+1)(2I+1)]_{H^*}}{[(2J+1)(2I+1)]_H}\left(\frac{m_{H^*}}{m_H}\right)^{3/2} e^{-(m_{H^*}-m_H)/T}$$

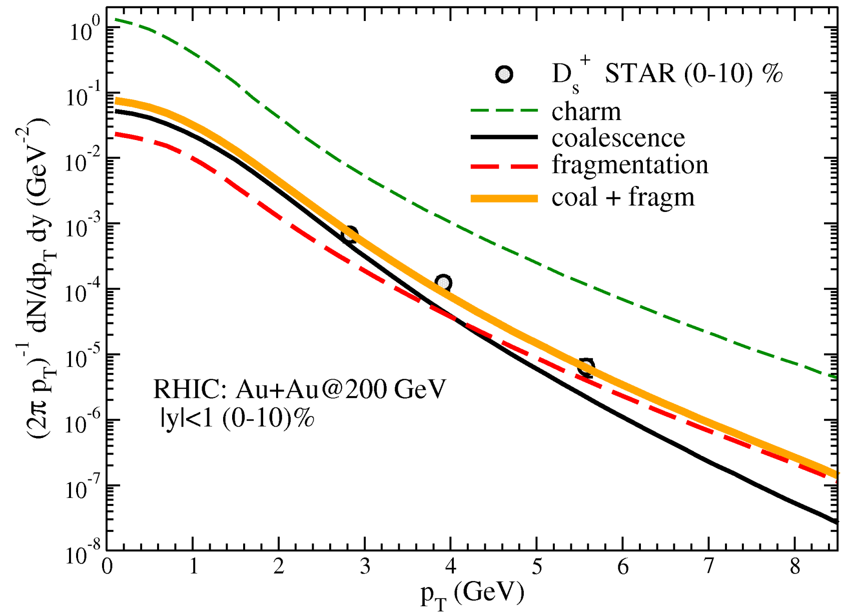
RHIC: results

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



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

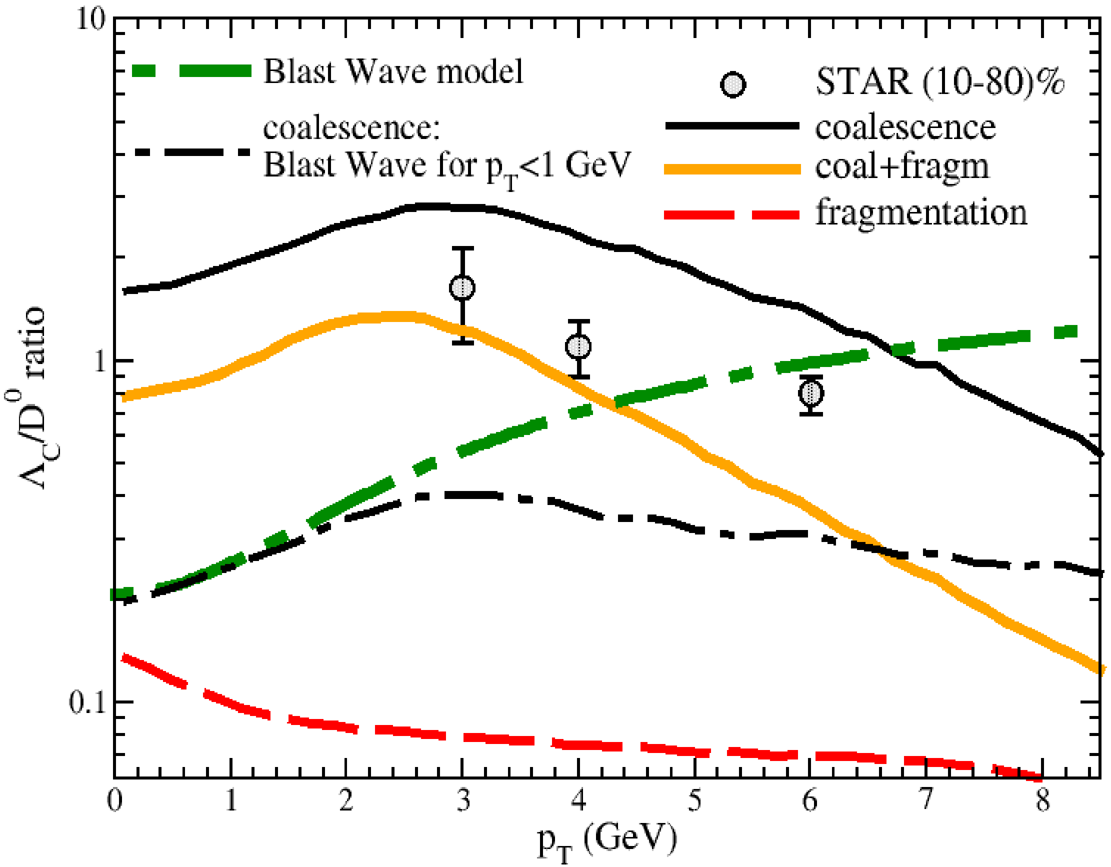




- For D^0 coalescence and fragmentation comparable at 2 GeV
- fragmentation fraction for D^+_s are small and less than about 8% of produced total heavy hadrons
- Λ_c^+ fragmentation is even more smaller, coalescence gives the dominant contribution

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

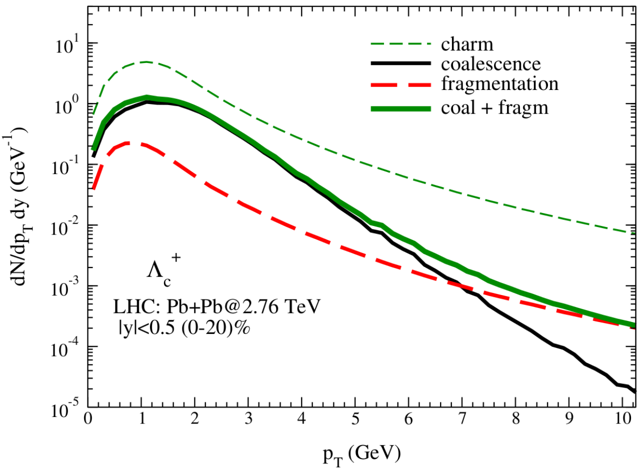
Needed data at low p_T

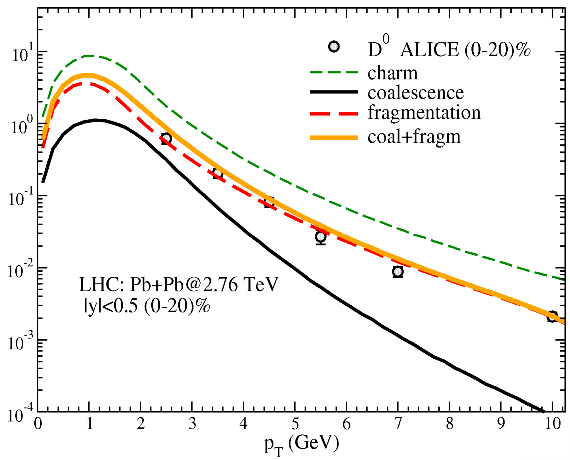
S. Plumari, V. Minissale et al., Eur. Phys. J. ***C78*** *no. 4, (2018) 348*

LHC: results

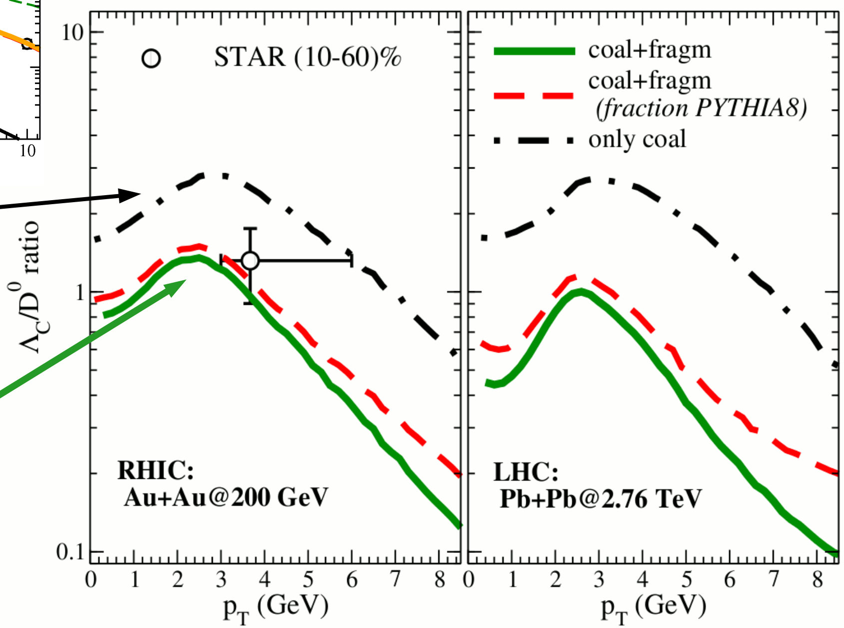
<u>wave function widths σ_p of baryon and mesons are the same at RHIC and LHC!</u>

Data from ALICE Coll. JHEP 1209 (2012) 112





Coalescence lower than at RHIC → main contribution from Fragmentation



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.

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

Small systems: Coalescence in pp?

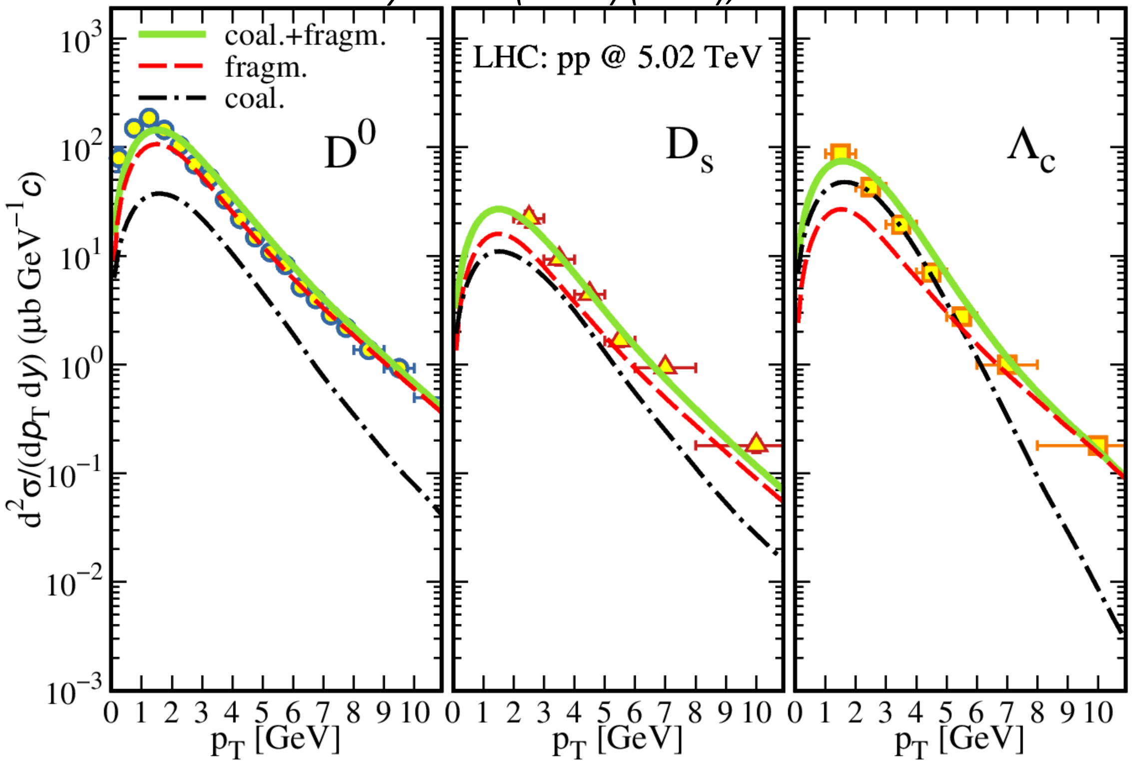
Common consensus of possible presence of QGP in smaller system.

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

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

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, arXiv:2012.12001

LIGHT

- Thermal Distribution (p_T< 2 GeV)

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

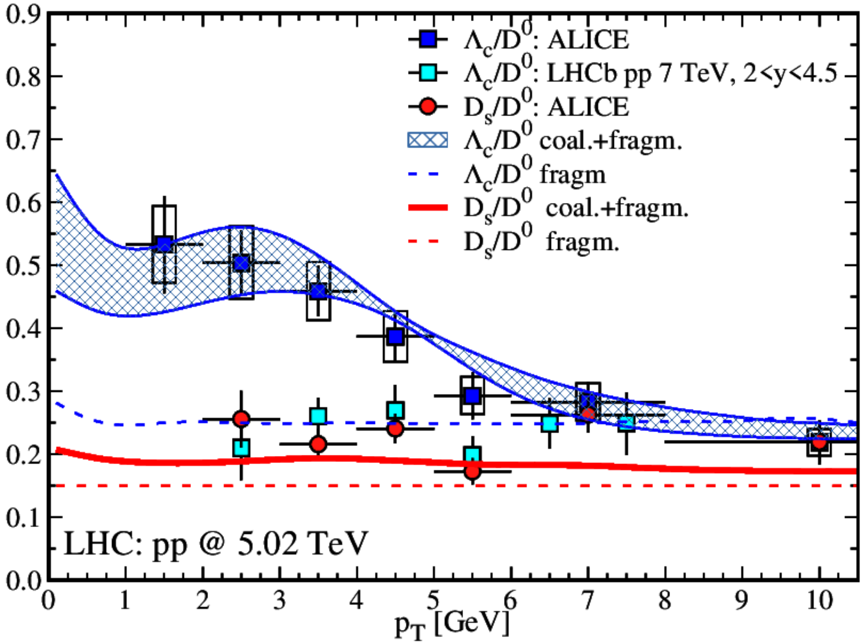
- Minijet Distribution (p_T> 2 GeV)
  NO QUENCHING

CHARM

FONLL Distribution

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

Small systems: Coalescence in pp?



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

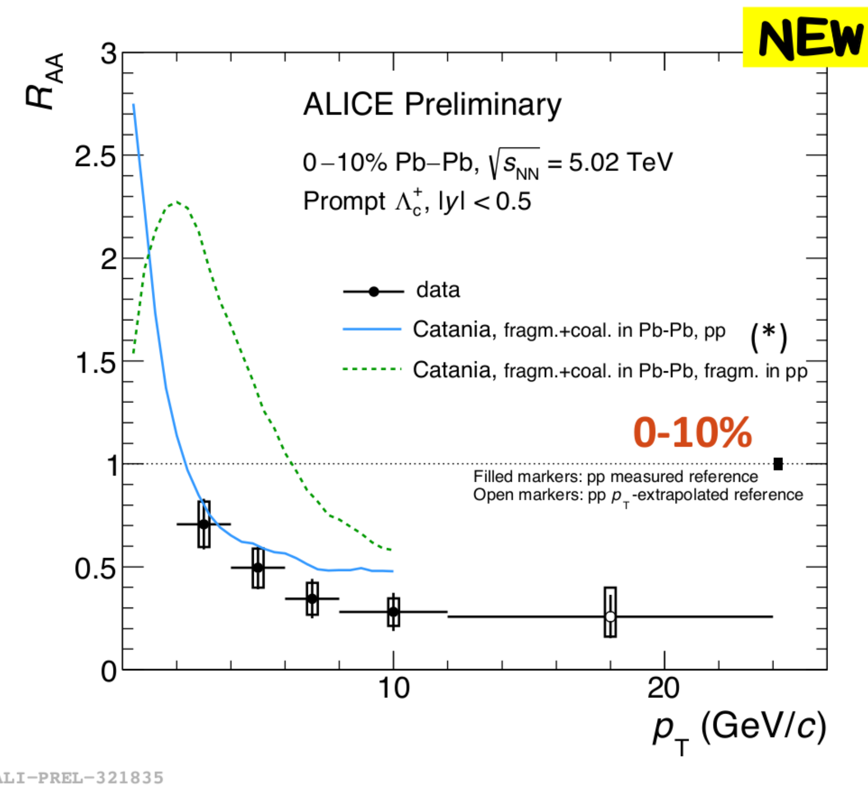
Reduction of rise-and-fall behaviour in Λ_c / D^0 ratio:

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

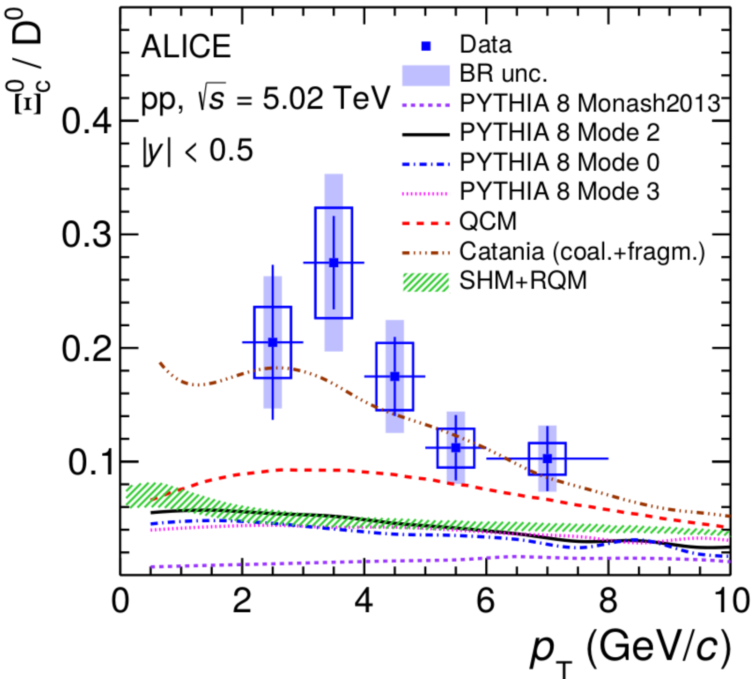
-FONLL distribution flatter w/o evolution trough QGP

-Volume size effect

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

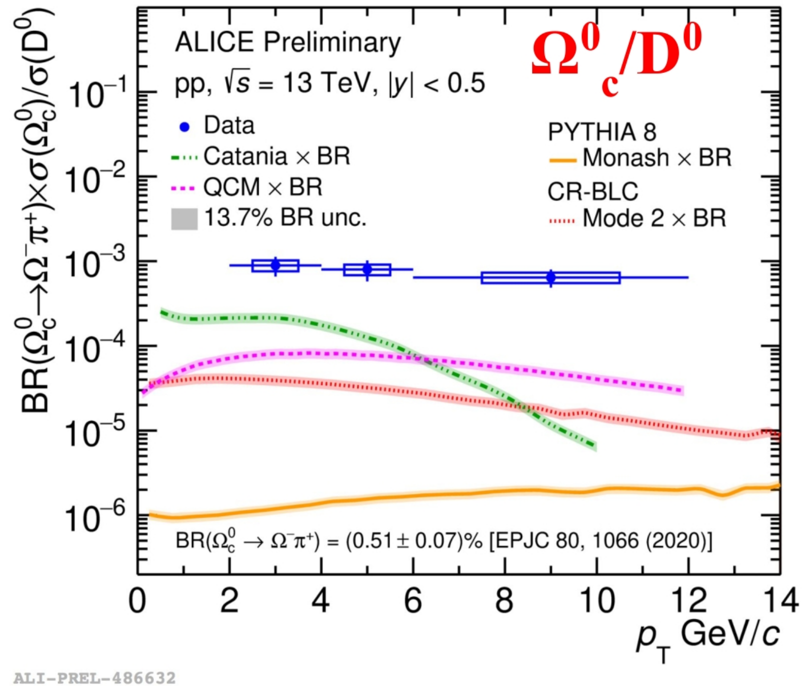


Small systems: Coalescence in pp?



New measurements of heavy hadrons at ALICE:

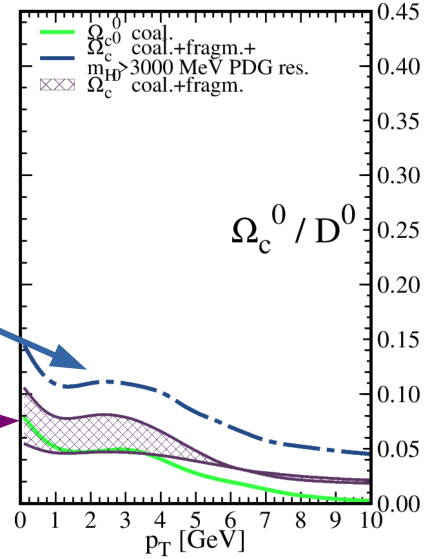
- Ξ_c/D^0 ratio, same order of Λ_c/D^0: coalescence gives enhancement
- very large Ω_c/D^0 ratio, our model does not get the big enhancement



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 $\langle r^2 \rangle$ uncertainty in quark model



ALICE Collaboration, arXiv:2105.05616
V. Minissale, S. Plumari, V. Greco, arXiv:2012.12001

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

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

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

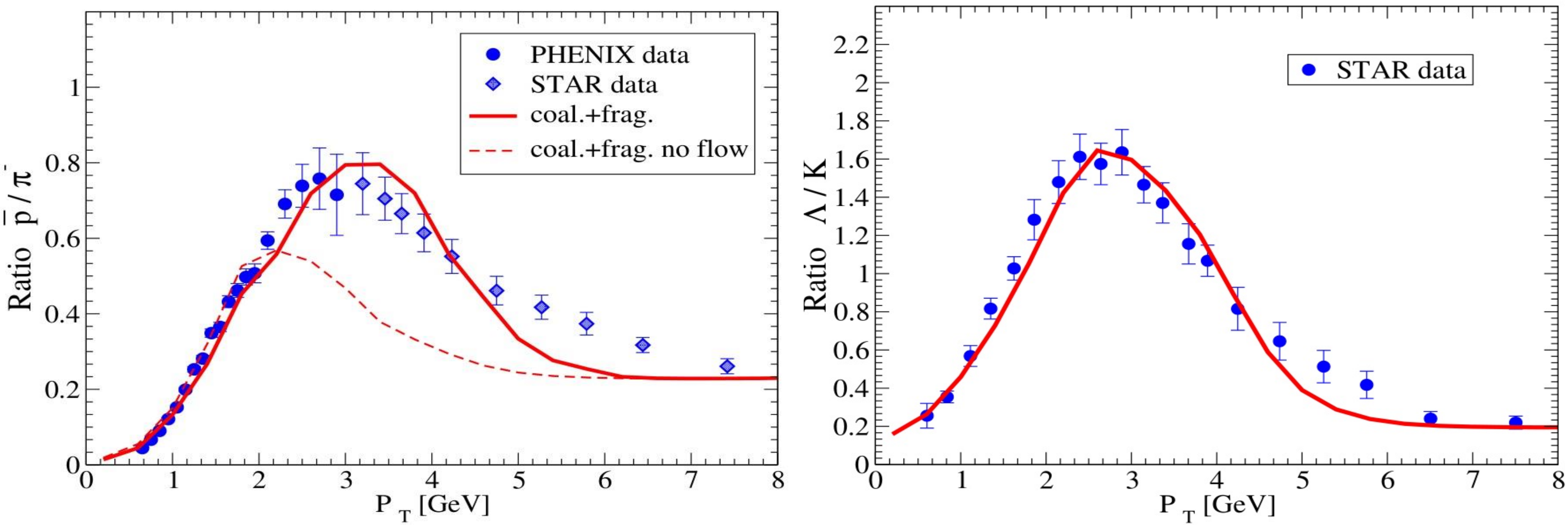
Partonic elliptic flow

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 $p_T \simeq 2{-}4 GeV$ 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

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

free-streaming

field interaction
ε-3p≠0

collisions
η≠0

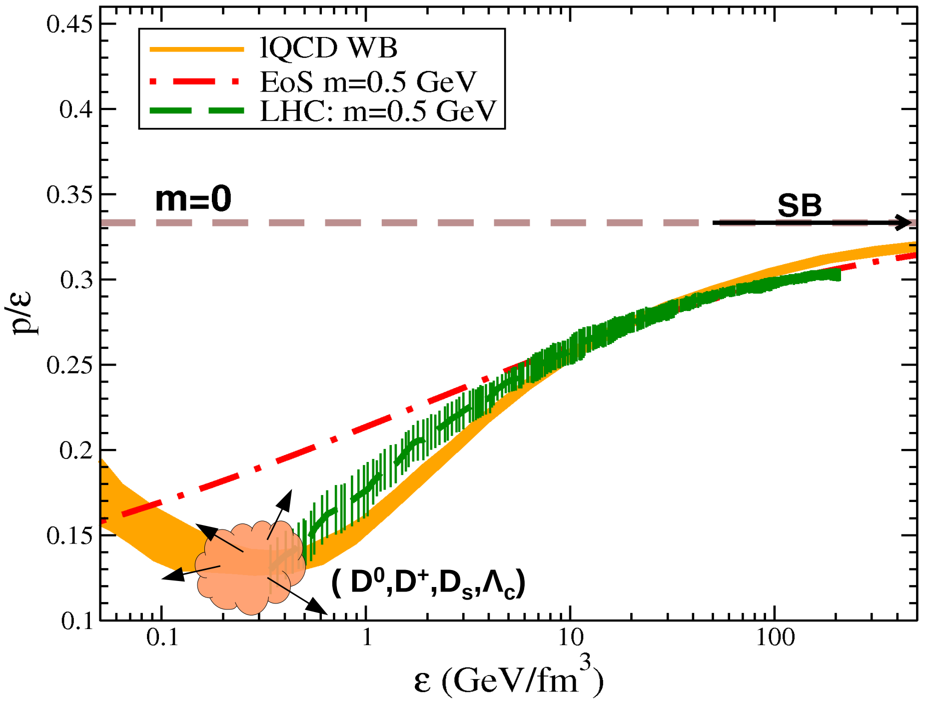
Heavy quark evolution

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

·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).