The 18th International Conference on

Strangeness in Quark Matter (SQM 2019)

10-15 June 2019, Bari (Italy)

Heavy quark baryon and meson production in pp and AA at RHIC and LHC within a coalescence plus fragmentation model

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<u>In collaboration with</u>: S. Plumari, G. Coci, S. K. Das, V. Greco

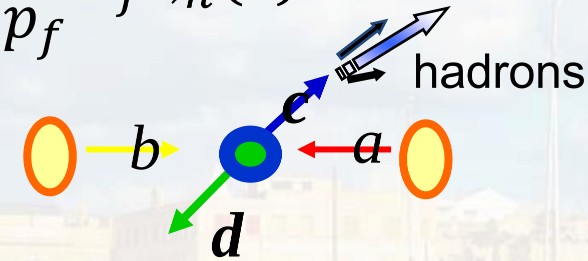
Outline

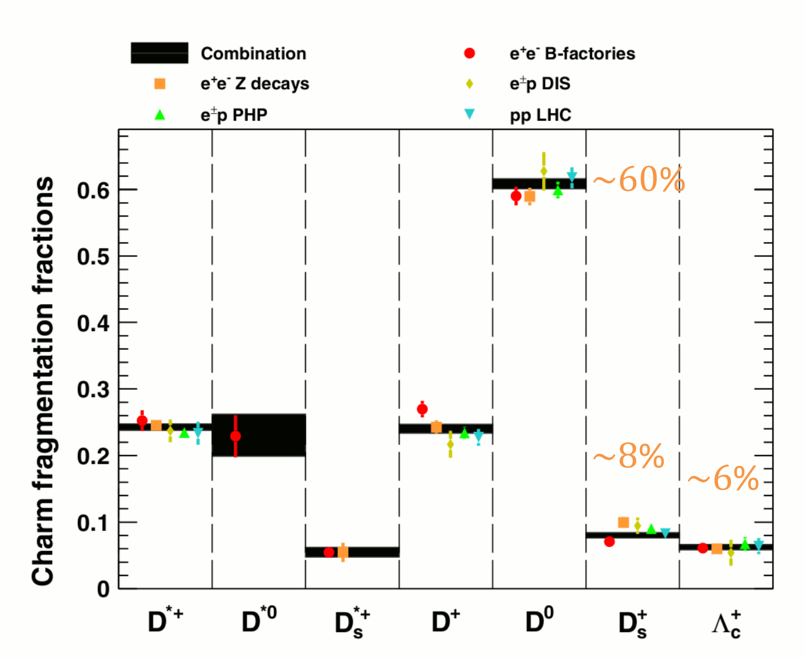
- Hadronization:
  - Fragmentation
  - Coalescence model

- Results:
  - Λ_c and D mesons spectra for RHIC and LHC energies
  - Λ_c/D^0 ratio
  - Bottom
  - pp

Heavy flavour Hadronization: Fragmentation

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





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

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

We use the Peterson fragmentation function

C. Peterson, D. Schalatter, I. Schmitt, P.M. Zerwas PRD **27** (1983) 105

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

The parameter ε for fixed by *pp*, *e⁺+e⁻* collisions as done in *S.K. Das et al, PRD94 (2016) no.11, 114039.*

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

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

Charm Fragmentation Fraction (c into h)

Measurement in $e^\pm p$, *pp* and e^+e^- are in agreement within uncertainties: fragmentation at most independent of the specific production process

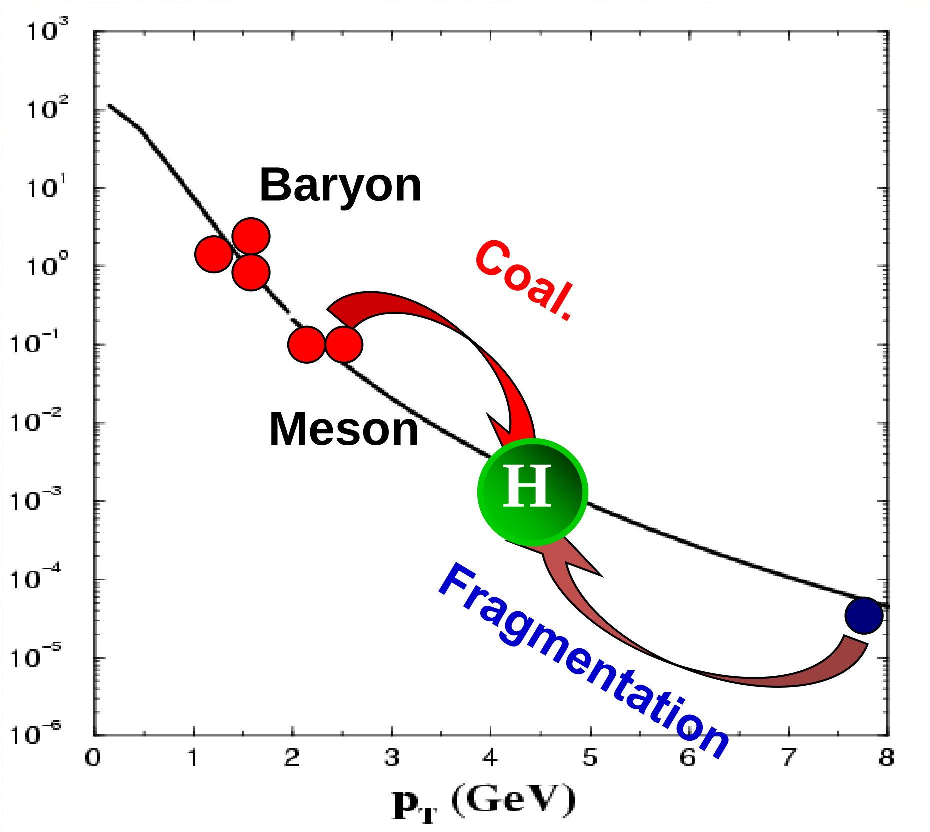
Hadronization: Coalescence

Statistical factor colour-spin-isospin

Parton Distribution function

Hadron Wigner function

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



Used to describe first observations on light hadrons 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

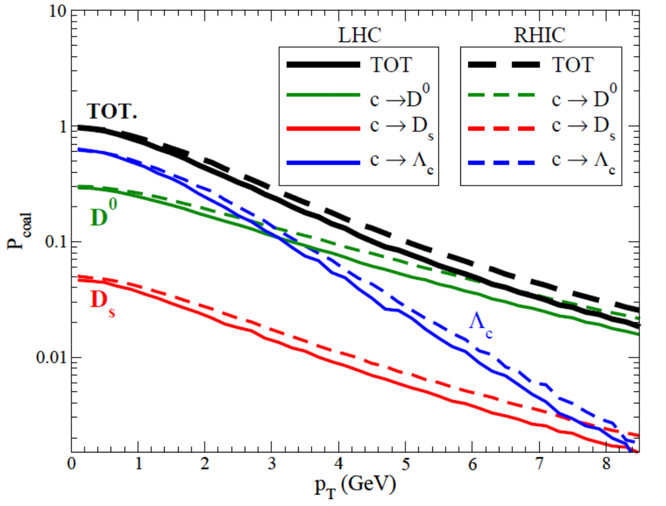
Parton Distribution function

Hadron Wigner function

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

charm distribution function at mid-rapidity from parton simulations solving relativistic Boltzmann transport equation

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



• *The width parameters σ in f_W(...) fixed by the root-mean-square charge radius as predicted by quark models*

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

$$\langle r^2\rangle_{D^+} = 0.184 fm^2; \langle r^2\rangle_{D_s^+} = 0.124 fm^2;$$
$$\langle r^2\rangle_{\Lambda_c^+} = 0{,}152 fm^2$$

• Normalization in f_W(...) *fixed by requiring that P_{coal}=1 for p=0*

Heavy flavour: 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

MESONS

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

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%*

Statistical factor

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

BARYONS

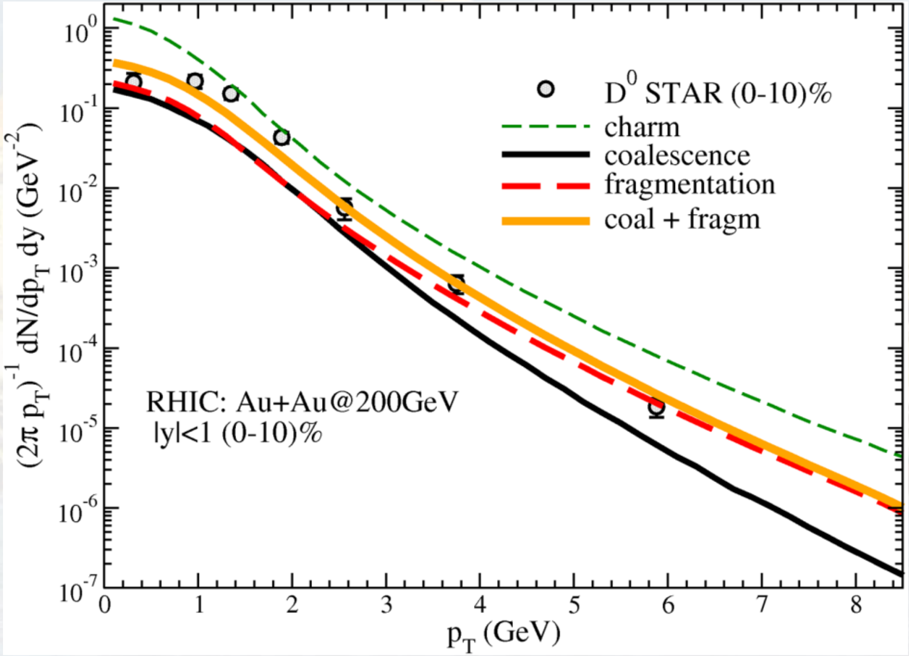
- **Λ_c^+** *(I=0, J=1/2)*

Resonances

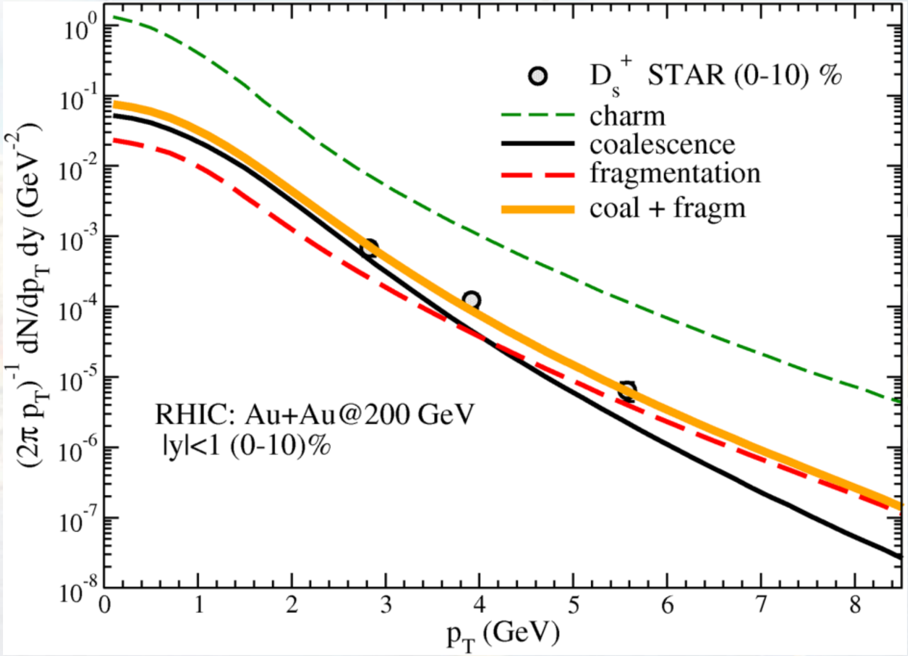
- **$\Lambda_c^+(2595)$** *(I=0,J=1/2)* → **Λ_c^+** *B.R. 100%*
- **$\Lambda_c^+(2625)$** *(I=0,J=3/2)* → **Λ_c^+** *B.R. 100%*
- **$\Sigma_c^+(2455)$** *(I=1,J=1/2)* → **$\Lambda_c^+\pi$** *B.R. 100%*
- **$\Sigma_c^+(2520)$** *(I=1,J=3/2)* → **$\Lambda_c^+\pi$** *B.R. 100%*

RHIC: results

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



Data from STAR Coll., arXiv:1704.04364 [nucl-ex].

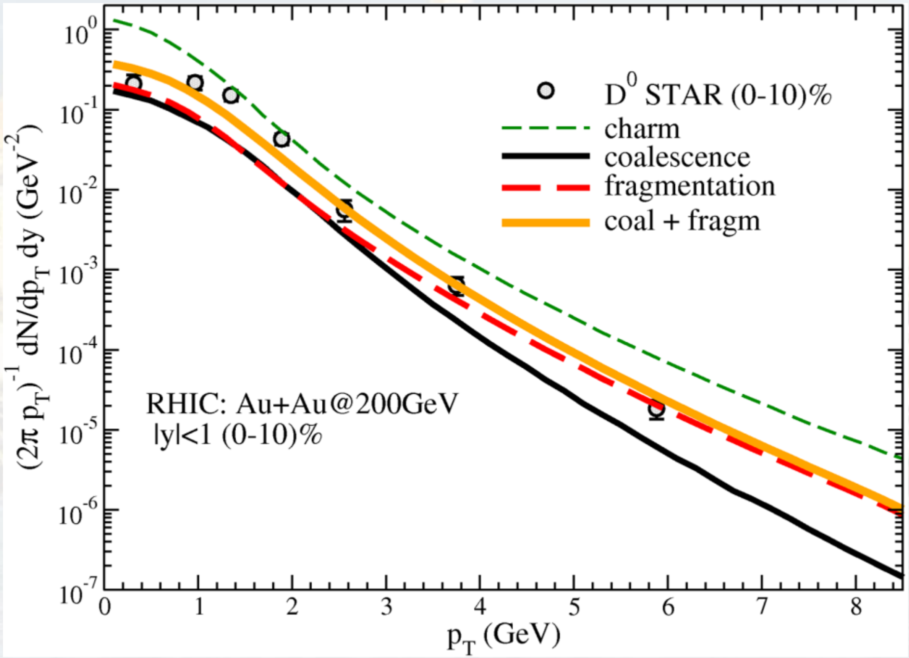


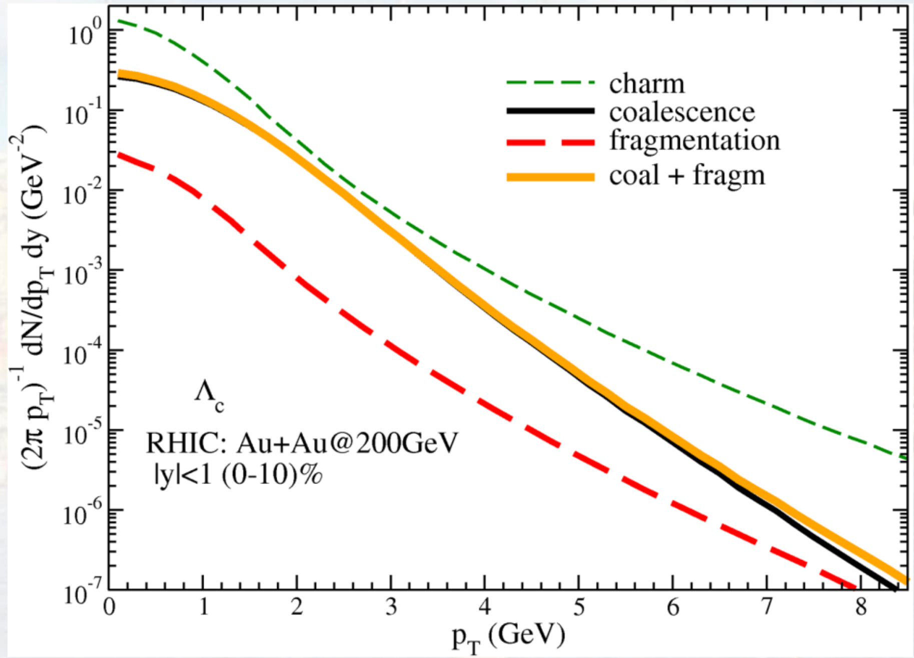
S. Plumari, V. Minissale et al., Eur. Phys. J. ***C78*** *no. 4, (2018) 348*

- 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

RHIC: results

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



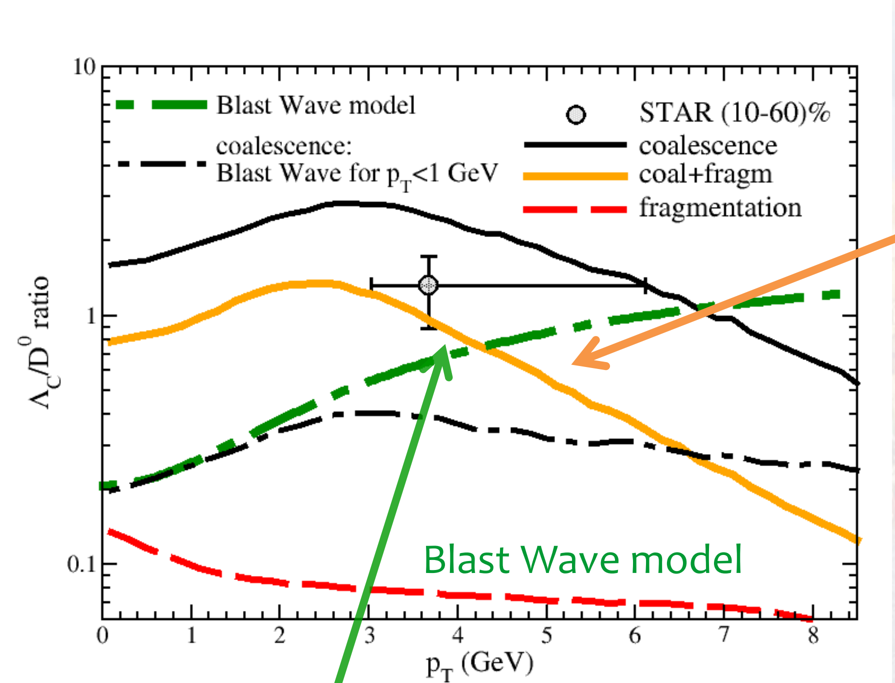


S. Plumari, V. Minissale et al., Eur. Phys. J. ***C78*** *no. 4, (2018) 348*

- For D^0 coalescence and fragmentation comparable at 2 GeV
- Λ_c^+ fragmentation is even more smaller, coalescence gives the dominant contribution

RHIC: Baryon/meson

Data from STAR Coll., L. Zhou, Nucl. Phys. A967, 620 (2017).



- Compared to light baryon/meson ratio the Λ_c/D^0 ratio has a larger width (flatter)
- Similar to the one predicted in
  Y. Oh, C.M. Ko, S.H. Lee, S. Yasui PRC 79,044905 (2009)

Blast Wave model:

$$\frac{\Lambda_c^+}{D^0} = \frac{g_\Lambda}{g_D}\frac{m_T^\Lambda}{m_T^D}\frac{K_1(m_T^\Lambda/T_C)}{K_1(m_T^D/T_C)}$$

$$for\ p_T << m \qquad \approx \frac{g_\Lambda}{g_D}\left(\frac{m_T^\Lambda}{m_T^D}\right)^{1/2} e^{-(m^\Lambda - m^D)/T_C} \approx 0.17$$

Following:
L.W.Chen, C.M. Ko, W. Liu, M. Nielsen, PRC 76, 014906 (2007).
K.-J. Sun, L.-W. Chen, PRC 95, 044905 (2017).
For hypersurface of proper time τ and non relativistic limit:

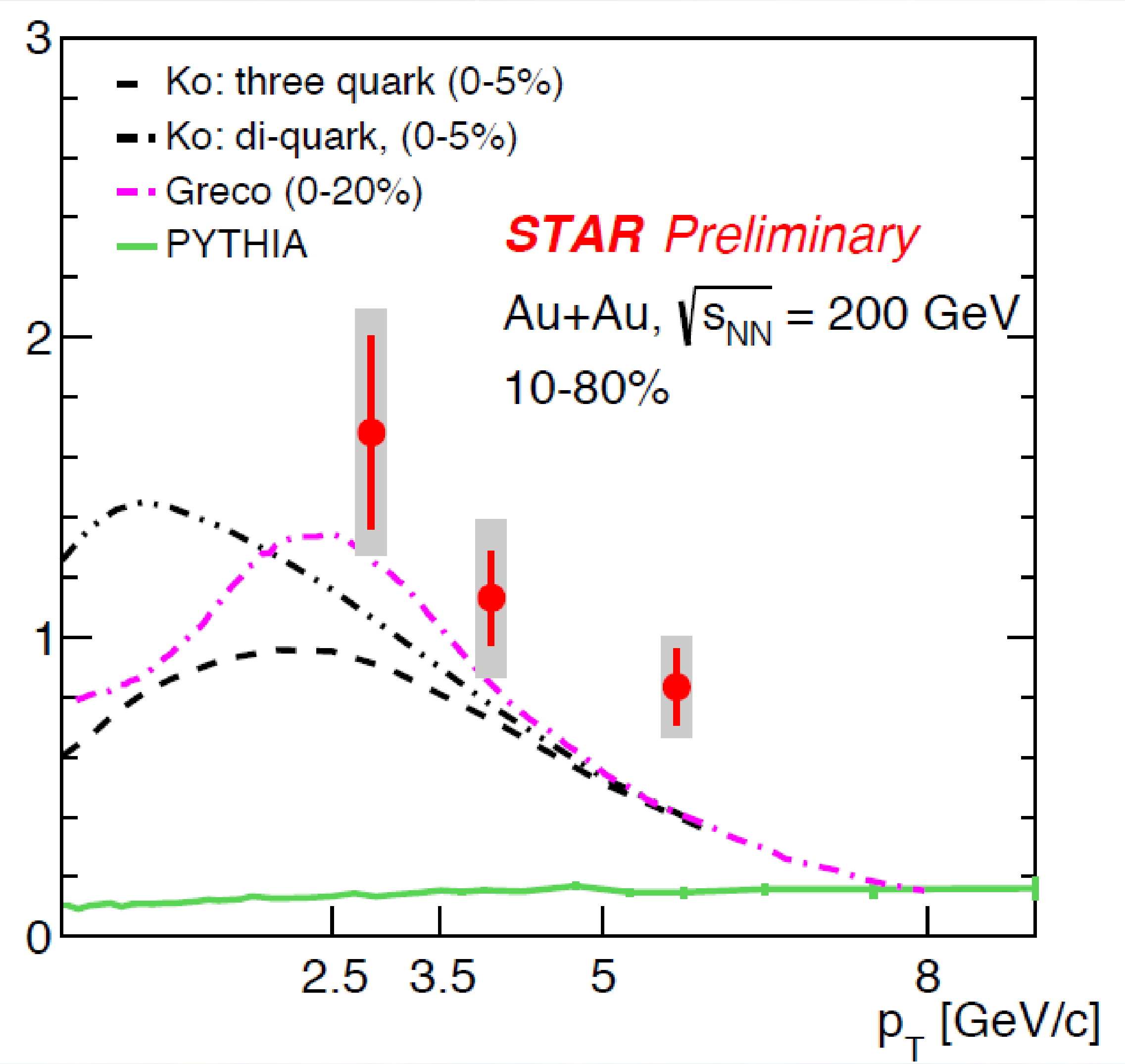
$$for\ p_T << m \qquad \frac{\Lambda_c^+}{D^0} \propto \frac{g_\Lambda}{g_D}\left(\frac{m_T^\Lambda}{m_T^D}\right) e^{-(m^\Lambda - m^D)/T_C}\mu_2$$

$$\mu_2 = \frac{m_3(m_1+m_2)}{m_1+m_2+m_3}$$

Is the reduced mass of the baryon

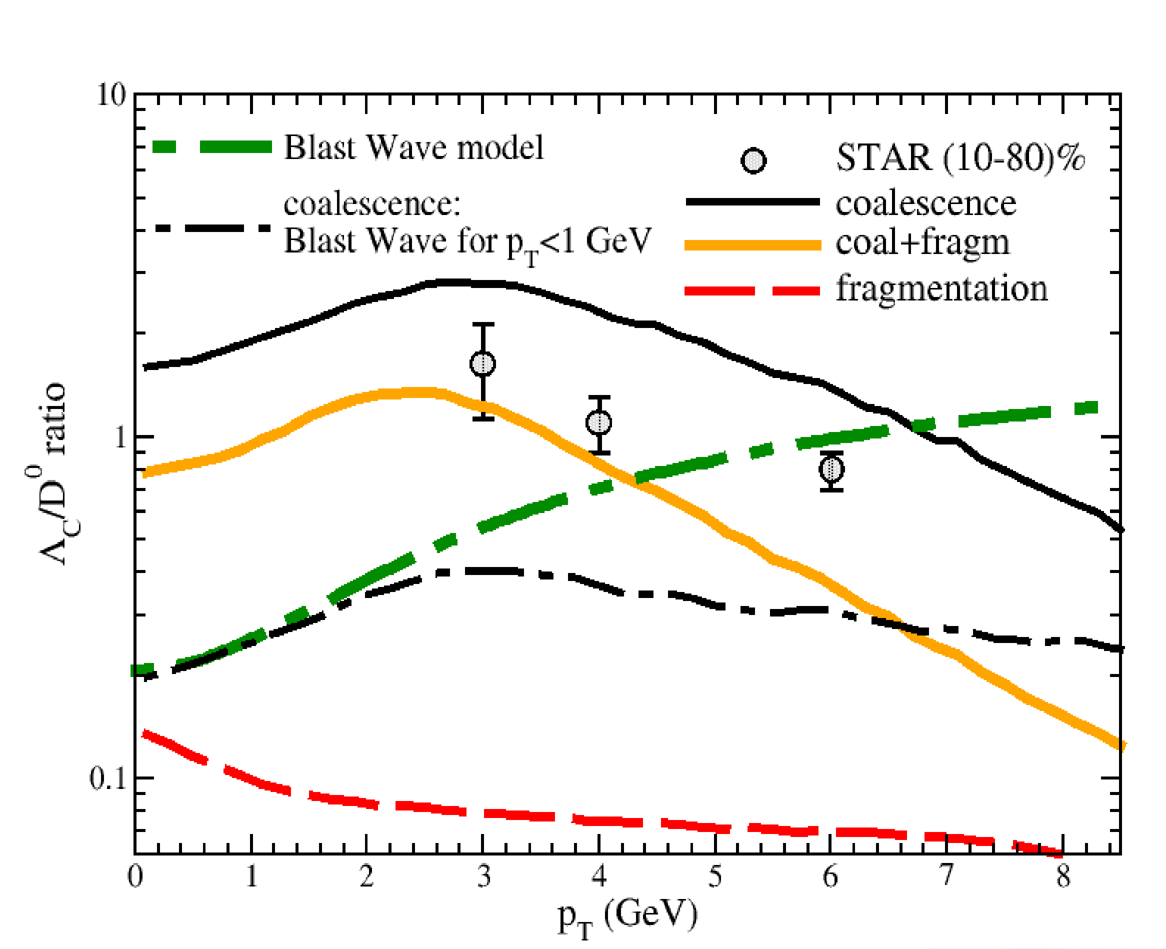
*S. Plumari, V. Minissale et al., Eur. Phys. J. **C78** no. 4, (2018) 348*

RHIC: Baryon/meson



QM2018 New data from STAR…

RHIC: Baryon/meson



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

QM2018 New data from STAR

- More flatter → does coalescence extend to higher pt? Indication also in light sector
  V. Minissale, F. Scardina, V. Greco PRC 92, 054904 (2015)

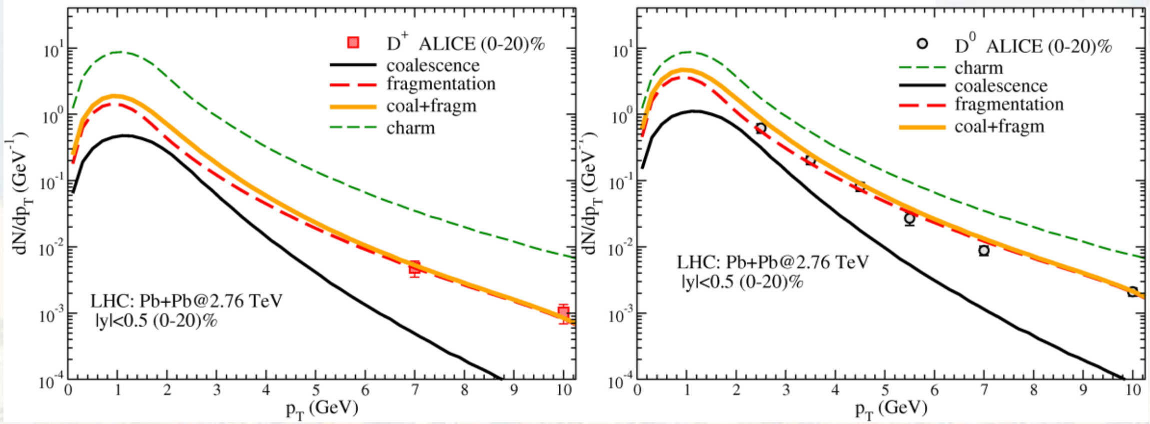
Recent paper:
Cho, Sun, Ko et al.,**arXiv:1905.09774**

- Needed data at low p_T

LHC: results

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

Data from ALICE Coll. JHEP 1209 (2012) 112

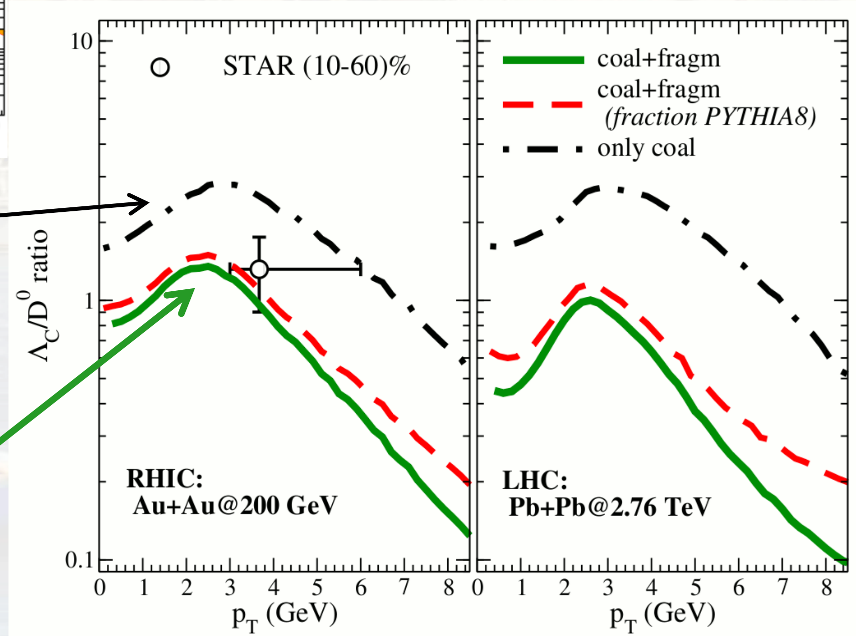


Coalescence lower than at RHIC → main contribution from Fragmentation

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*

LHC: results

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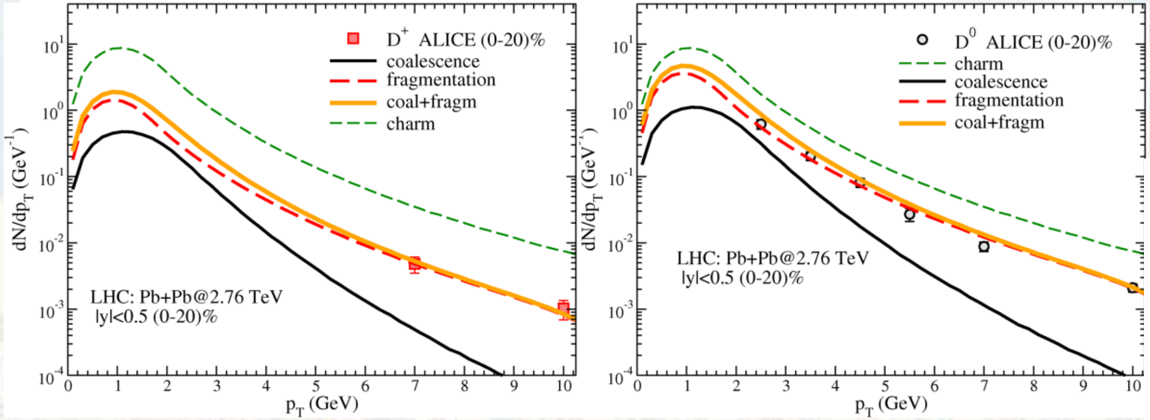
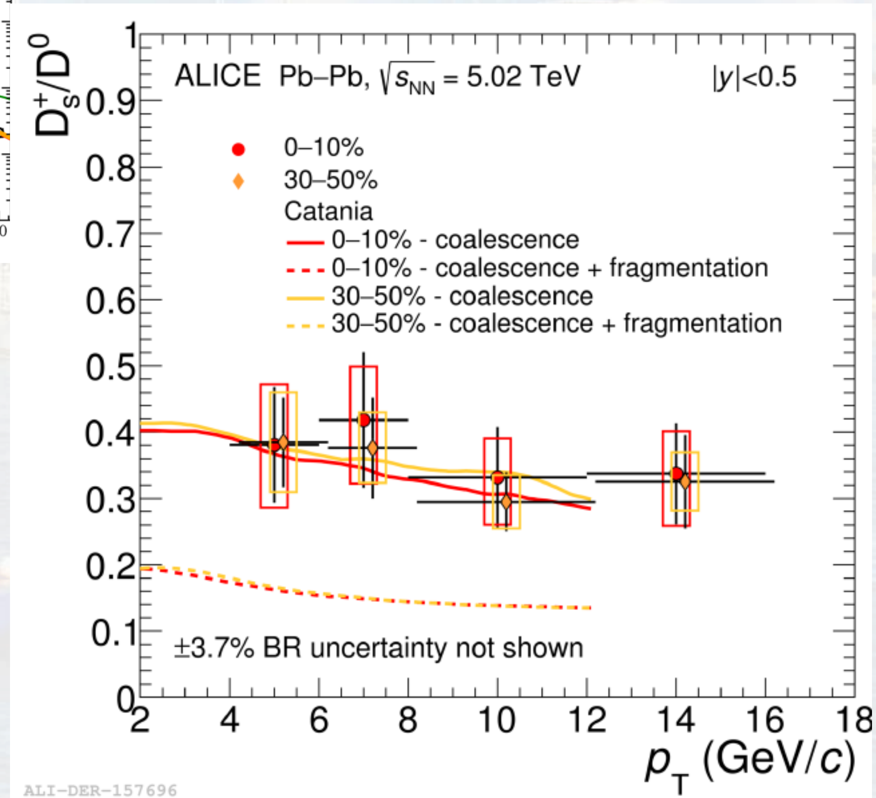


D_s/D^0 ratio

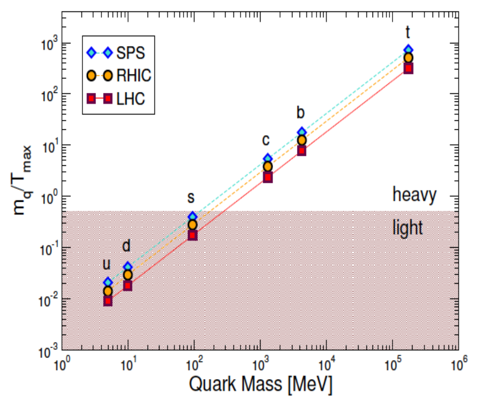
- larger ratio respect to only fragmentation
- does not change with centrality with simple coalescence
- Possible strangeness enhancement?



Xinye Peng, ALICE, Nucl.Phys. A982 (2019) 667-670

Specific of Heavy Quarks

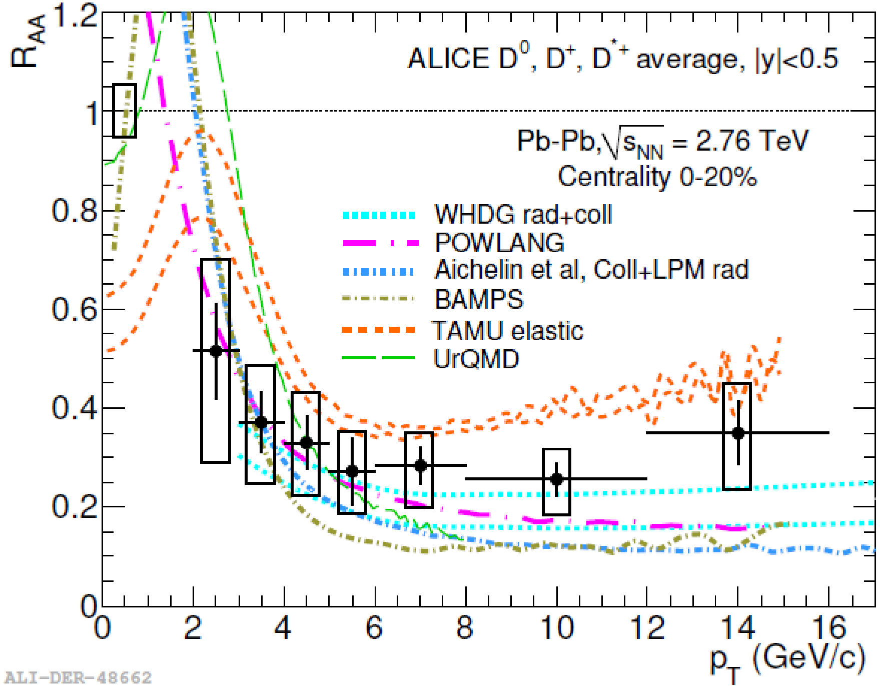
- ❑ $m_{c,b} >> \Lambda_{QCD}$ produced by pQCD process (out of equilibrium)
- ❑ $m_{c,b} >> T_0$ no thermal production
- ❑ $\tau_0 << \tau_{QGP}$ probes all the QGP life time



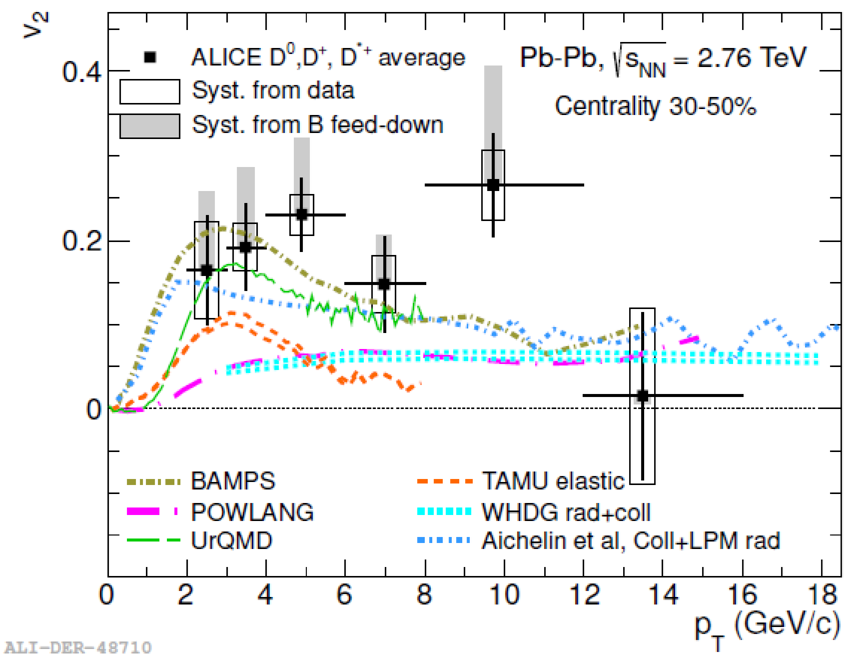
more on Plumari's Talk

Simultaneous description of R_{AA} and v_2 is a tough challenge for all models

JHEP **1209** (2012) 112



arXiv:1305.2707



RHIC results: R_{AA} - v_2

BEFORE THE STUDY OF Λ_c / D^0 (early 2017)

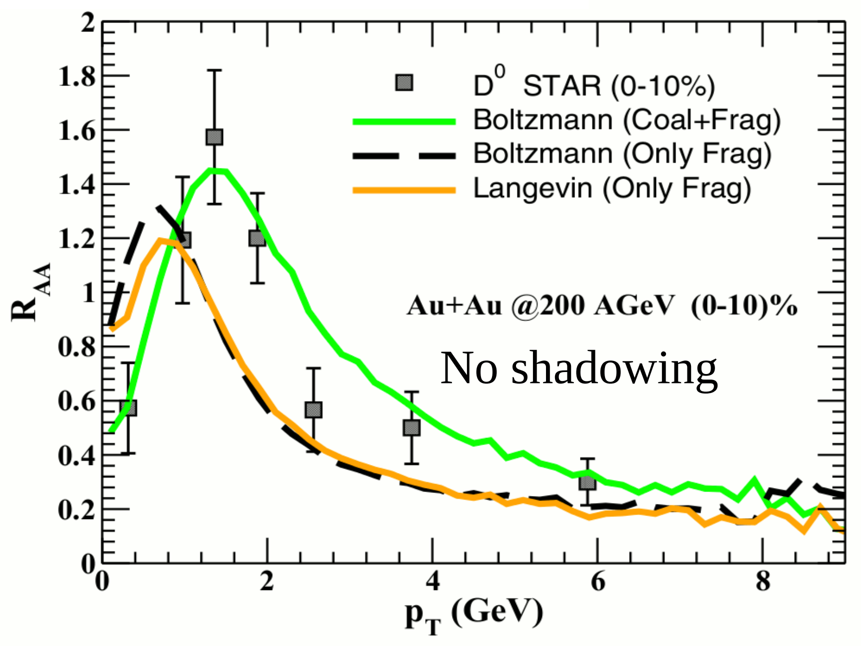
Charmed hadrons production given by D mesons

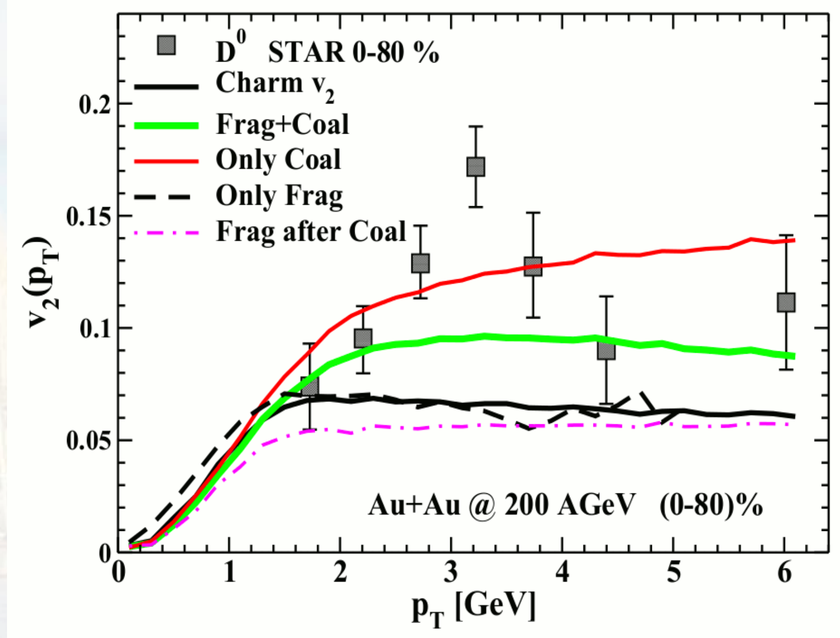
F. Scardina, S. K. Das, V. Minissale, S. Plumari, V. Greco, PRC96 (2017) no.4, 044905

RHIC results: R_{AA} - v_2

Without Λ_c production

Data from STAR Coll. PRL 118, 212301 (2017)





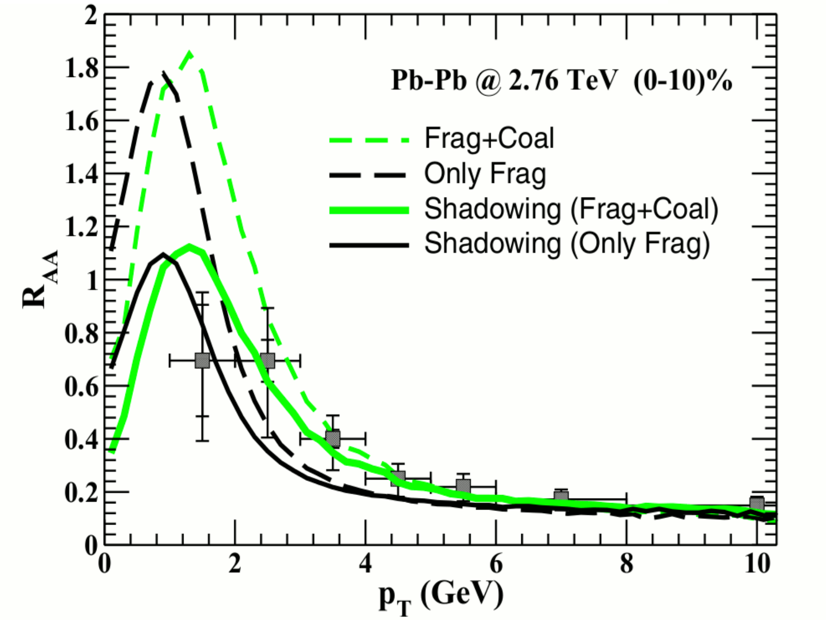
- In 0-10% coalescence implies an increase of the R_{AA} for p_T > 1 GeV.
- The impact of coalescence decreases with p_T and fragmentation is dominant at high p_T.
- In 0-80% the $v_2(p_T)$ due to only coalescence increase a factor 2 compared to the $v_2(p_T)$ charm.
- In 0-80% coalescence+fragmentation give a good description of exp. Data

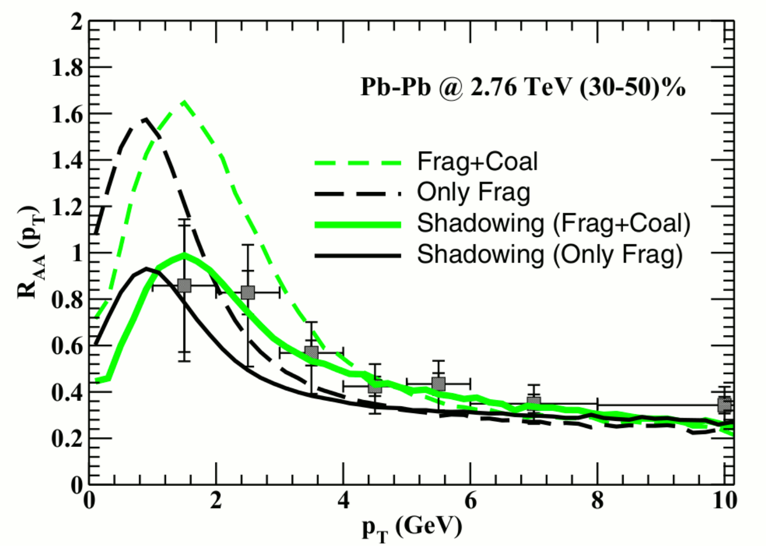
Coalescence brings up both R_{AA} and v_2

F. Scardina, S. K. Das, V. Minissale, S. Plumari, V. Greco, PRC96 (2017) no.4, 044905.

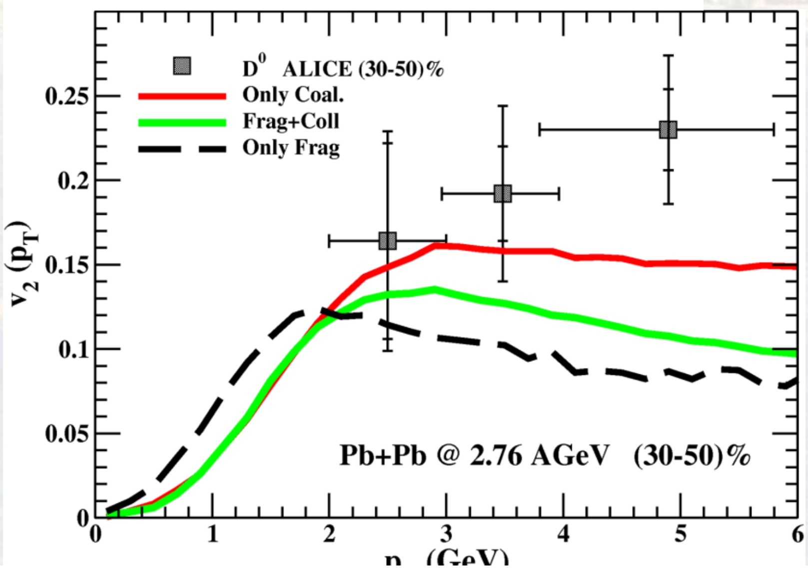
LHC results: R_{AA} - v_2

Data from ALICE Coll. JHEP 03 (2016) 081





Data from ALICE Coll.PRC 90, 034904 (2014)



- At LHC the coalescence implies an increasing of the R_{AA} for p_T>1GeV similar to RHIC energies.
- At LHC the effect of coalescence is less significant than RHIC energy
- Due to hadronization D meson $v_2(p_T)$ get an enhancement of about 20% respect to charm $v_2(p_T)$.

F. Scardina, S. K. Das, V. Minissale, S. Plumari, V. Greco, PRC96 (2017) no.4, 044905.

RHIC results: R_{AA}

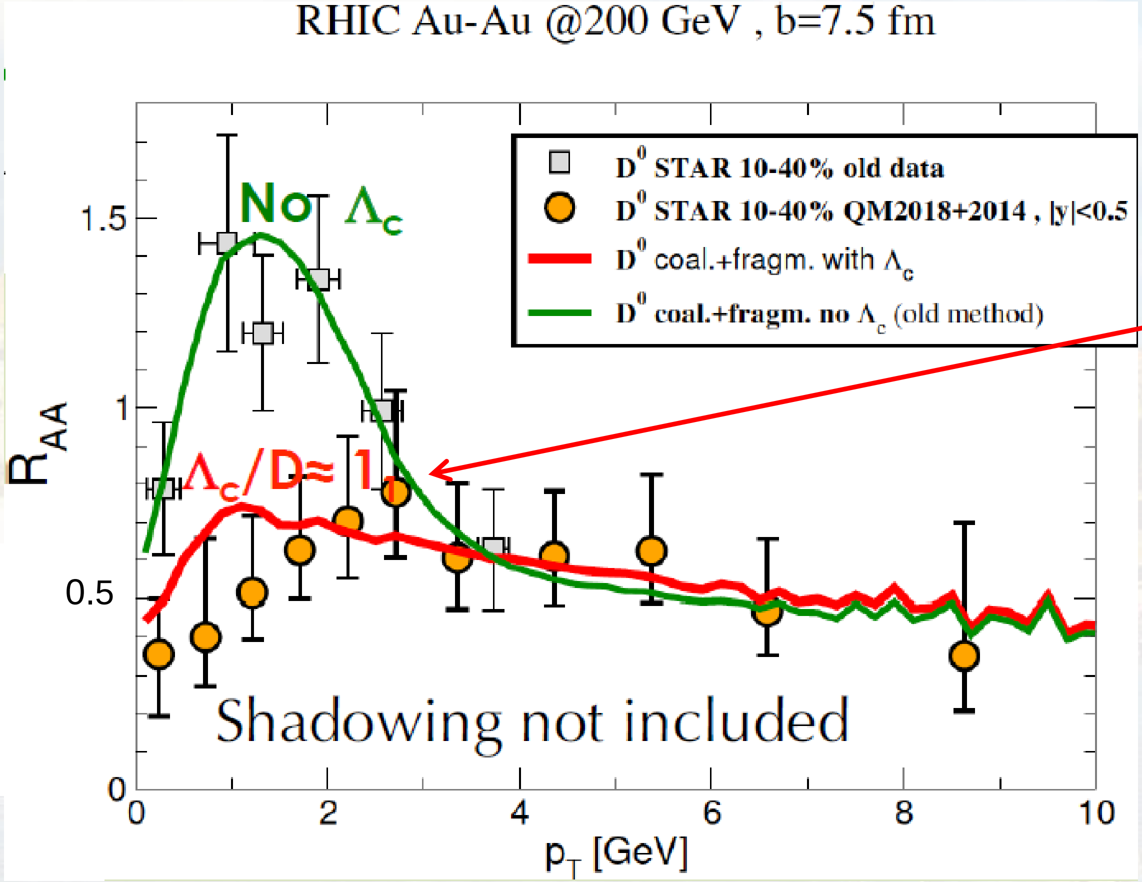
AFTER THE STUDY OF Λ_c / D^0 (late 2017)

Eur.Phys.J. C78 (2018) no.4, 348

Charmed hadrons production given by D mesons and Λ_c

Consequence: D^0 meson R_{AA} dumped at low p_T

RHIC results: R_{AA}

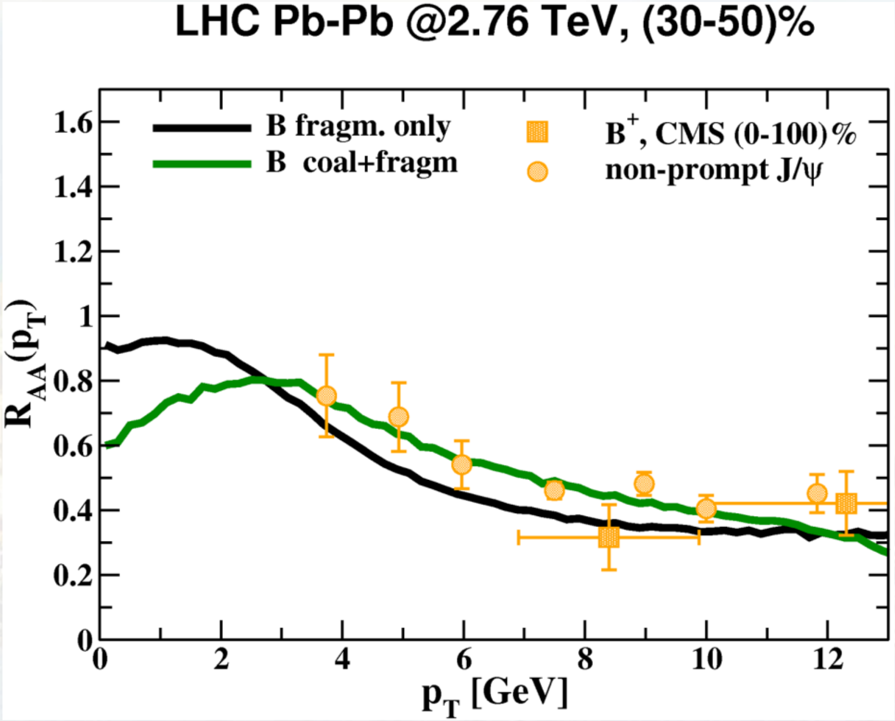


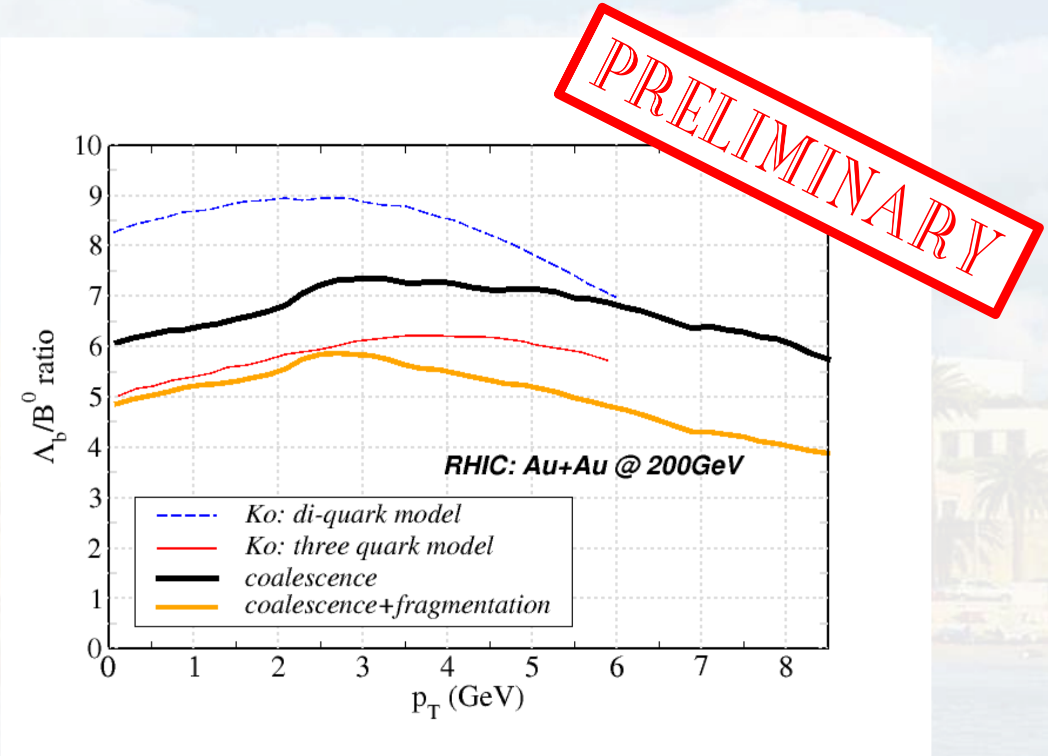
New STAR data in QM2018

- Big effect at RHIC where coalescence dominates
- Smaller but still significant also at LHC

R_{AA} of D^0 decreases because part of charm quark makes coalescence in charmed Lambdas, while in pp charm quarks fragment mainly in D mesons

Bottomed hadrons





Extended to study B quarks:

Within current uncertainties B and D can be explained with the same underlying model which imply also a very similar D_S

Λ_b / B^o including Σ_b resonances as in *Oh, Ko et al., Phys.Rev. C **79**, 044905 (2009)*

ATTENTION: sensible to the presence of other possible resonances

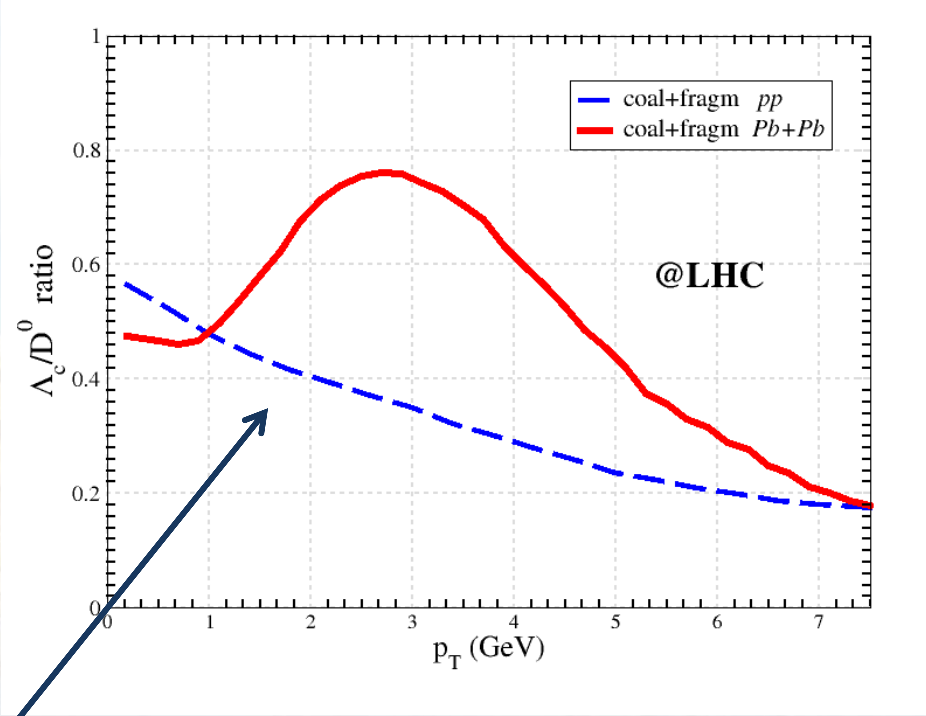
Coalescence in pp?

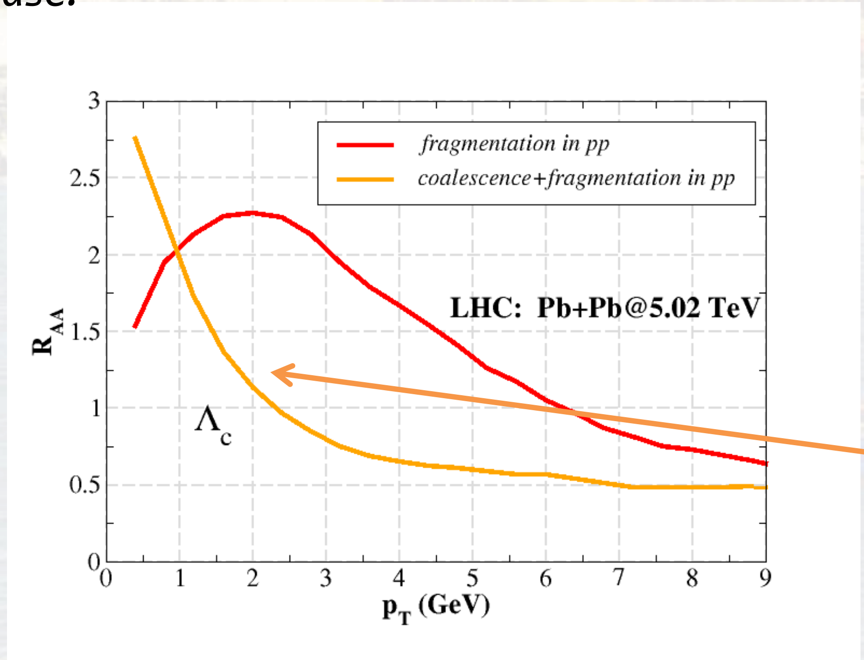
Common consensus of *possible* presence of QGP in smaller system.

What if:

Assuming QGP formation also in *pp* ?

What coalescence+fragmentation predicts in this case?





- No peak in Λ_c / D^0 ratio
- Big effect on Λ_c R_{AA} (sensible because of really small pp fragmentation production) → different behaviour expecially at low momenta

Conclusions

- Good agreement with experimental data of D^0, D^+ mesons spectra
- Λ_c production at intermediate p_T dominant role of coalescence mechanism: Λ_c/D^0 ~1.5 for p_T ~3 GeV with Coal.+fragm. Model
- Effect of Λ_c production on D^0 R_{AA}
- Extension to study Λ_b and B^0 spectra and their ratio
- Extension to pp

The 18th International Conference on
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Backup Slides

Elliptic Flow – Quark Number Scaling

Fourier expansion of the azimuthal distribution

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

n=2 Elliptic flow

momentum anisotropy in the transverse plane

coalescence brings to

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

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

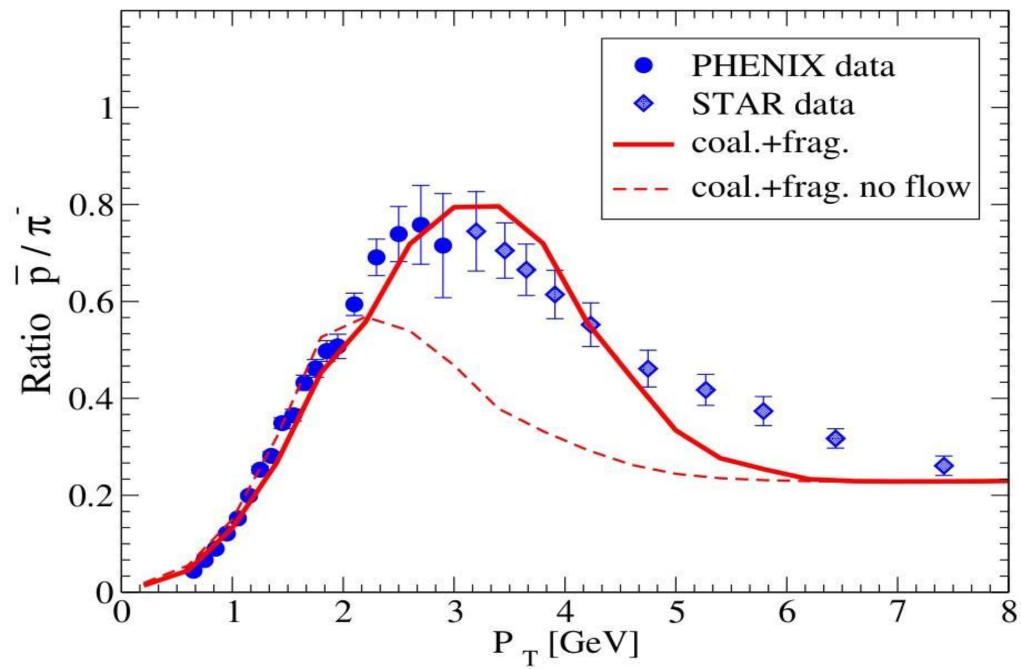
Partonic elliptic flow

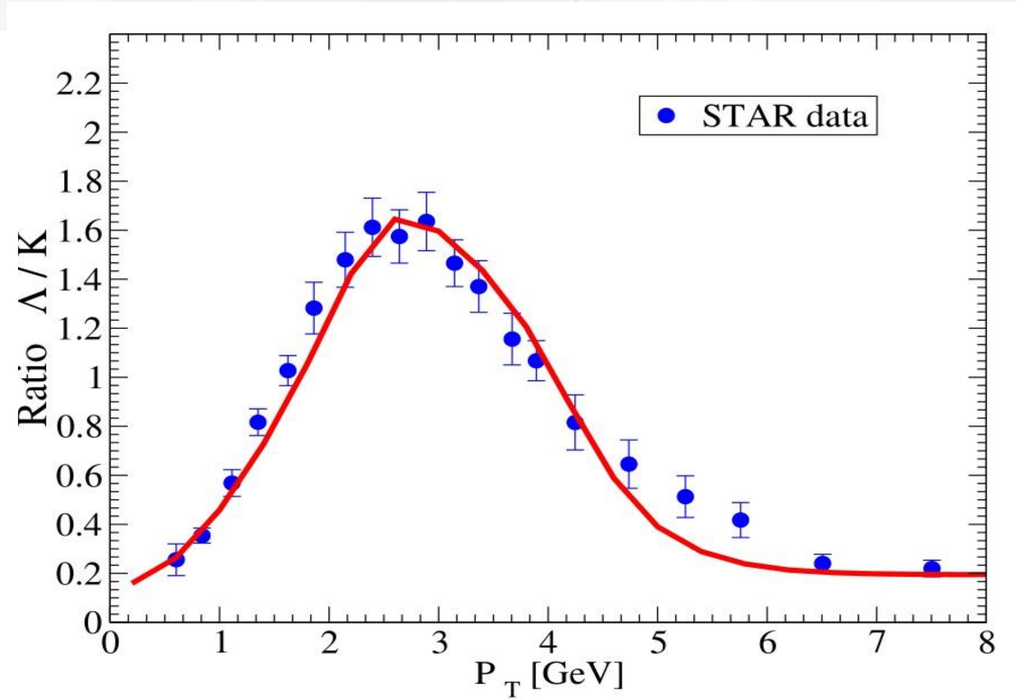
Hadronic elliptic flow

Assumption

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

Baryon to meson ratio at RHIC





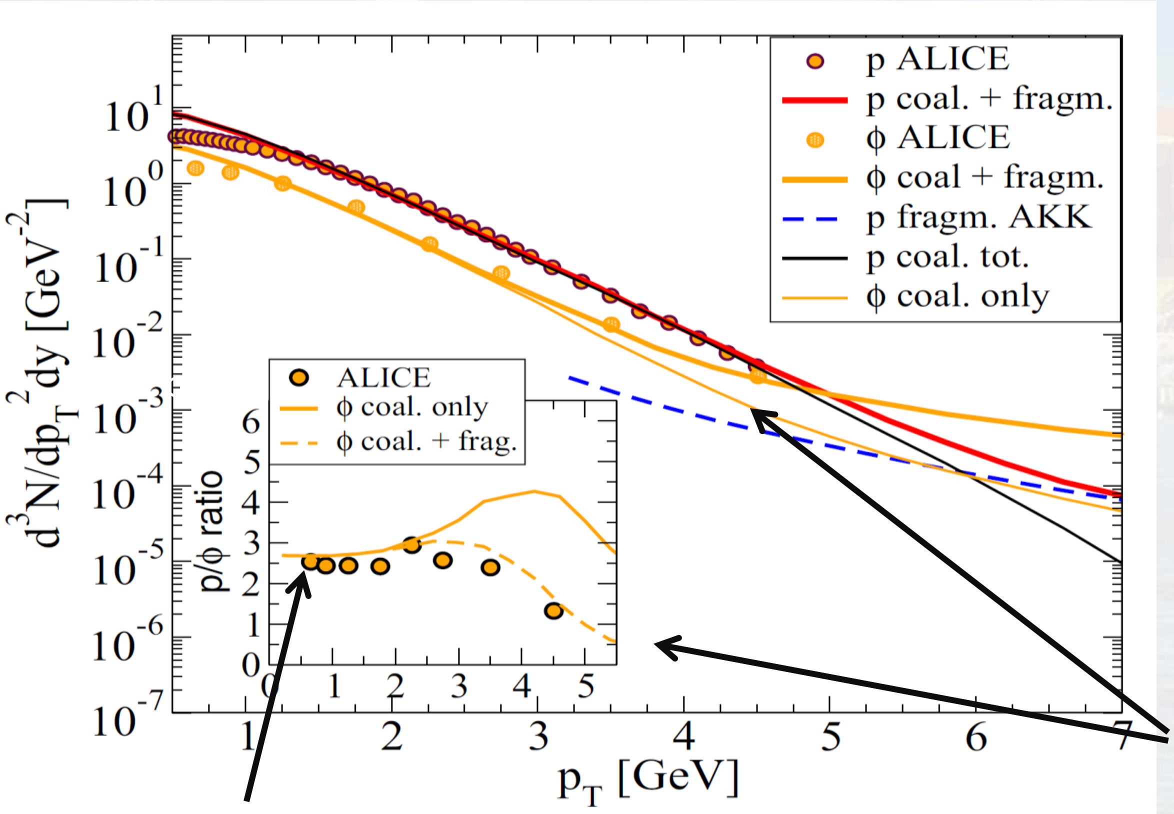
- ✓ coalescence naturally predict a baryon/meson enhancement in the region $p_T \simeq 2{-}4GeV$ with respect to *pp* collisions
- ✓ Lack of baryon yield in the region $p_T \simeq$ 5−7GeV

LHC: φ meson

Discussed question for long time:

φ meson behaviour → *meson-like* or *mass effect*

Coalescence predicts a similar slope for φ and p.



Proton is a combination of 3 quarks flowing each with a mass of about *330 MeV* and ***φ*** is composed by 2 quarks flowing each with a mass of about *550 MeV*

Missing fragmentation Contribution usually half of the yield at $p_T \approx 4$ GeV

Soft part same slope φ and p

V. Minissale, F. Scardina, V. Greco PRC 92, 054904 (2015)

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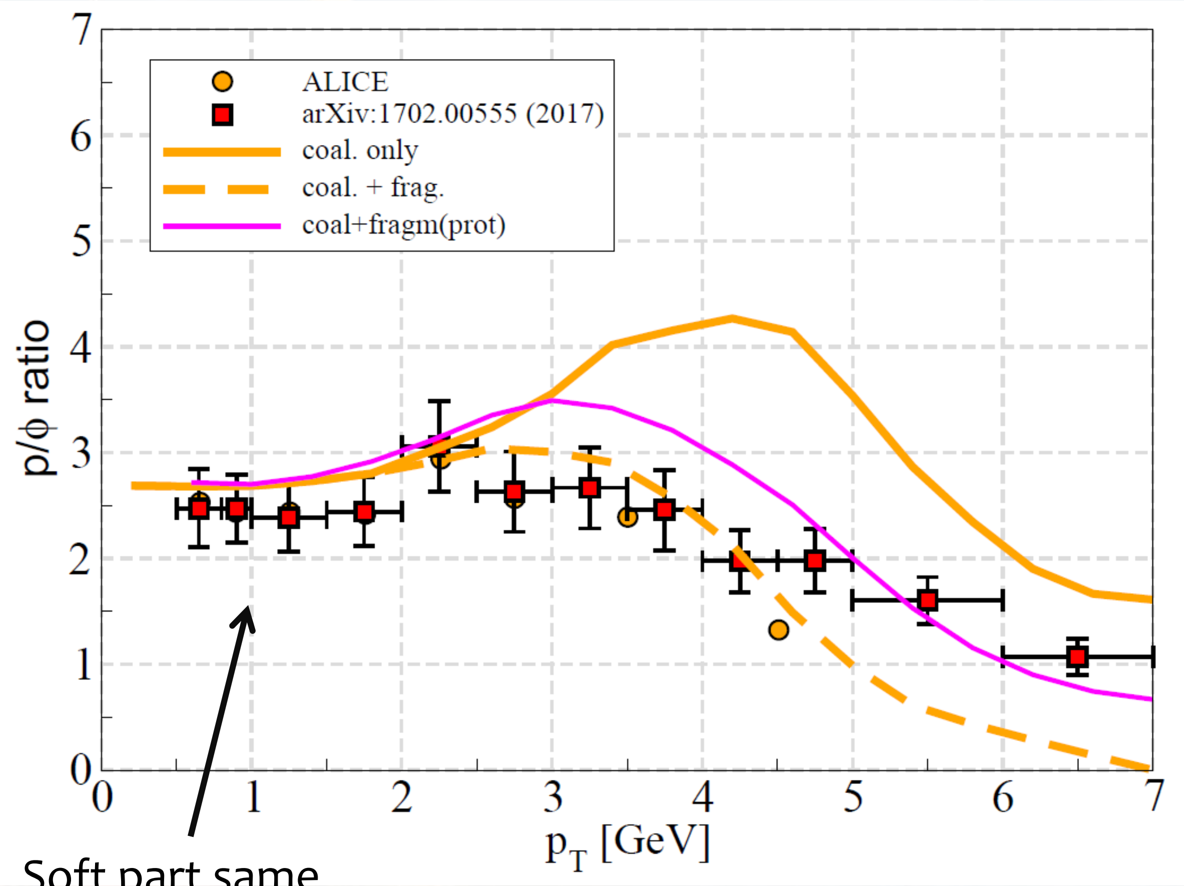

Soft part same slope φ and p

Proton is a combination of 3 quarks flowing each with a mass of about 330 *MeV* and *φ* is composed by 2 quarks flowing each with a mass of about 550 *MeV*

V. Minissale, F. Scardina, V. Greco PRC 92, 054904 (2015)

Summary on the build-up of v2 at ≈ fixed RAA