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Heavy hadrons production by coalescence plus fragmentation in AA collisions at RHIC and LHC

In collaboration with: S. Plumari, G. Coci, S. K. Das, V. Greco

Hot Quarks 2018 *12 September 2018*

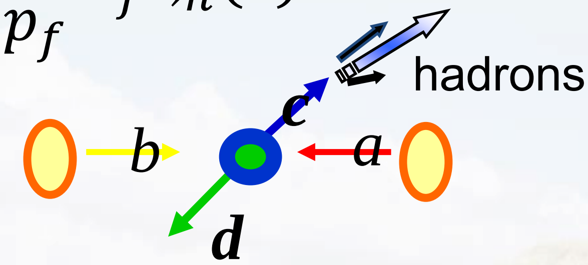
Outline

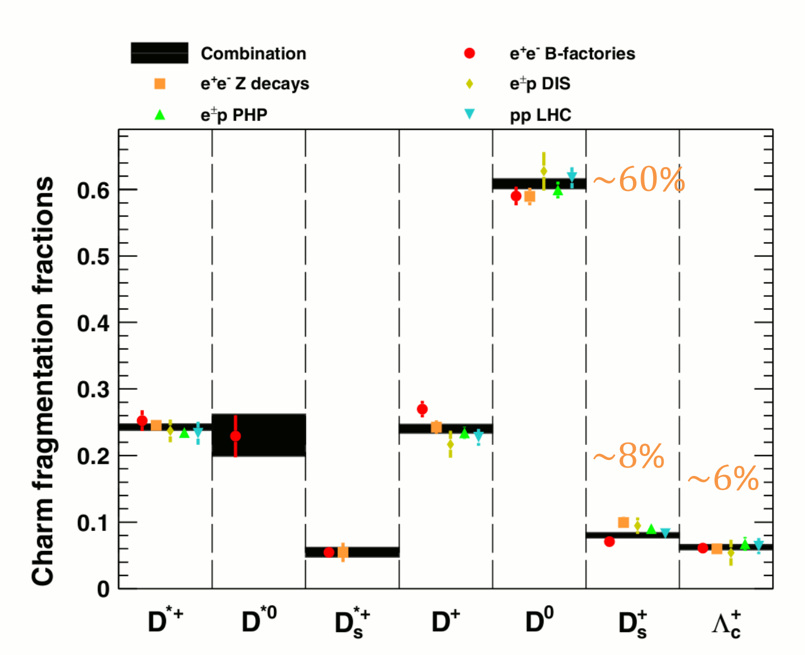
- Hadronization:
  - Fragmentation
  - Coalescence model

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

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.*

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

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

3 and 2 times smaller respect to the one expected from thermal models

A. Andronic et al., Phys. Lett. **B**571, 36 (2003)

I. Kuznetsova, J. Rafelski, EPJ C51, 113 (2007)

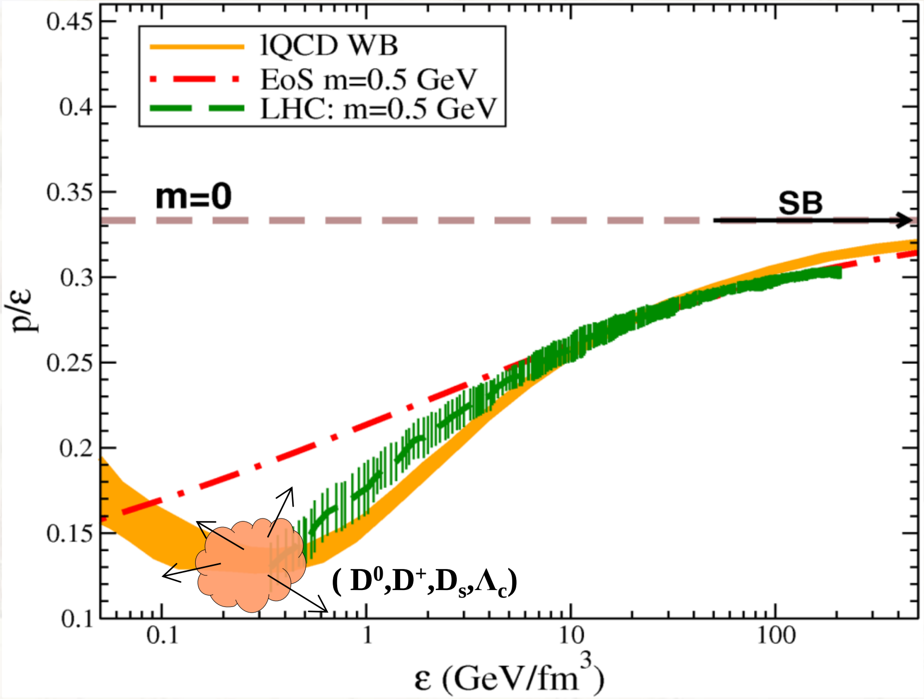
Relativistic Boltzmann transport at finite η/s

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

- 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

$$C_{22} = \int d^3k\left[\omega(p+k,k)f(p+k) - \omega(p,k)f(p)\right]$$

$$\omega(p,k) = \int \frac{d^3q}{(2\pi)^3} f'(q) v_{rel}\sigma_{p,q\rightarrow p-k,q+k}$$



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

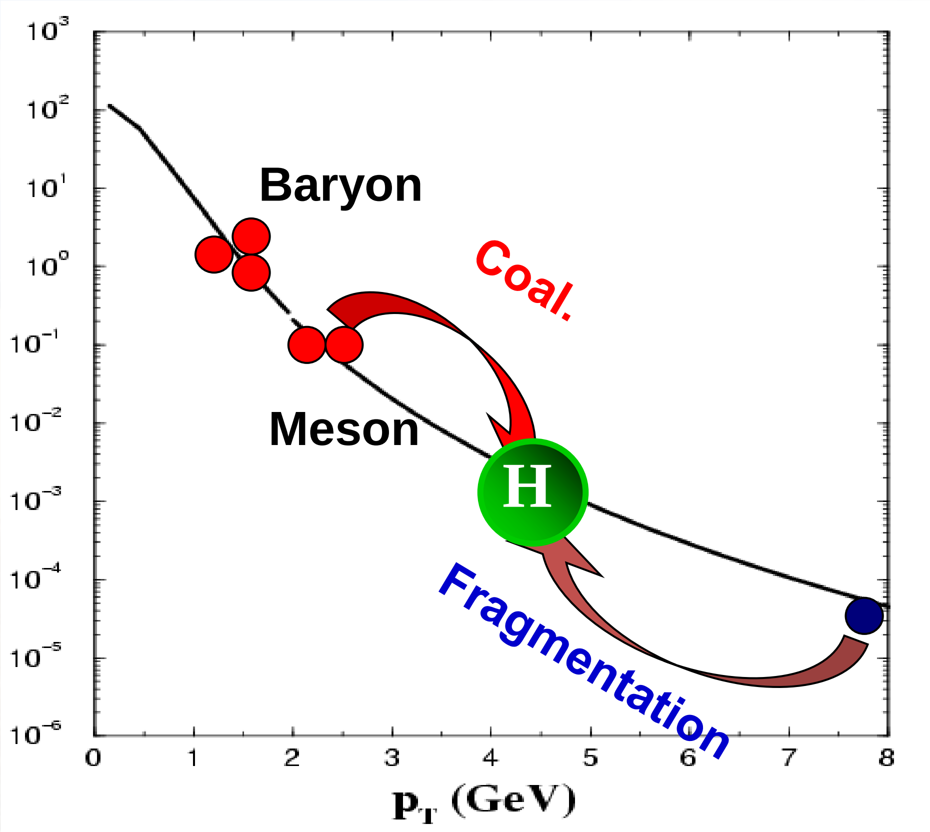
Hadronization: Coalescence

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

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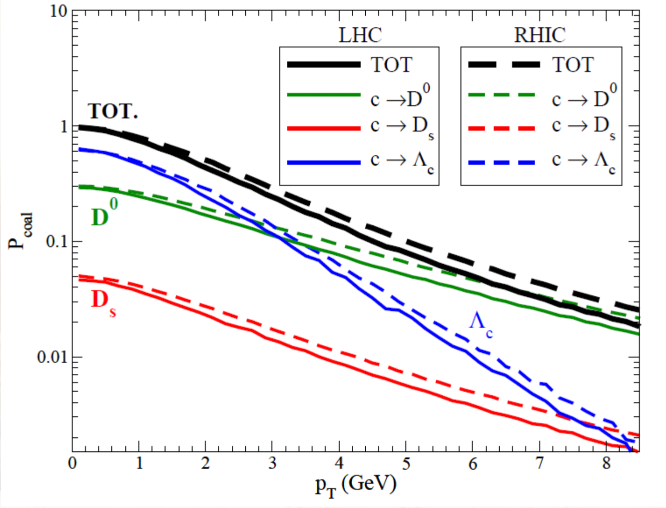
$$\frac{dN_{Hadron}}{d^2p_T} = g_H \int \prod_{i=1}^{n} p_i \cdot d\sigma_i \frac{d^3p_i}{(2\pi)^3} f_q(x_i, p_i) f_W(x_1, \ldots, x_n; p_1, \ldots, p_n) \delta\left(p_T - \sum_i p_{iT}\right)$$

charm distribution function at mid-rapidity from parton simulations solving Boltzmann transport eq.
that give good description of both R_{AA} and $v_2(p_T)$ from RHIC to LHC energies.



- *The width parameters σ in $f_W(\ldots)$ 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 $f_W(\ldots)$ *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)* $\longrightarrow$ **$D^0\,\pi^+$** *B.R. 68%*
  $\longrightarrow$ **$D^+\,X$** *B.R. 32%*
- **D^{*0}** *(I=1/2,J=1)* $\longrightarrow$ **$D^0\,\pi^0$** *B.R. 62%*
  $\longrightarrow$ **$D^0\,\gamma$** *B.R. 38%*
- **D_s^{*+}** *(I=0,J=1)* $\longrightarrow$ **$D_s^+\,X$** *B.R. 100%*
- **D_{s0}^{*+}** *(I=0,J=0)* $\longrightarrow$ **$D_s^+\,X$** *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)*

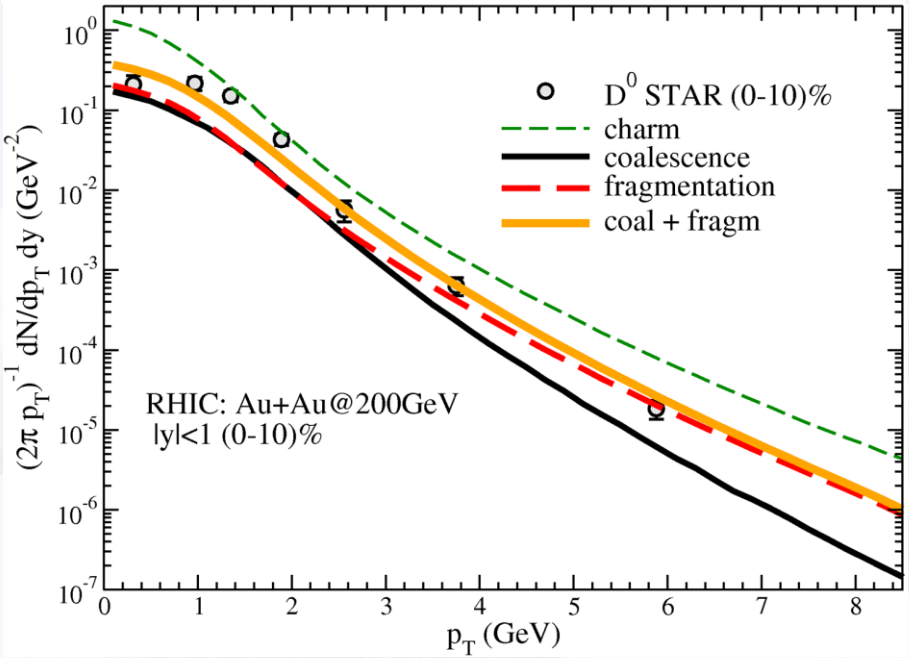
Resonances

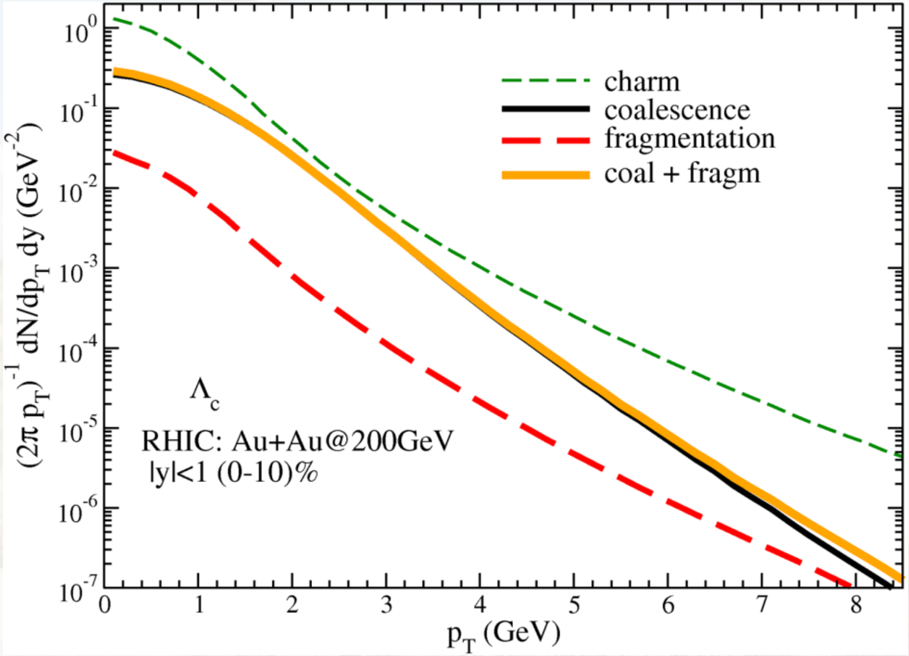
- **$\Lambda_c^+(2595)$** *(I=0,J=1/2)* $\longrightarrow$ **Λ_c^+** *B.R. 100%*
- **$\Lambda_c^+(2625)$** *(I=0,J=3/2)* $\longrightarrow$ **Λ_c^+** *B.R. 100%*
- **$\Sigma_c^+(2455)$** *(I=1,J=1/2)* $\longrightarrow$ **$\Lambda_c^+\pi$** *B.R. 100%*
- **$\Sigma_c^+(2520)$** *(I=1,J=3/2)* $\longrightarrow$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

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

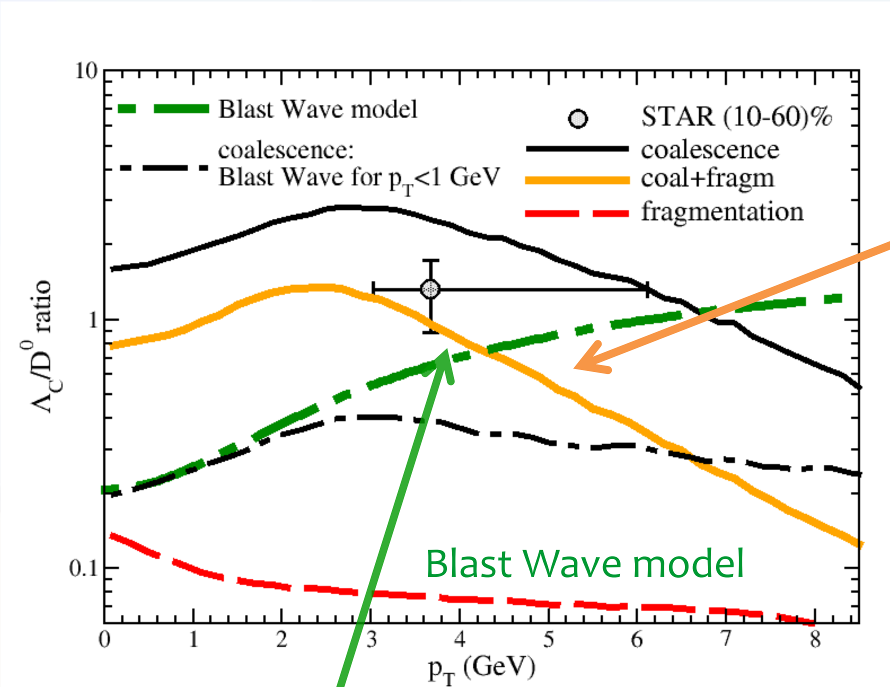




- For D^0 coalescence and fragmentation comparable at 2 GeV
- Λ_c^+ fragmentation is even more smaller, coalescence gives the dominant contribution

RHIC: Baryon/meson

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



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:

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

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

Is the reduced mass of the baryon

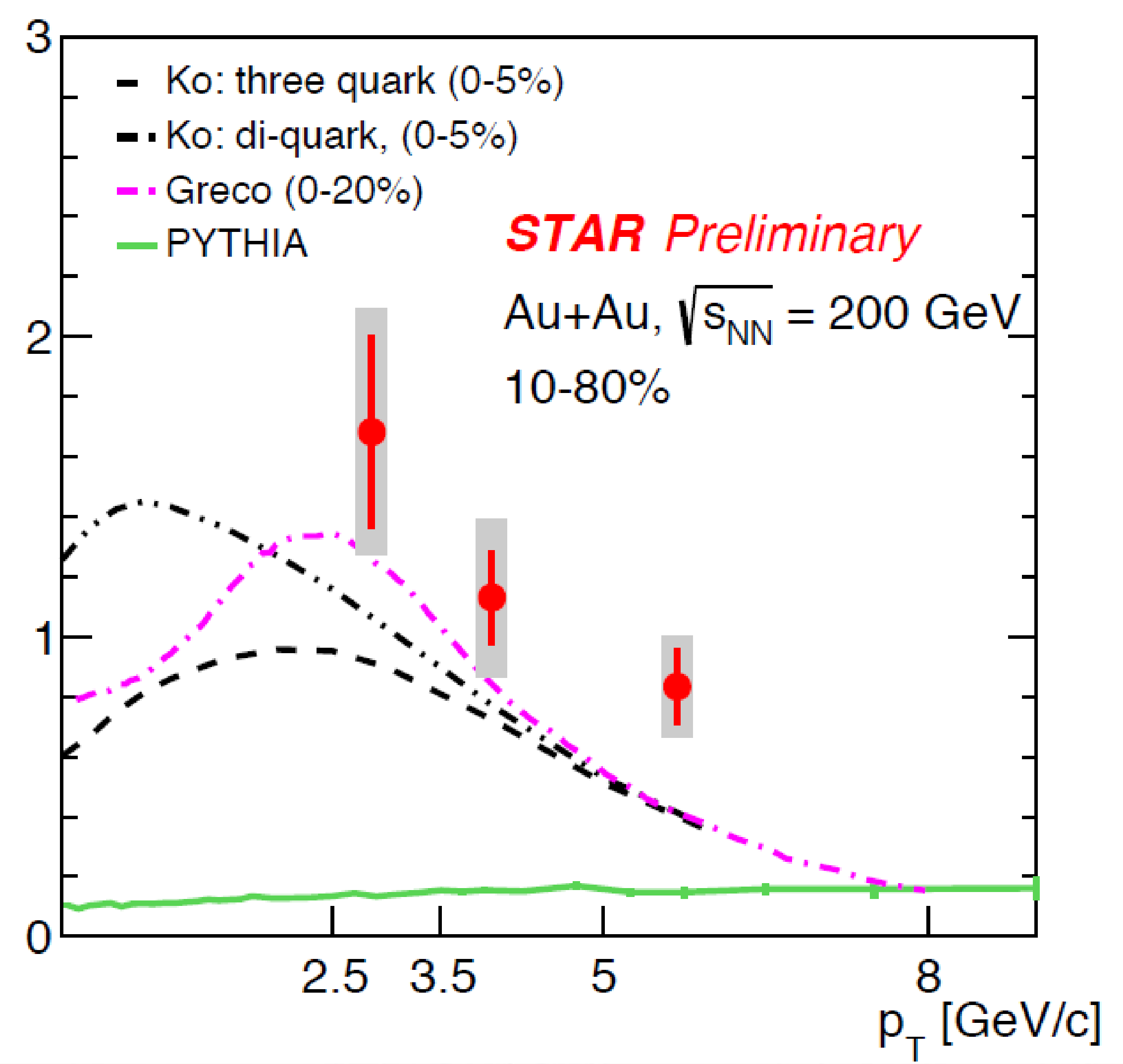
Blast Wave model:

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

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

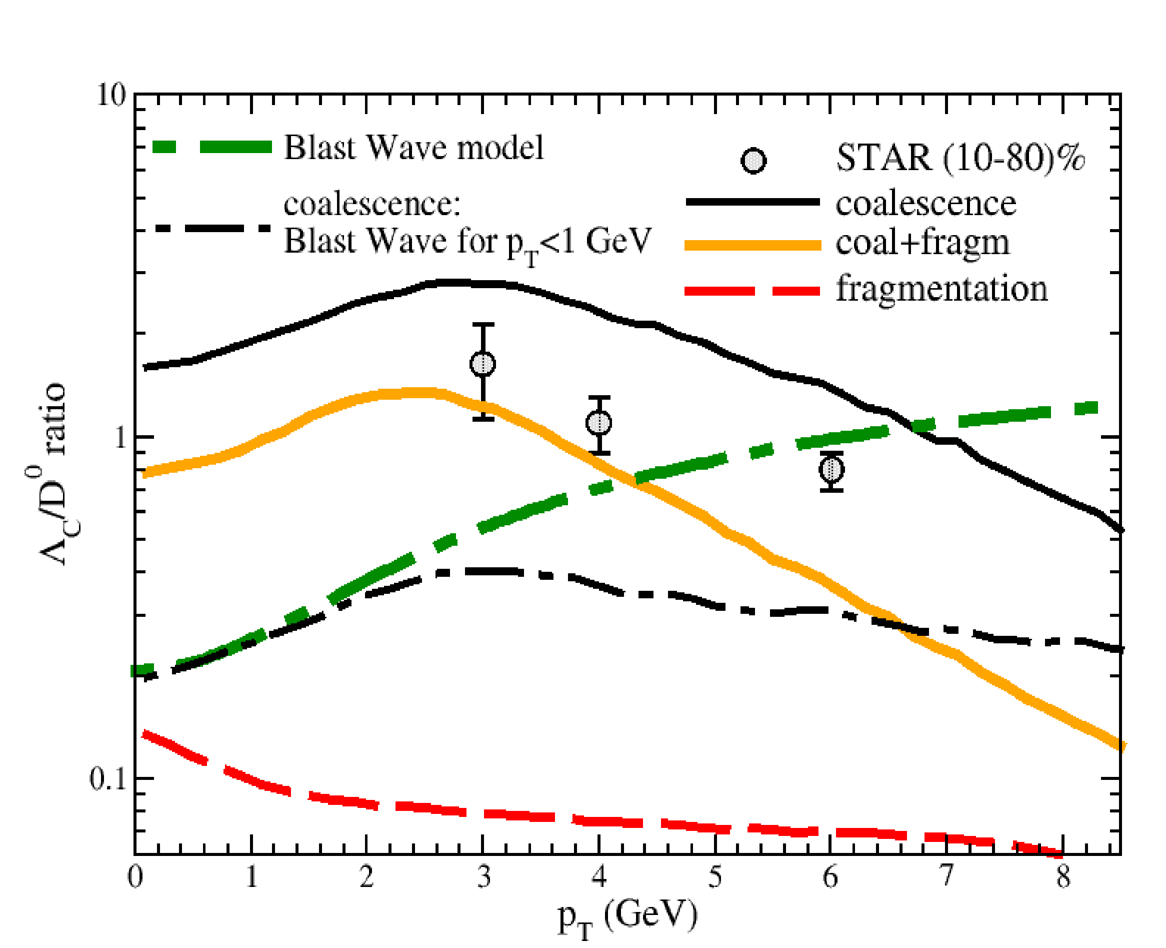
S. Plumari, V. Minissale et al., Eur. Phys. J. ***C78*** *no. 4, (2018) 348*

RHIC: Baryon/meson



QM2018 New data from STAR…

RHIC: Baryon/meson



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)

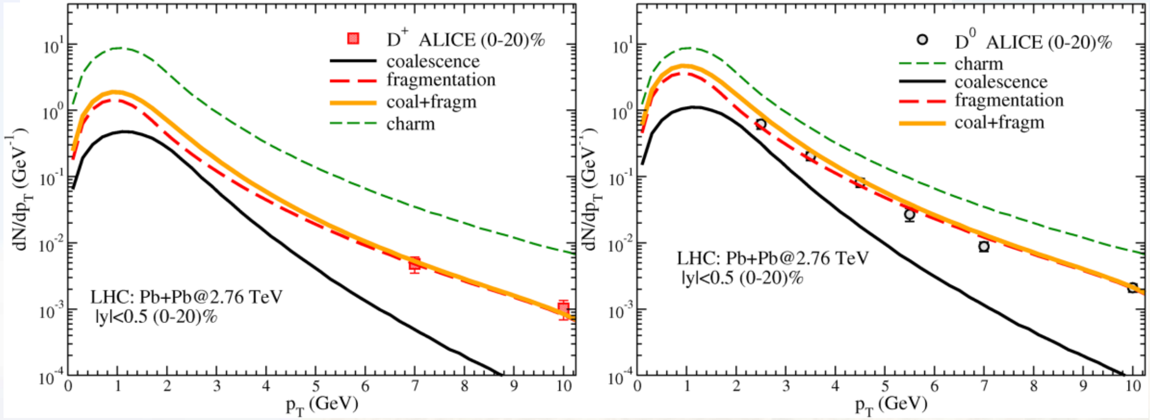
Needed data at low p_T

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

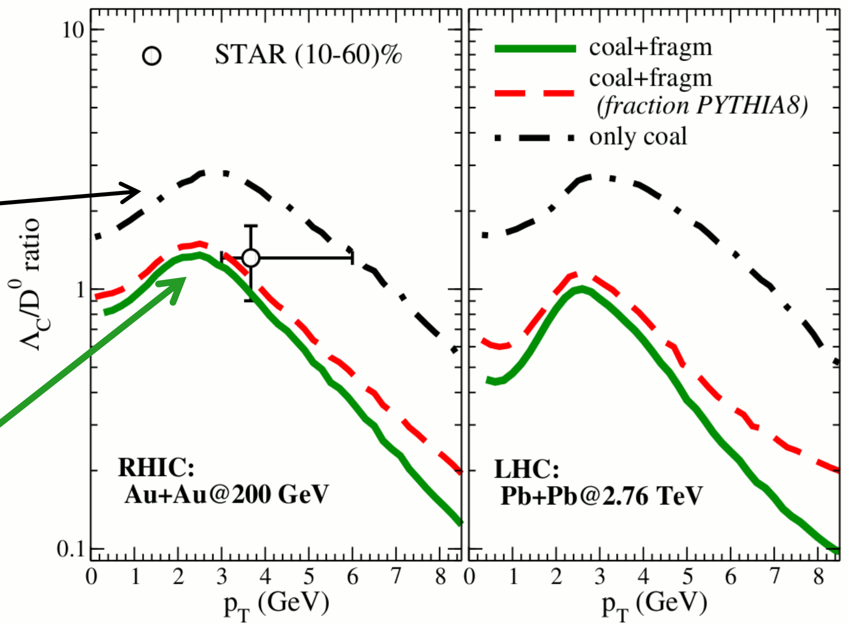
LHC: results

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 ~ 0.09 at both energies.

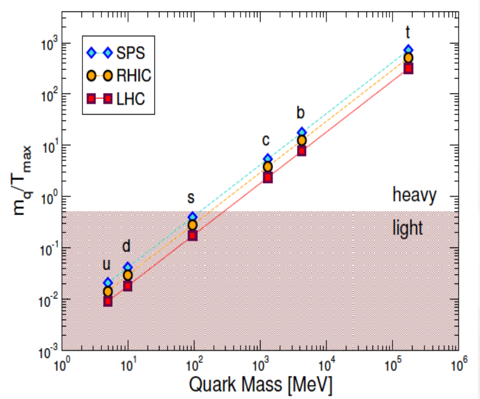
the **combined ratio is different** because the coalescence over fragmentation ratio at LHC is smaller than at RHIC

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

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

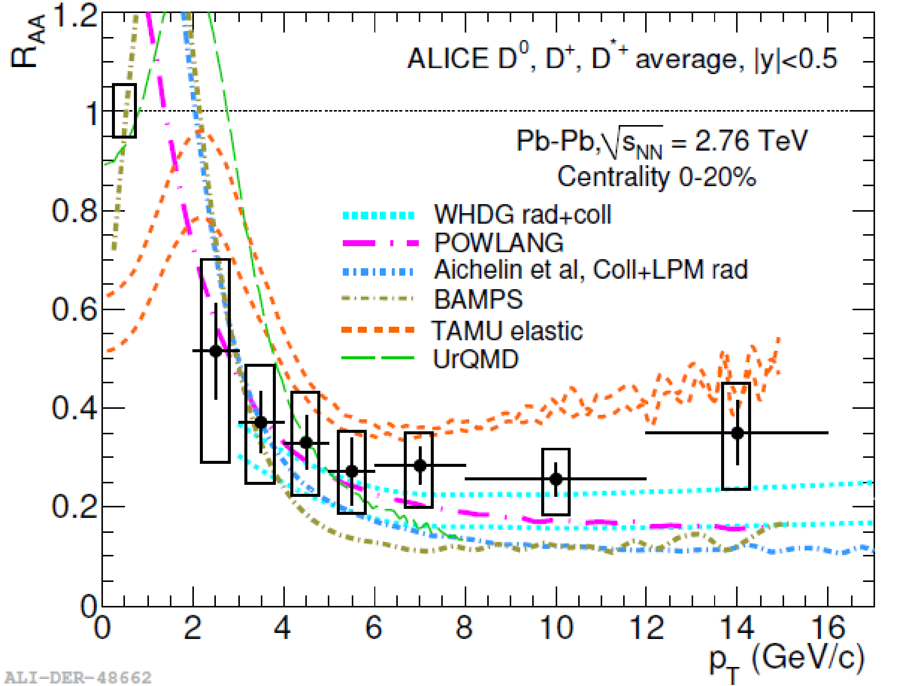
Specific of Heavy Quarks

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

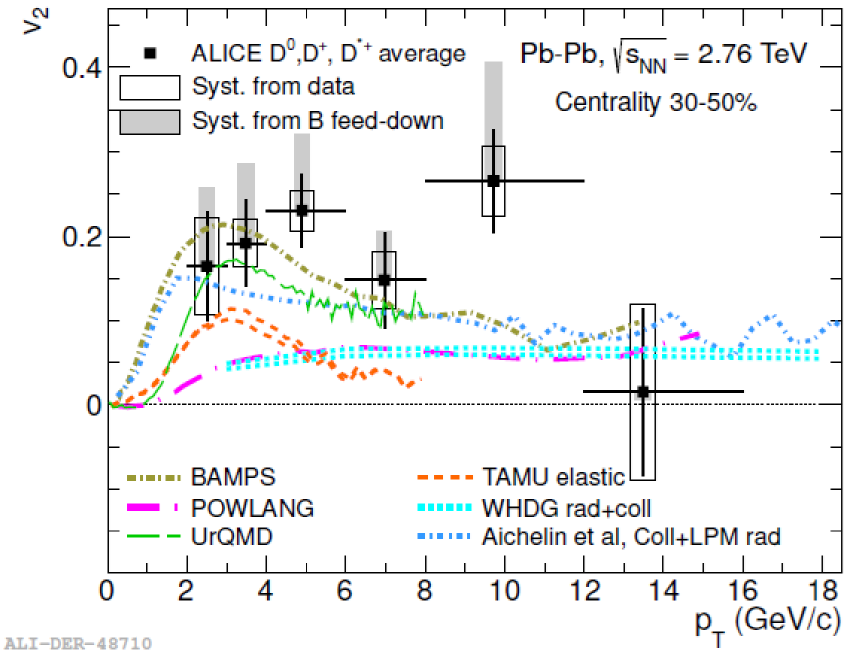


Simultaneous description of R_{AA} and v_2 is a tough challenge for all models

JHEP **1209** (2012) 112



arXiv:1305.2707



RHIC results: R_{AA} - v_2

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

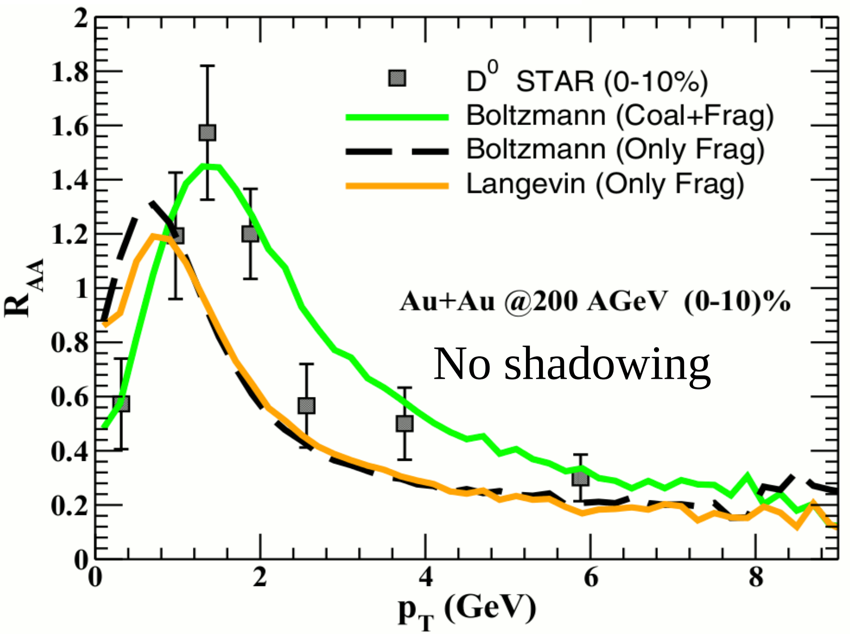
Charmed hadrons production given by D mesons

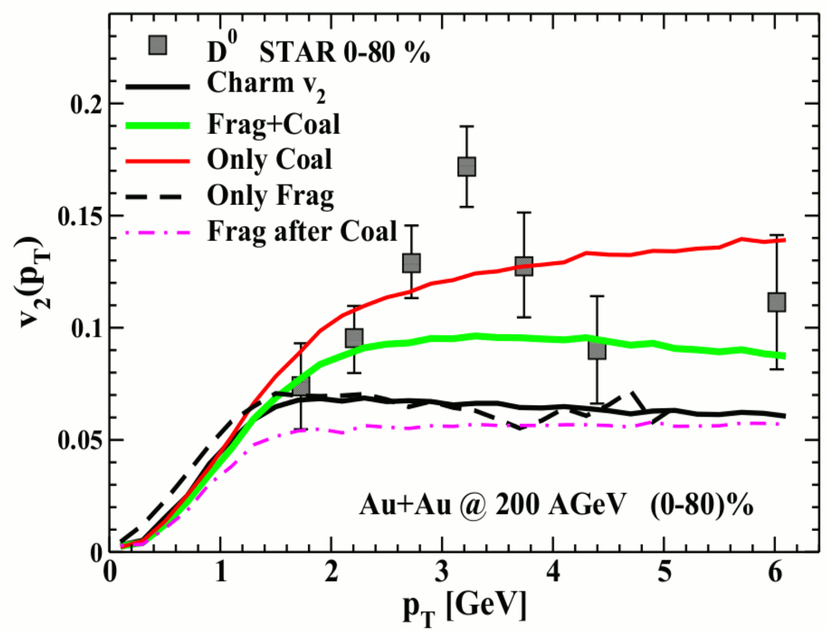
F. Scardina, S. K. Das, V. Minissale, S. Plumari, V. Greco, PRC96 (2017) no.4, 044905

RHIC results: R_{AA} - v_2

Without Λ_c production

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





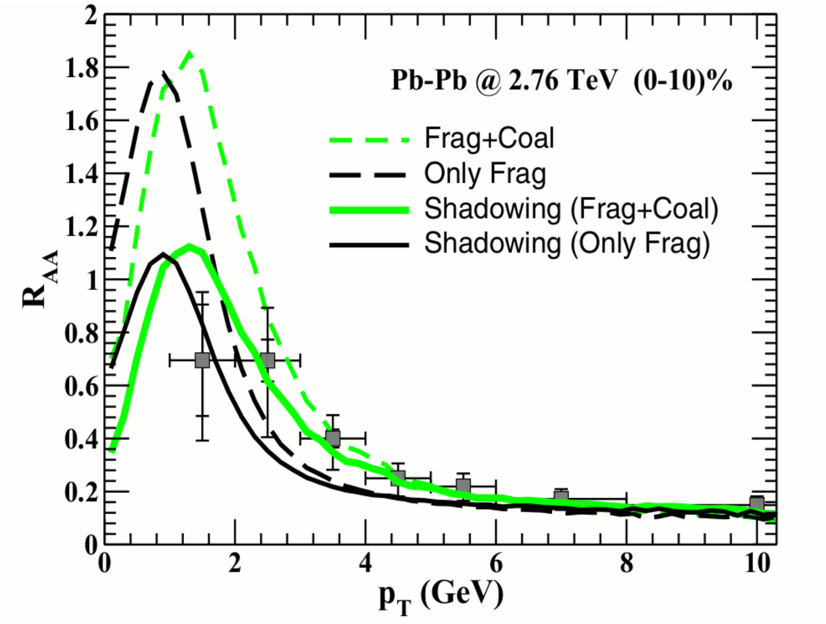
- In 0-10% coalescence implies an increase of the R_{AA} for $p_T > 1$ GeV.
- The impact of coalescence decreases with p_T and fragmentation is dominant at high p_T.
- In 0-80% the $v_2(p_T)$ due to only coalescence increase a factor 2 compared to the $v_2(p_T)$ charm.
- In 0-80% coalescence+fragmentation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

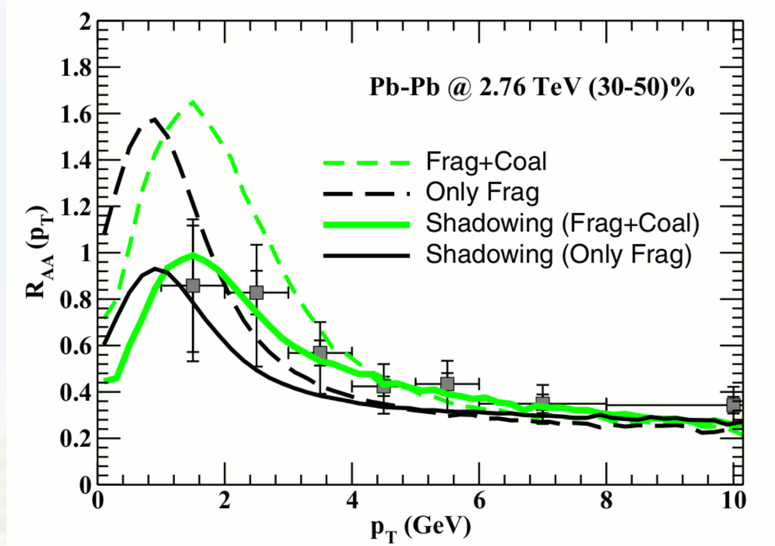
Opposite to energy loss Coalescence brings up both R_{AA} and v_2

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

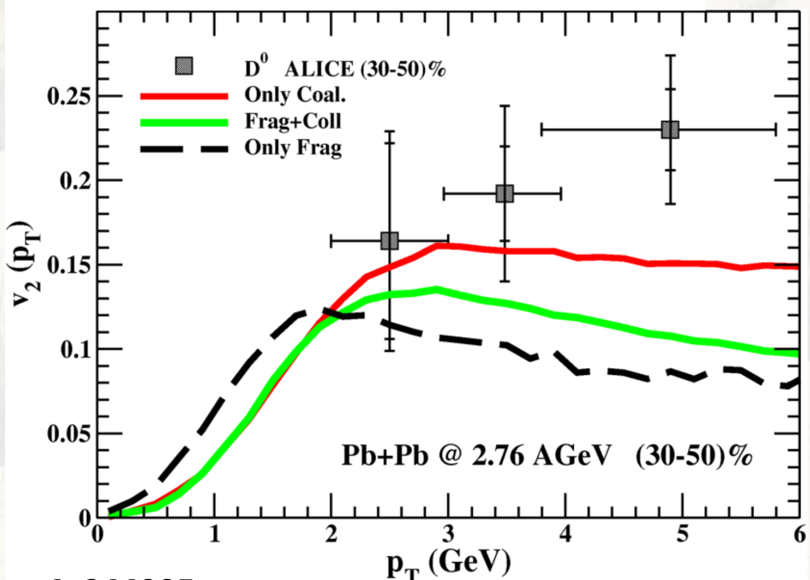
LHC results: R_{AA} - v_2

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 $v_2(p_T)$.
- Hadronic rescattering can increase by 15% v_2

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

RHIC results: R_{AA}

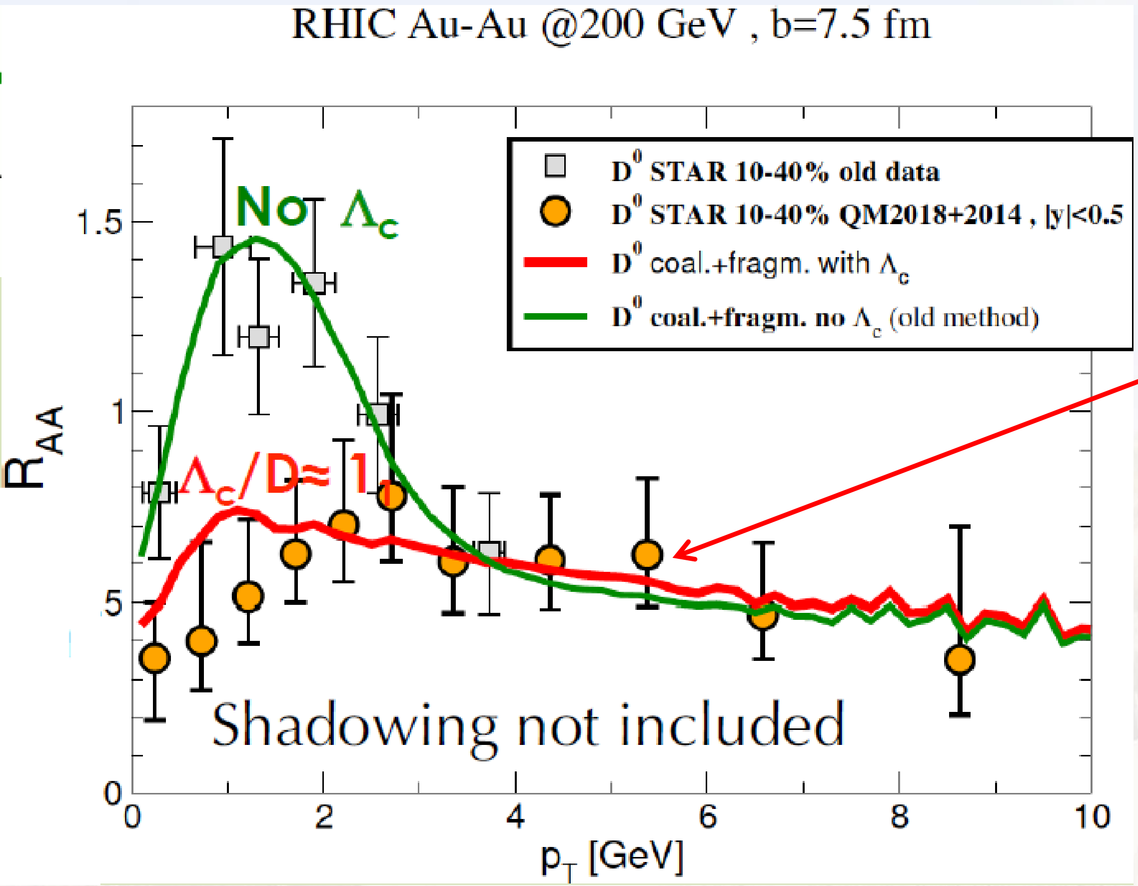
AFTER THE STUDY OF Λ_c / D^0 (late 2017)

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

Charmed hadrons production given by D mesons and Λ_c

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

RHIC results: R_{AA}



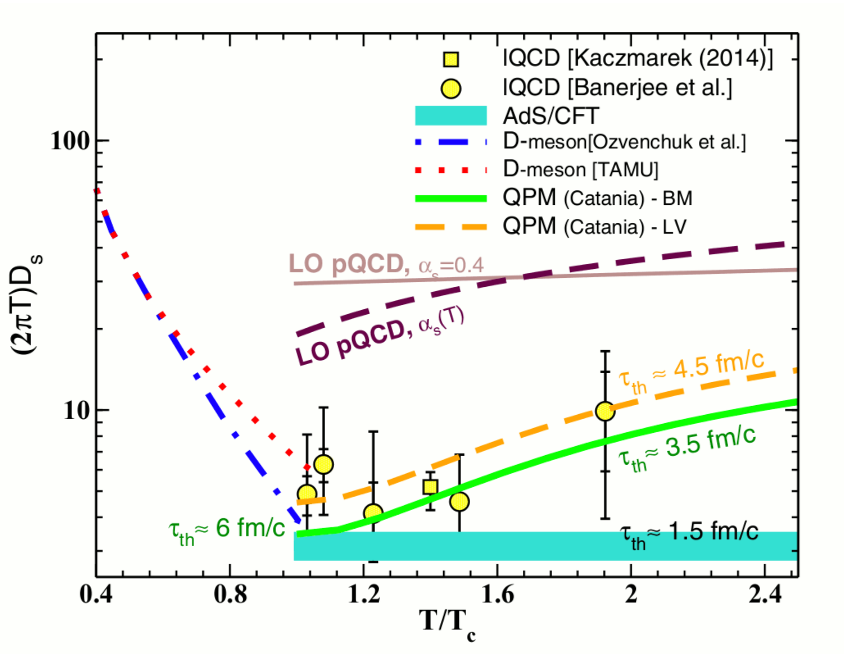
New STAR data in QM2018

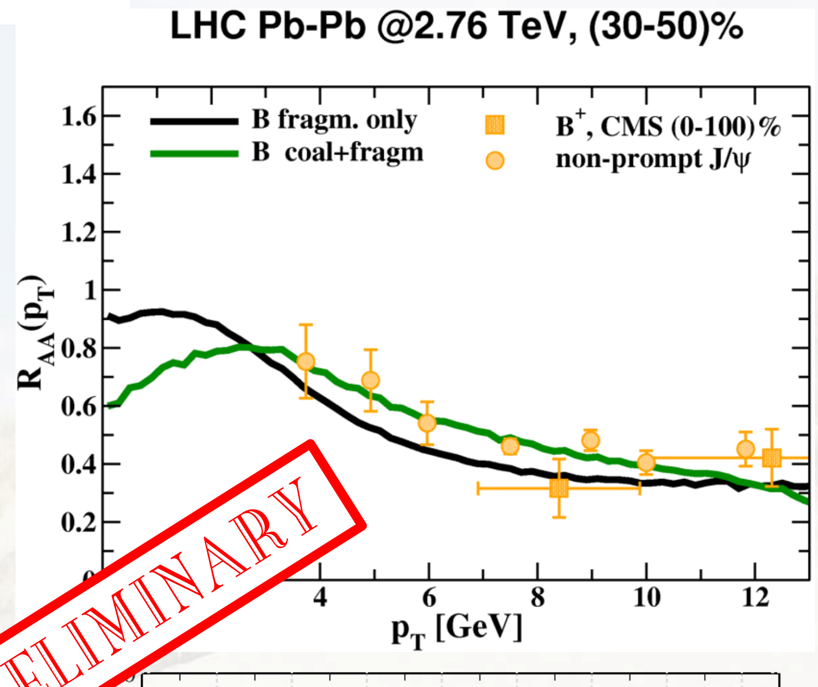
- Big effect at RHIC where coalescence dominates
- Smaller but still significant also at LHC

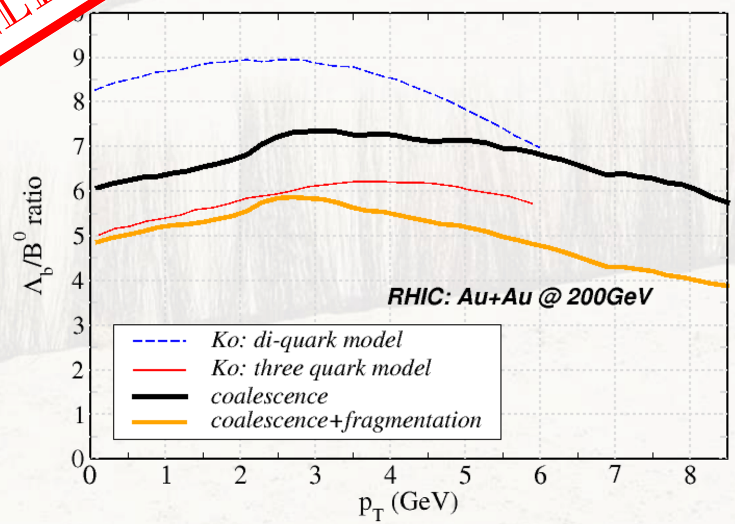
R_{AA} of D^0 decreases because part of charm quark makes coalescence in charmed Lambdas, while in pp charm quarks fragment mainly in D mesons

Bottomed hadrons

F. Scardina, S. K. Das, V. Minissale, S. Plumari, V. Greco, PRC**96** (2017) no.4, 044905.







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^0 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

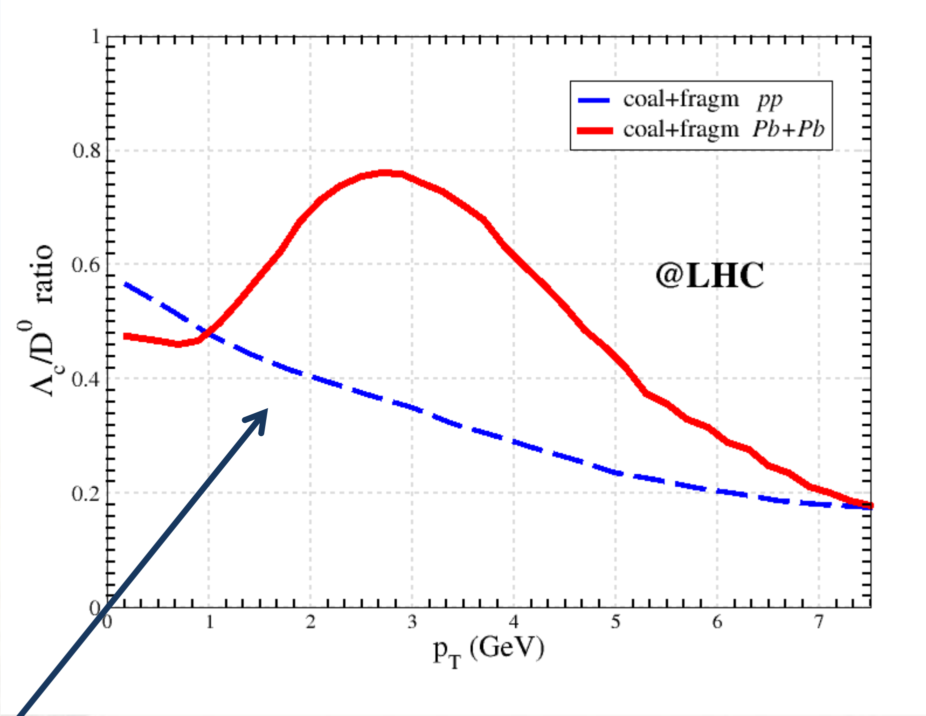
A provocation?

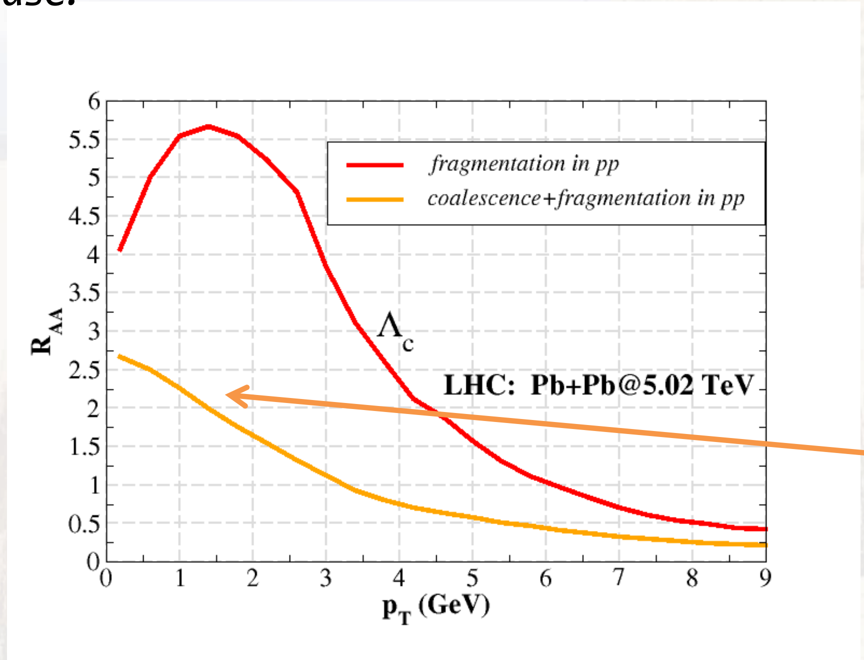
Common consensus of *possible* presence of QGP in smaller system.

What if:

<u>**Assuming QGP formation also in *pp* ?**</u>

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

THANK YOU

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

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

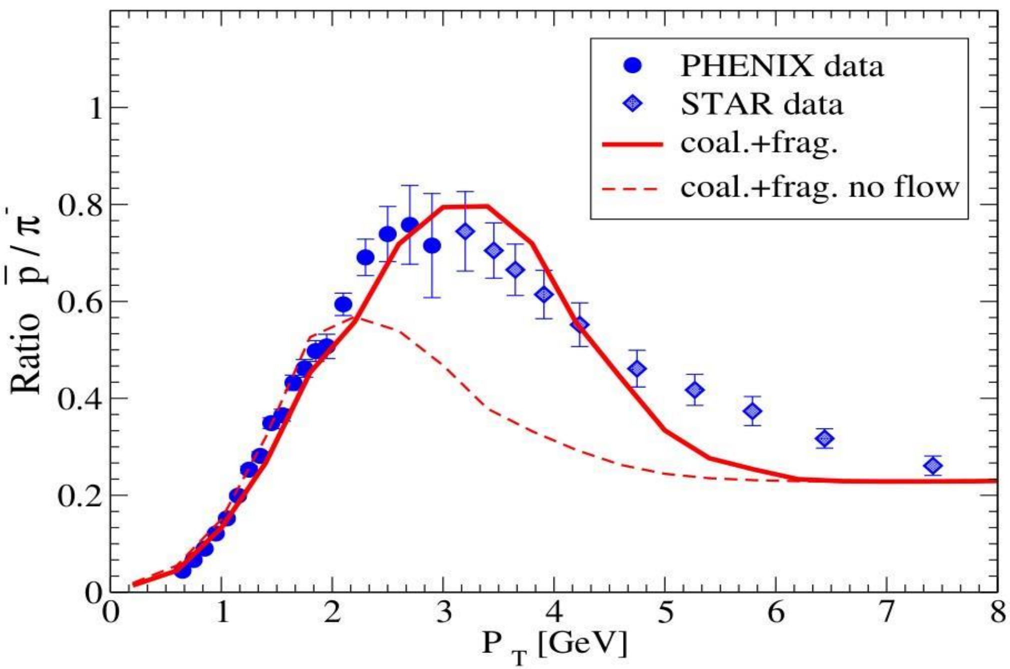
Partonic elliptic flow

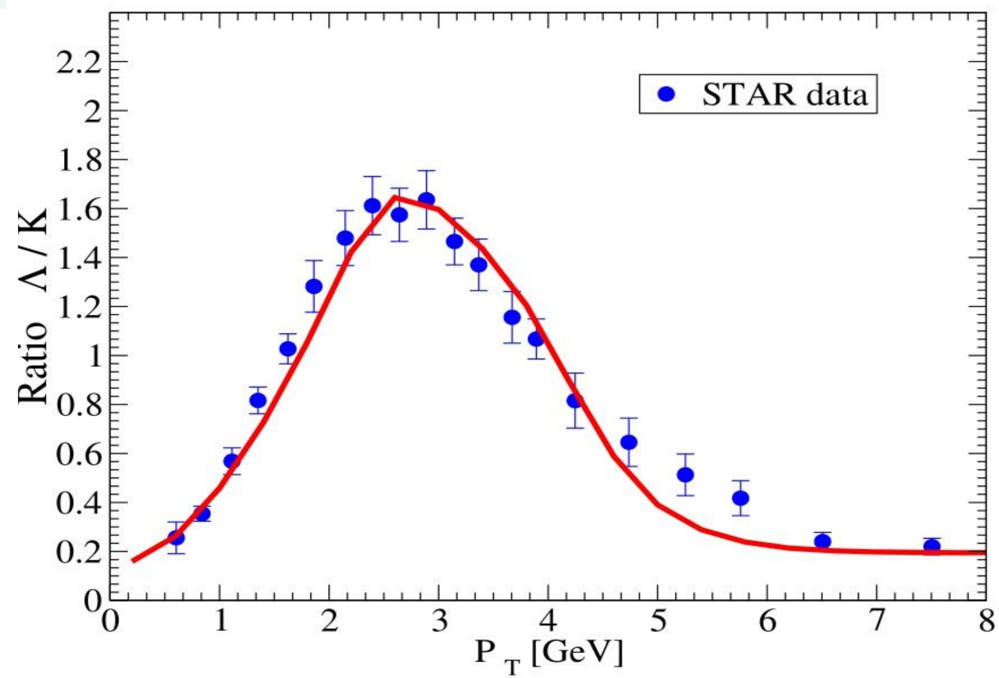
Hadronic elliptic flow

Assumption

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

Baryon to meson ratio at RHIC





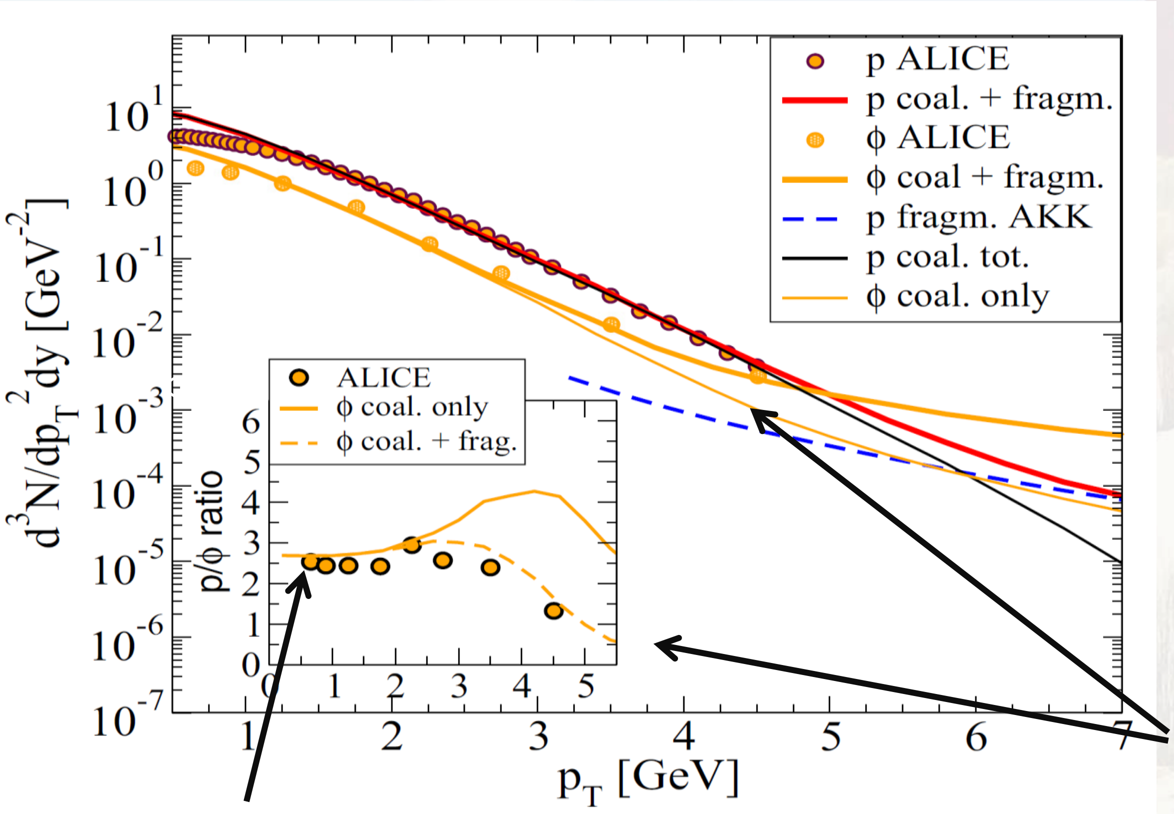
- ✓ coalescence naturally predict a baryon/meson enhancement in the region $p_T \simeq 2\text{–}4 GeV$ with respect to *pp* collisions
- ✓ Lack of baryon yield in the region $p_T \simeq 5\text{–}7$GeV

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)

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