Vincenzo Minissale
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Light and heavy hadron production in heavy-ion collisions from a coalescence model

In collaboration with: S. Plumari, V. Greco, F. Scardina, S.K. Das

TNPI2017 XVI Conference on Theoretical Nuclear Physics in Italy

Outline

- **Hadronization:**
  - **Fragmentation**
  - **Coalescence model**
  - ***p,π, k, Λ spectra and baryon/meson ratio***
- **Heavy Quarks:**
  - **Λ_c and D mesons spectra for RHIC and LHC energies**
  - **Λ_c/D^0 ratio**
- **Conclusions**

Quark Gluon Plasma

- Nuclear matter: Critical Energy and Temperature in the transition between confined and deconfined phase

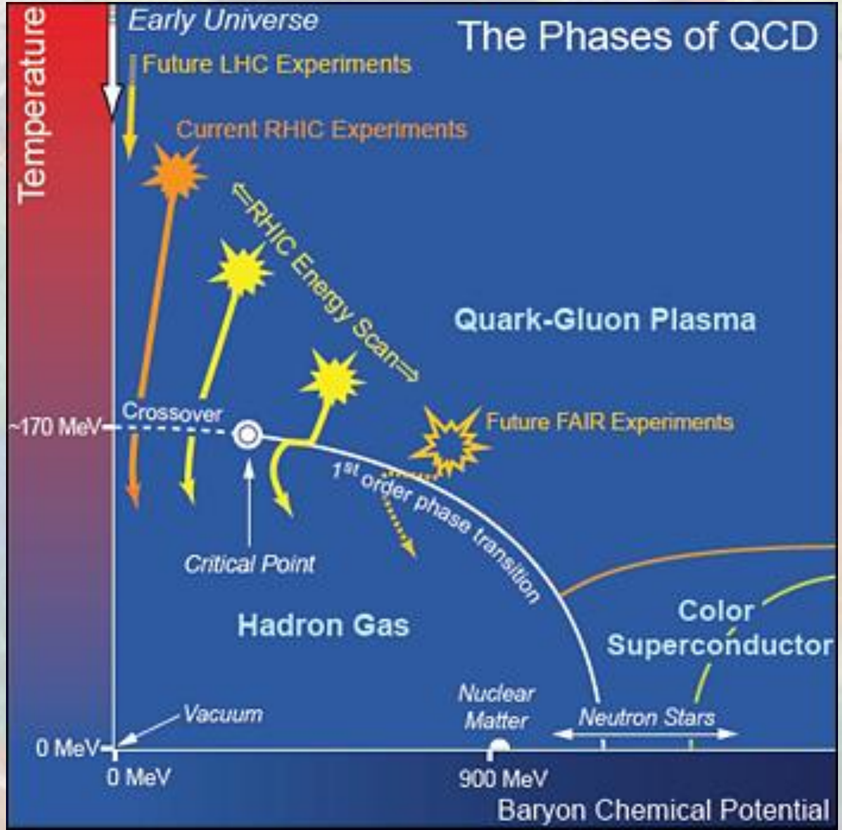
$$\varepsilon_c \approx 0.7\, GeV / fm^3$$

$$T_c \cong 165\, MeV \approx 10^{12}\, K$$

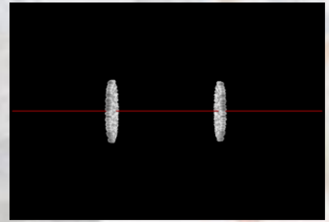
- If $T>T_C$ colour charges are deconfined in a Quark Gluon Plasma (QGP)

- Different value of T and ρ for deconfinement

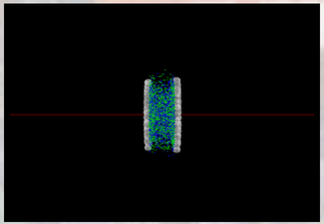
→ Phase Diagram



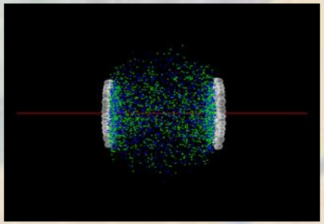
Ultra-relativistic heavy ion collisions



Initial Stage



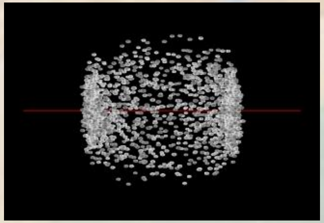
Pre-equilibrium stage



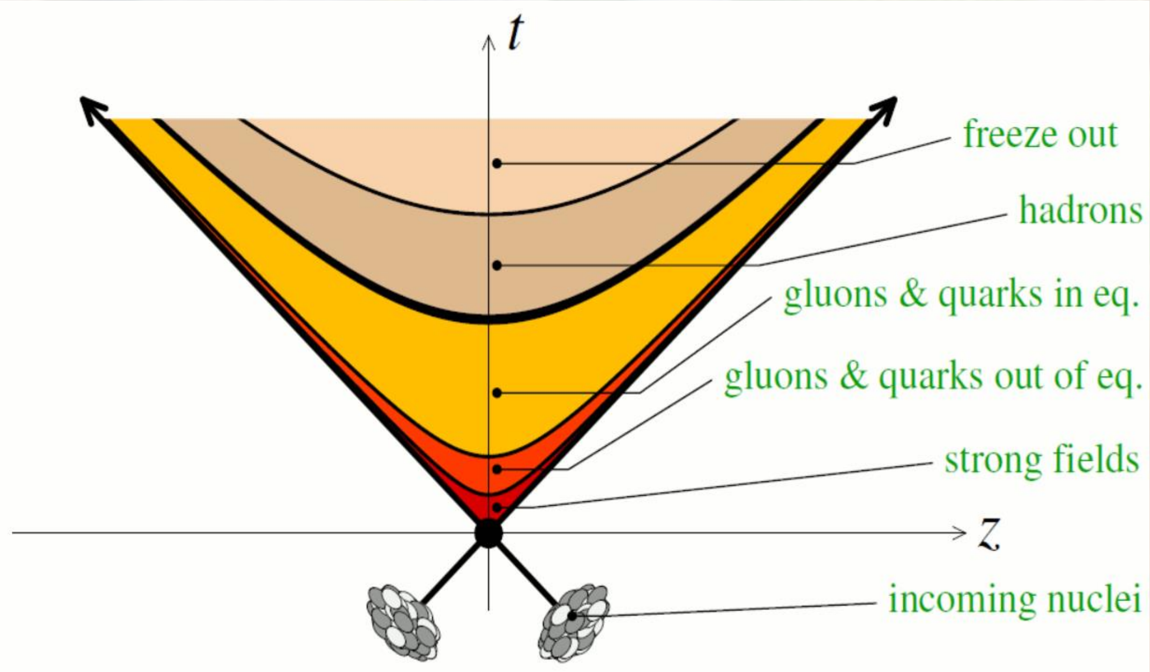
Expansion

QGP

Hadronization



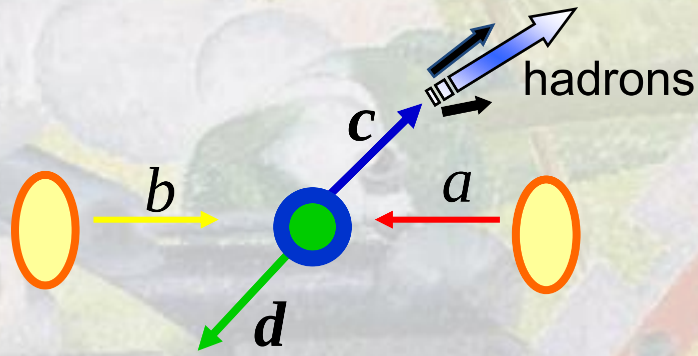
Chemical and kinetic freeze-out



Hadronization

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

Fragmentation function



We use the AKK fragmentation function

S. Albino, B.A. Kniehl, G. Kramer, NPB 803 (2008)

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Proton to pion ratio Enhancement:

In vacuum from fragmentation functions the ratio is small

$$\frac{D_{c\to p}(z)}{D_{c\to \pi}(z)} < 0.25$$

Elliptic flow splitting:

For $p_T > 2$ GeV Both hydro and fragmentation predicts similar v_2 for pions and protons

Another hadronization mechanism is by coalescence

V. Greco, C.M. Ko, P. Levai PRL 90, 202302 (2003).
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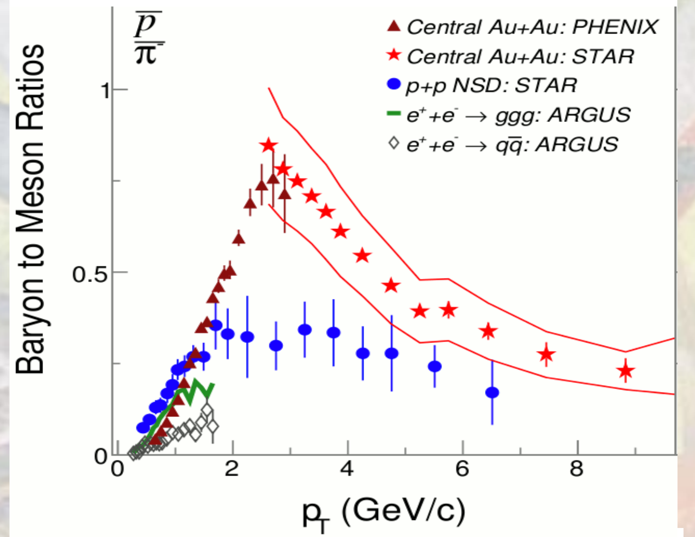
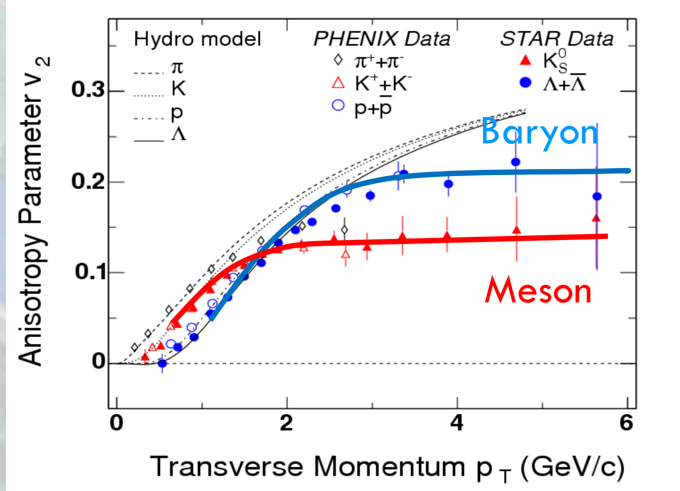
R.J. Fries, B. Muller, C. Nonaka, S.A. Bass PRL 90, 202303 (2003).
R.J. Fries, B. Muller, C. Nonaka, S.A. Bass PRC 68,044902 (2003).

R. J. Fries, V. Greco, P. Sorensen Ann.Rev.Nucl.Part.Sci. 58 (2008) 177



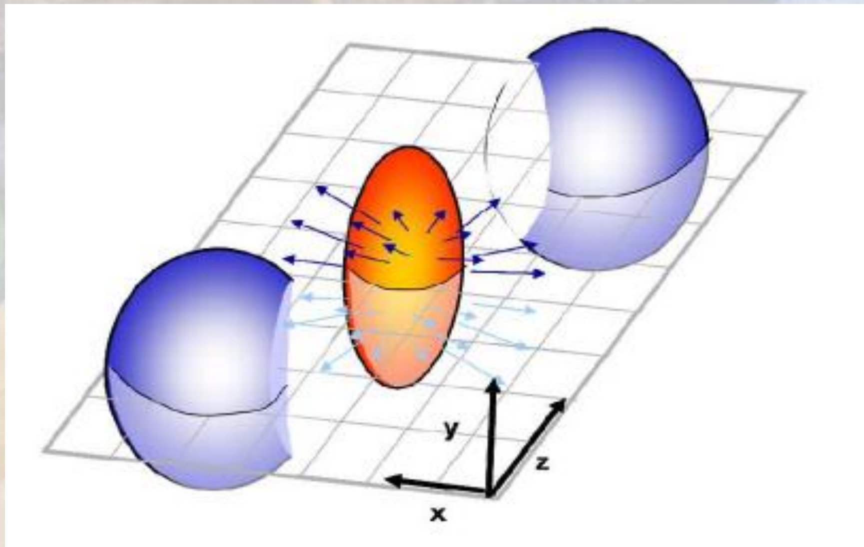


Elliptic Flow

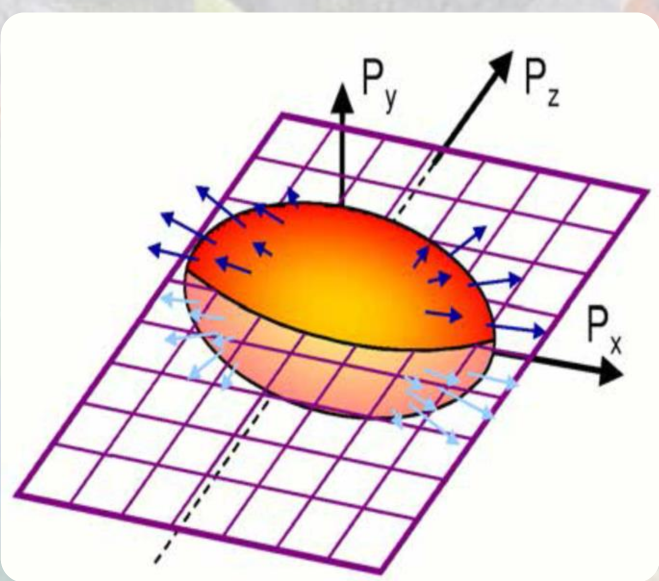
Fourier expansion of the azimuthal distribution

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

n=2 Elliptic flow



Coordinate space: initial anisotropy



Momentum space: final anisotropy

Free streaming v_2=0

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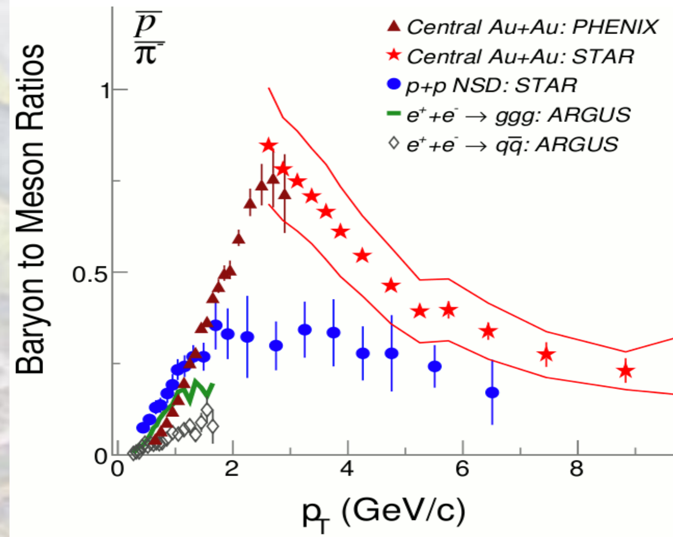

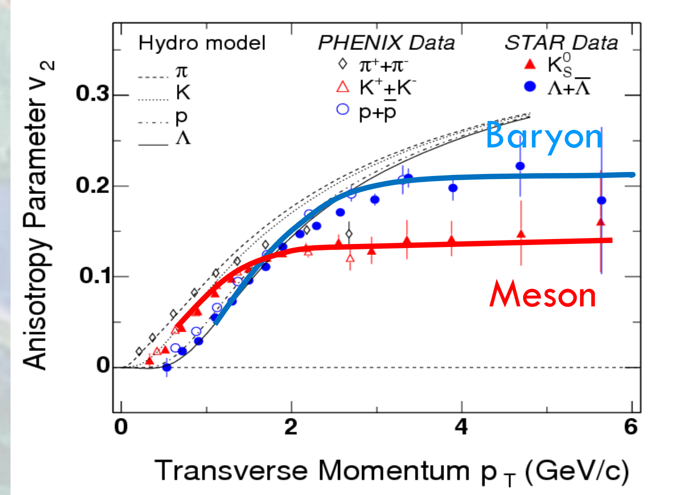

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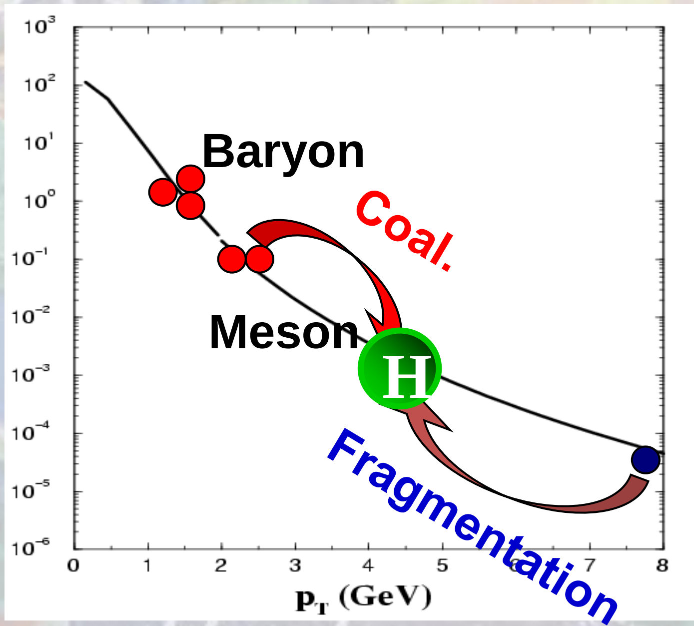


Hadronization: Coalescence

Statistical factor colour-spin-isospin

Parton Distribution function

Hadron Wigner function

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

Constraints from experiments

- Thermal Distribution (p_T< 2 GeV)

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

  - Collective flow $\beta_T = \beta_0 \frac{r}{R}$

- Minijet Distribution (p_T> 2 GeV)
- Fireball radius+radial flow constraints dN_{ch}/dy and dE_T/dy

$$f_{Meson} = \frac{9\pi}{2} \Theta(\sigma_x^2 - x_{r1}^2) \Theta(\sigma_p^2 - p_{r1}^2 + \Delta m_{12}^2)$$

$$f_{Baryon} = \frac{9\pi}{2} \Theta\left(\sigma_x^2 - \frac{1}{2} x_{r1}^2\right) \Theta(\sigma_p^2 - p_{r1}^2 + \Delta m_{12}^2) \times \frac{9\pi}{2} \Theta(\sigma_x^2 - x_{r2}^2) \Theta(\sigma_p^2 - p_{r2}^2 + \Delta m_{123}^2)$$

$\sigma_x = 1/\sigma_p$ *Only one free parameter in f_W*

V. Greco, C.M. Ko, P. Levai PRC 68, 034904 (2003)
V. Minissale, F. Scardina, V. Greco PRC 92, 054904 (2015)

Fireball

Central Collision 0-10% impact parameter b=2.5 fm

From Experiment

RHIC → LHC

dE_T/dy ~ 740 GeV → 2100 GeV

dN_{ch}/dy ≈ 670 → 1600

T_c ~ 160 MeV

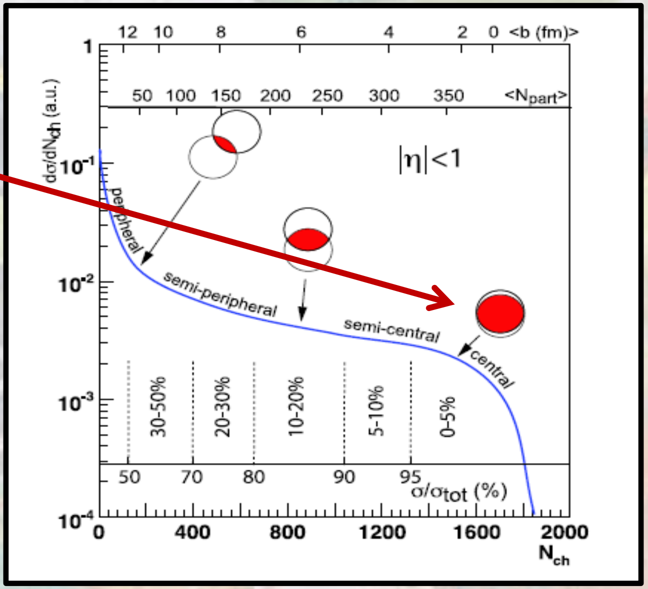
Lifetime and Volume implied

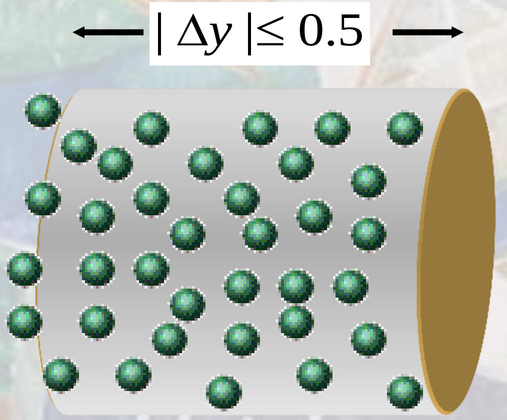
τ ~ 4.5 fm/c → 8 fm/c

β_0 = 0.37 → 0,63

V ~ 1100 fm^3 → 2500 fm^3

In agreement with HBT





Resonance decay

mesons

- π (*I* = 1, *J* = 0)

Resonances:

  - k^* (*I* = 1, *J* = 1/2) $\longrightarrow k\pi$
  - ρ (*I* = 1, *J* = 1) $\longrightarrow \pi\pi$
  - Δ (*I* = 3/2, *J* = 3/2) $\longrightarrow N\pi$

- $k^{\pm}$ (*I* = 0, *J* = 1/2)

Resonances:

  - k^* (*I* = 1, *J* = 1/2) $\longrightarrow k\pi$

Main hadronic channels including the ground states and the first excited states have been taken into account

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

- p (*I* = 1/2, *J* = 1/2)

Resonances:

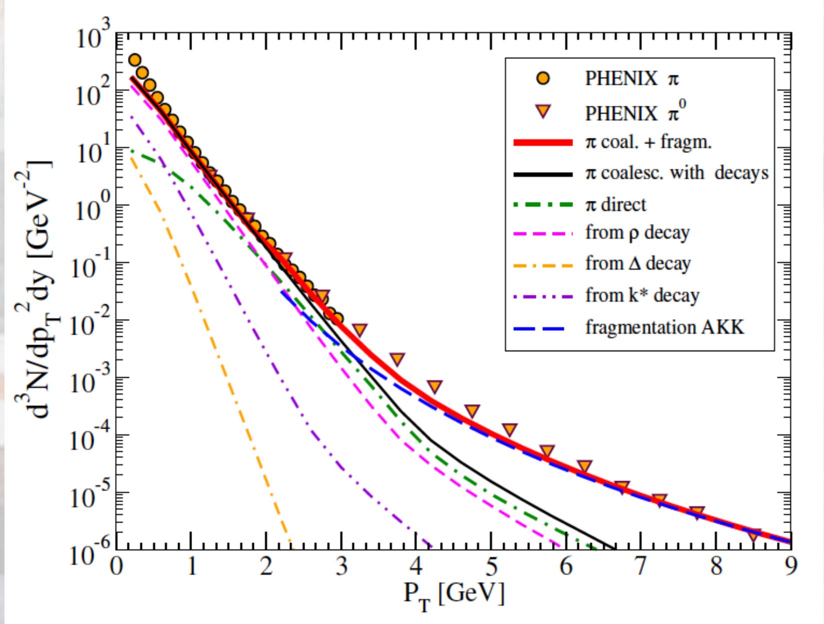
  - Δ (*I* = 3/2, *J* = 3/2) $\longrightarrow N\pi$

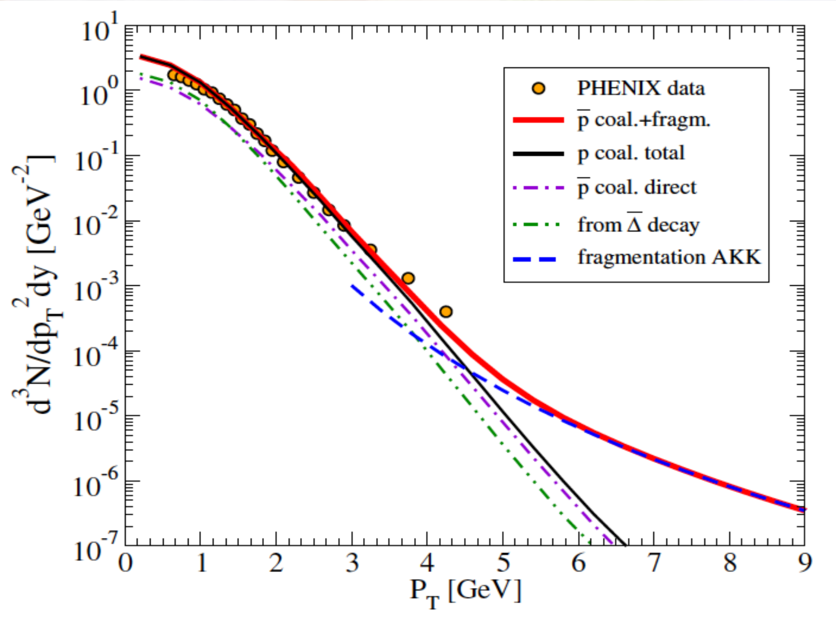
- Λ (1116) (*I* = 0, *J* = 1/2)

Resonances:

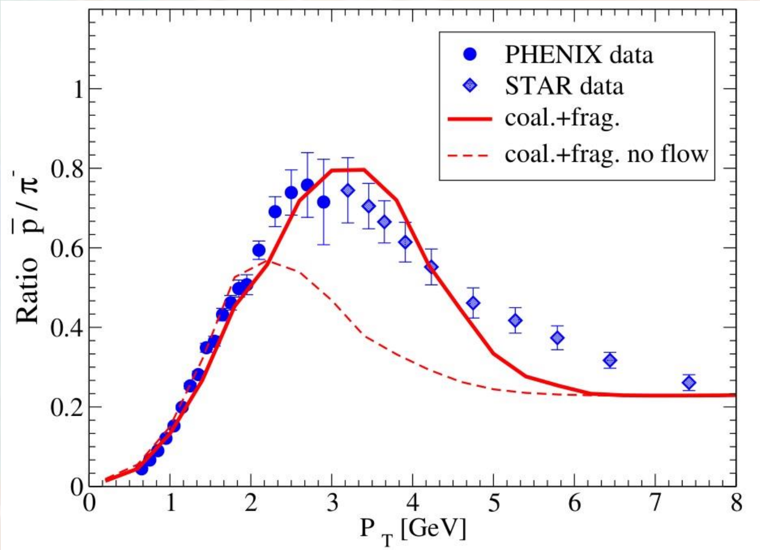
  - Σ^0(1193) (*I* = 1, *J* = 1/2) $\longrightarrow \Lambda\gamma$
  - Λ (1405) (*I* = 0, *J* = 1/2) $\longrightarrow \Sigma\pi$
  - Σ^0(1385) (*I* = 1, *J* = 3/2) $\longrightarrow \Lambda\pi$ *with B. R. = 88%*
    $\longrightarrow \Sigma\pi$ *with B. R. = 11,7%*

RHIC: spectra and baryon/meson





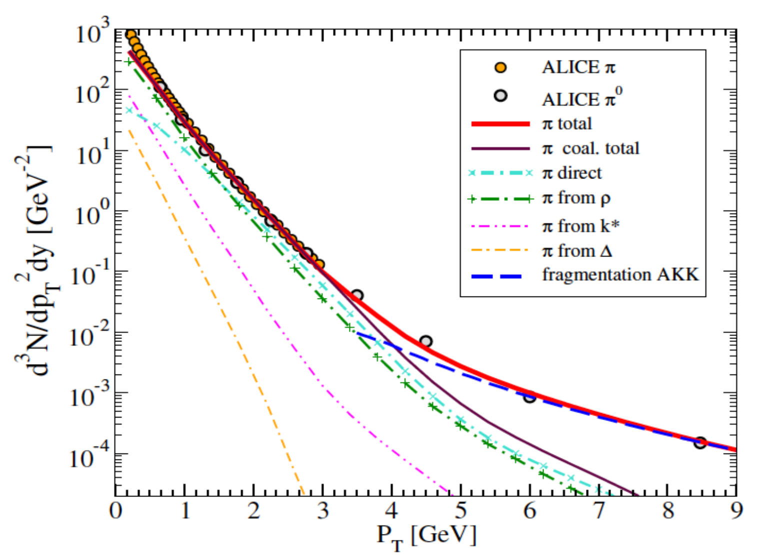
- Resonances improve the description at low p_T
- Height and p_T position of the peak well described
- Lack of fragmentation at $p_T \approx 5$ GeV (seen in pp with AKK)
- Without radial flow … (similar to pp collisions but not exactly)

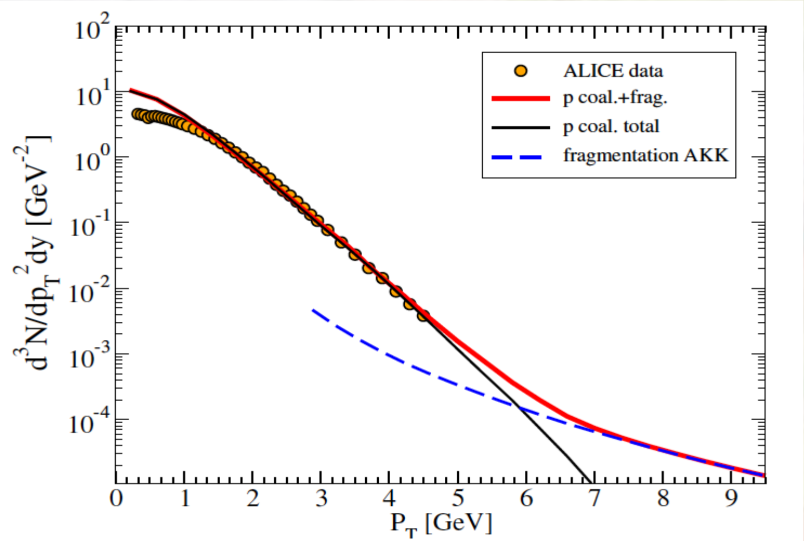


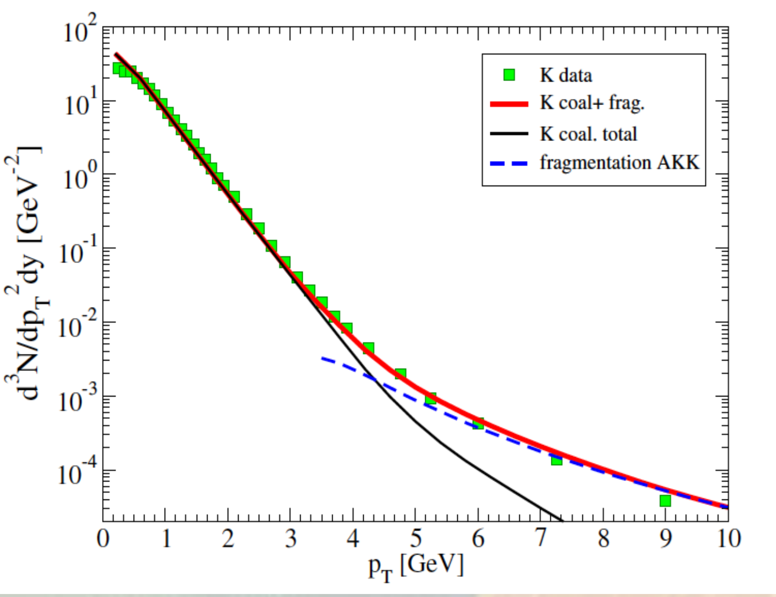
V. Minissale, F. Scardina, V. Greco PRC 92, 054904 (2015)

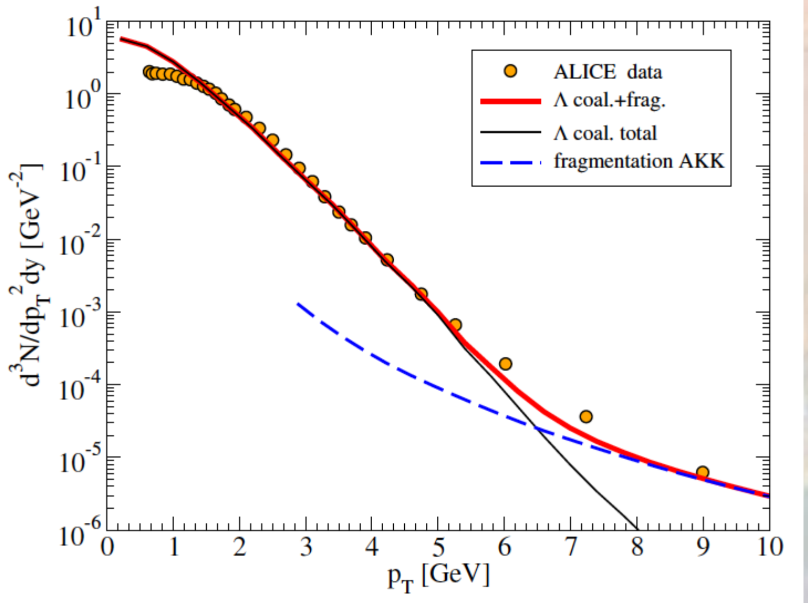
LHC: spectra π, p, k, Λ

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









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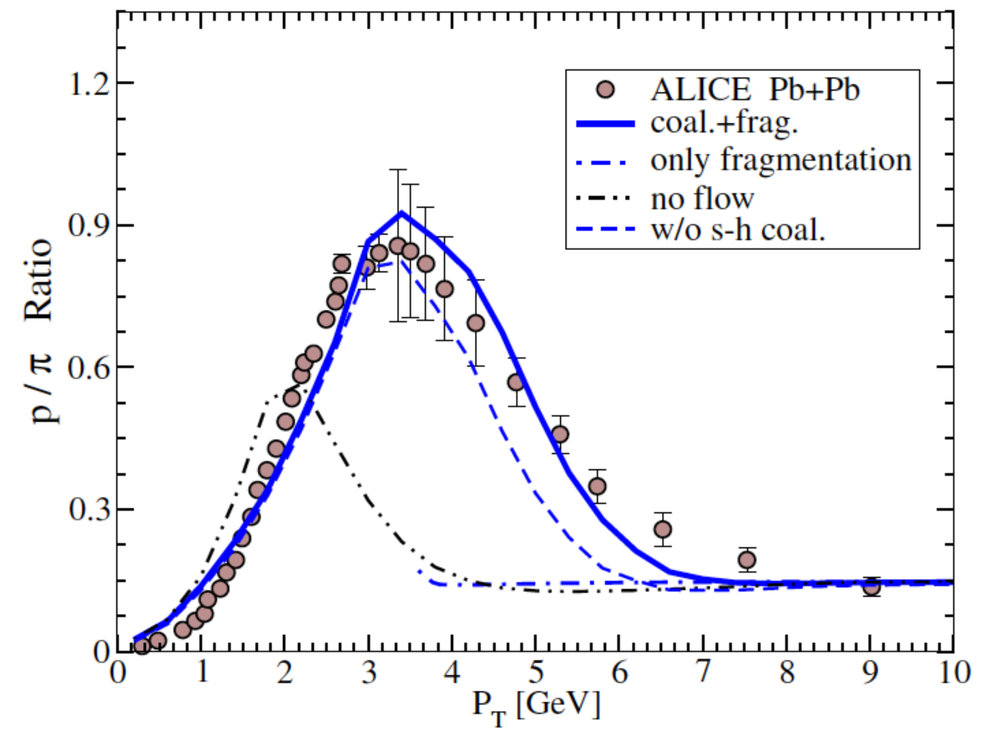
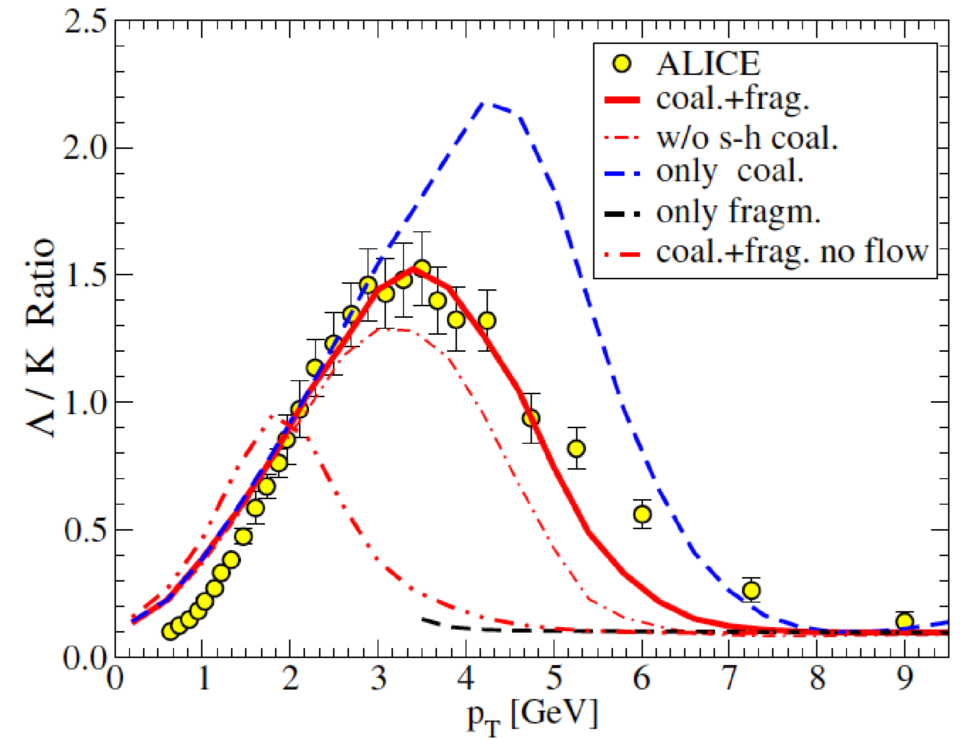




✓Height and p_T position of the peak well described.

✓Soft-minijet coalesc. contribution around and above the peak

✓Lack of fragmentation at $p_T \approx 6$ GeV (seen also in pp with AKK)

✓in-medium fragmentation as a quark recombination of shower partons taking into account also the gluon splitting into quark pairs that recombine

→ Rainer J. Fries, Kyongchol Han, and Che Ming Ko, Nucl. Phys.**A956**, 601 (2016).

Heavy flavour Hadronization: Fragmentation

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

The distribution function is evaluated at the Fixed-Order plus Next-to-Leading-Log (FONLL)

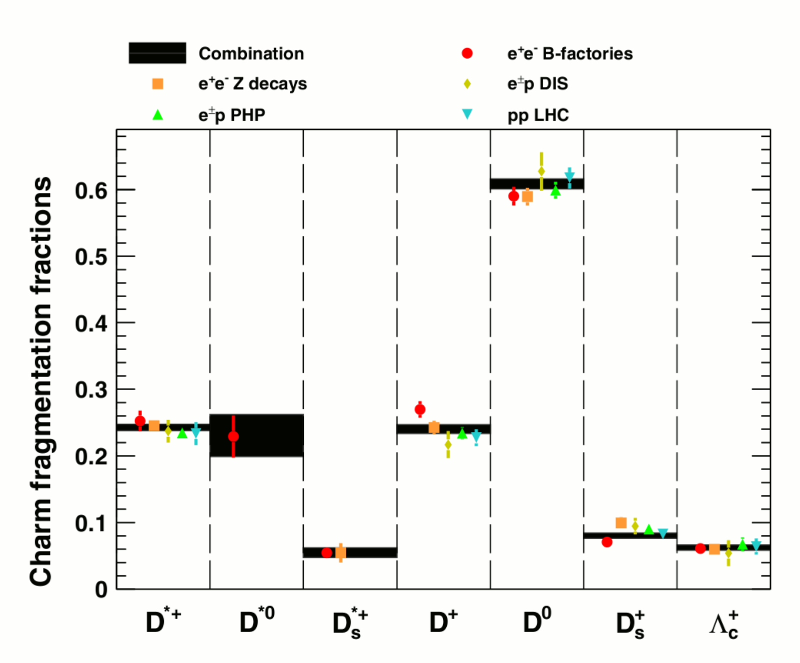
M. Cacciari, P. Nason, R. Vogt, PRL 95 (2005) 122001

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 D meson hadronization fixed by pp collisions data. For baryons we fix it in accordance with e^++e^- collisions as done in <u>*S.K. Das et al, PRD94 (2016) no.11, 114039.*</u> Measurement in *$e^\pm$ p, pp* and *e^+ e^-* are in agreement within uncertainties: fragmentation at most independent of the specific production process



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

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

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)

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 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

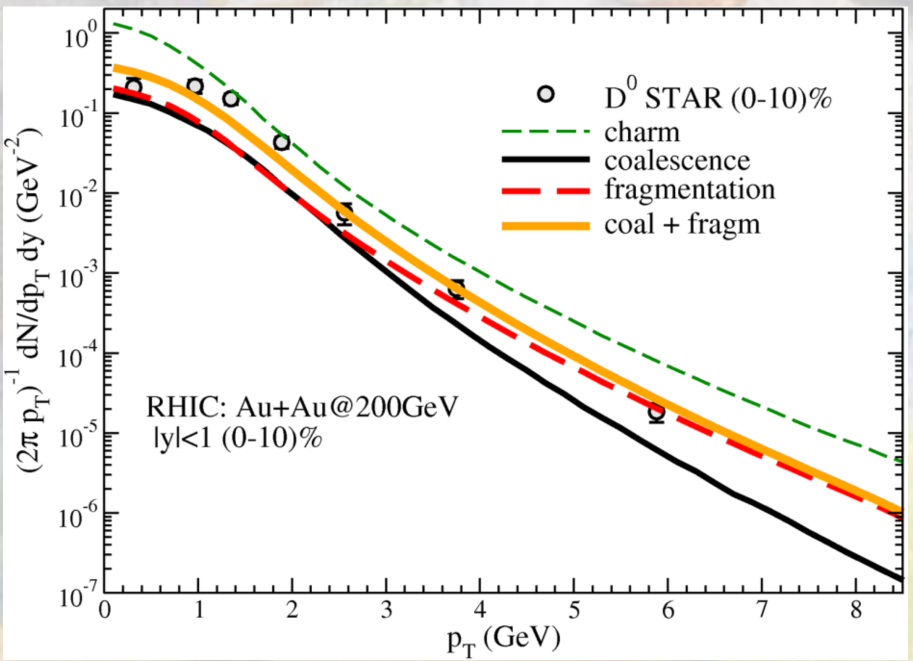
- **Λ_c^+** *(I=0, J=1/2)*

Resonances

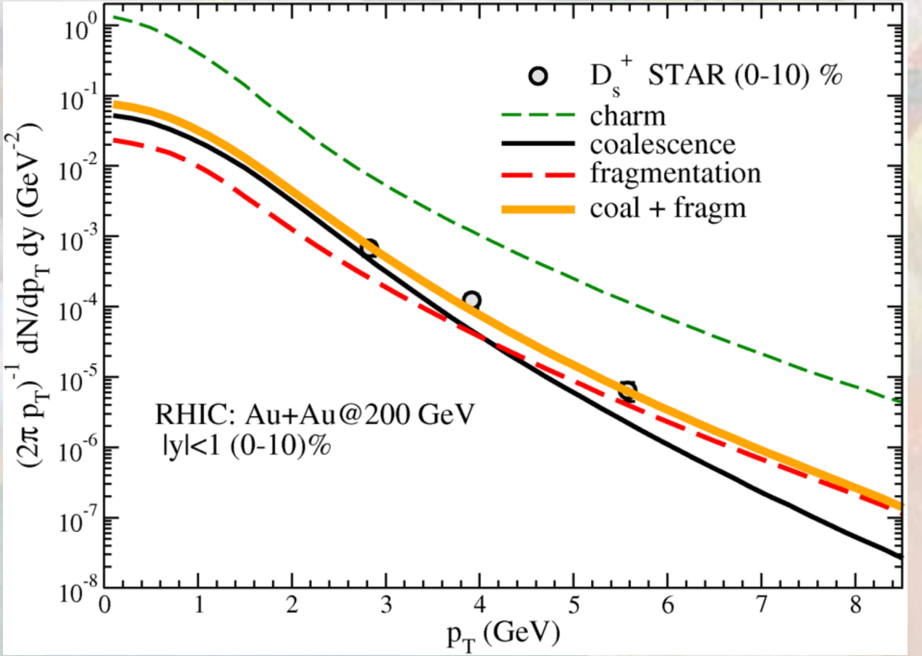
- **$\Lambda_c^+(2595)$** *(I=0,J=1/2)* $\longrightarrow$ **Λ_c^+** *B.R. 100%*
- **$\Lambda_c^+(2625)$** *(I=0,J=3/2)* $\longrightarrow$ **Λ_c^+** *B.R. 100%*
- **$\Sigma_c^+(2455)$** *(I=1,J=1/2)* $\longrightarrow$ **$\Lambda_c^+\pi$** *B.R. 100%*
- **$\Sigma_c^+(2520)$** *(I=1,J=3/2)* $\longrightarrow$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

RHIC: results

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



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



- 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

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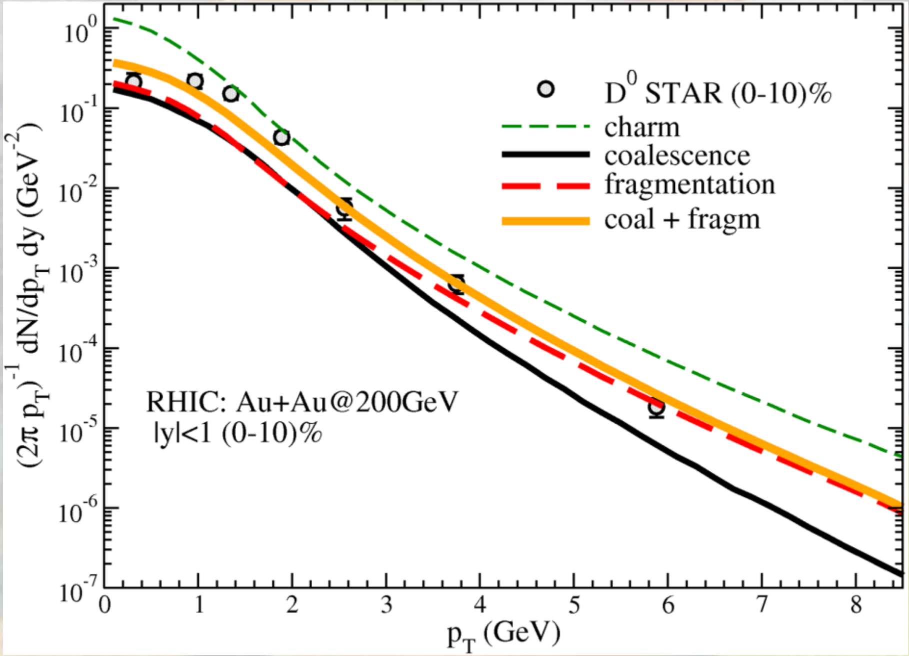
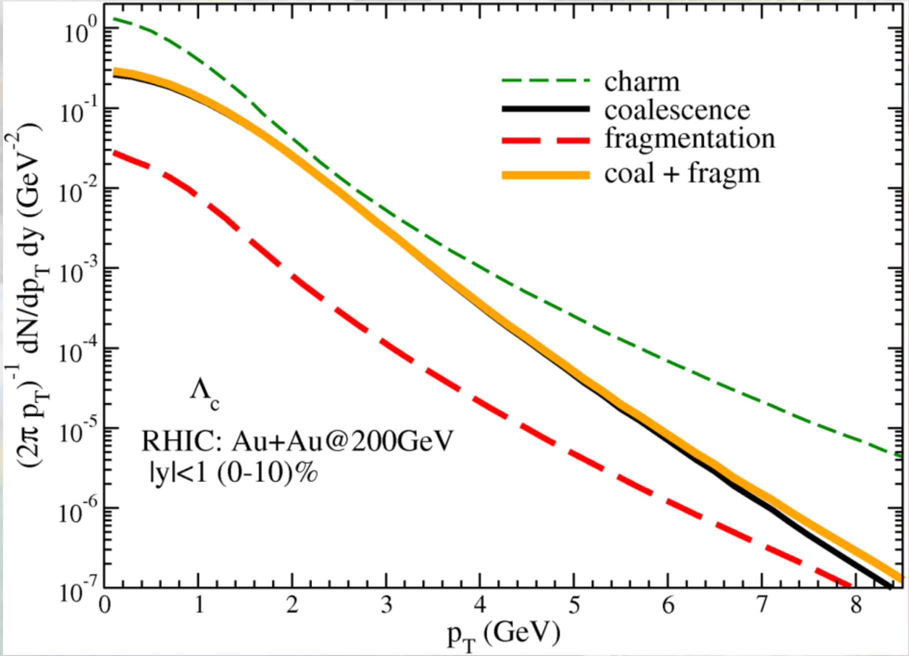
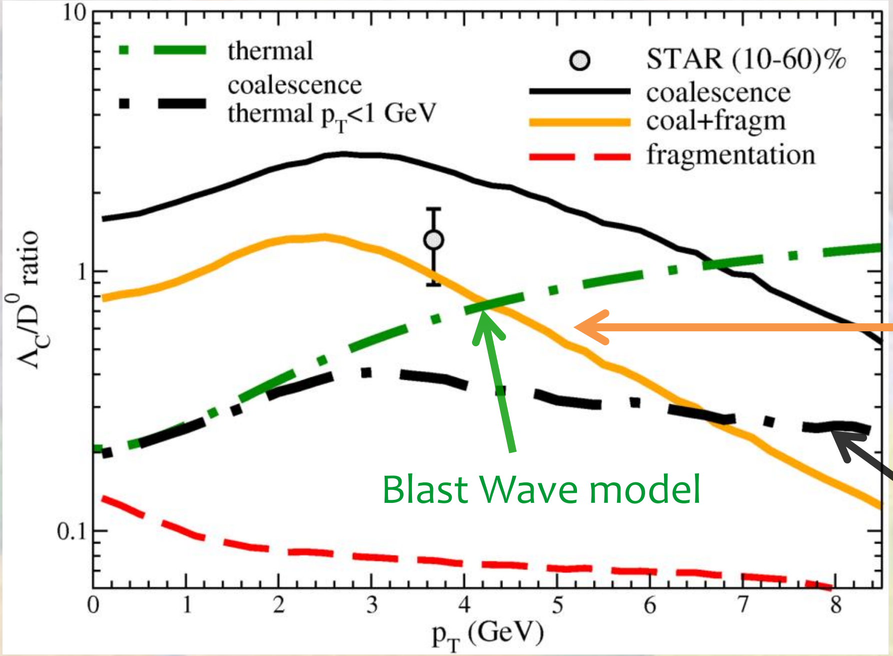




- For D^0 coalescence and fragmentation comparable at 2 GeV
- fragmentation fraction for D^+_s are small and less than about 8% of produced total heavy hadrons
- Λ_c^+ fragmentation is even more smaller, coalescence gives the dominant contribution

RHIC: Baryon/meson

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



- 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)

Coal with wave function width σ_p of D^0 and Λ_c changed to have Λ_c/D^0=thermal ratio at $p_T \longrightarrow 0$

Some more calculations on Λ_c/D can be found in:

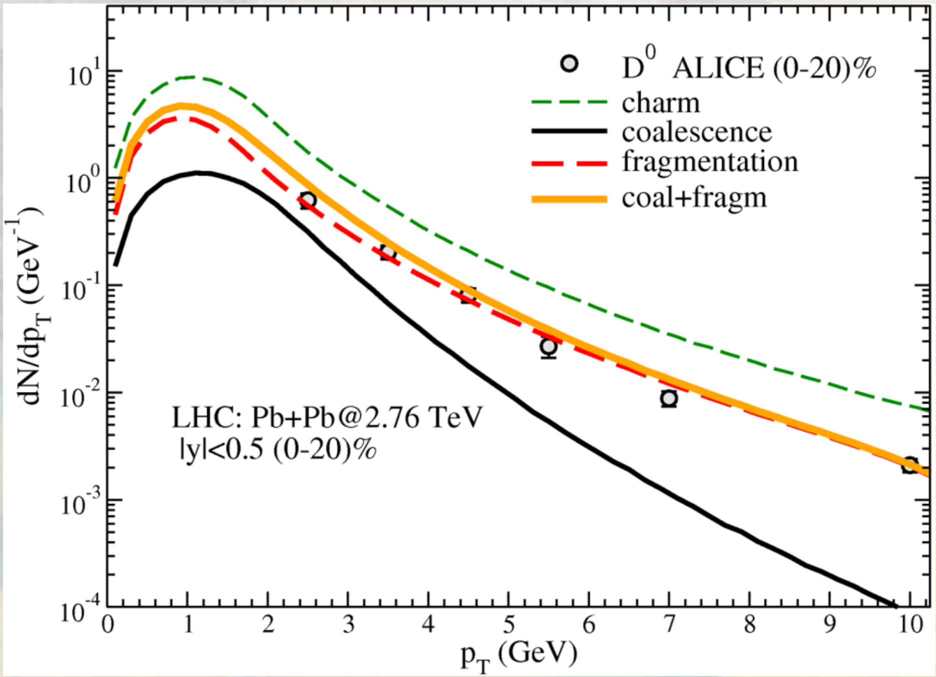
S. Ghosh, S. K. Das, V. Greco, S. Sarkar, J. Alam, PRD90 (2014) no.5, 054018.

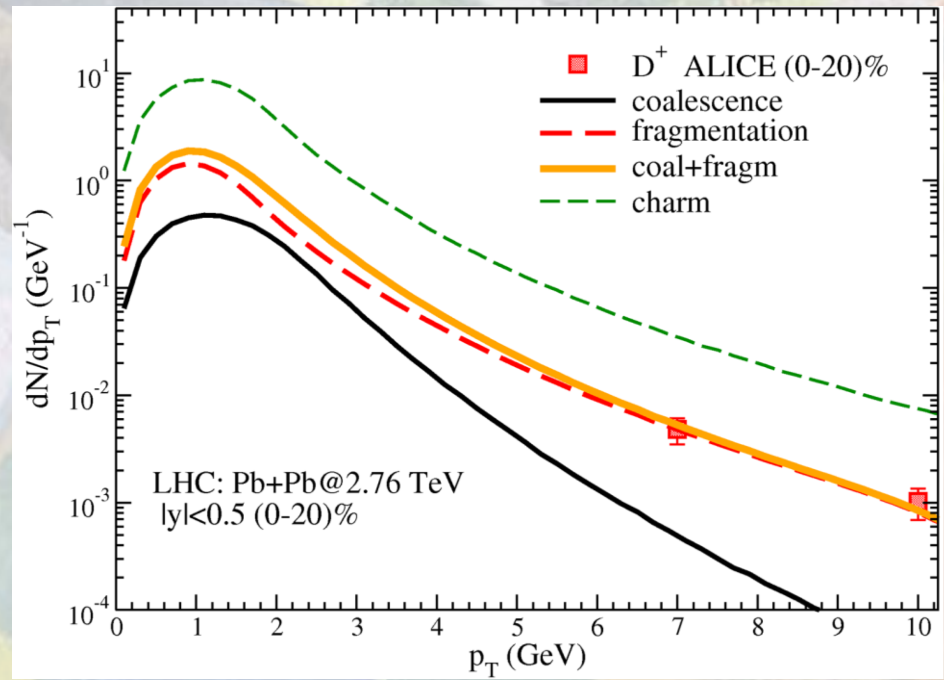
S. K. Das, J. M. Torres-Rincon, L. Tolos, V. Minissale, F. Scardina, V. Greco, PRD94 (2016) no.11,114039.

LHC: results

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

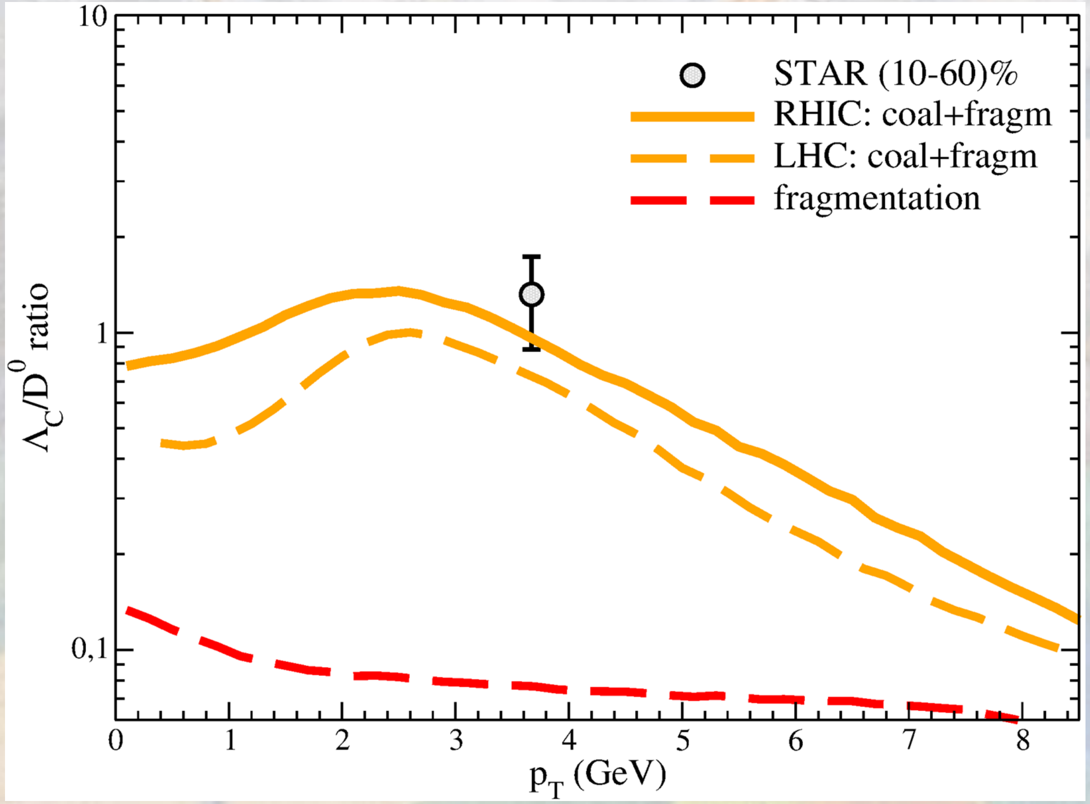
Data from ALICE Coll. JHEP 1209 (2012) 112





LHC: results

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



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

Conclusions

- **Good agreement with RHIC and LHC data:**
  - ***p, π, k, Λ spectra***
  - **baryon/meson ratio**

- **Heavy Quarks:**
  - **Good agreement with experimental data of D^0, D^+, D_s^+ 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**

- ***Extension to study Λ_b and B^0* spectra and their ratio**

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

With a partonic thermal distribution

$$f_{th} \approx Ae^{-p/T}$$

for a two-quark hadron with coalescence

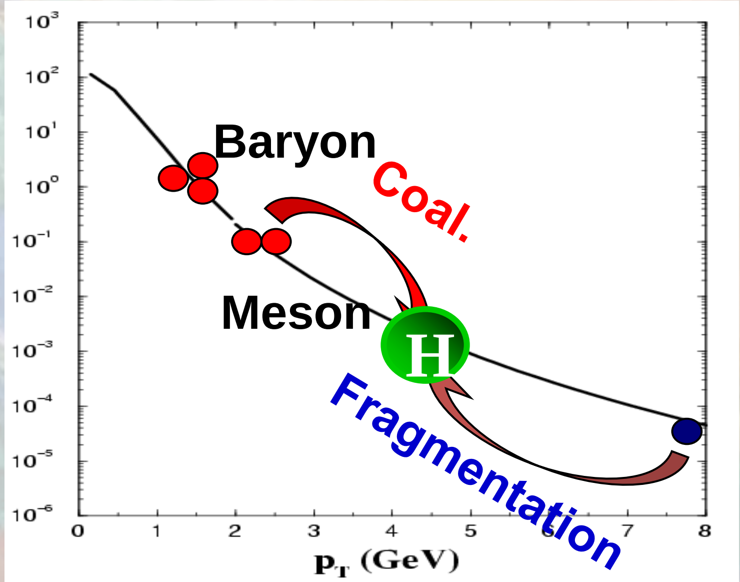
final Hadron momentum

$$e^{-p_1/T}e^{-p_2/T} \Rightarrow e^{-xP/T}e^{-(1-x)P/T} = e^{-P/T}$$

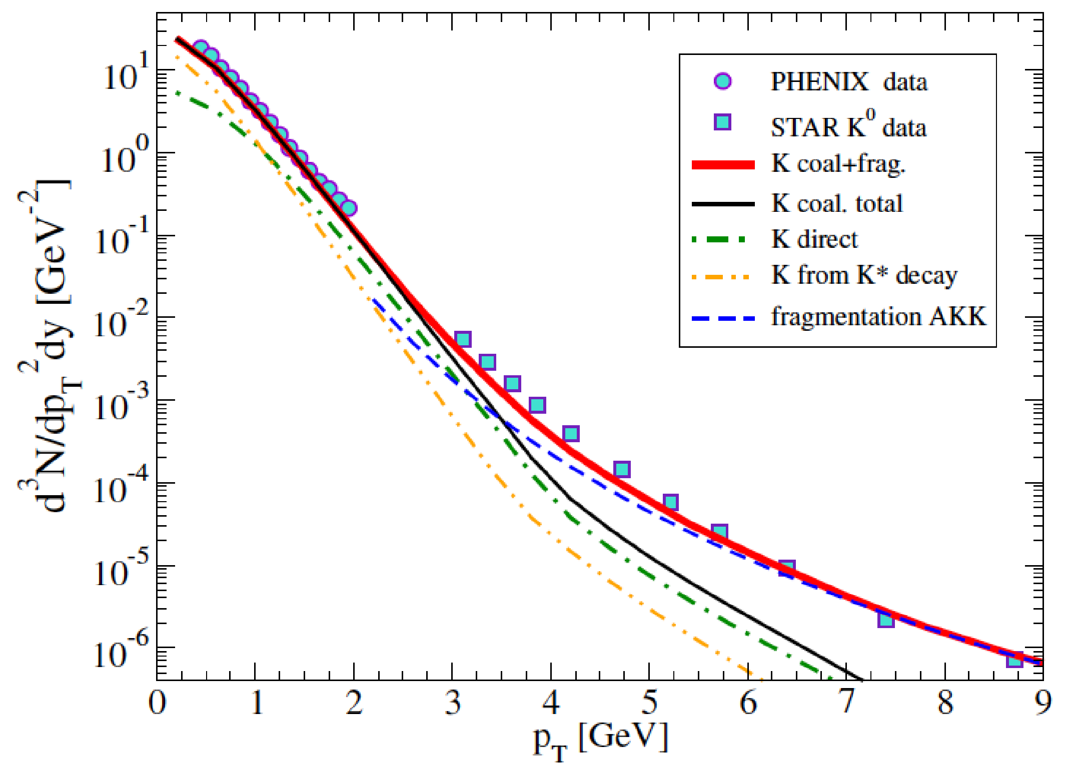
n-quark case

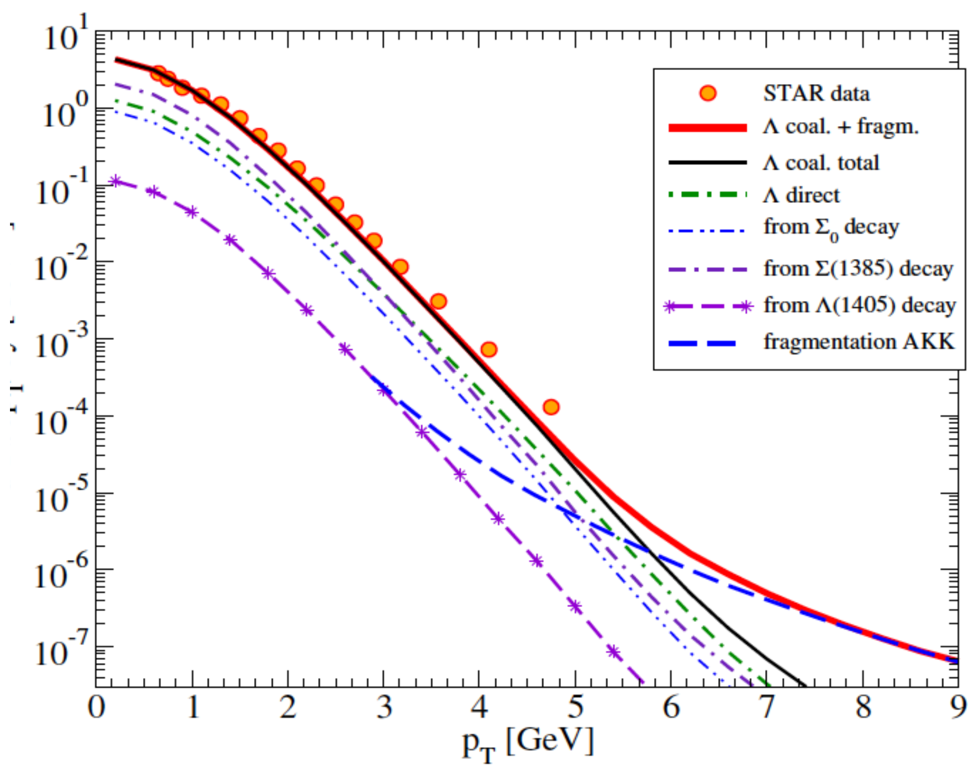
$$\prod_n e^{-p_n/T} \rightarrow e^{-n\frac{P}{n}\frac{1}{T}} \propto e^{-\frac{P}{T}}$$

Baryon/Meson Ratio = 1



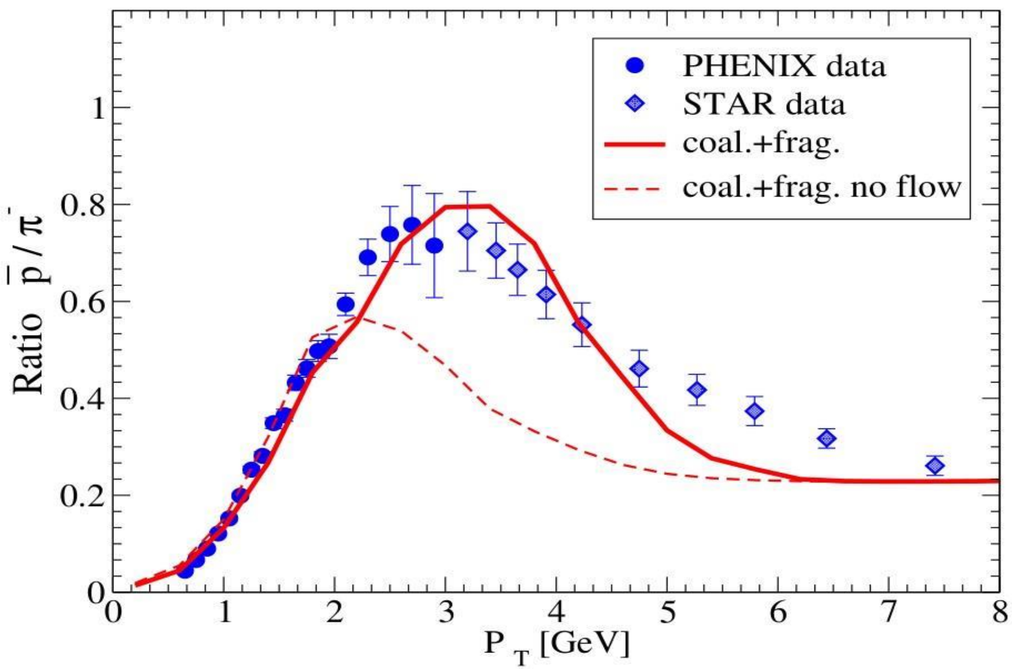
Kaon and Lambda at RHIC

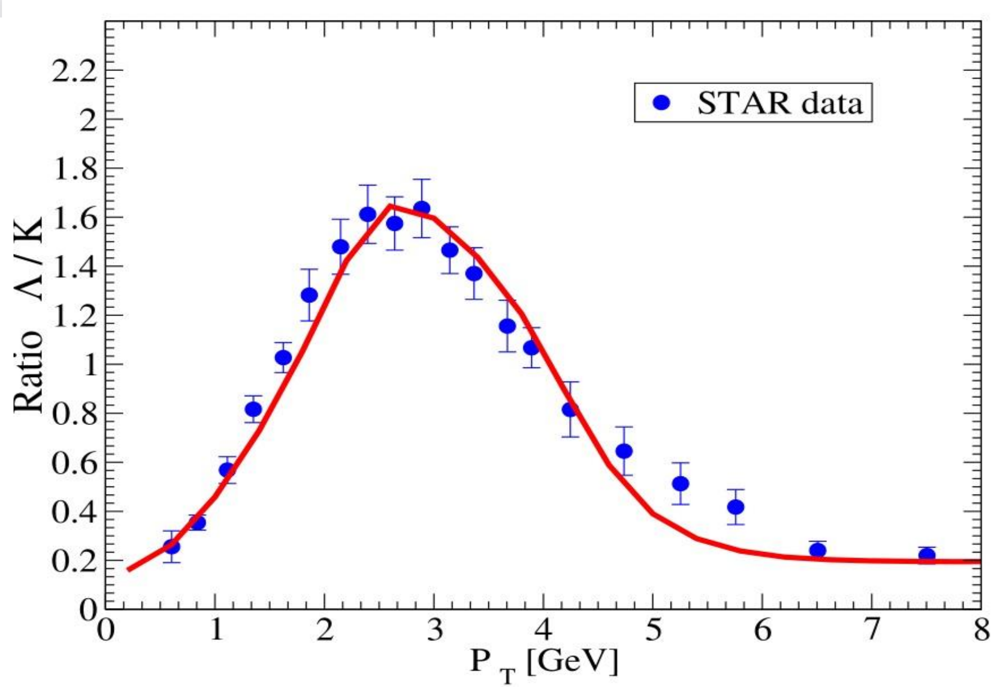




- *For Kaon* some lack of yield at $p_T \simeq 4GeV$ where the fragmentation is starting to be dominant
- For *Λ* there are several hadronic states that have a significant contribution

Baryon to meson ratio at RHIC





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

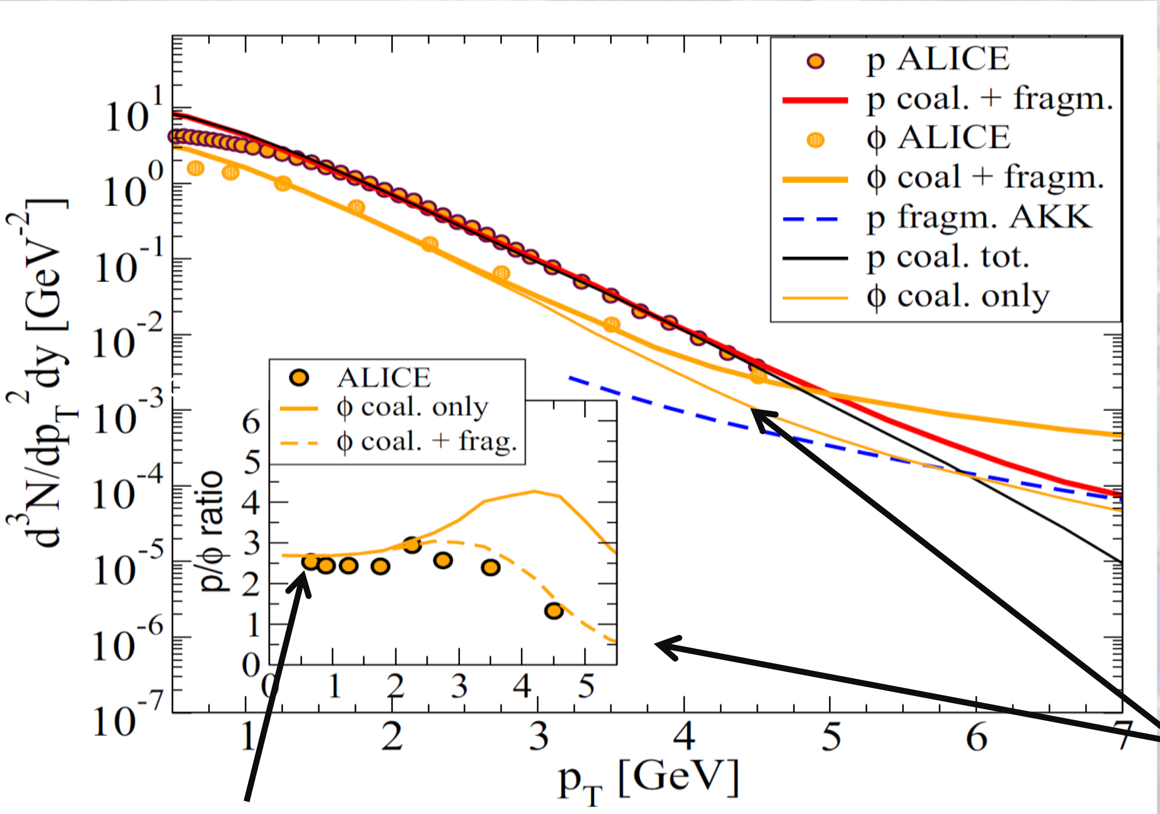
LHC: φ meson

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*

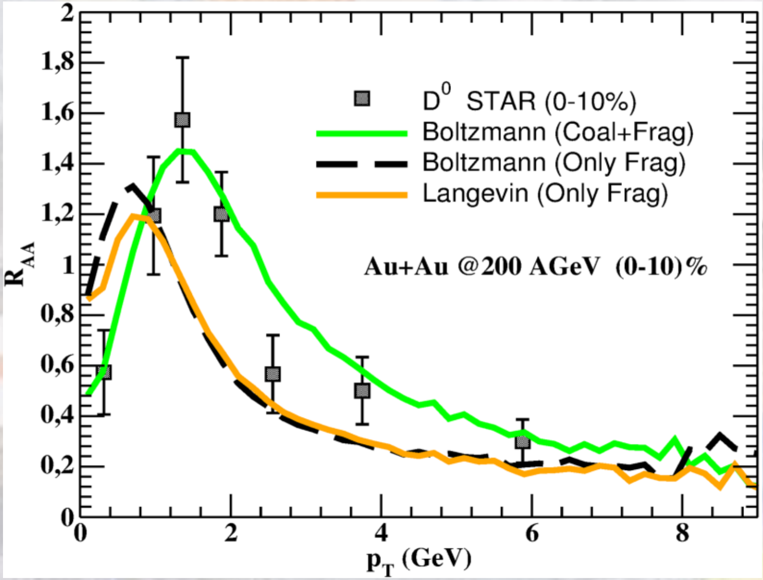


Missing fragmentation Contribution usually half of the yield at $p_T \approx 4$ GeV

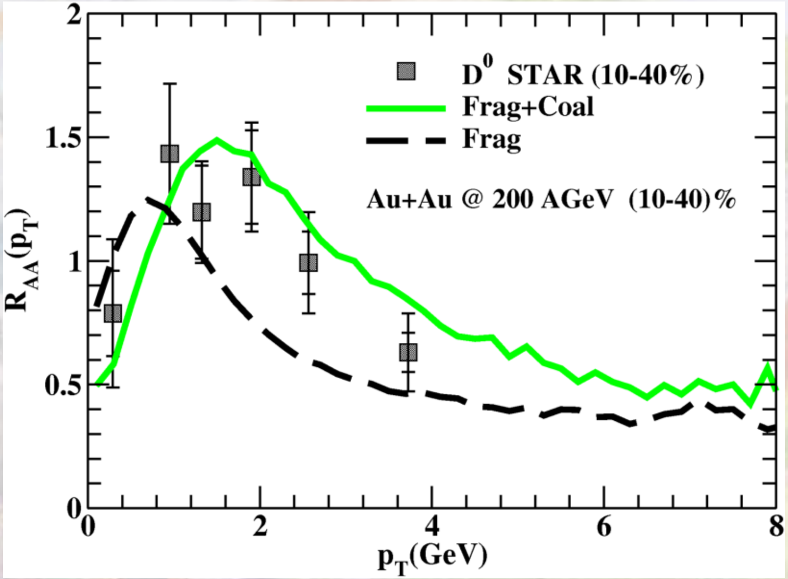
Soft part same slope φ and p

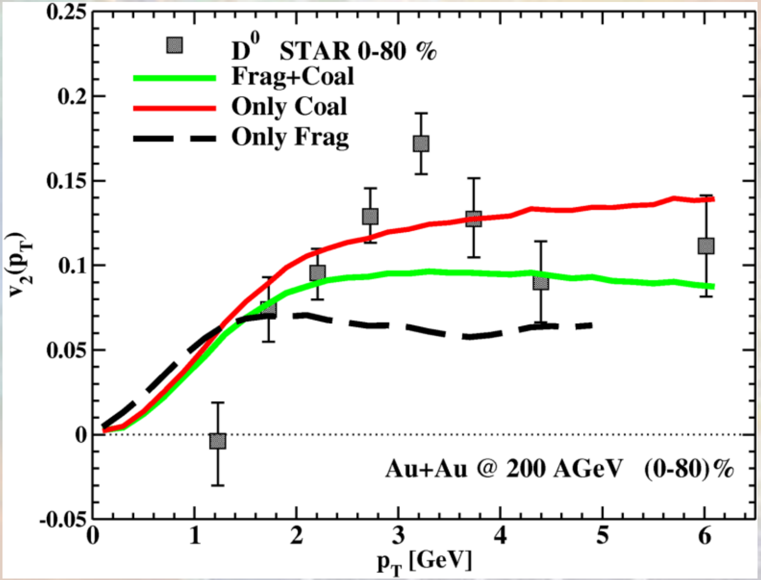
V. Minissale, F. Scardina, V. Greco PRC 92, 054904 (2015)

Data from STAR Coll. , PRL 113, 142301 (2014)



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.