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Hadronization by coalescence plus fragmentation from RHIC to LHC

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Francesco Scardina
arXiv:1502.06213

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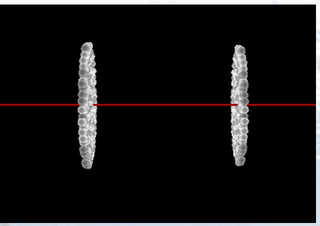
Outline

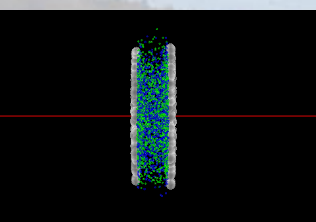
- Hadronization:
  - Coalescence
  - Fragmentation
- Coalescence model and Parameters
- Comparison with data
  - RHIC Au+Au $\sqrt{s} = 200\ GeV$
  - LHC Pb+Pb $\sqrt{s} = 2.76\ TeV$
- Elliptic Flow

Ultrarelativistic heavy-ion collisions

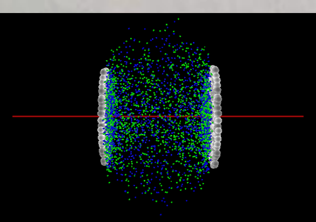
HIC sequence



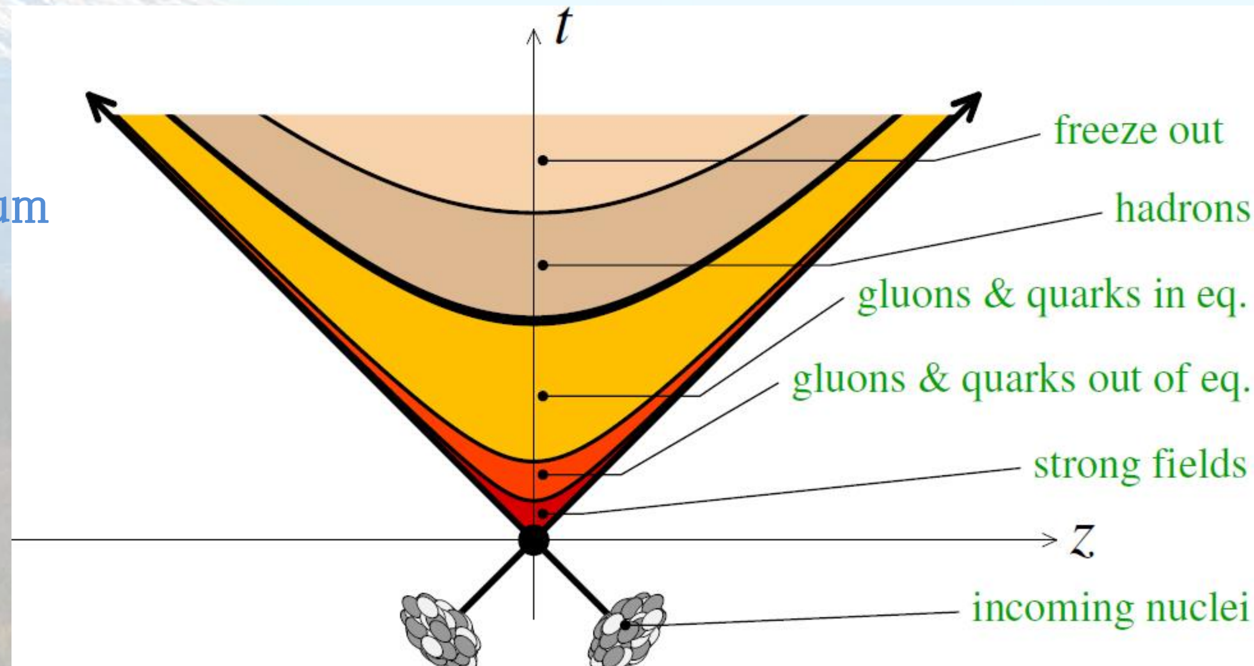
Initial Stage



Pre-equilibrium stage

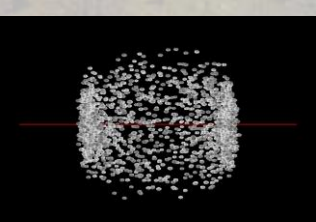


Expansion



QGP

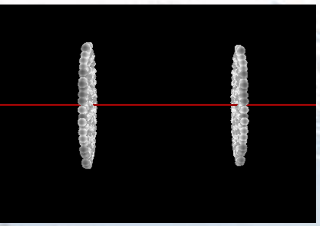
Hadronization



Chemical and kinetic freeze-out

Ultrarelativistic heavy-ion collisions

HIC sequence



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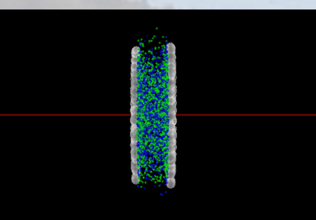

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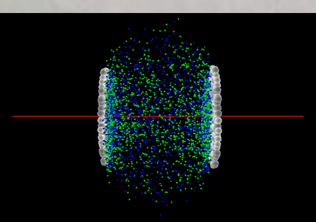

Expansion

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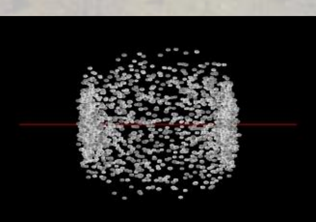
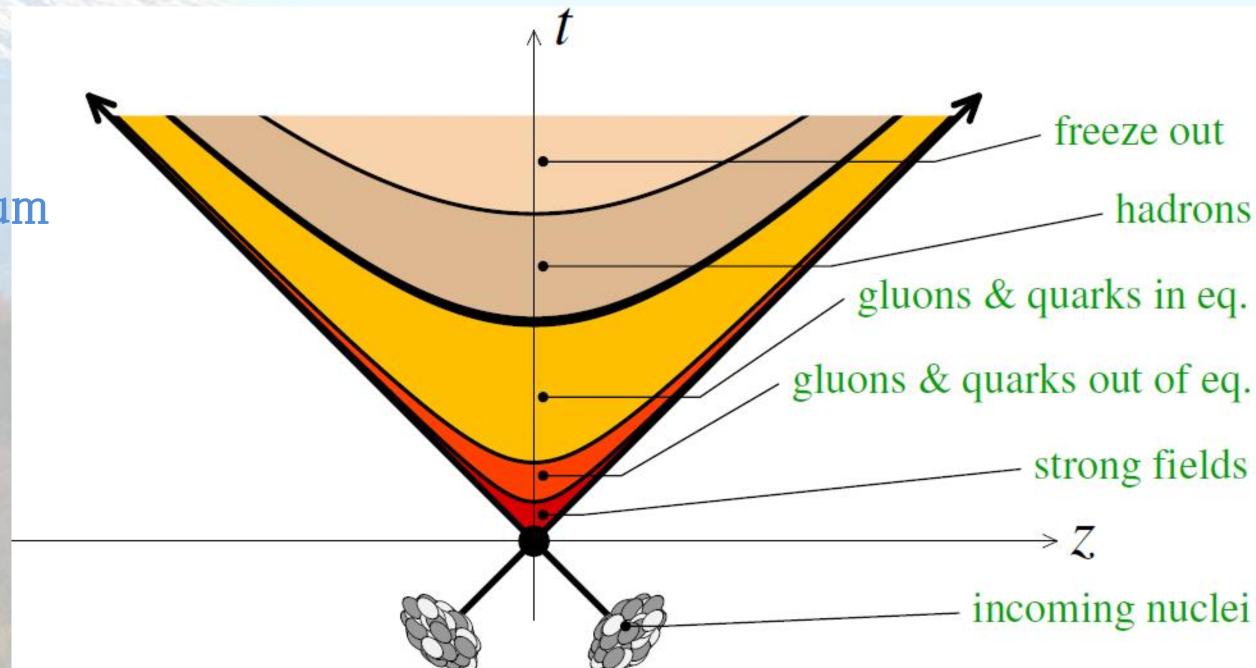


Hadronization

Chemical and kinetic freeze-out



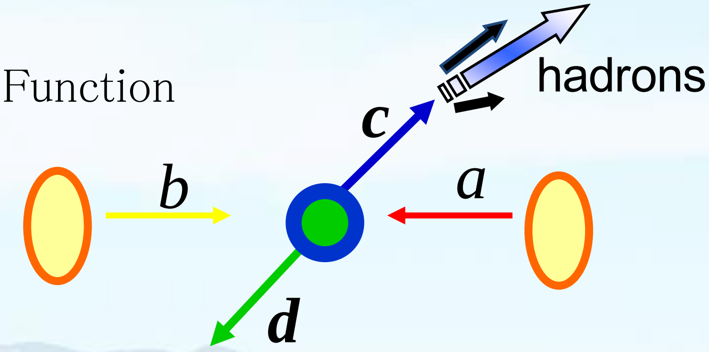
Hadronization

- Fragmentation

Fragmentation Function

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

$0 < z < 1$



S. Albino, B.A. Kniehl, G. Kramer, Nucl.Phys. B803 (2008)

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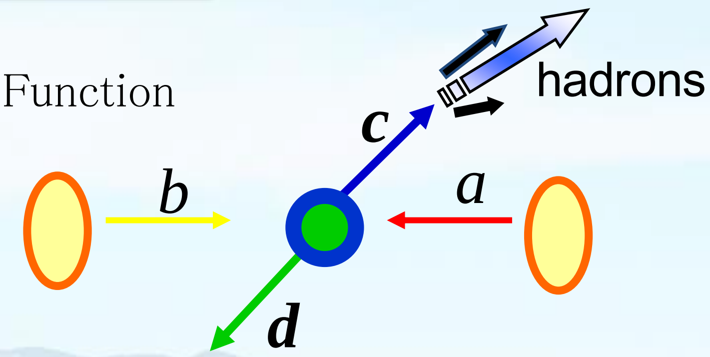

- Coalescence

R. Fries, B. Muller, C. Nonaka, and S. Bass, Phys.Rev.Lett. 90, 202303 (2003)
V. Greco, C. Ko, and P. Levai, Phys.Rev. C68, 034904 (2003)

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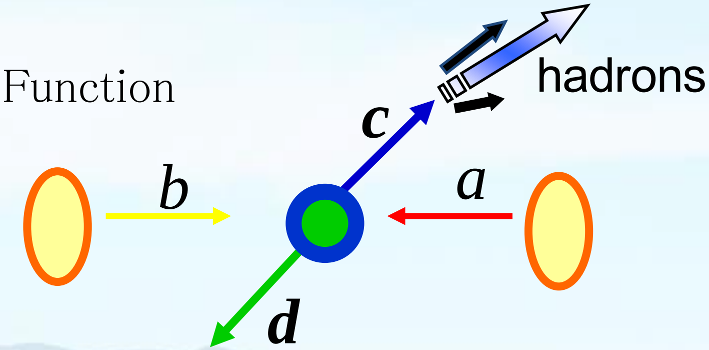

- Coalescence

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

Parton Distribution Function

Statistical factor colour-spin-isospin

Hadron Wigner Function

Hadronization

- Fragmentation

Fragmentation Function

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

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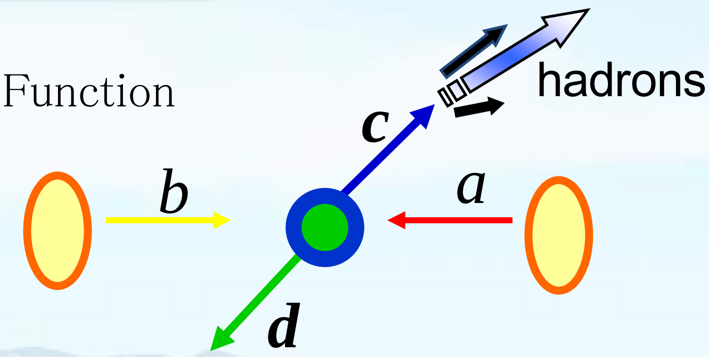

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Parton Distribution Function

Statistical factor colour–spin–isospin

Hadron Wigner Function

$$f_M = \frac{9\pi}{2} \Theta\left(\Delta_x^2 - (x_1 - x_2)^2\right) \Theta\left(\Delta_p^2 - (p_1 - p_2)^2 + (m_1 - m_2)^2\right)$$

$\Delta_x = 1/\Delta_p$ *free parameter*

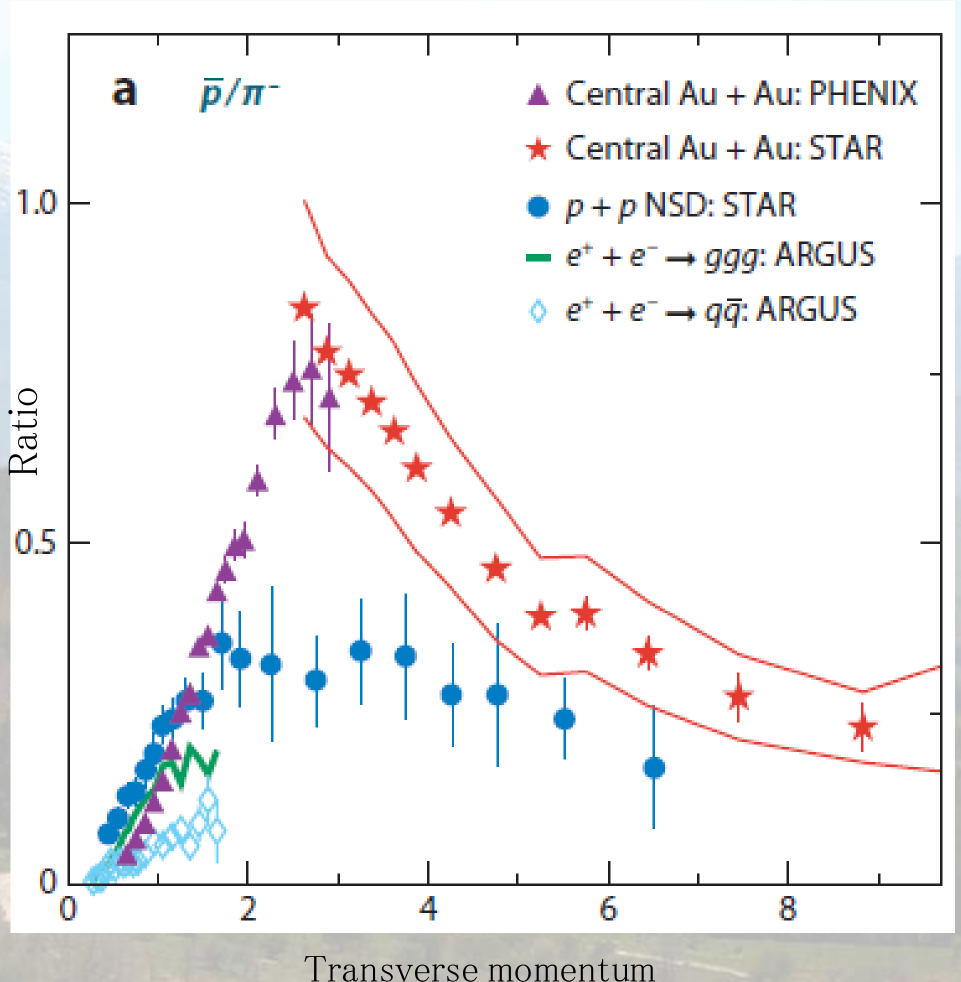
RHIC Observables

Proton to pion ratio Enhancement

In the vacuum, from fragmentation functions the ratio is

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

Elliptic Flow Splitting



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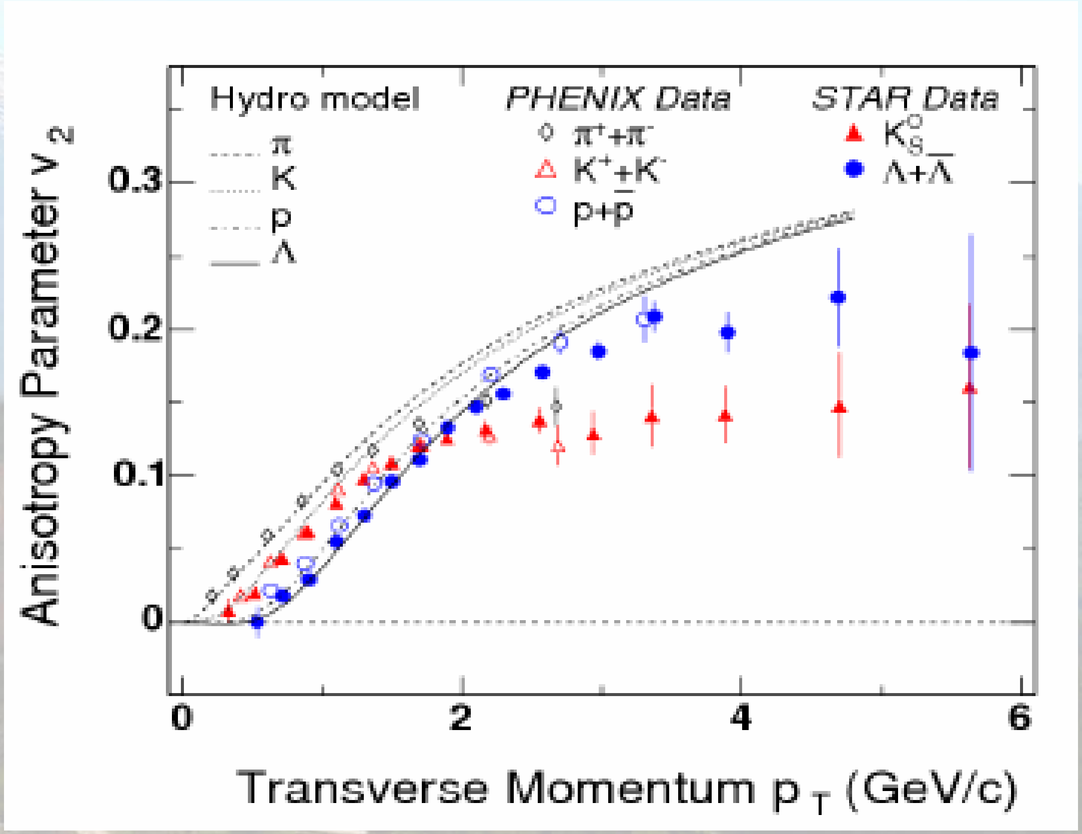

Coalescence code

- Consider i particles
- Give a probability $P(i)$ from the partonic distribution
- Compute the coalescence integral

$$\frac{dN_M}{d^2 p_T} = g_M \sum_{i,j} P_q(i) P_{\bar{q}}(j) \delta^{(2)}(p_T - p_{iT} - p_{jT}) f_M(x_i, x_j; p_i, p_j)$$

Fireball parameters

- Central collision (0–10%)
- Temperature $T = 160\ MeV$
- Collective flow $\beta_T = \beta_{max}\frac{r}{R}$ ← Fireball transverse radius

  β_{max} from radial expansion $R = R_0 + \beta_{max} ax\tau$
- Uniform in (x, y); $z = \tau \sinh y$
- $V = \pi {r_T}^2 \tau$
- Fireball radius+radial flow constraints $\frac{dN_{ch}}{dy}$; $\frac{dE_T}{dy}$

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

  β_{max} from radial expansion $R = R_0 + \beta_{max} a x \tau$
- Uniform in (x, y); $z = \tau \sinh y$
- $V = \pi {r_T}^2 \tau$
- Fireball radius+radial flow constraints $\frac{dN_{ch}}{dy}$; $\frac{dE_T}{dy}$

Typical QGP lifetime

RHIC $= 4.5\ fm/c$

LHC $= 7.8\ fm/c$

Fireball parameters

- Central collision (0–10%)
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β_{max} from radial expansion $R = R_0 + \beta_{max} ax\tau$

- Uniform in (x, y); $z = \tau \sinh y$
- $V = \pi {r_T}^2 \tau$ $\sim 1000\ fm^3\ RHIC \sim 2500\ fm^3\ LHC$
- Fireball radius+radial flow constraints $\frac{dN_{ch}}{dy}$; $\frac{dE_T}{dy}$

$R_T = 8.7\ fm\ \ at\ RHIC$ $\beta_{max} = 0.37\ at\ RHIC$

$R_T = 10.2\ fm\ \ at\ LHC$ $\beta_{max} = 0.63\ at\ LHC$

Typical QGP lifetime
RHIC $= 4.5\ fm/c$
LHC $= 7.8\ fm/c$

Parton Distibution

- Thermal Distribution $(< 2\ GeV)$

$$\frac{dN_{q,\bar{q}}}{d^2 r_T d^2 p_T} = \frac{g_{q,\bar{q}} \tau m_T}{(2\pi)^3} \exp\left(- \frac{\gamma_T (m_T - p_T \cdot \beta_T \mp \mu_q)}{T} \right)$$

- Minijet Distribution $(> 2\ GeV)$

$$\frac{dN_{jet}}{d^2 p_T} = A \left(\frac{B}{B + p_T} \right)^n$$

RHIC

$$\frac{dN_{jet}}{d^2 p_T} = \frac{A_1}{\left[1 + \left(\frac{p_T}{A_2} \right)^2 \right]^{A_3}} + \frac{A_4}{\left[1 + \left(\frac{p_T}{A_5} \right)^2 \right]^{A_6}}$$

LHC

Resonance Decay

- $\pi\ (I = 1, J = 0)$
  - $k^*(I = 1, J = 1/2) \rightarrow k\pi$
  - $\rho(I = 1, J = 1) \rightarrow \pi\pi$
  - $\Delta(I = 3/2, J = 3/2) \rightarrow N\pi$

- p $(I = 1/2, J = 1/2)$
  - $\Delta(I = 3/2, J = 3/2) \rightarrow N\pi$

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

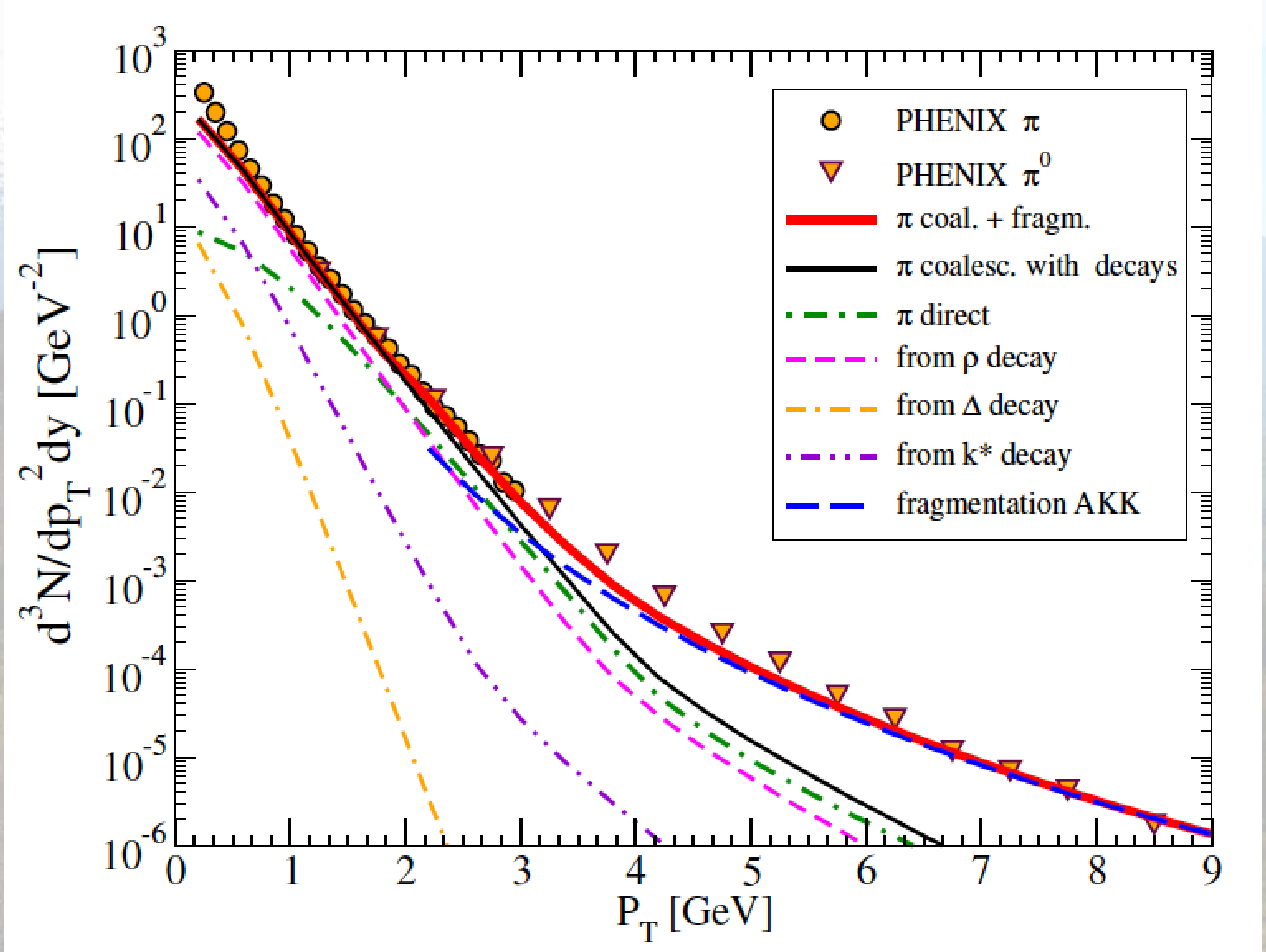
- $\Lambda(1116)\ (I = 0, J = 1/2)$
  - $\Sigma^0\ (1193)\ (I = 1, J = 1/2) \rightarrow \Lambda\gamma$
  - $\Lambda(1405)\ (I = 0, J = 1/2) \rightarrow \Sigma\pi$
  - $\Sigma^0\ (1385)\ (I = 1, J = 3/2) \rightarrow \Lambda\pi \quad with\ B.R. = 88\%$
    $\rightarrow \Sigma\pi \quad with\ B.R. = 11{,}7\%$

Suppression factor

$$\left(\frac{m_{H^*}}{m_H}\right)^{3/2} e^{-\frac{E_{H^*} - E_H}{T}}$$

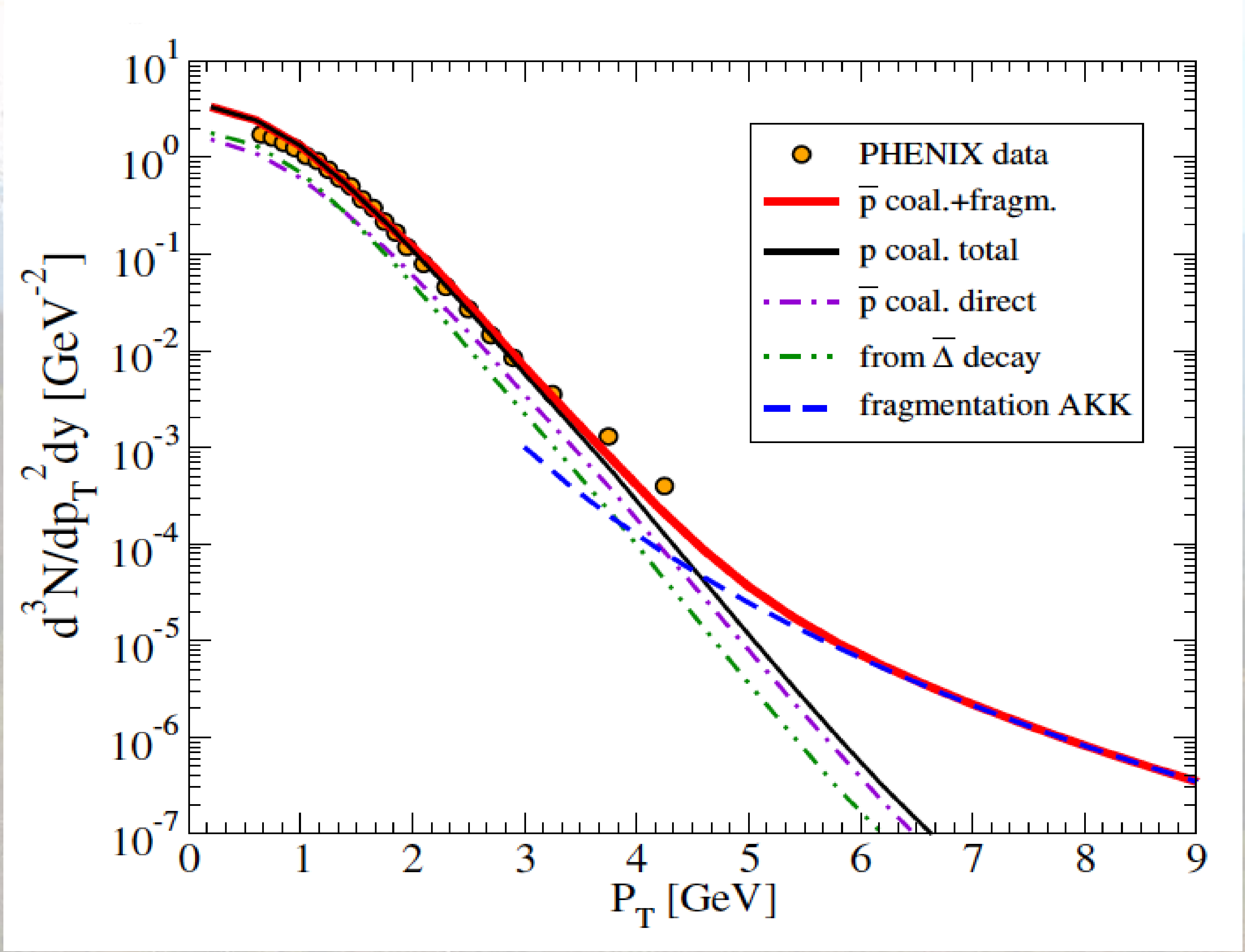
Results RHIC

RHIC – Pion

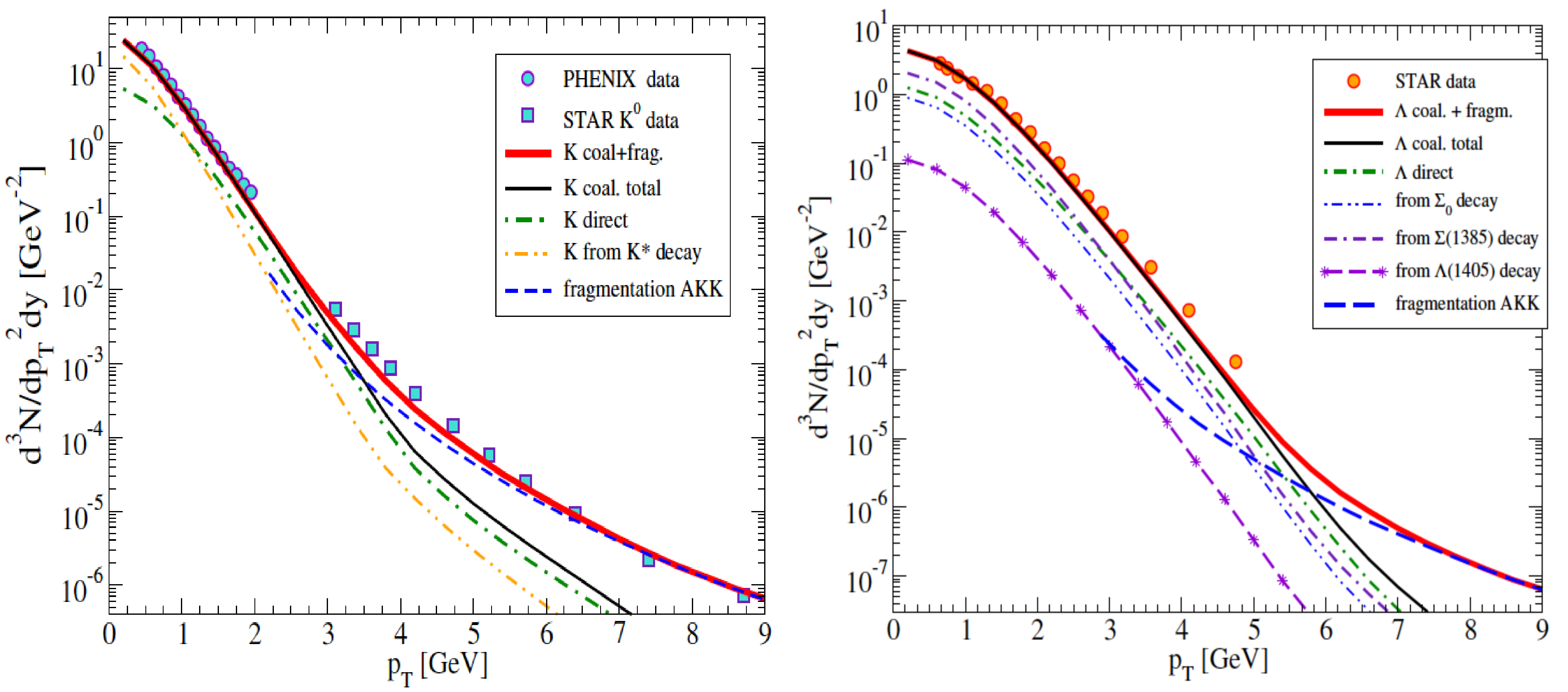


PHENIX π
PHENIX π⁰
π coal. + fragm.
π coalesc. with decays
π direct
from ρ decay
from Δ decay
from k* decay
fragmentation AKK
d³N/dp_T²dy [GeV⁻²]
P_T [GeV]

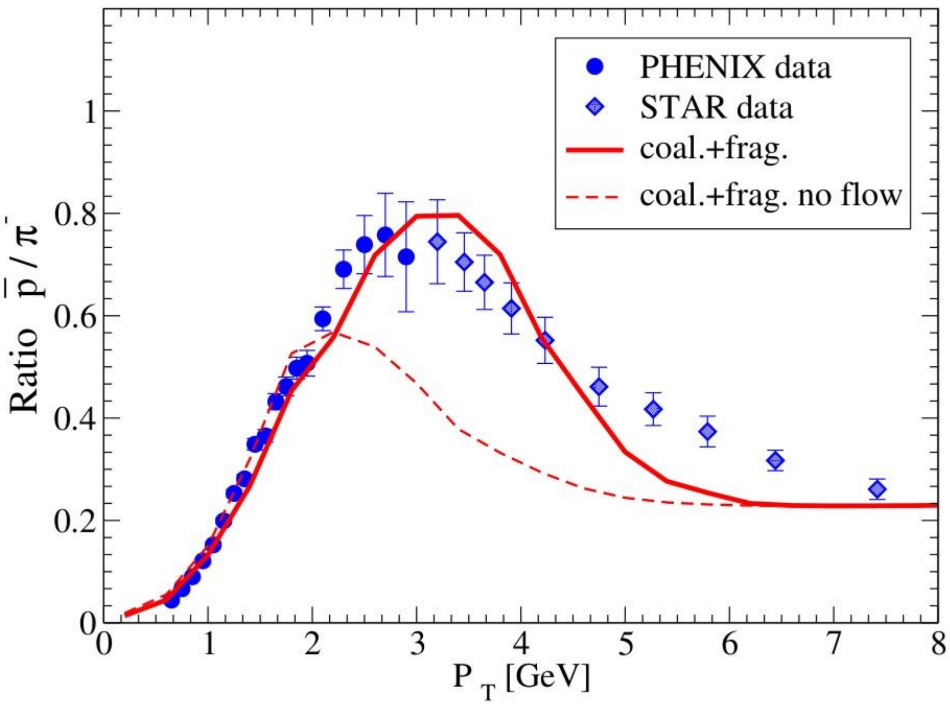
RHIC – Antiproton



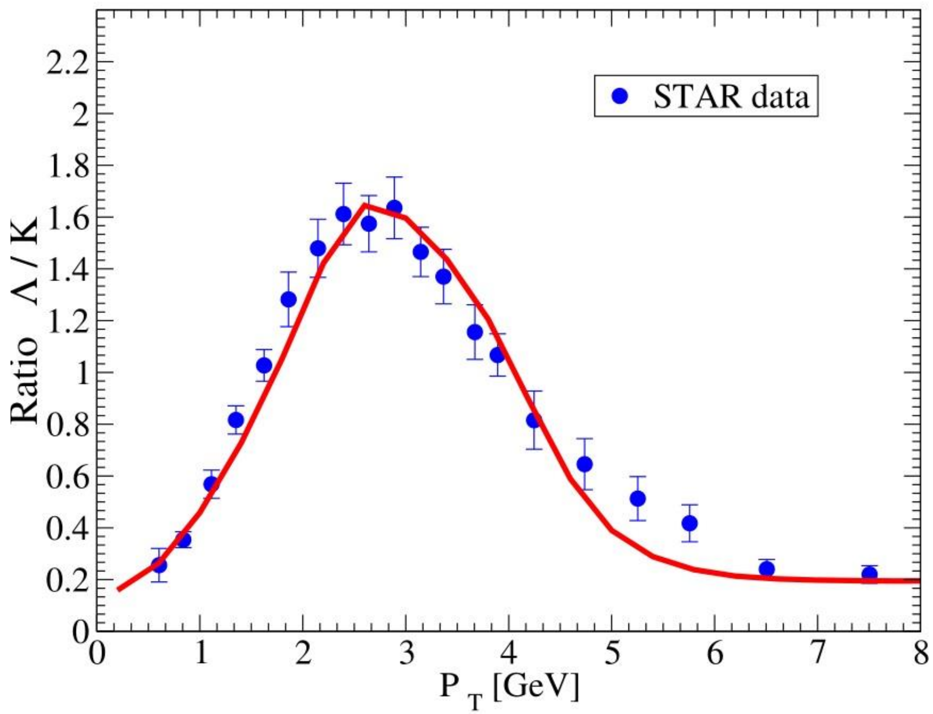
RHIC - Kaon & Lambda



RHIC - Ratios



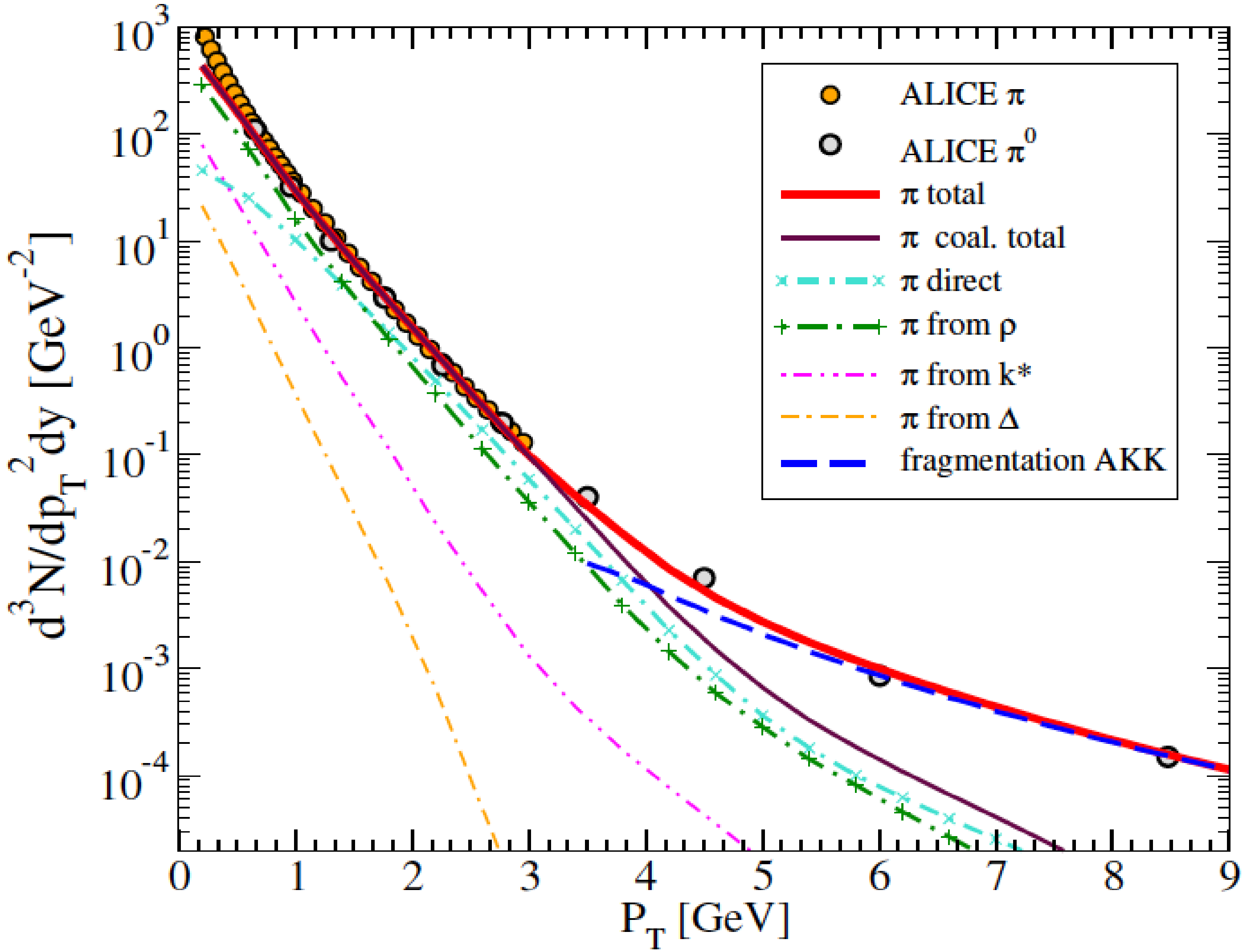
PHENIX data
STAR data
coal.+frag.
coal.+frag. no flow
Ratio $\bar{p} / \pi^-$
P T [GeV]



STAR data
Ratio Λ / K
P T [GeV]

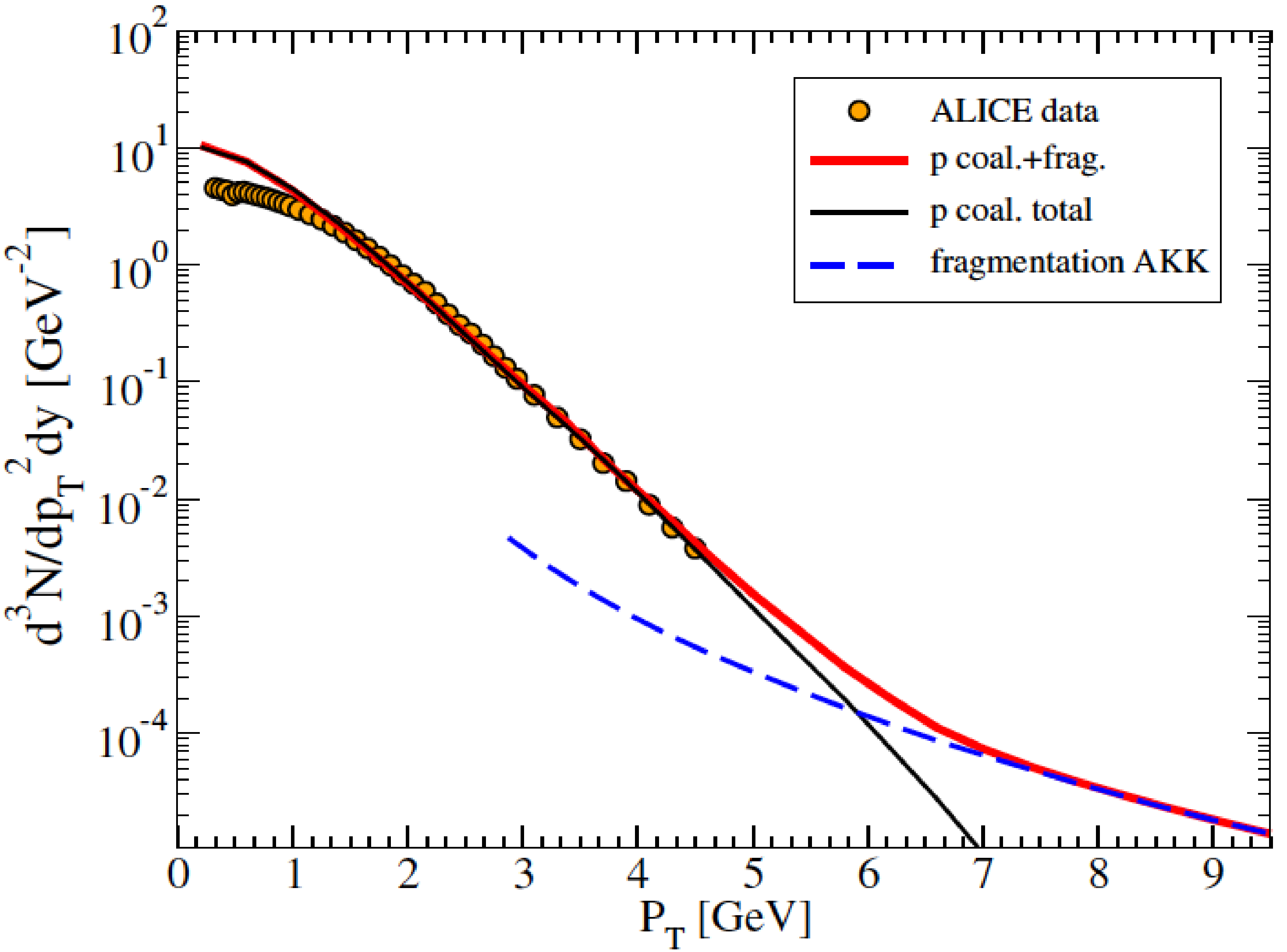

Results LHC

LHC – Pion



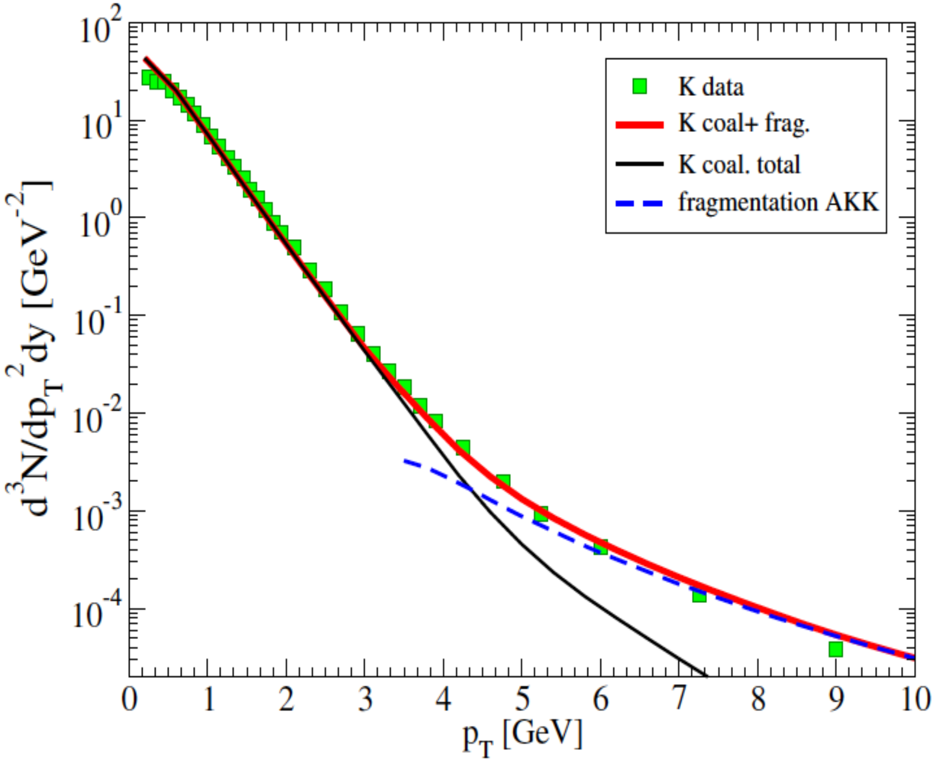
ALICE π
ALICE π⁰
π total
π coal. total
π direct
π from ρ
π from k*
π from Δ
fragmentation AKK
d³N/dp_T²dy [GeV⁻²]
P_T [GeV]
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
0
1
2
3
4
5
6
7
8
9

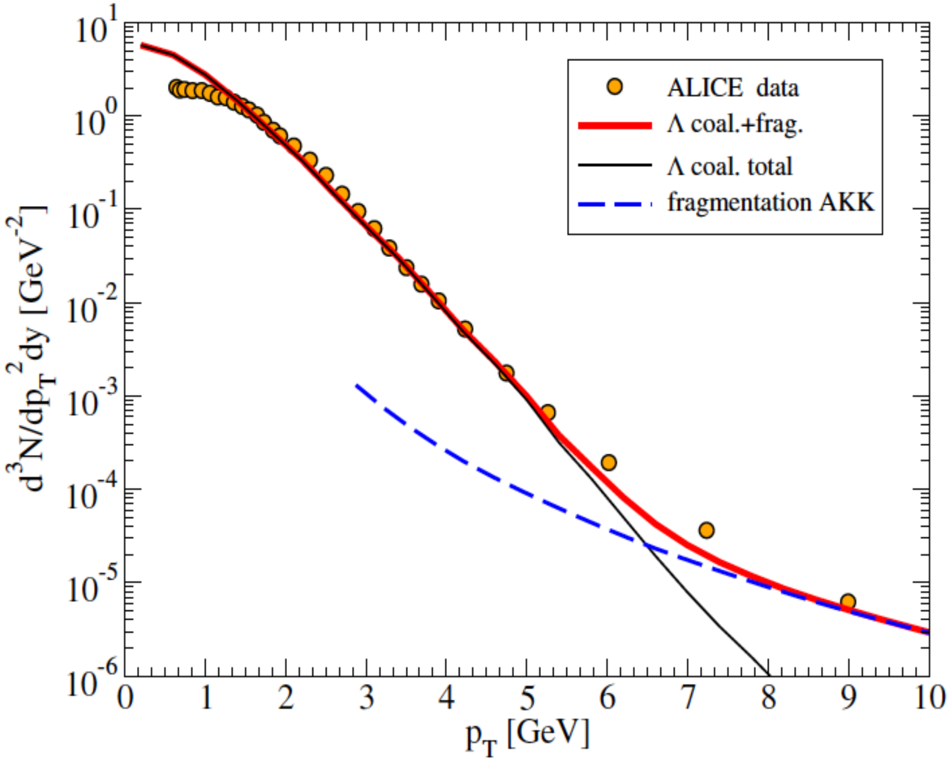
LHC – Proton



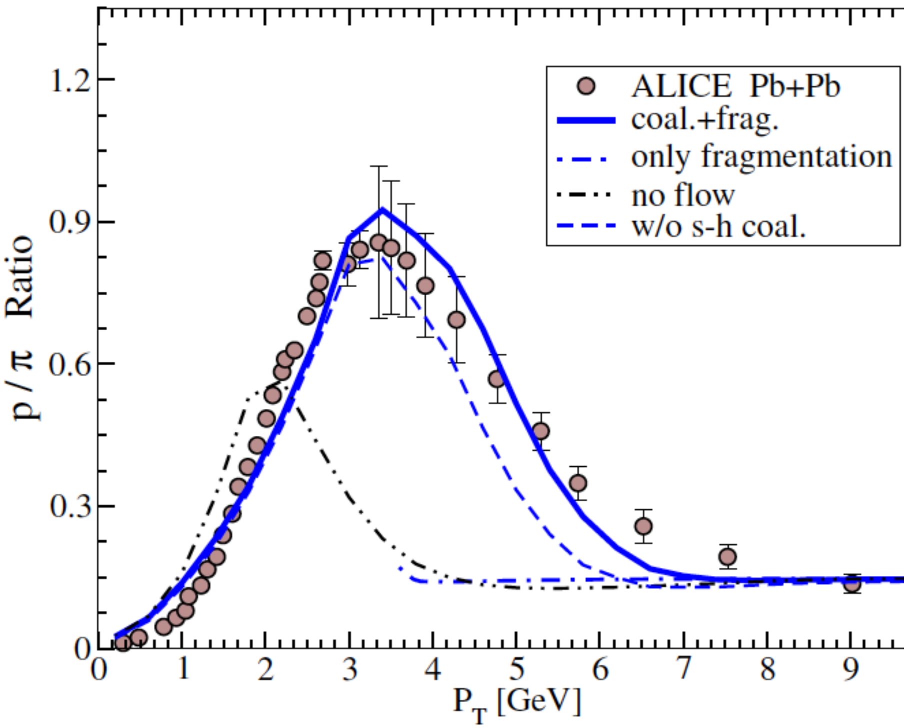
ALICE data
p coal.+frag.
p coal. total
fragmentation AKK
d^3N/dp_T^2dy [GeV^{-2}]
P_T [GeV]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6
7
8
9

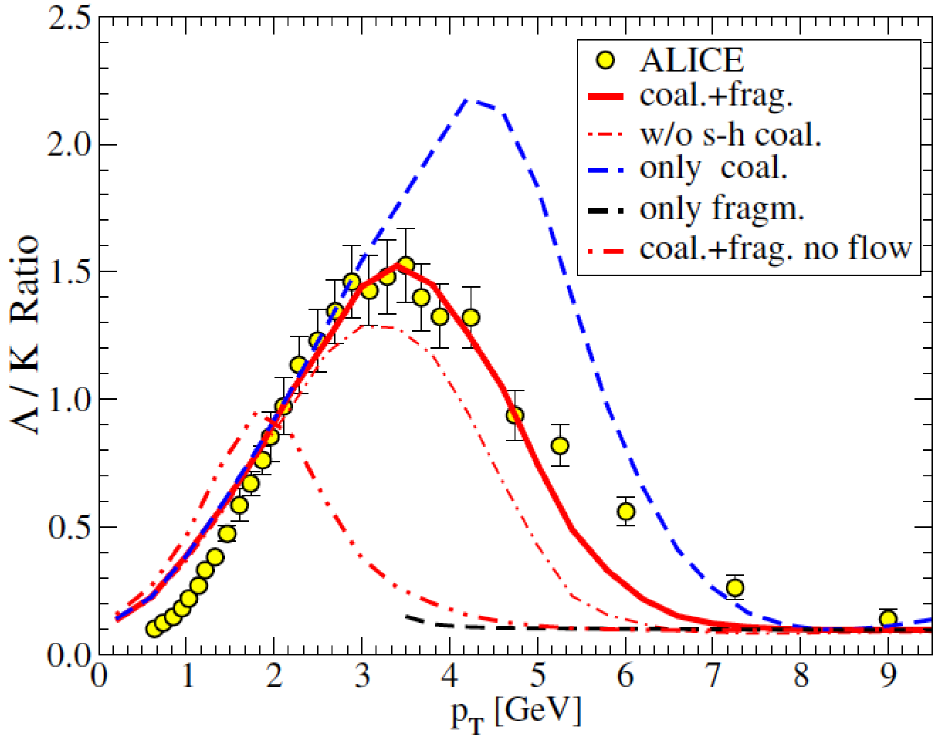
LHC - Kaon & Lambda





LHC – Ratios

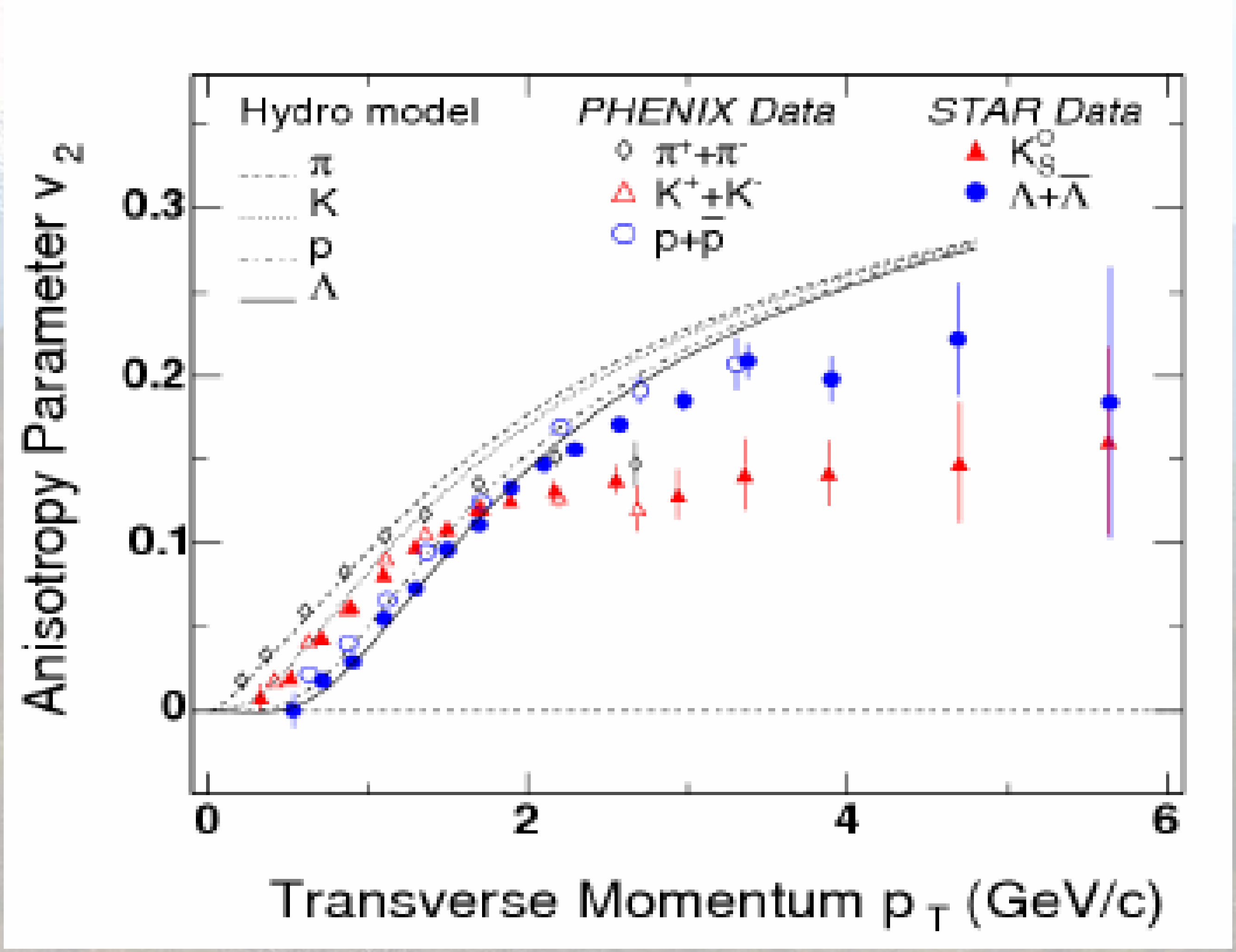




- ✓ Height and p_T position of the peak well described.
- ✓ Lack of fragmentation at $p_T \approx 6$ GeV (seen also in pp with AKK)
- ✓ Soft-minijet coalesc. contribution around and above the peak (similar to EPOS)
- ✓ Only colaescence would give higher peak shifted in p_T
- ✓ Without radial flow ··· (→ pp collisions but not exactly)

RHIC Observables

Elliptic Flow splitting



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

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

Elliptic Flow

- Fourier expansion of the azimuthal distribution

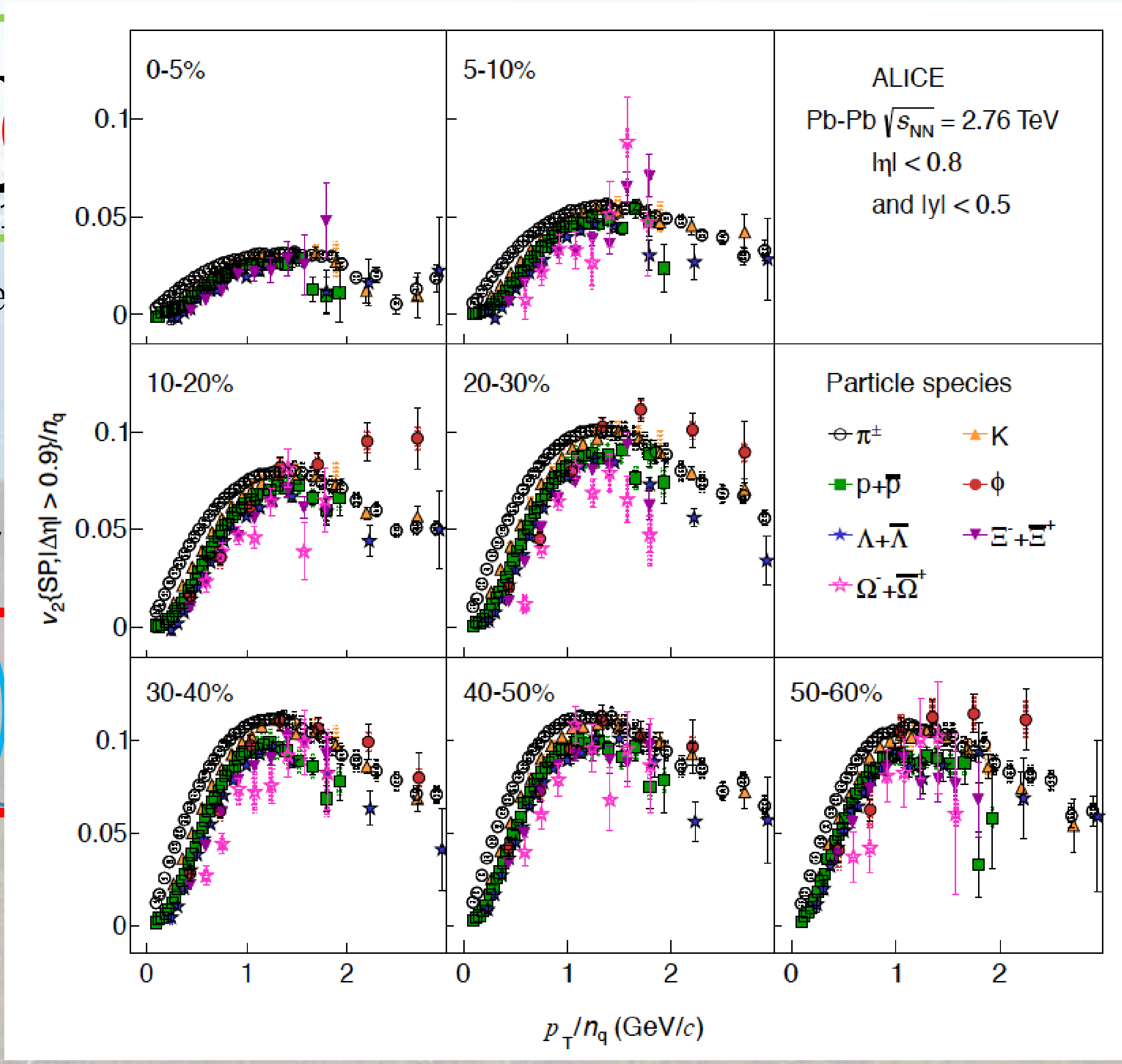
$$f(\varphi, p_T) = 1 + 2\sum_{n=1}^{\infty}$$

momentum anisotropy in the

coalescence brings t

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

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



Preliminary on radial flow impact

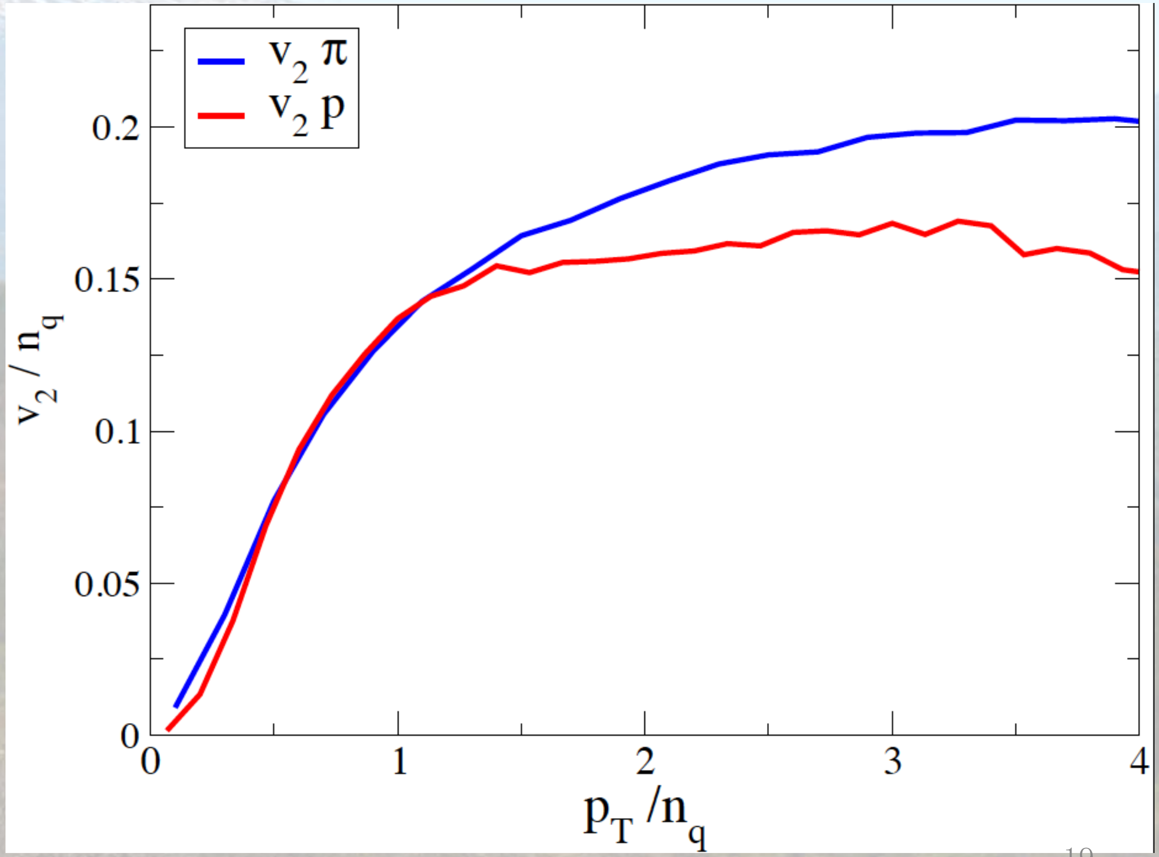
Same approach, but with an anisotropic radial flow in the quark distrib. function

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

$$\beta_T(r,\phi) = \beta_0(r) + \beta_2(r)\cos(2\phi)$$

About 20% quark number scaling breaking :

- 3D
- finite width wave function
- anisotropic radial flow



Summary

- Good agreement with RHIC & LHC data

  π, p, k, Λ spectra

  ratio peak shift at LHC

  with no parameters change

- v_2 QNS breaking

Outlooks

- other particles (ϕ, Ξ , Ω)
- other centrality
- Next order in v_n and effect of radial flow on the Quark Number Scaling

Backup slides

Elliptic Flow and v_3

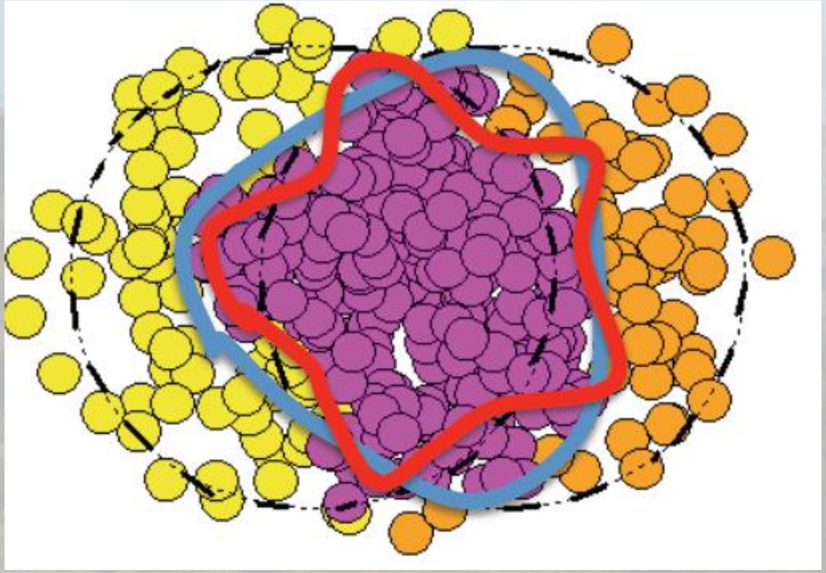
- Fourier expansion of the azimuthal distribution

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

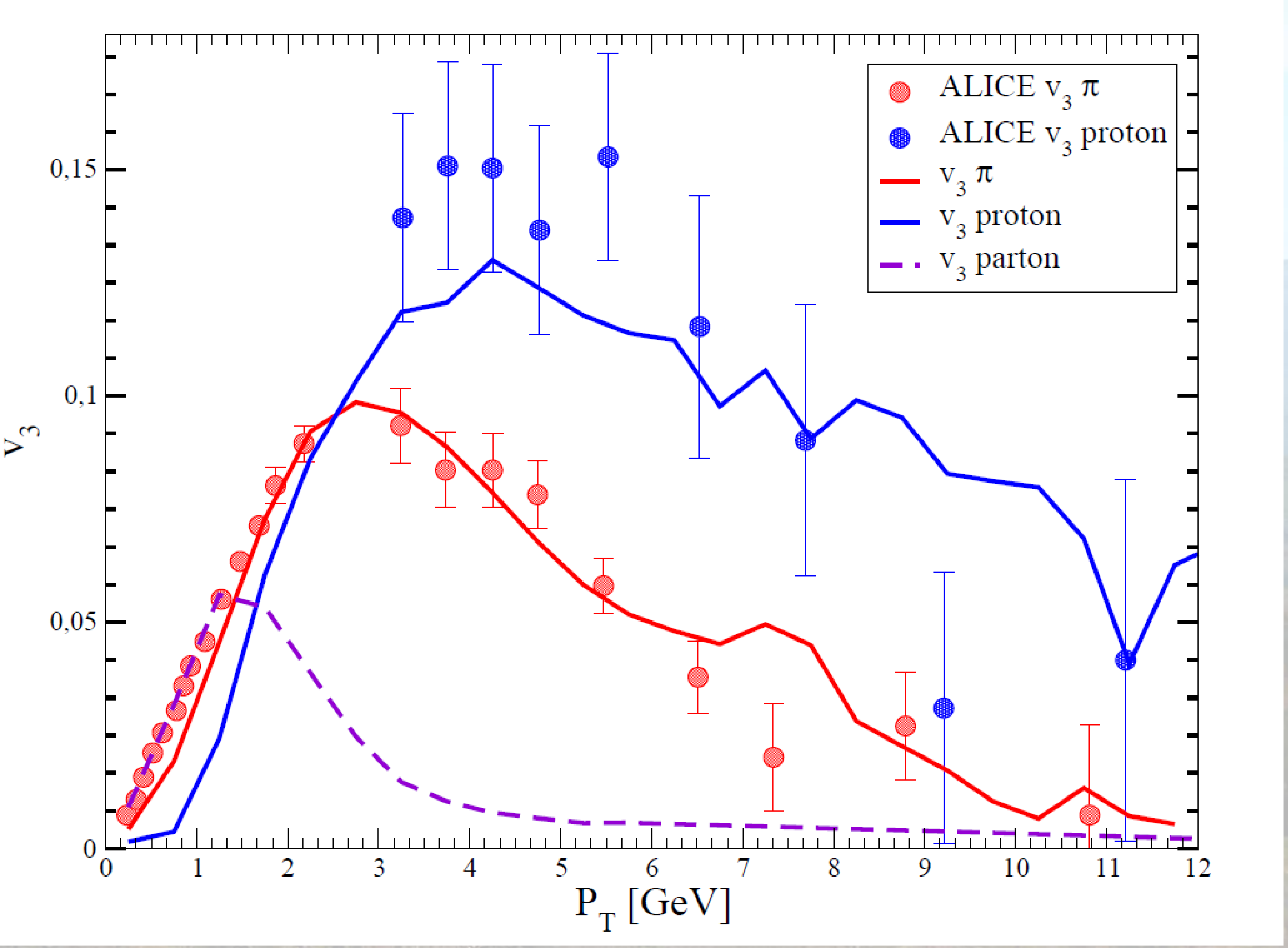
n=2　Elliptic flow

momentum anisotropy in the transverse plane

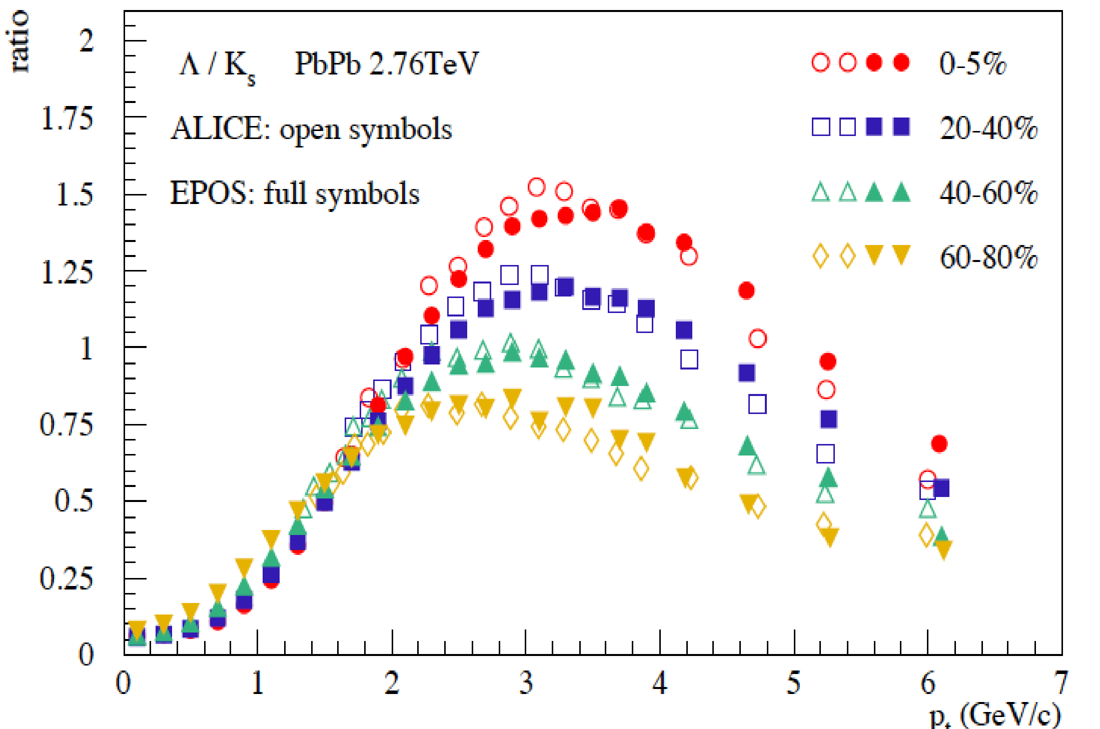
Fluctuations → n=3



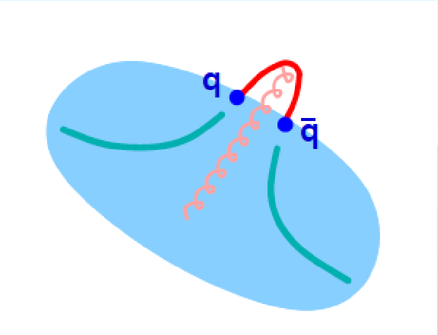
Next order: v_3– LHC



* What's the approach working in the range $p_T \approx$ 2–10 GeV?
* Is the coalescence necessary?



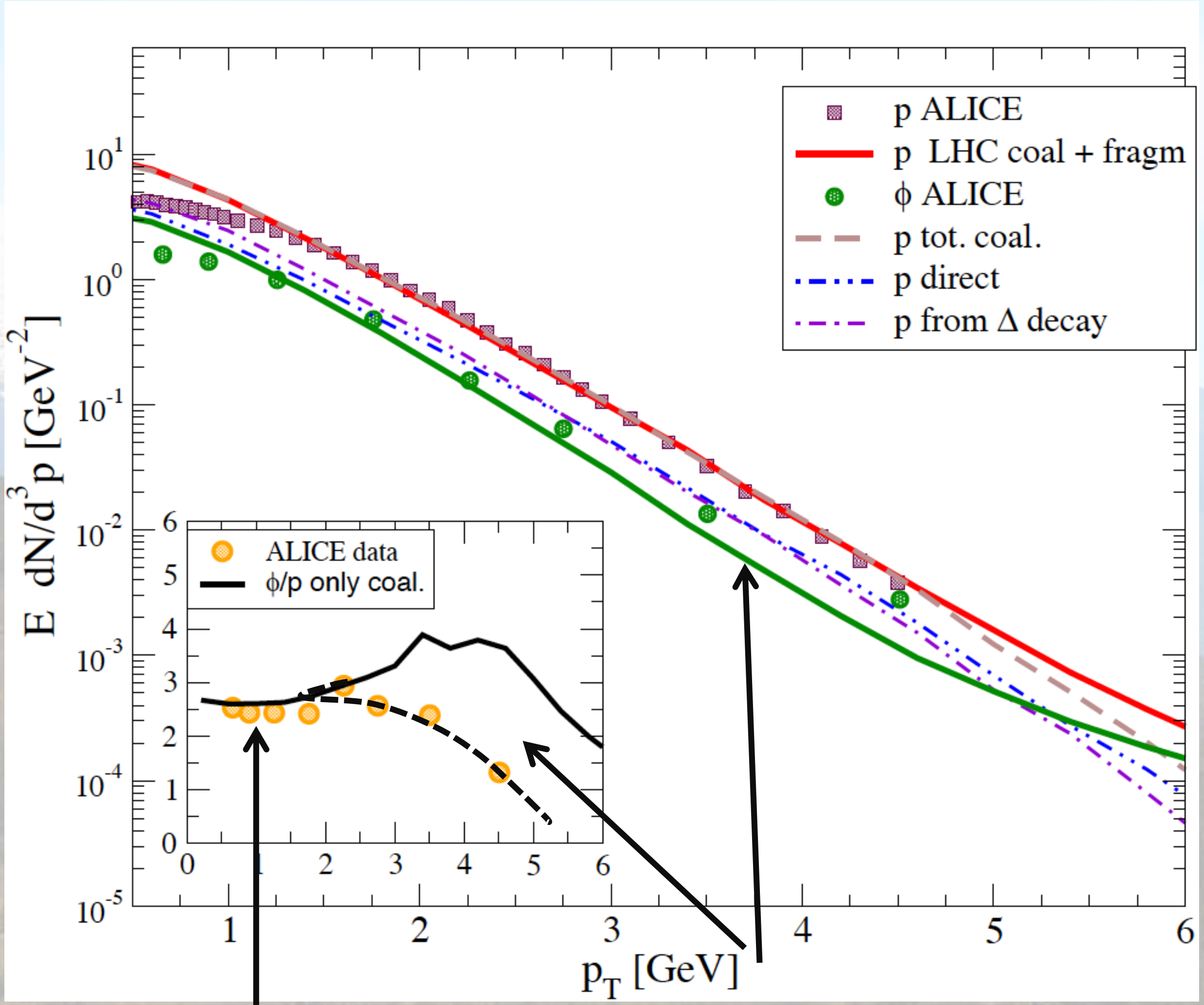
EPOS= (half)-viscous-hydro
+ soft-jet recombination



- p/π ?
- v_2 of Λ and K ?
- Also p_T spectra check

ues of p_t. We understand this effect to be due to a communication between the fluid and jet-hadrons: these hadrons are composed of a high p_t string segment (from the hard process) and (di)quarks from the fluid, carrying fluid properties. So the final hadrons are observed at relatively high p_t, but nevertheless providing information about the fluid, whereas the soft hadrons from fluid freeze out carry only small p_t. The reason for the strong

Prediction for ϕ at LHC – Preliminary



We do not have the fragm. function for ϕ

It is clear that coalescence predict a similar slope for ϕ and p

Soft part same slope ϕ and p

Missing fragmentation Contribution usually half of the yield at pT ≈4 GeV

In case of a partonic thermal distribution

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

for a two-quark hadron,

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

in the *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