Vincenzo Minissale
University of Catania - INFN LNS

Quark coalescence from RHIC to LHC

Prof. Vincenzo Greco
Francesco Scardina

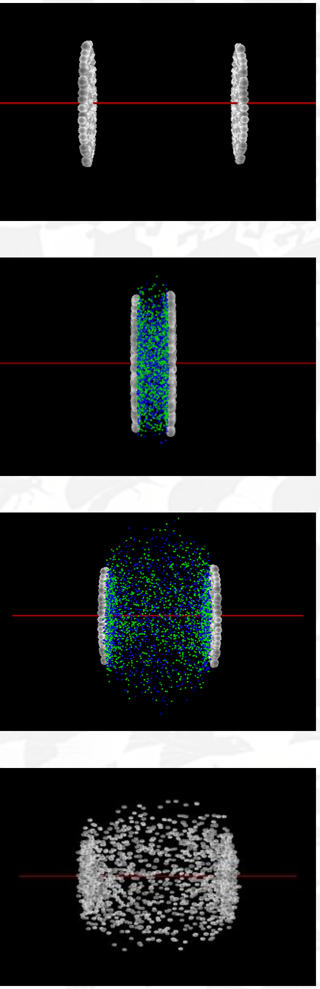
31st Winter Workshop on Nuclear Dynamics, 30January 2015

Outline

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

Ultrarelativistic heavy–ion collisions

HIC sequence



Initial Stage

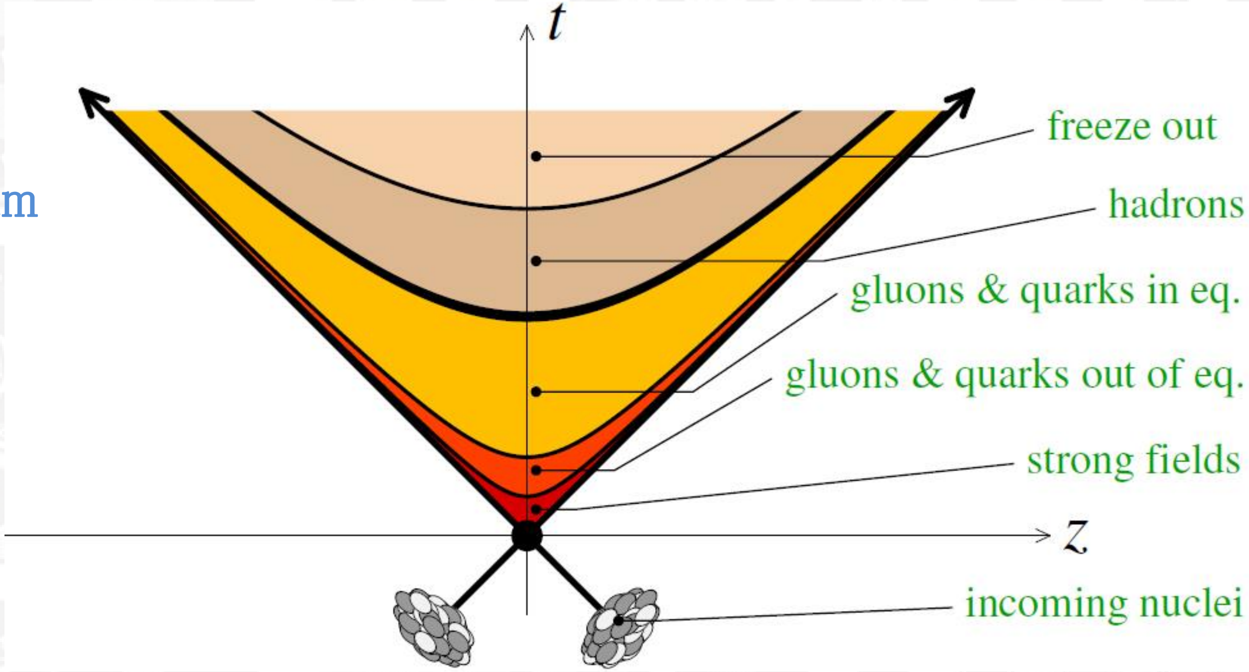
Pre–equilibrium stage

Expansion

QGP

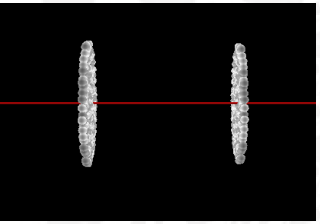
Hadronization

Chemical and kinetic freeze–out

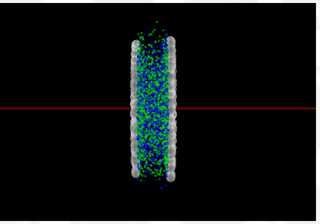


Ultrarelativistic heavy–ion collisions

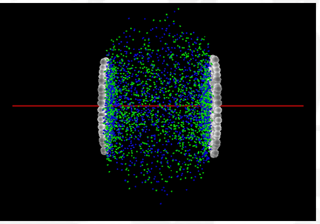
HIC sequence



Initial Stage

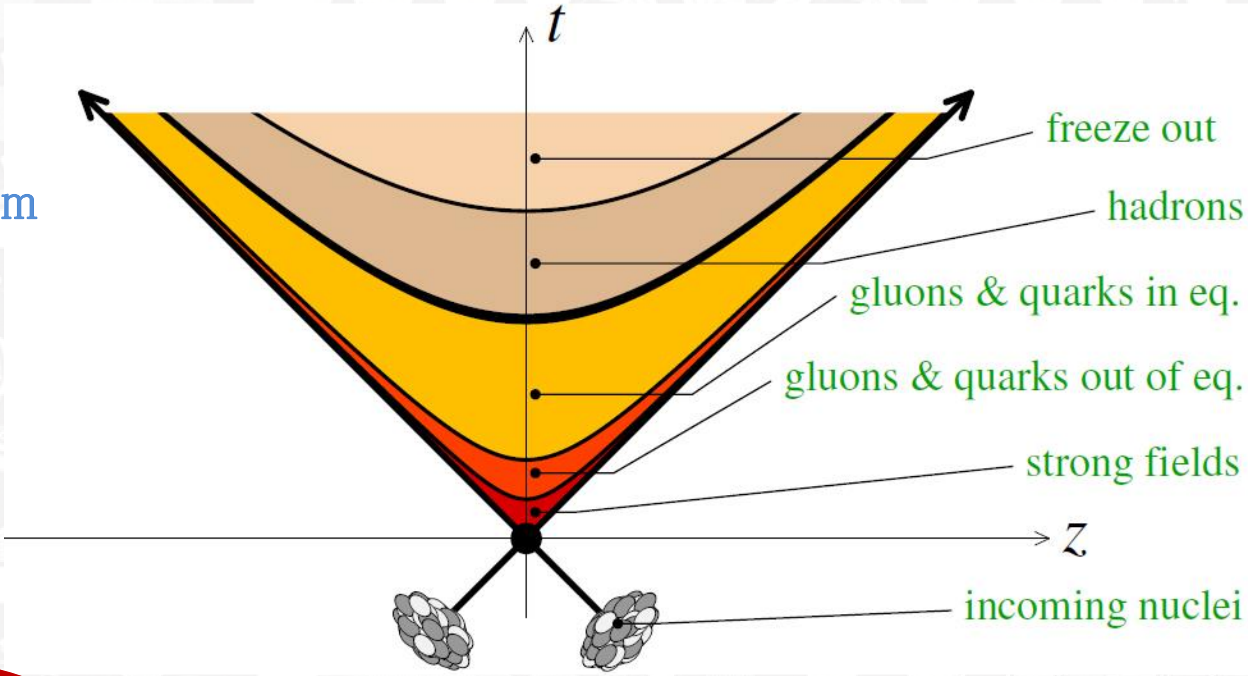


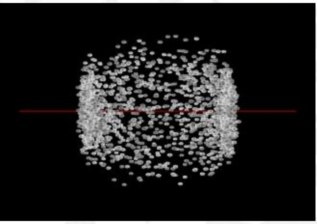
Pre–equilibrium stage



Expansion

QGP





Hadronization

Chemical and kinetic freeze–out

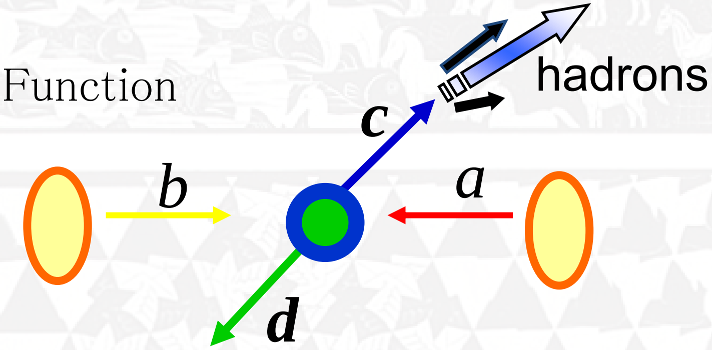
Hadronization

- Fragmentation

Fragmentation Function

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

$0 < z < 1$



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

Hadronization

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Fragmentation Function

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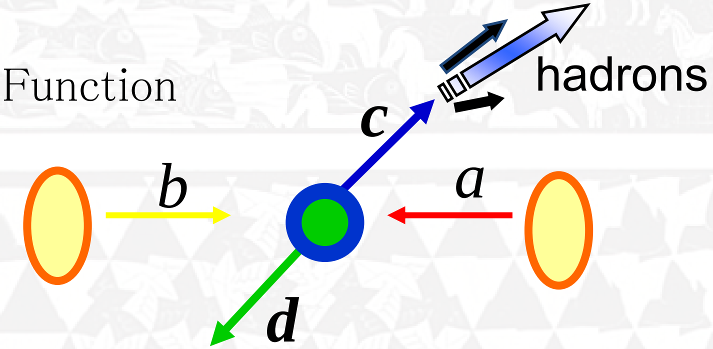


- Coalescence

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)

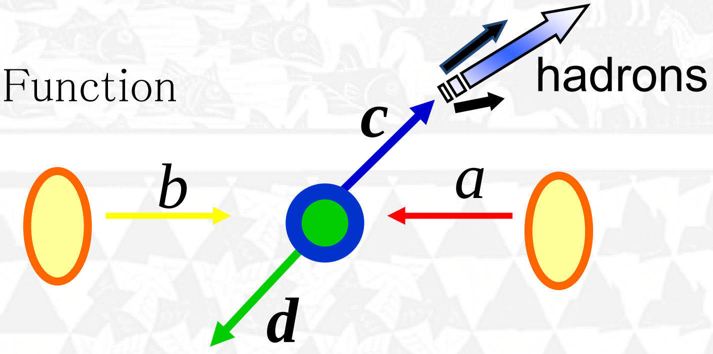
Hadronization

- Fragmentation

Fragmentation Function

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

$0 < z < 1$



- Coalescence

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

Parton Distribution Function

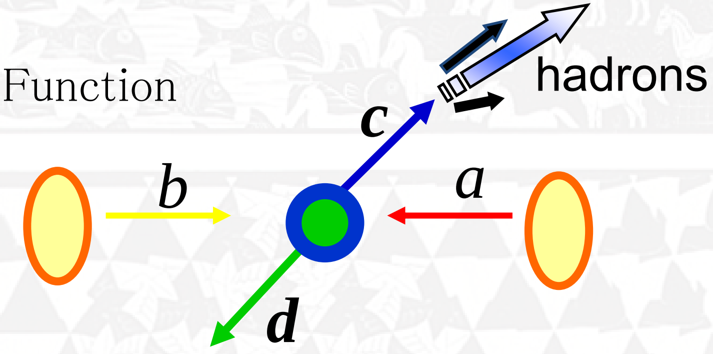
Statistical factor colour–spin–isospin

Hadron Wigner Function

Hadronization

- Fragmentation

Fragmentation Function



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

$$0 < z < 1$$

- Coalescence

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

Parton Distribution Function

Statistical factor colour-spin-isospin

Hadron Wigner Function

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

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

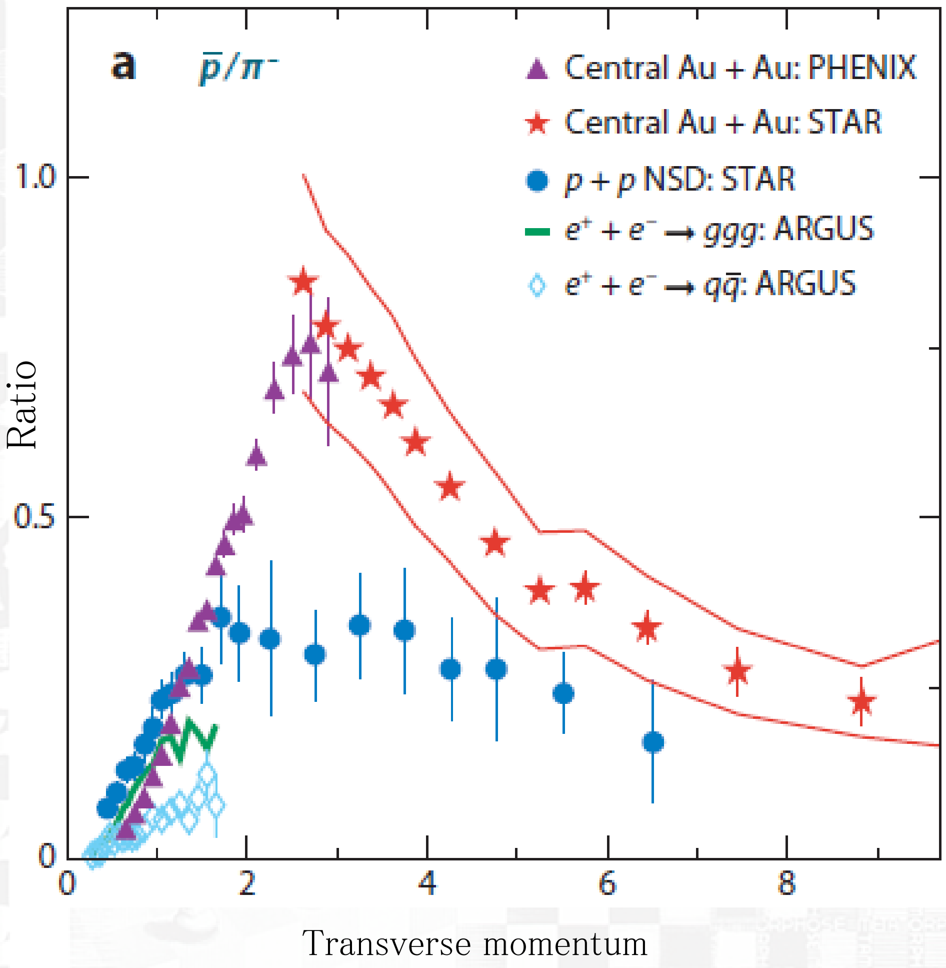
RHIC Observables

Proton to pion ratio Enhancement

In the vacuum, from fragmentation functions the ratio is

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

Elliptic Flow Splitting



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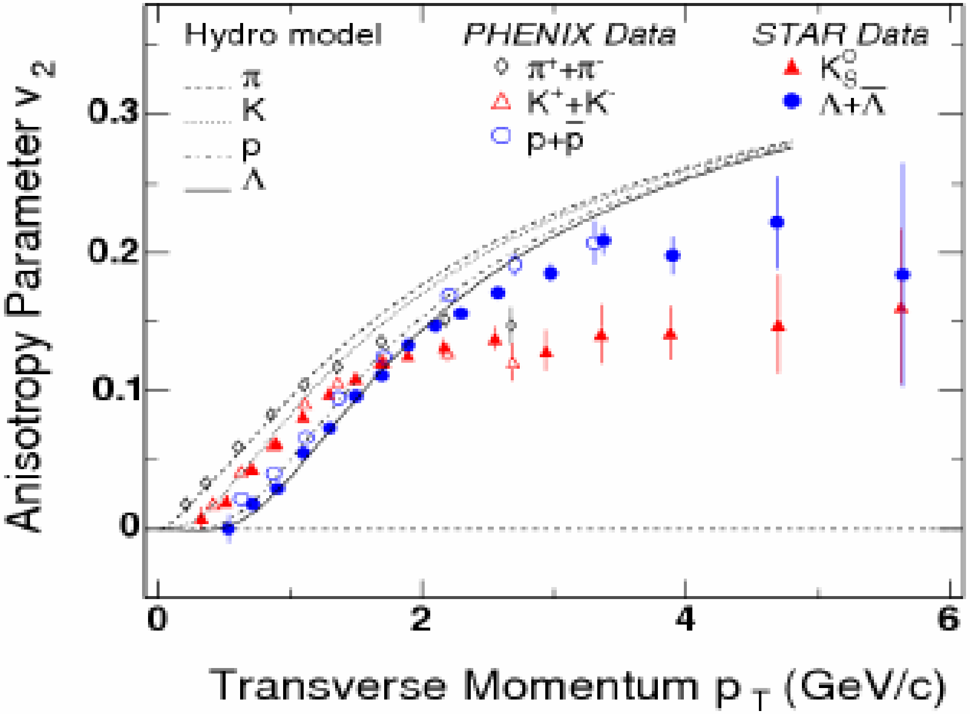


In case of a partonic thermal distribution

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

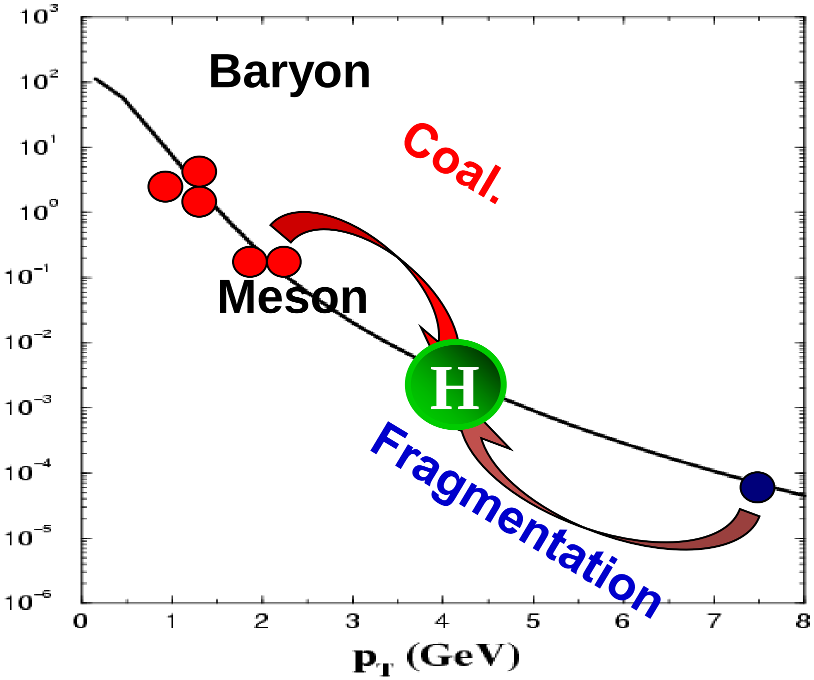
for a two-quark hadron,

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

in the *n* quark case

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

Baryon/Meson Ratio = 1



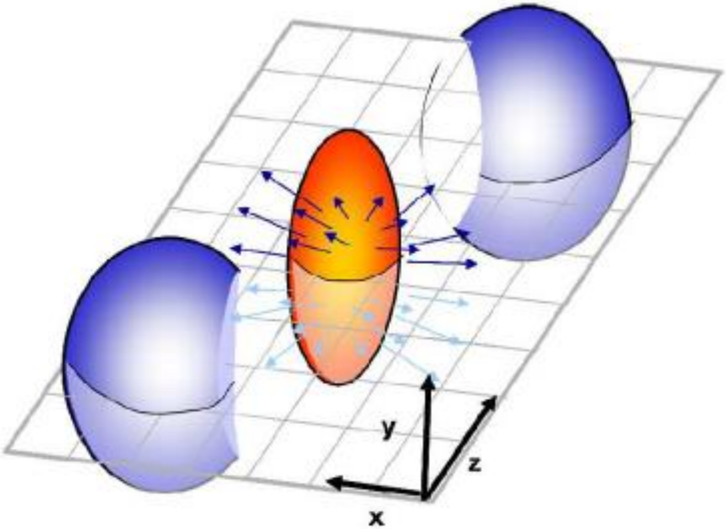
Elliptic Flow

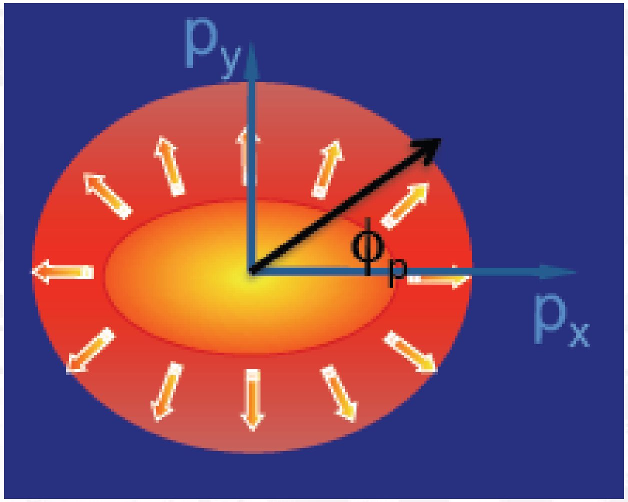
- Fourier expansion of the azimuthal distribution

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

n=2　Elliptic flow

momentum　anisotropy　in the transverse plane





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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

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 $\beta_T = \beta_{max}\frac{r}{\boxed{R}}$ 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 constraints $\frac{dN_{ch}}{dy}$; $\frac{dE_T}{dy}$

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

Fireball parameters

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

β_{max} from radial expansion $R = R_0 + \beta_{max} a x \enclose{circle}{\tau}$

- Uniform in (x, y); $z = \enclose{circle}{\tau} \sinh y$
- $V = \pi {r_T}^2 \enclose{circle}{\tau}$ $\sim 1000\ fm^3\ RHIC \sim 2500\ fm^3\ LHC$
- Fireball radius 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

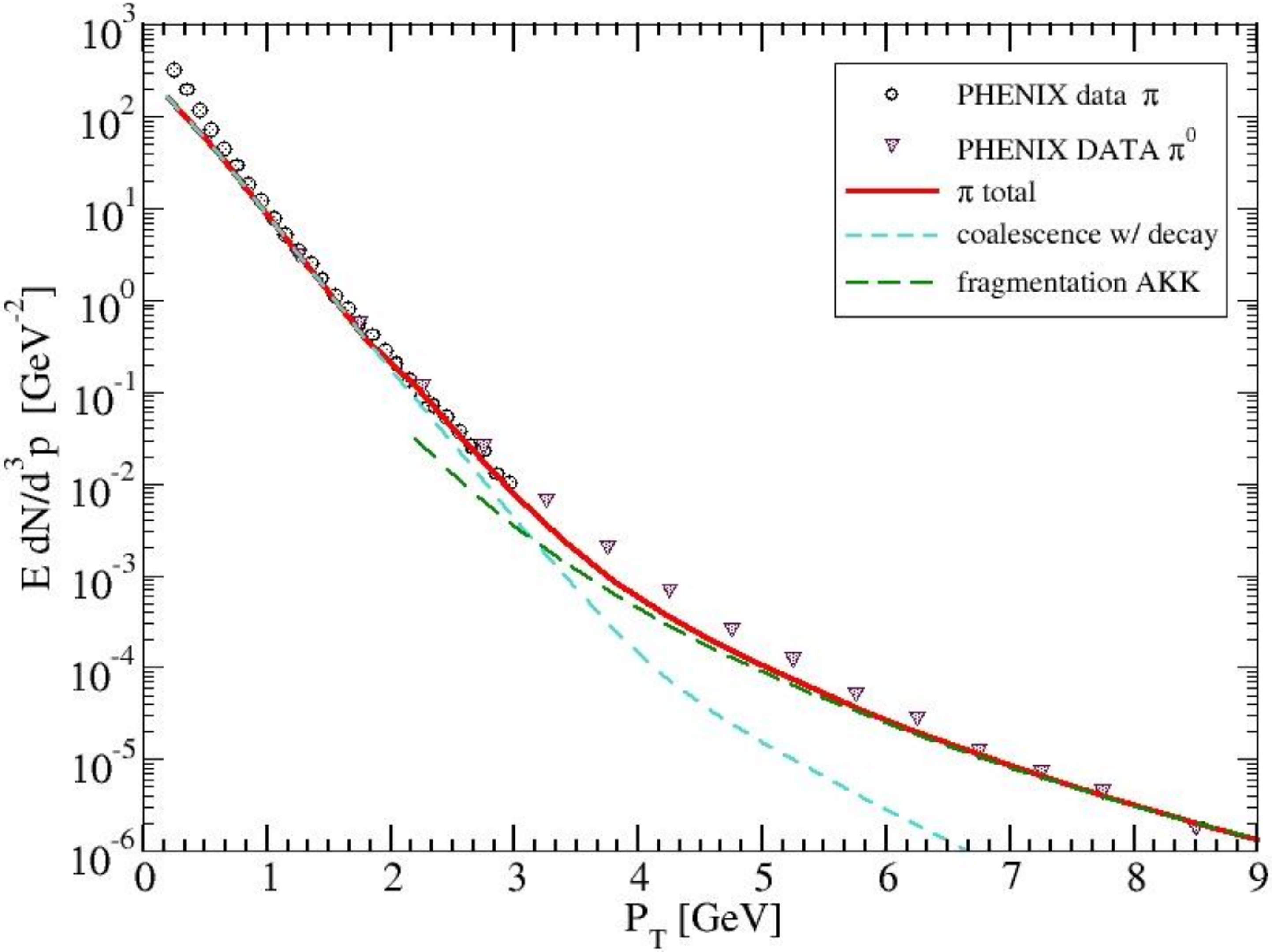
- $\pi\ (I = 1, J = 0)$
  - $k^{*}(I = 1, J = 1/2) \rightarrow k\pi$
  - $\rho(I = 1, J = 1) \rightarrow \pi\pi$
  - $\Delta(I = 3/2, J = 3/2) \rightarrow N\pi$
- p $(I = 1/2, J = 1/2)$
  - $\Delta(I = 3/2, J = 3/2) \rightarrow N\pi$
- $k^{\pm}\ (I = 0, J = 1/2)$
  - $k^{*}(I = 1, J = 1/2) \rightarrow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

Suppression factor

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

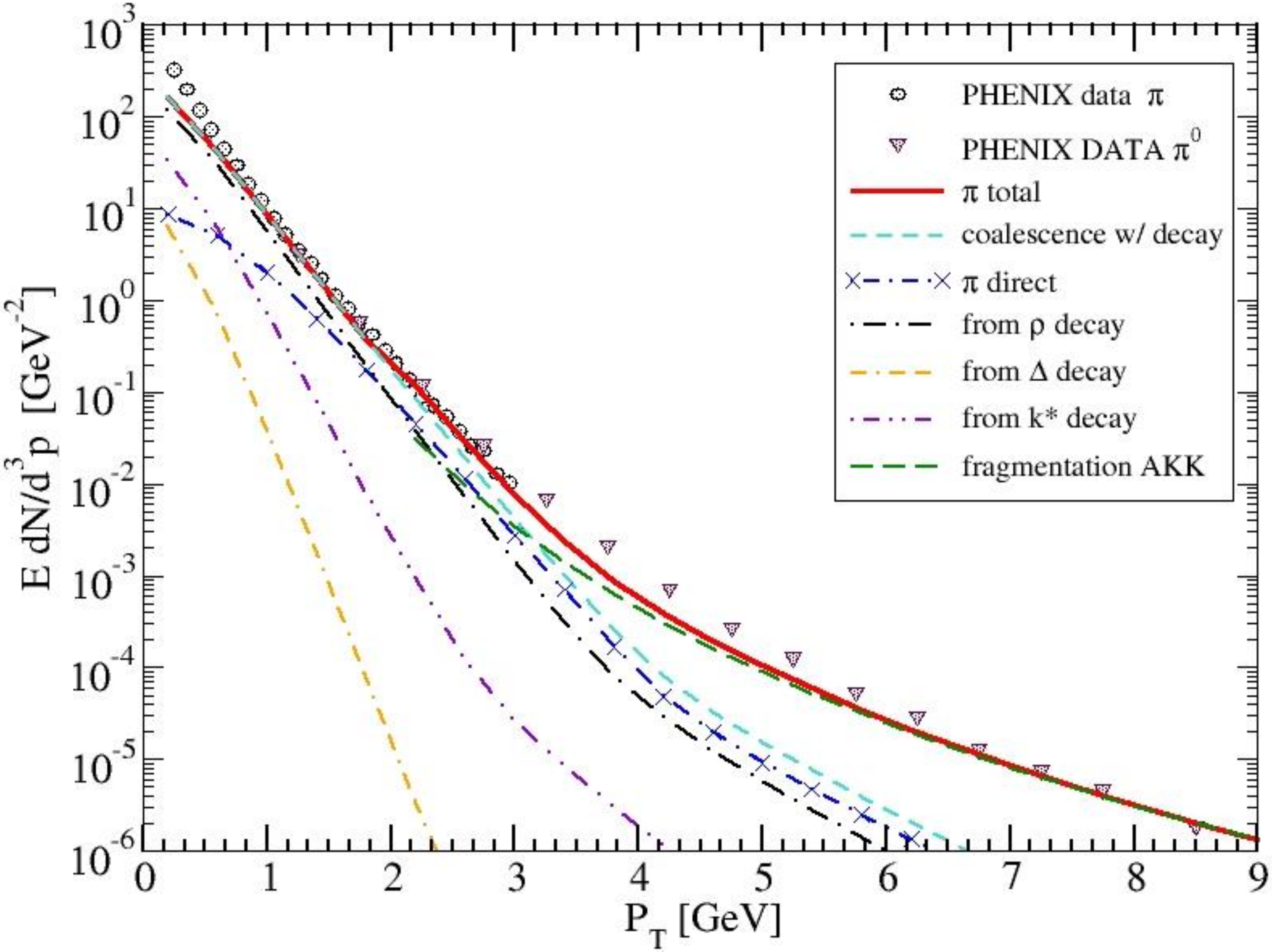
Results RHIC

RHIC – Pion



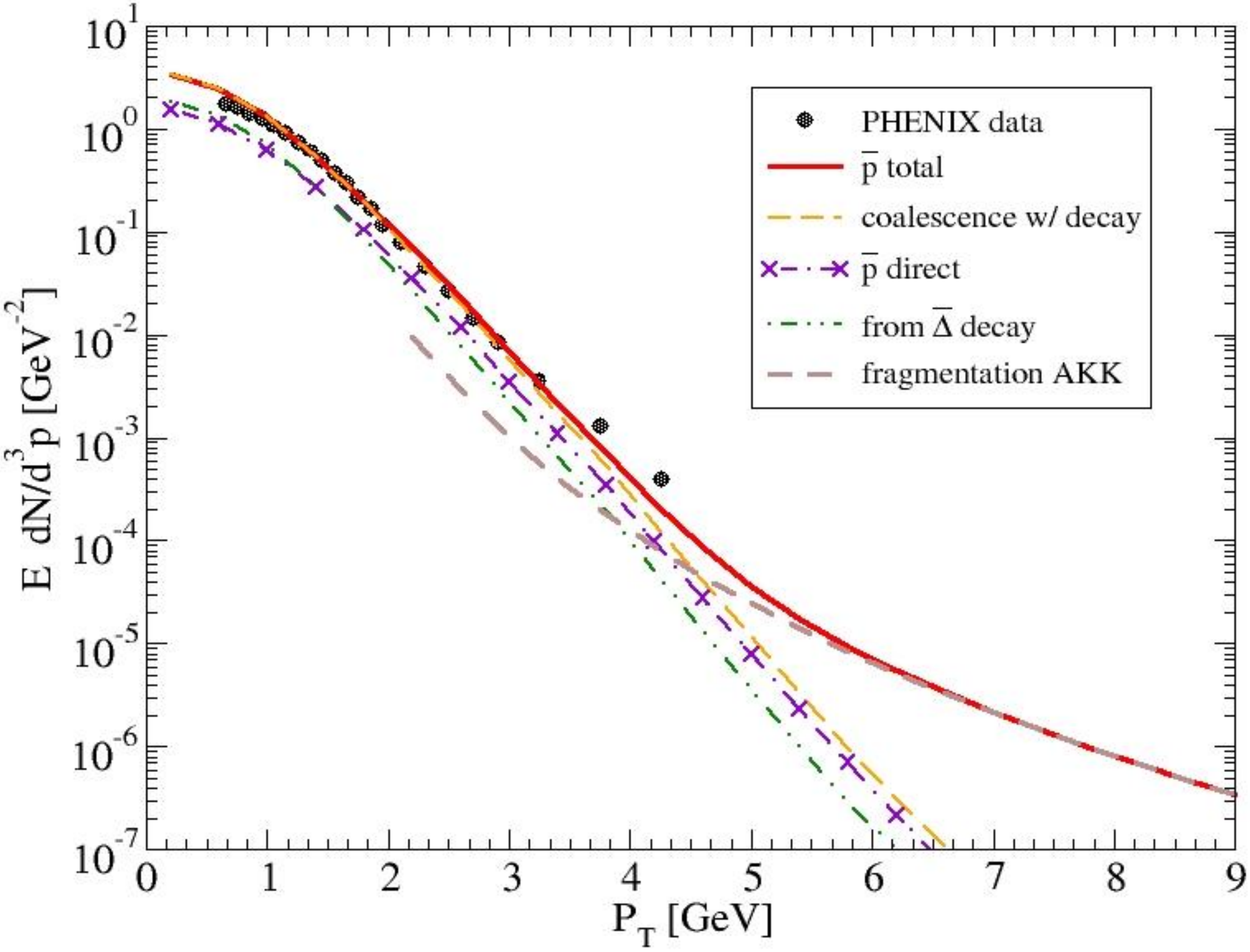
PHENIX data π
PHENIX DATA π^0
π total
coalescence w/ decay
fragmentation AKK
$E\, dN/d^3p$ [GeV^{-2}]
P_T [GeV]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
1
2
3
4
5
6
7
8
9

RHIC – Pion

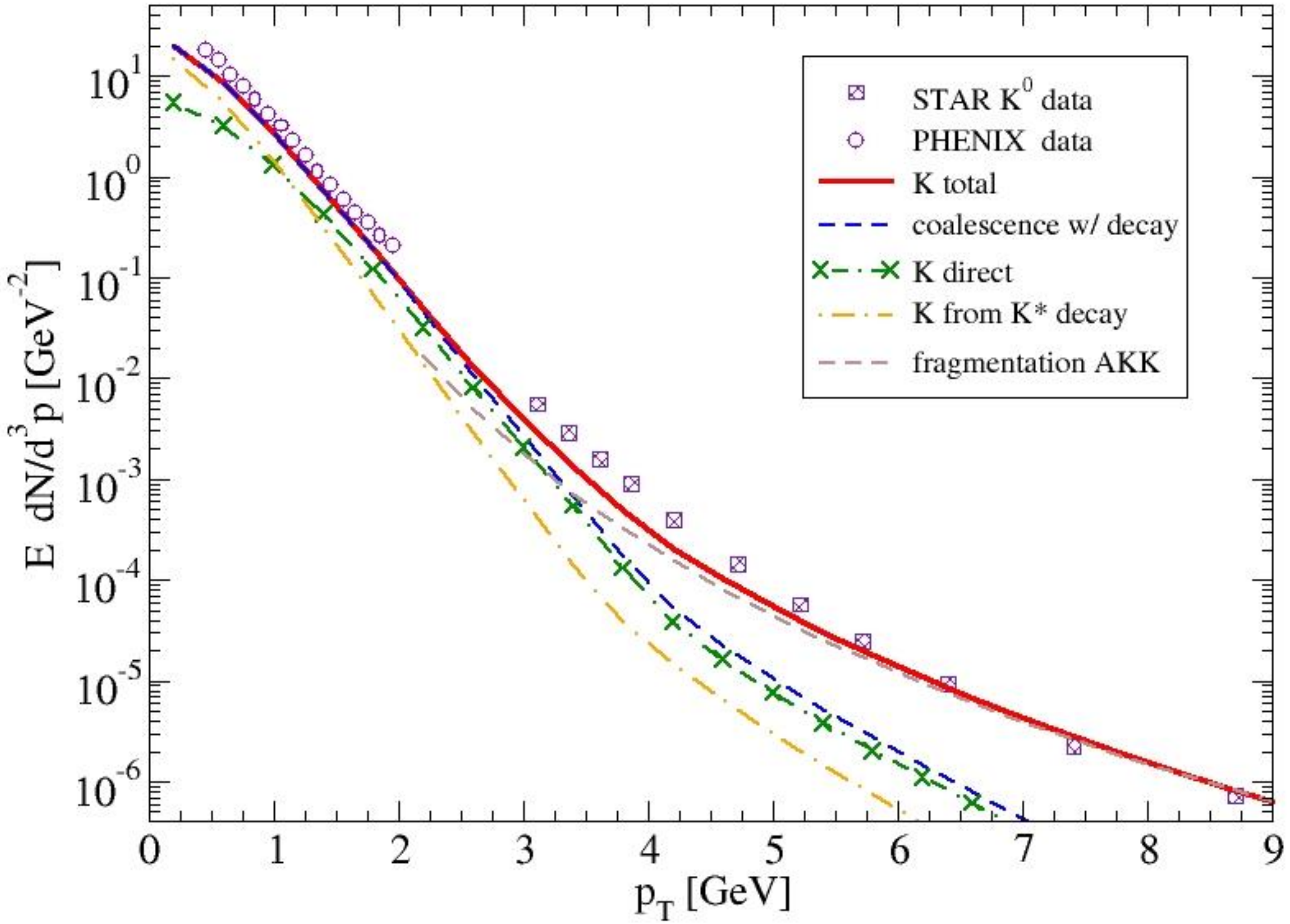


10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$E\,dN/d^3p$ [GeV^{-2}]
0
1
2
3
4
5
6
7
8
9
P_T [GeV]
PHENIX data π
PHENIX DATA π^0
π total
coalescence w/ decay
π direct
from ρ decay
from Δ decay
from k* decay
fragmentation AKK

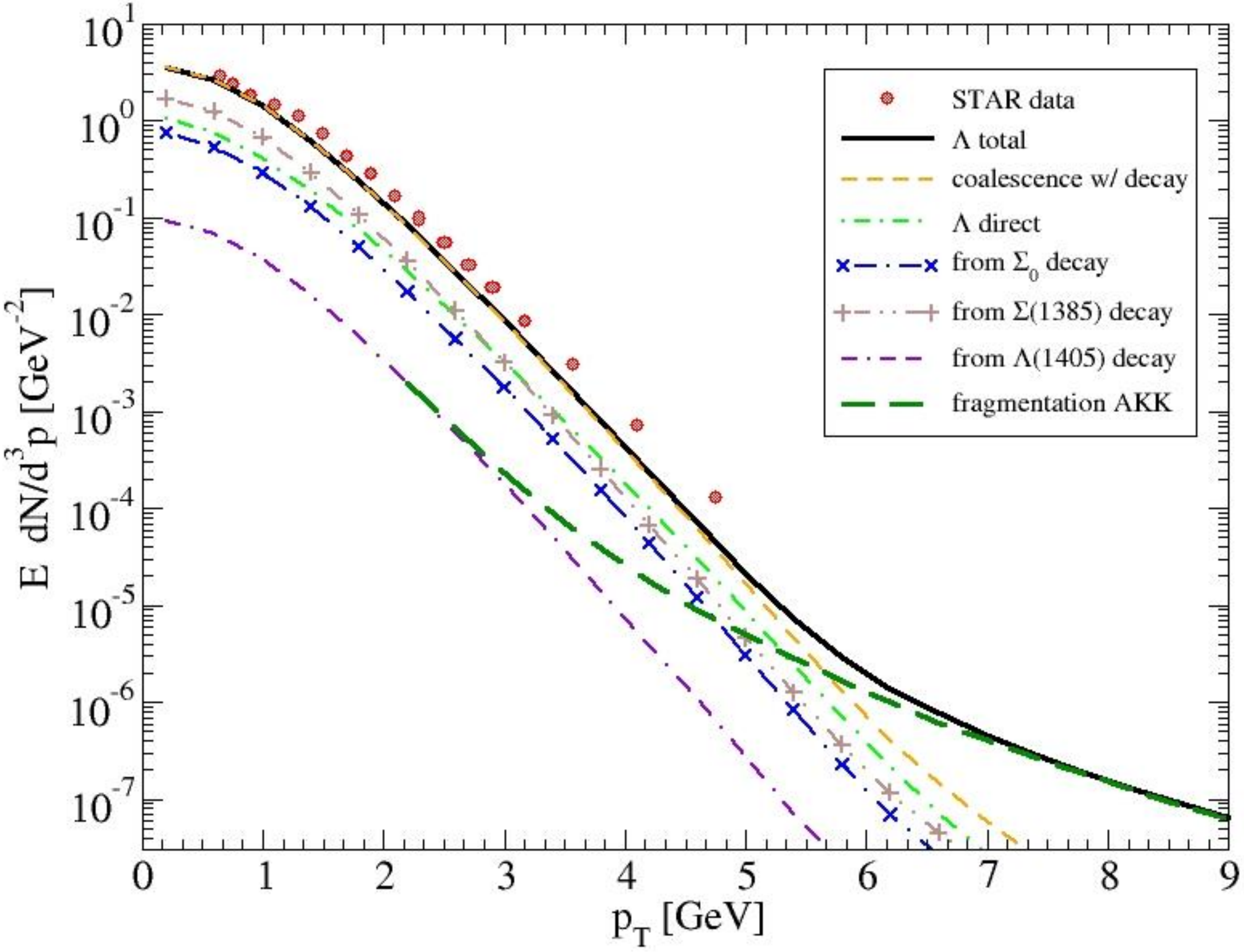
RHIC – Antiproton



RHIC – Kaon

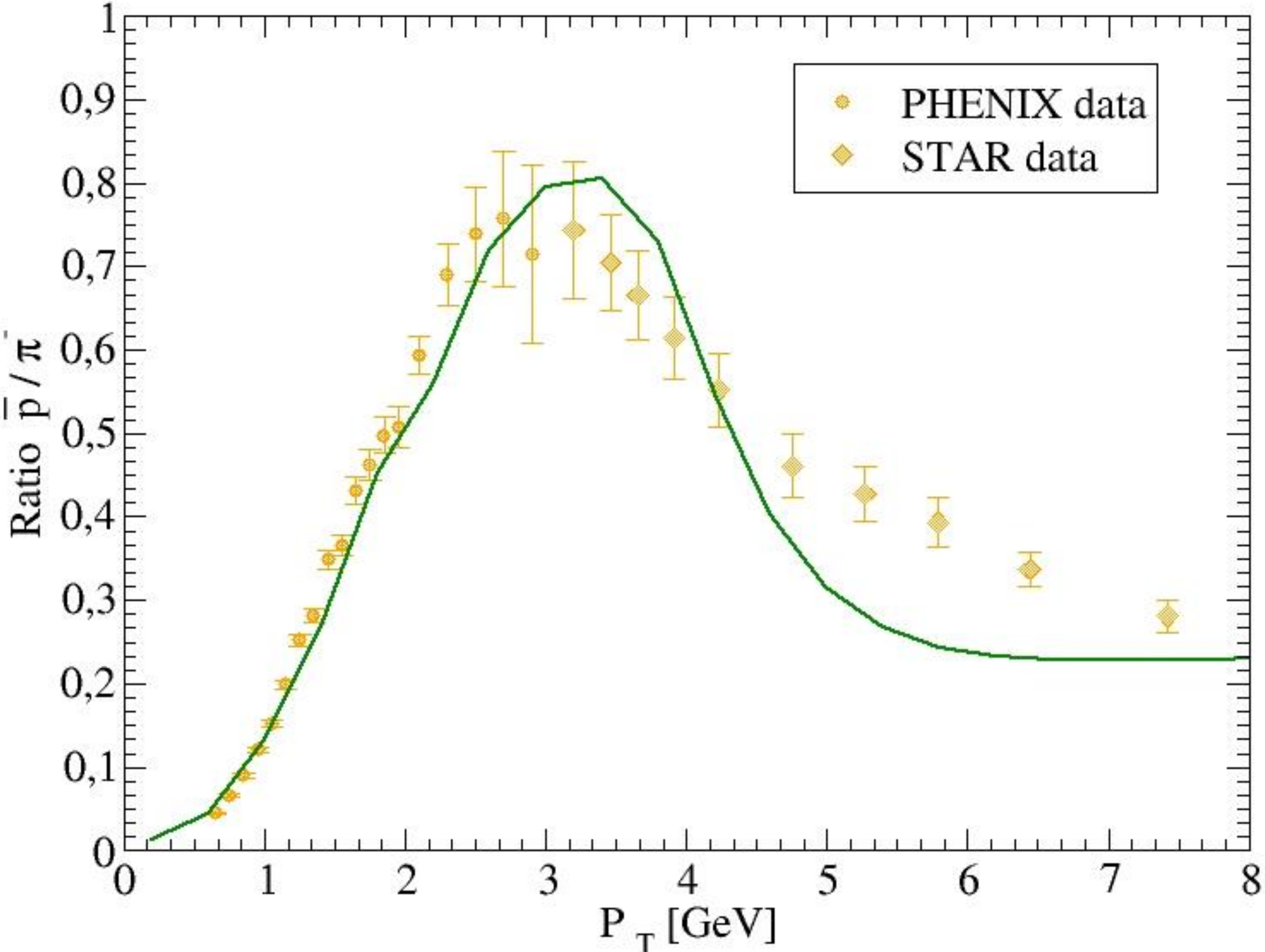

STAR K^0 data
PHENIX data
K total
coalescence w/ decay
K direct
K from K* decay
fragmentation AKK
E dN/d^3p [GeV^-2]
p_T [GeV]
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0
1
2
3
4
5
6
7
8
9

RHIC – Lambda



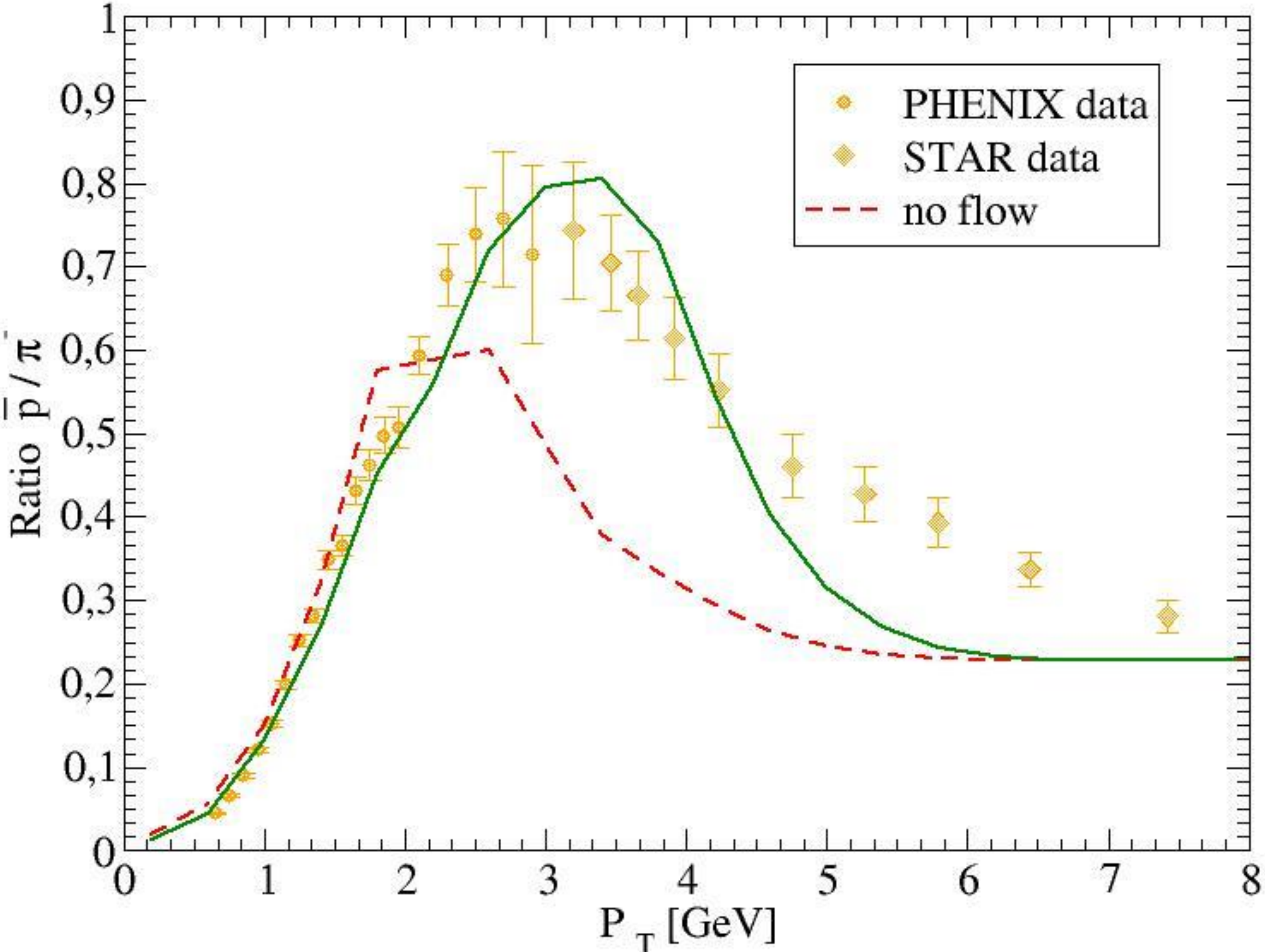
$E\ dN/d^3p\ [\mathrm{GeV}^{-2}]$
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
1
2
3
4
5
6
7
8
9
p_T [GeV]
STAR data
Λ total
coalescence w/ decay
Λ direct
from Σ_0 decay
from Σ(1385) decay
from Λ(1405) decay
fragmentation AKK

RHIC – Ratios

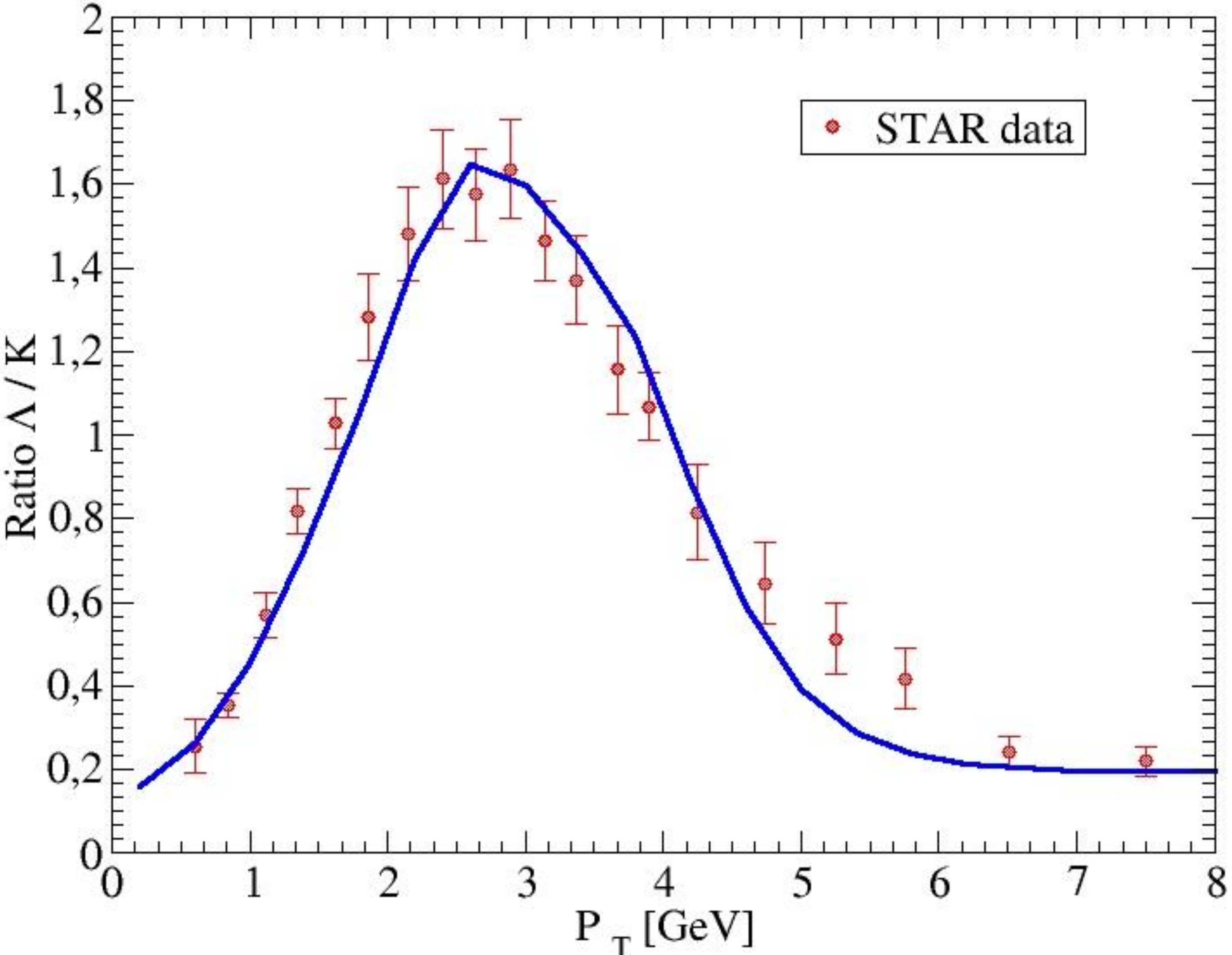


PHENIX data
STAR data
Ratio $\bar{p}/\pi^-$
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
0
1
2
3
4
5
6
7
8
P_T [GeV]

RHIC – Ratios

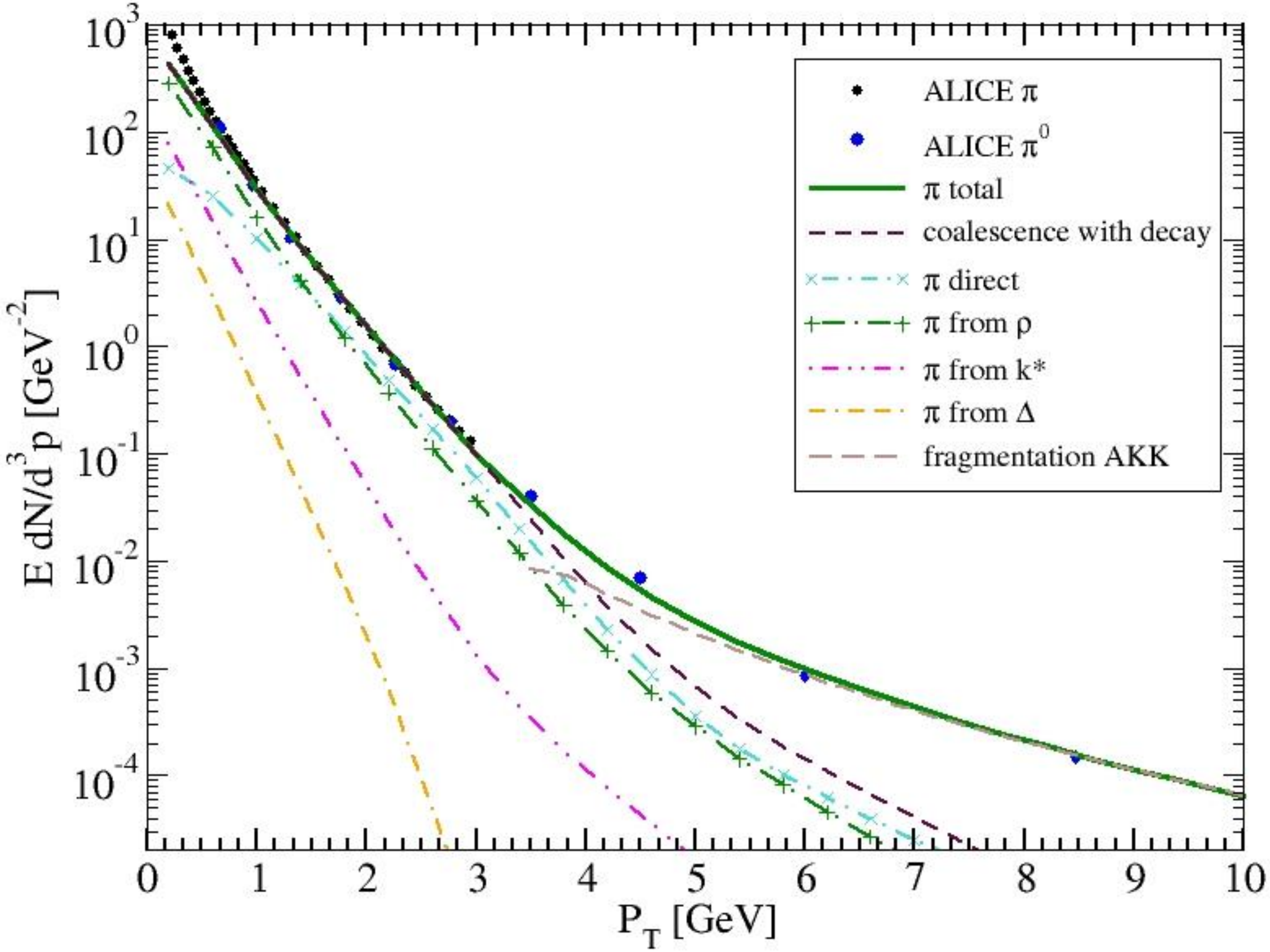

PHENIX data
STAR data
no flow
Ratio $\bar{p}/\pi^-$
P_T [GeV]
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
0
1
2
3
4
5
6
7
8

RHIC – Ratios



Results LHC

LHC – Pion


ALICE π
ALICE π^0
π total
coalescence with decay
π direct
π from ρ
π from k*
π from Δ
fragmentation AKK
$E\, dN/d^3p\ [\mathrm{GeV}^{-2}]$
P_T [GeV]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
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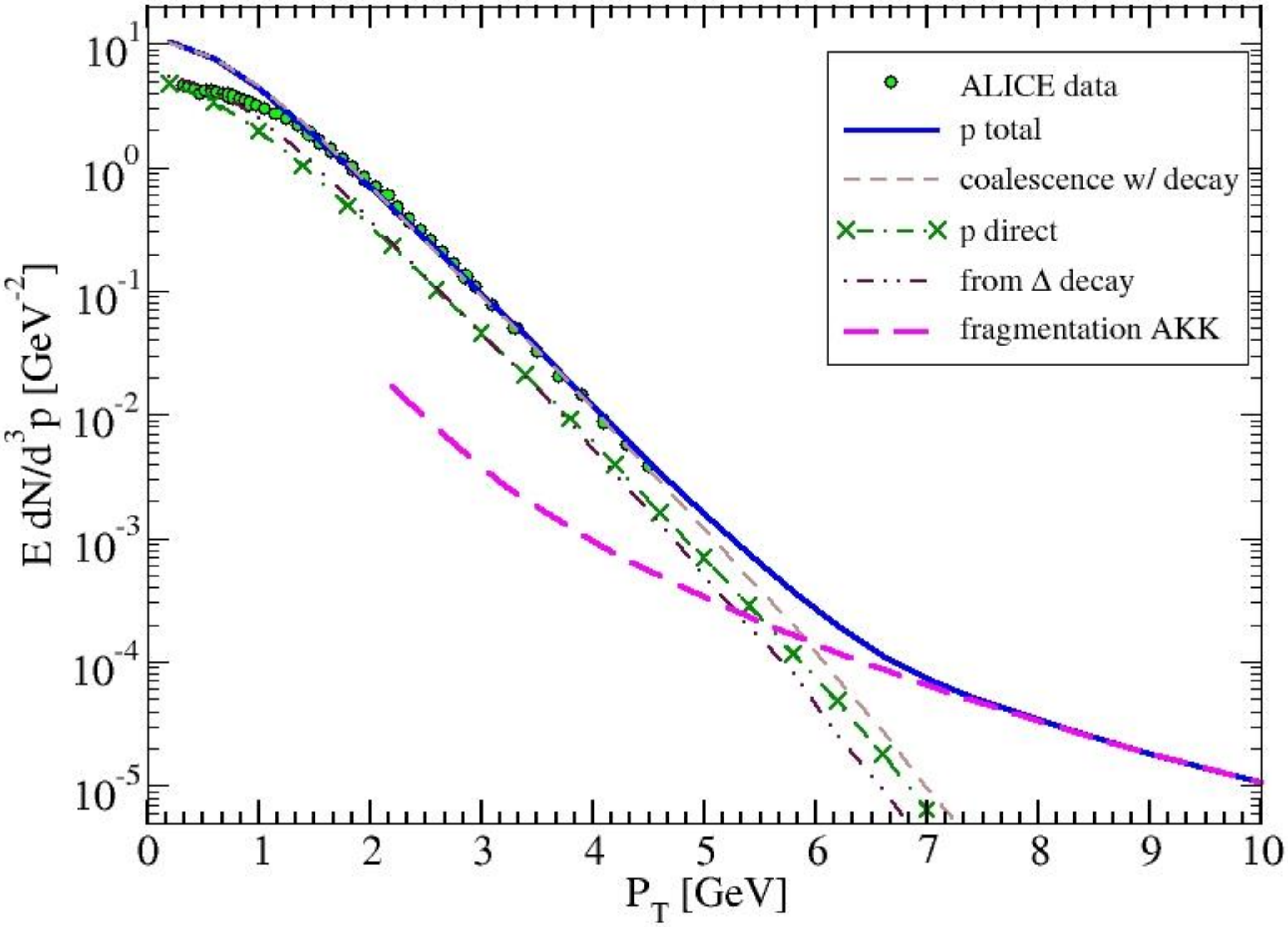
10

LHC – Proton



ALICE data
p total
coalescence w/ decay
p direct
from Δ decay
fragmentation AKK
E dN/d^{3}p [GeV^{-2}]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
1
2
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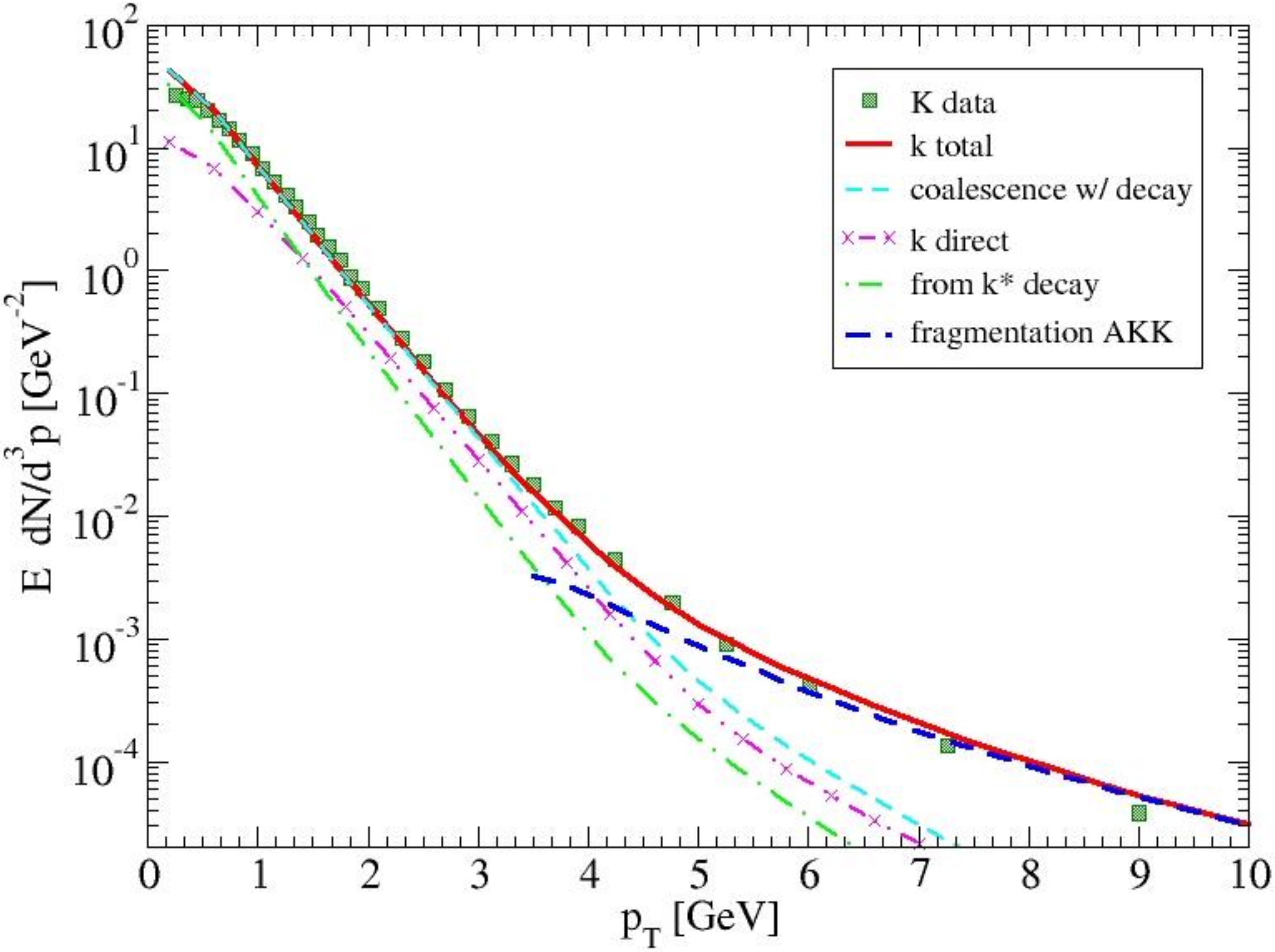
5
6
7
8
9
10
P$_T$ [GeV]

LHC – Kaon


K data
k total
coalescence w/ decay
k direct
from k* decay
fragmentation AKK
$E\ dN/d^3p\ [GeV^{-2}]$
p_T [GeV]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
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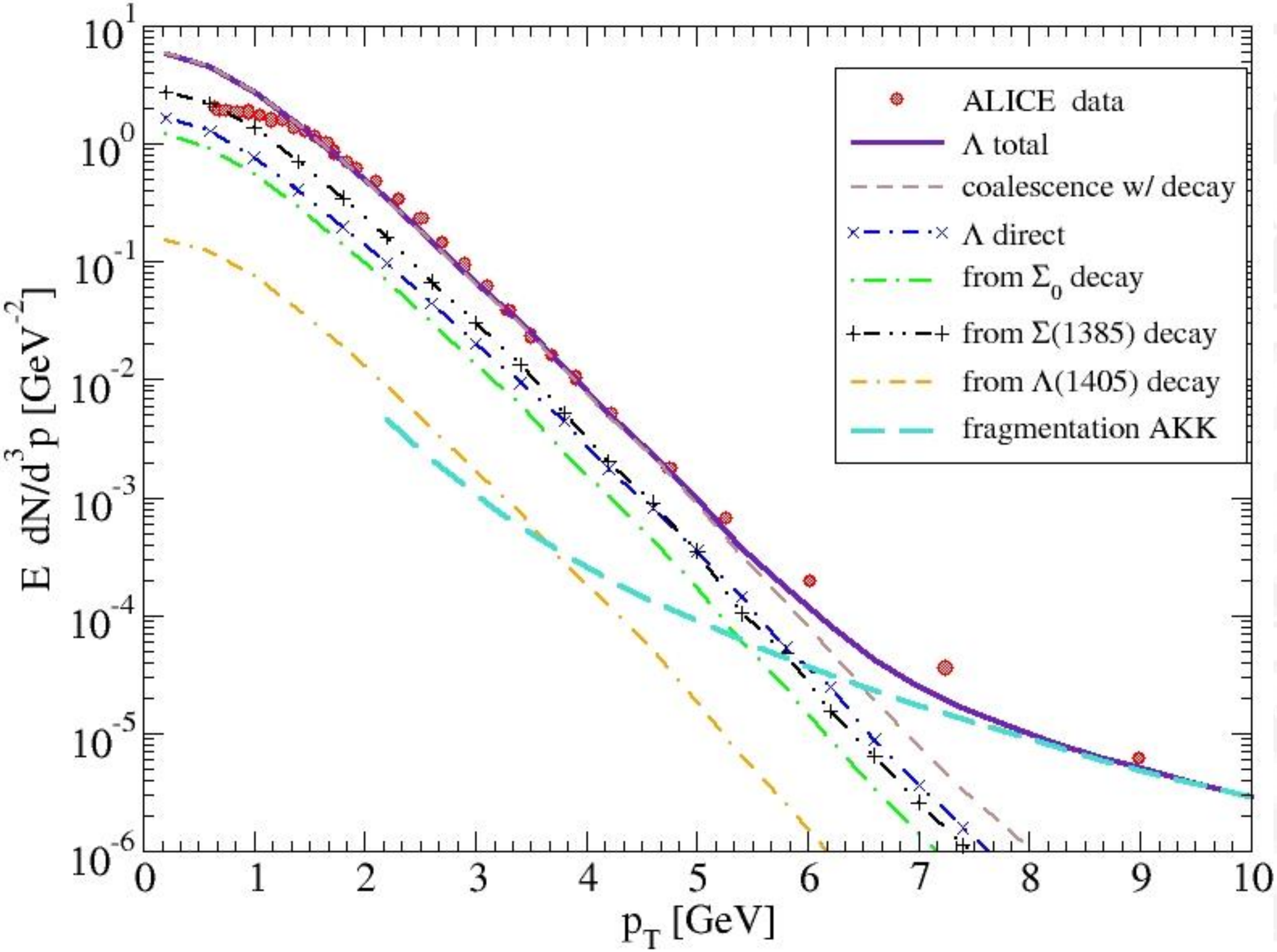
LHC – Lambda


ALICE data
Λ total
coalescence w/ decay
Λ direct
from Σ_0 decay
from Σ(1385) decay
from Λ(1405) decay
fragmentation AKK
E dN/d^{3}p [GeV^{-2}]
p_T [GeV]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
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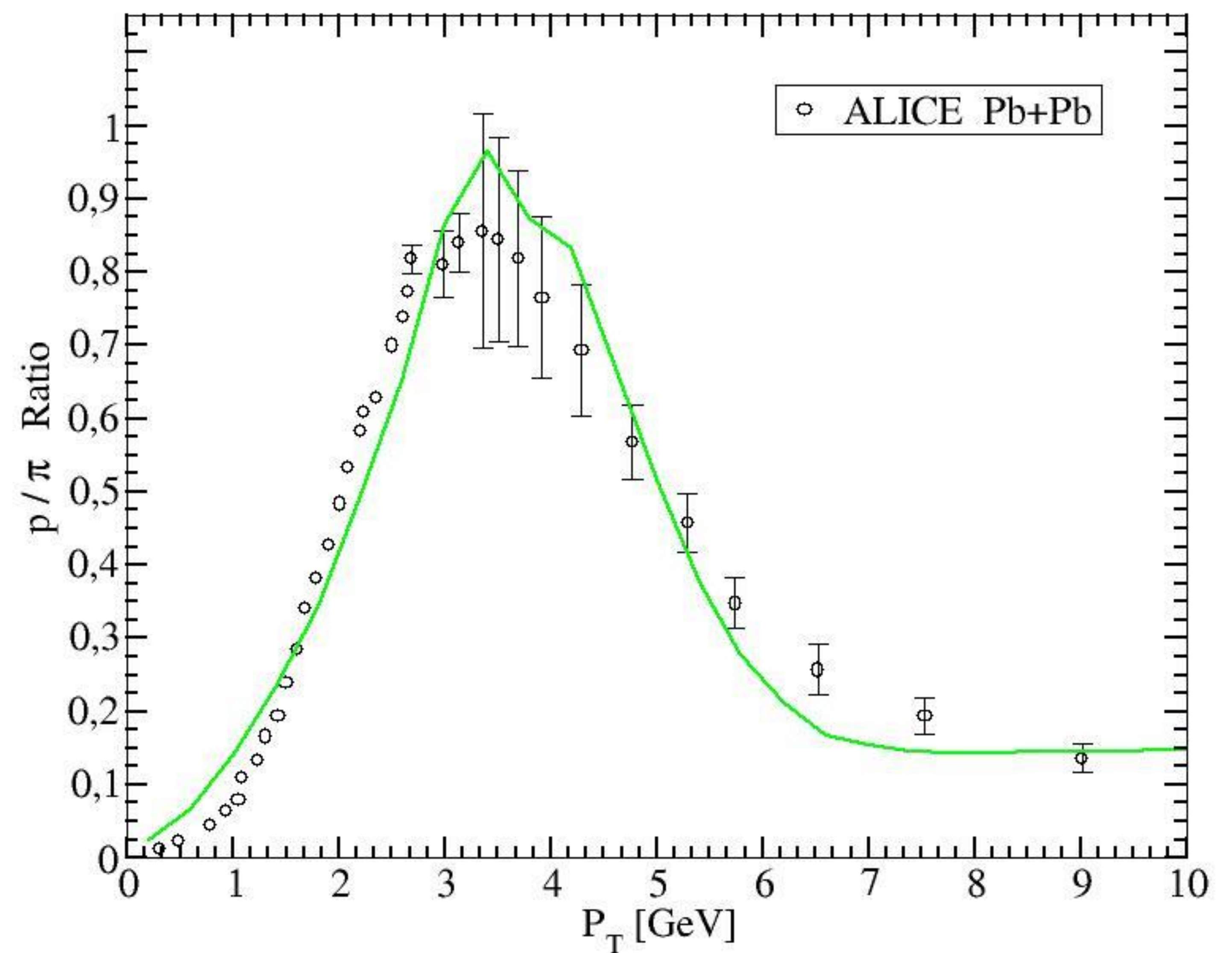
LHC - Ratios


ALICE Pb+Pb
p / π Ratio
P_T [GeV]
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
0
1
2
3
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5
6
7
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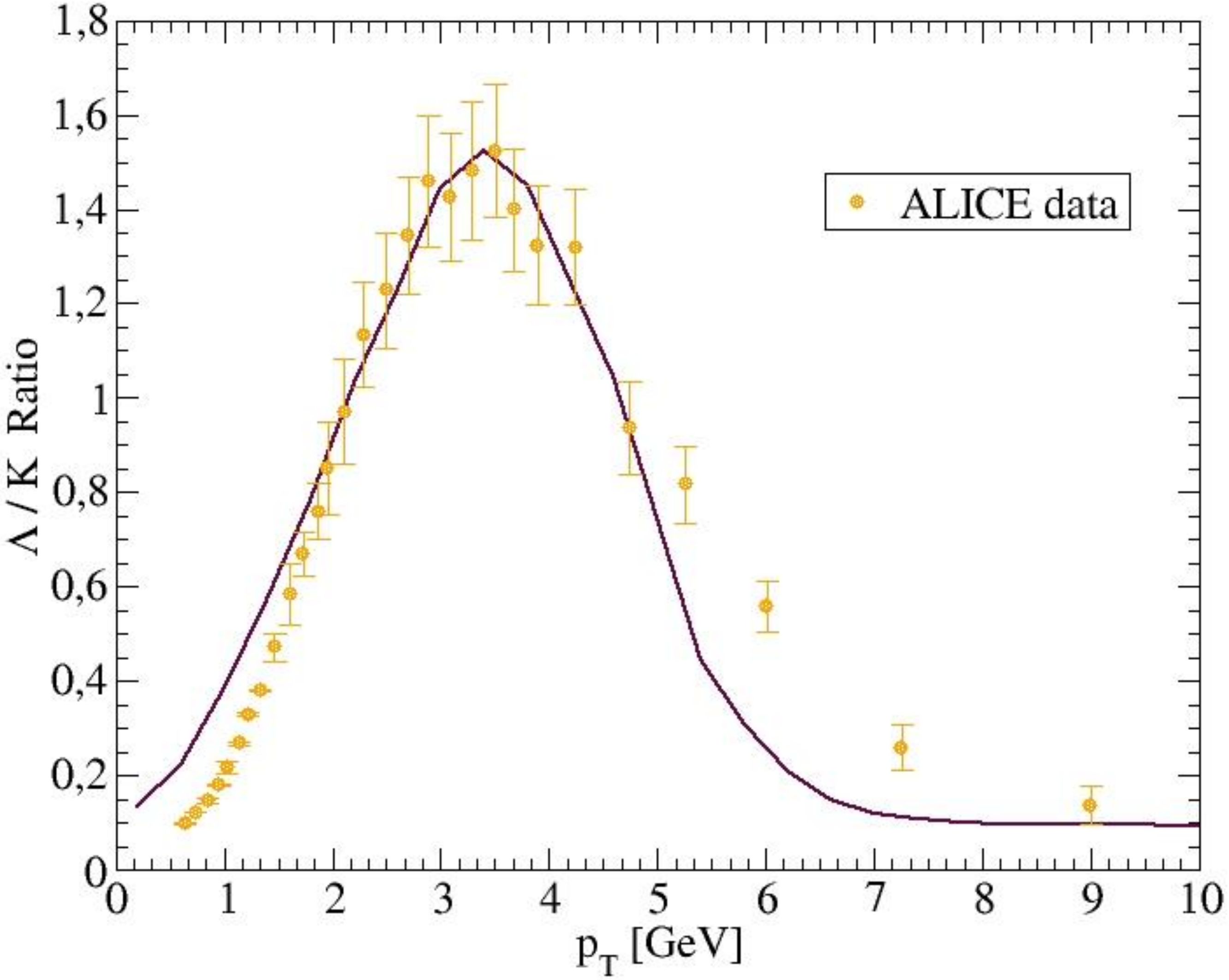
9
10

LHC – Ratios



1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
Λ / K Ratio
0
1
2
3
4
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6
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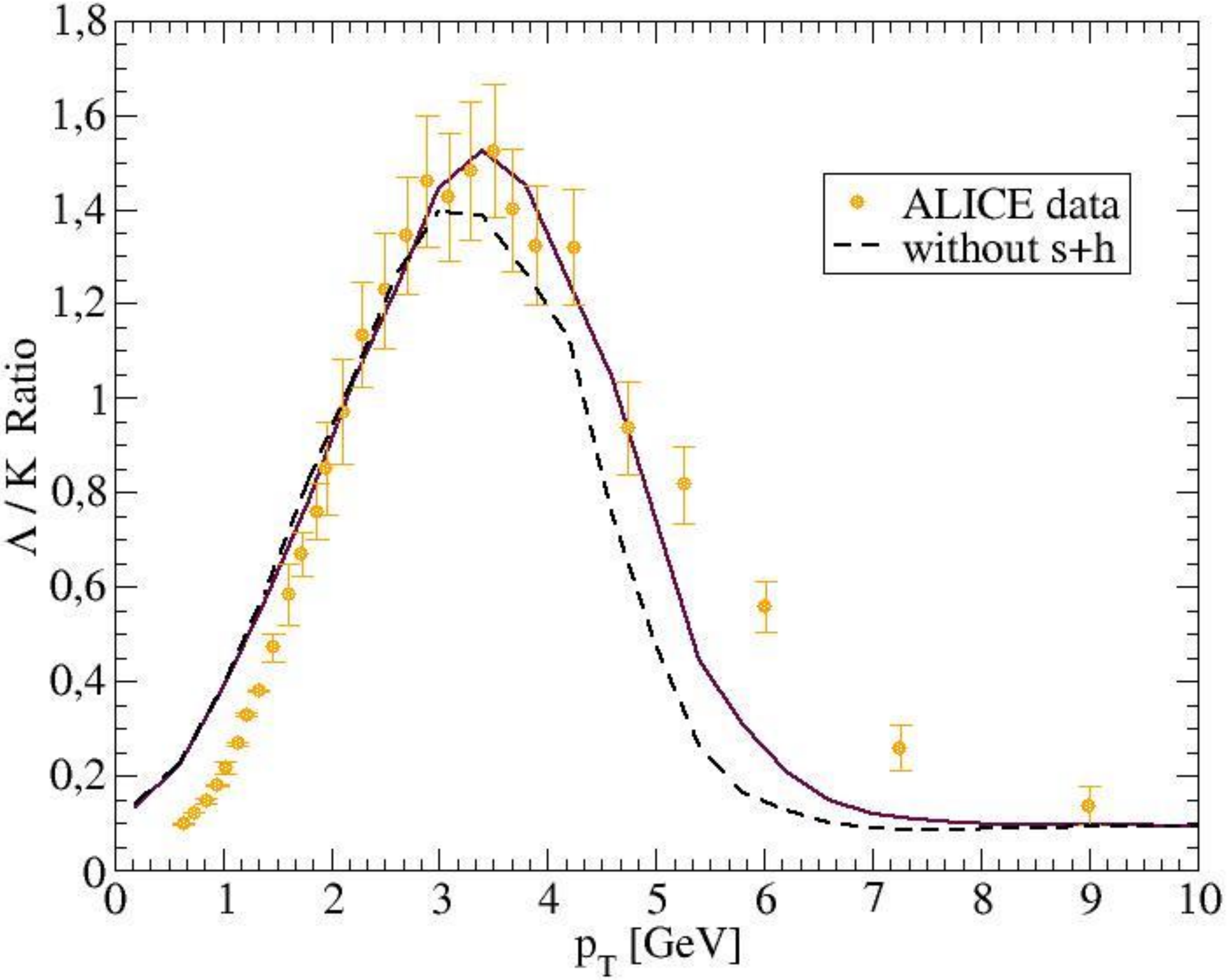
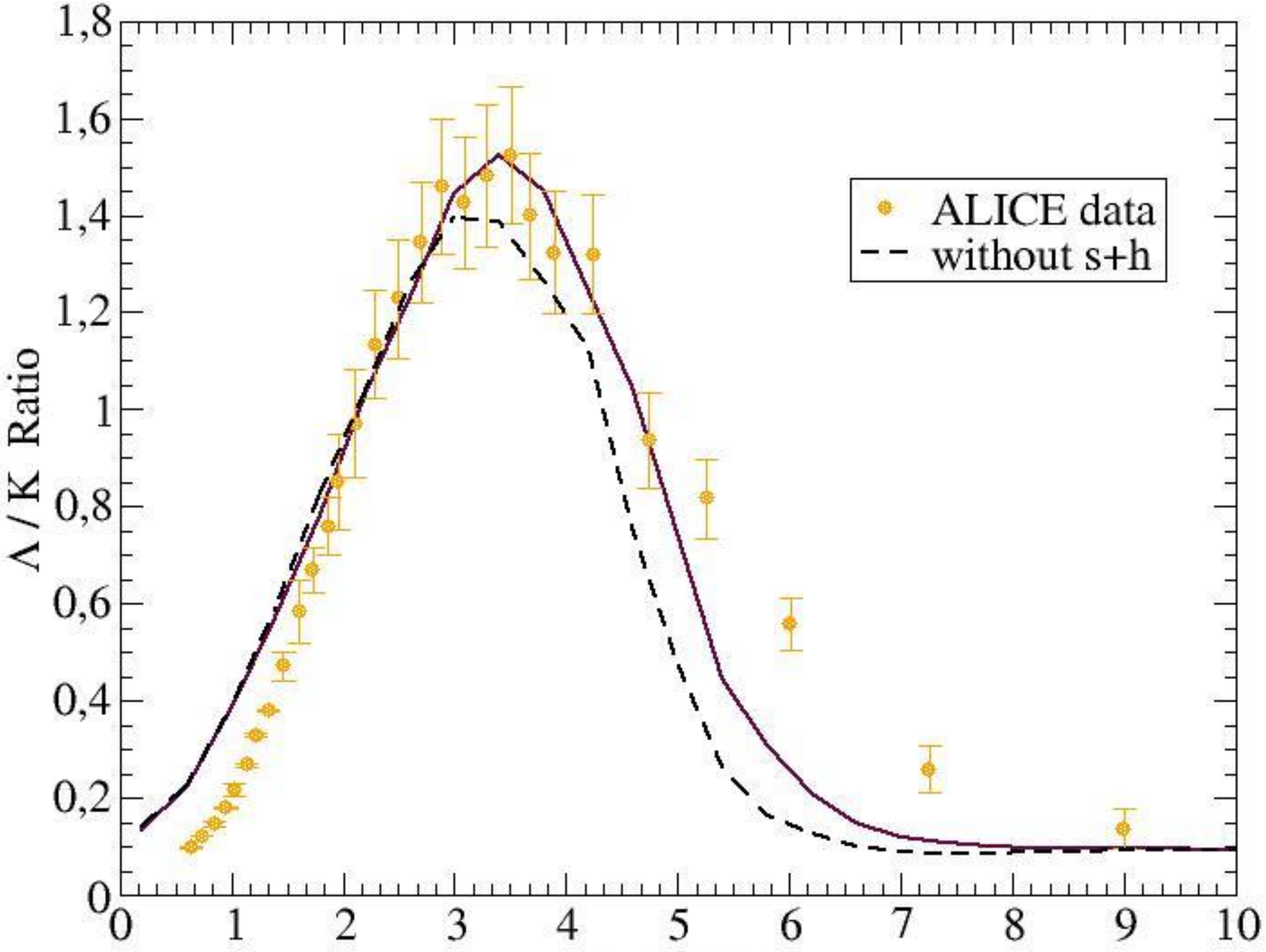
9
10
p_T [GeV]
ALICE data

LHC – Ratios


1,8
1,6
1,4
1,2
1
0,8
0,6
0,4
0,2
0
Λ / K Ratio
0
1
2
3
4
5
6
7
8
9
10
p_T [GeV]
ALICE data
without s+h

LHC – Ratios



K. C. Han, R. J. Fries, and C. M. Ko, J.Phys.Conf.Ser.420, 012044 (2013), 1209.1141.

Elliptic Flow and v_3

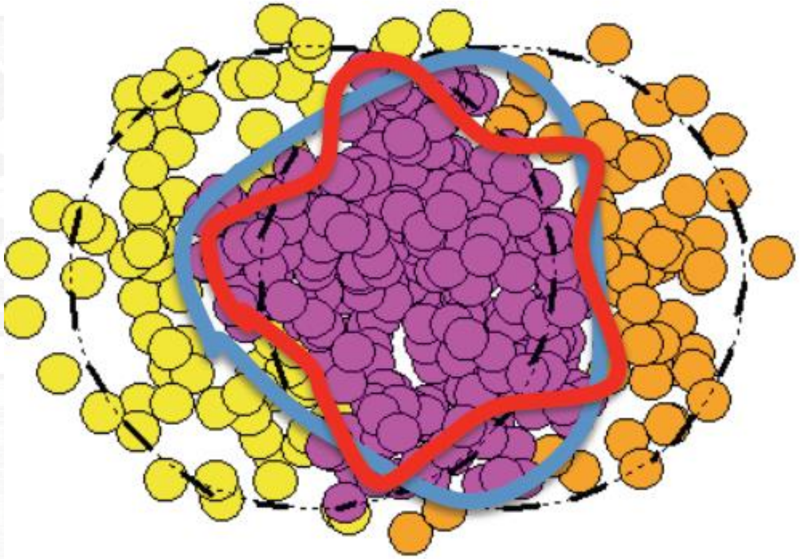
- Fourier expansion of the azimuthal distribution

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

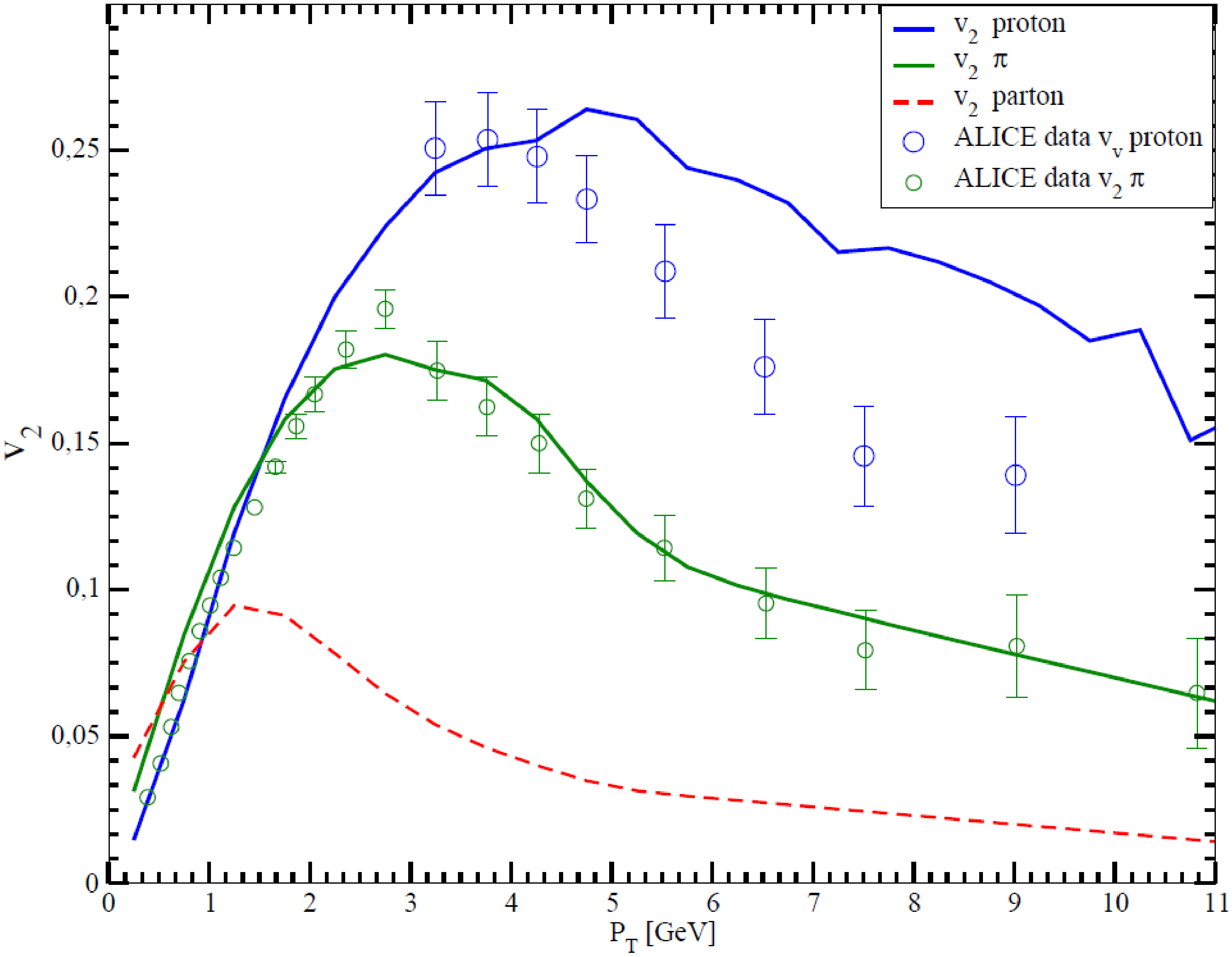
n=2　Elliptic flow

momentum　anisotropy　in the transverse plane

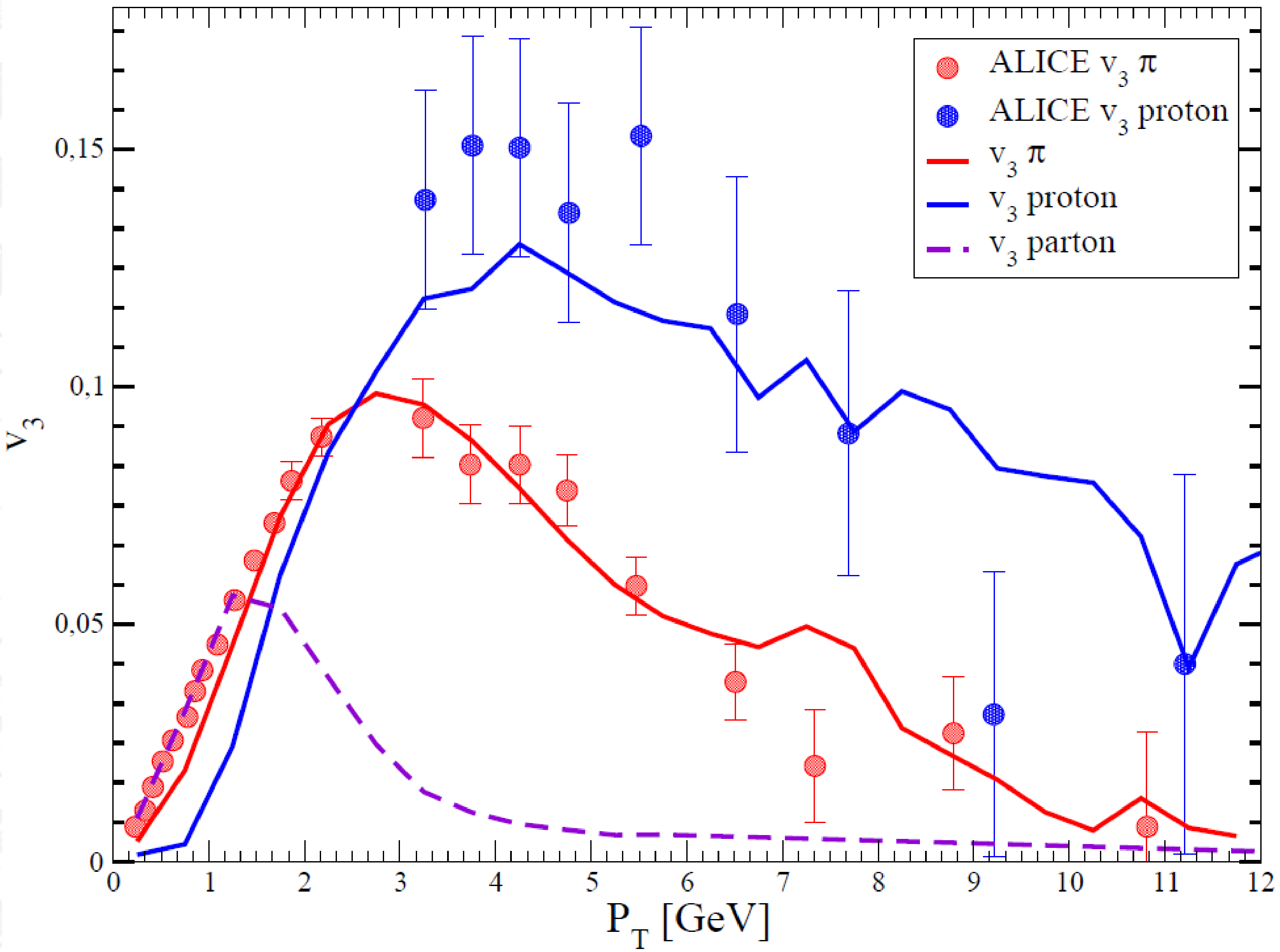
Fluctuations → n=3



Elliptic Flow – LHC



v_3 – LHC


ALICE v_3 π
ALICE v_3 proton
v_3 π
v_3 proton
v_3 parton
v_3
0
0,05
0,1
0,15
0
1
2
3
4
5
6
7
8
9
10
11
12
P_T [GeV]

Summary

- Good agreement with RHIC & LHC data
  - π, p, k, Λ spectra
  - ratio peak shift at LHC
  - splitting v_2 and v_3

Outlooks

- other particles (ϕ, Ξ, Ω)
- Heavy quarks
- other centrality
- Next order in v_n

$\Delta_{p\,\Omega}$? $rms_{\Omega} < rms_{p}$

Checked with 0.7 fm

Fragmentation needed