Does HBT interferometry probe thermalization?

Clément Gombeaud, Tuomas Lappi and J-Y Ollitrault
IPhT Saclay

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Outline

- Introduction- the HBT Puzzle at RHIC
- Motivation of our study
- Transport model
  - Numerical solution of the Boltzmann equation
  - Dimensionless numbers

Gombeaud JYO Phys. Rev C 77, 054904

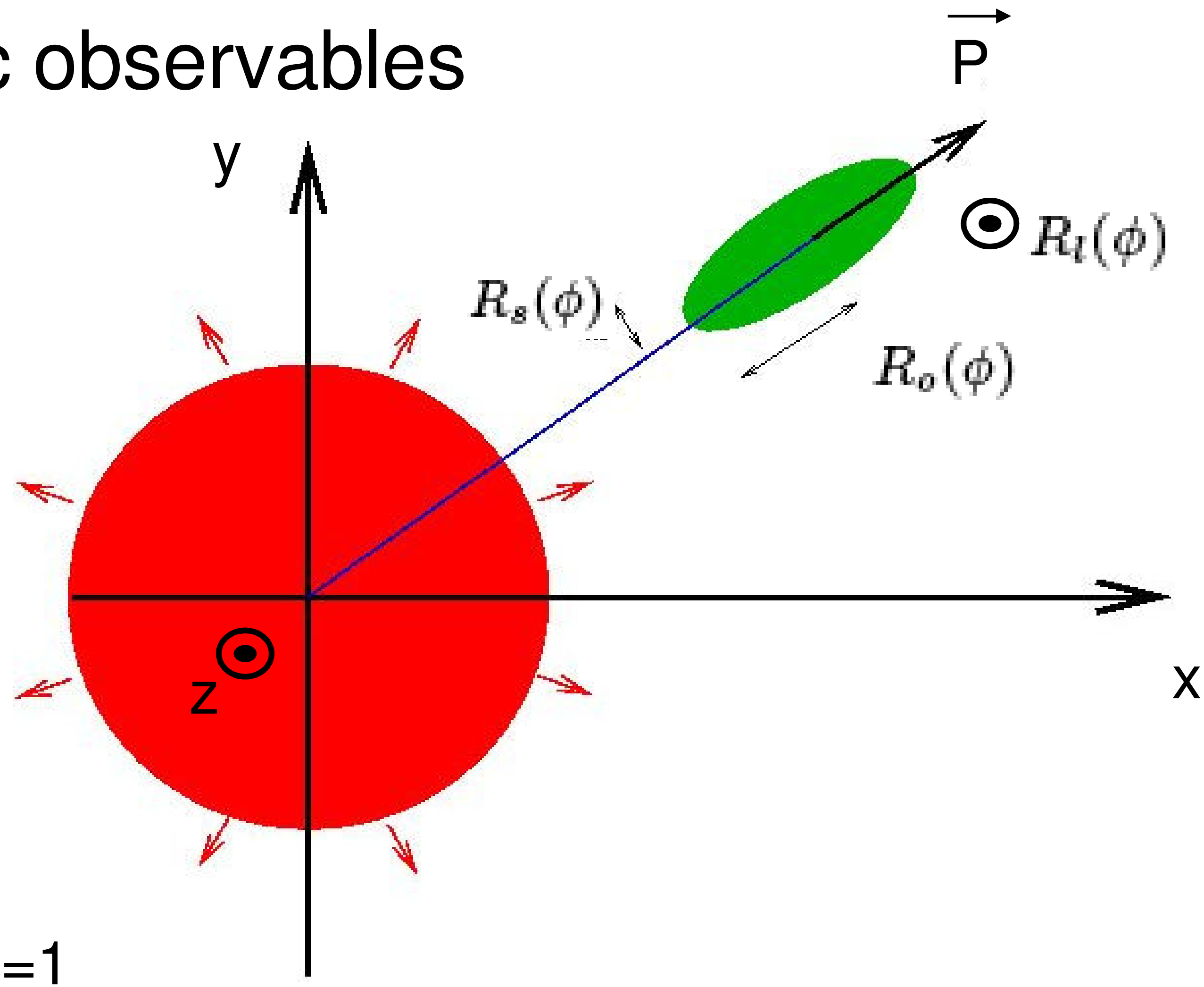
- HBT for central HIC
  - Boltzmann versus hydro
  - Partial solution of the HBT-Puzzle
  - Effect of the EOS

Gombeaud Lappi JYO Phys. Rev. C79, 054914

- Azimuthally sensitive HBT (AzHBT)
- Conclusions

Introduction

- Femtoscopic observables



HBT puzzle:

Experiment $R_o/R_s=1$
Ideal hydro $R_o/R_s=1.5$

Motivation

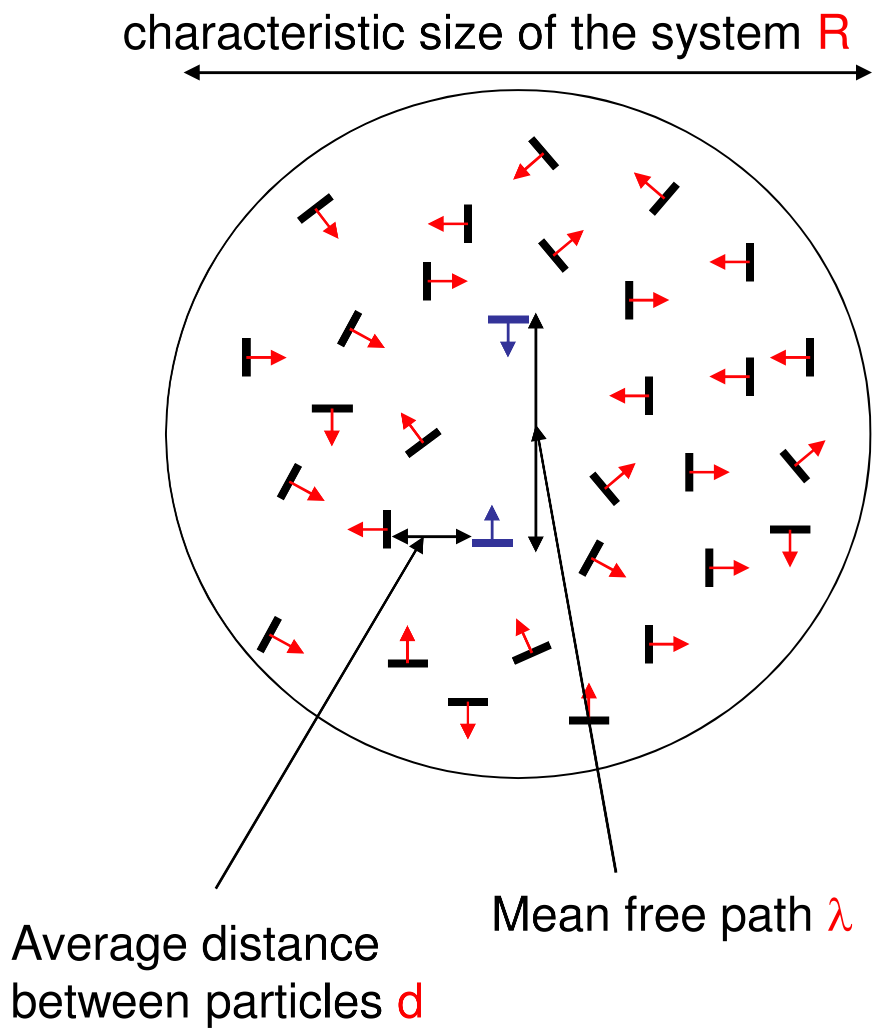
- Ideal hydrodynamics gives a good qualitative description of soft observables in ultrarelativistic heavy-ion collisions at RHIC
- But hydro is unable to quantitatively reproduce data: Full thermalization not achieved

- Using a transport simulation, we study the sensitivity of the HBT radii to the degree of thermalization, and if partial thermalization can explain the HBT puzzle

Solving the Boltzmann equation

- The Boltzmann equation describes the dynamics of a dilute gas *statistically,* through its 1-particle phase-space distribution f(x,t,p)
- Dilute means ideal gas equation of state (“conformal”)
- A dilute gas can behave as an ideal fluid if the mean free path is small enough
- Additional simplifications: 2+1 dimensional geometry (transverse momenta only), massless particles
- The Monte-Carlo method solves this equation by
  - drawing *randomly* the initial positions and momenta of particles according to the phase-space distribution
  - following their trajectories through 2 to 2 elastic collisions
  - *averaging* over several realizations.

Dimensionless quantities



We define 2 dimensionless quantities

- Dilution $D=d/\lambda$
- Knudsen $K=\lambda/R\sim 1/N_{coll\_part}$

Boltzmann requires $D<<1$

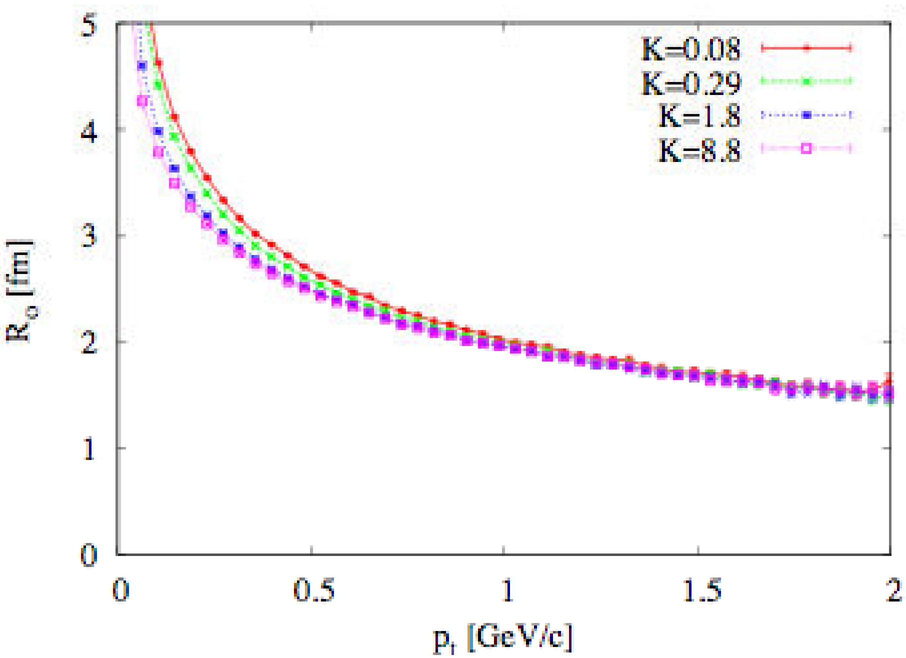
Ideal hydro requires $K<<1$

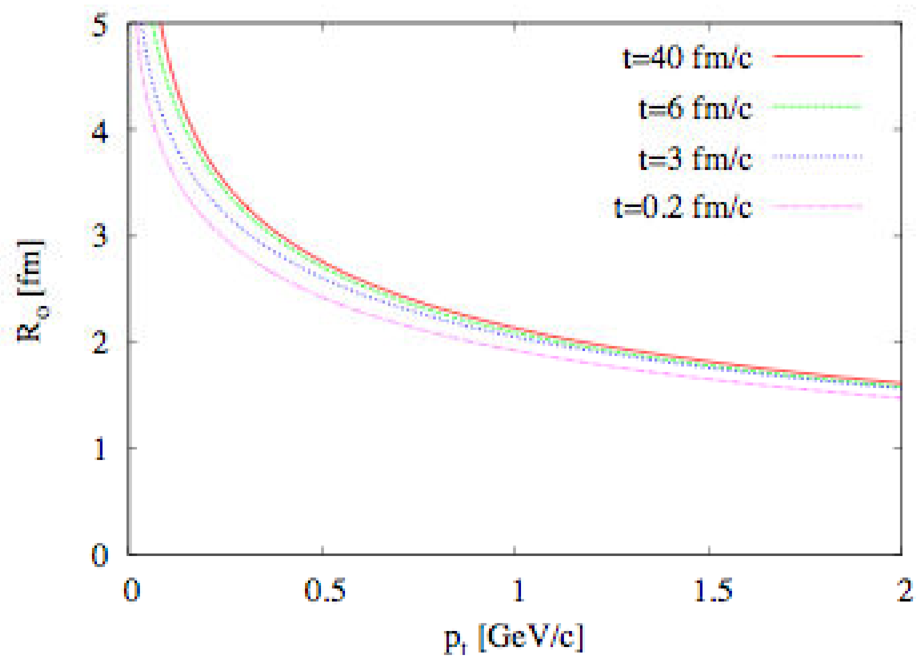
Our previous study of v_2 in Au-Au collisions at RHIC suggests

Central collisions ⇔ $K=0.3$

Drescher & al, Phys. Rev. C**76,** 024905 (2007)

Boltzmann versus hydro





Small sensitivity of Pt dependence to thermalization

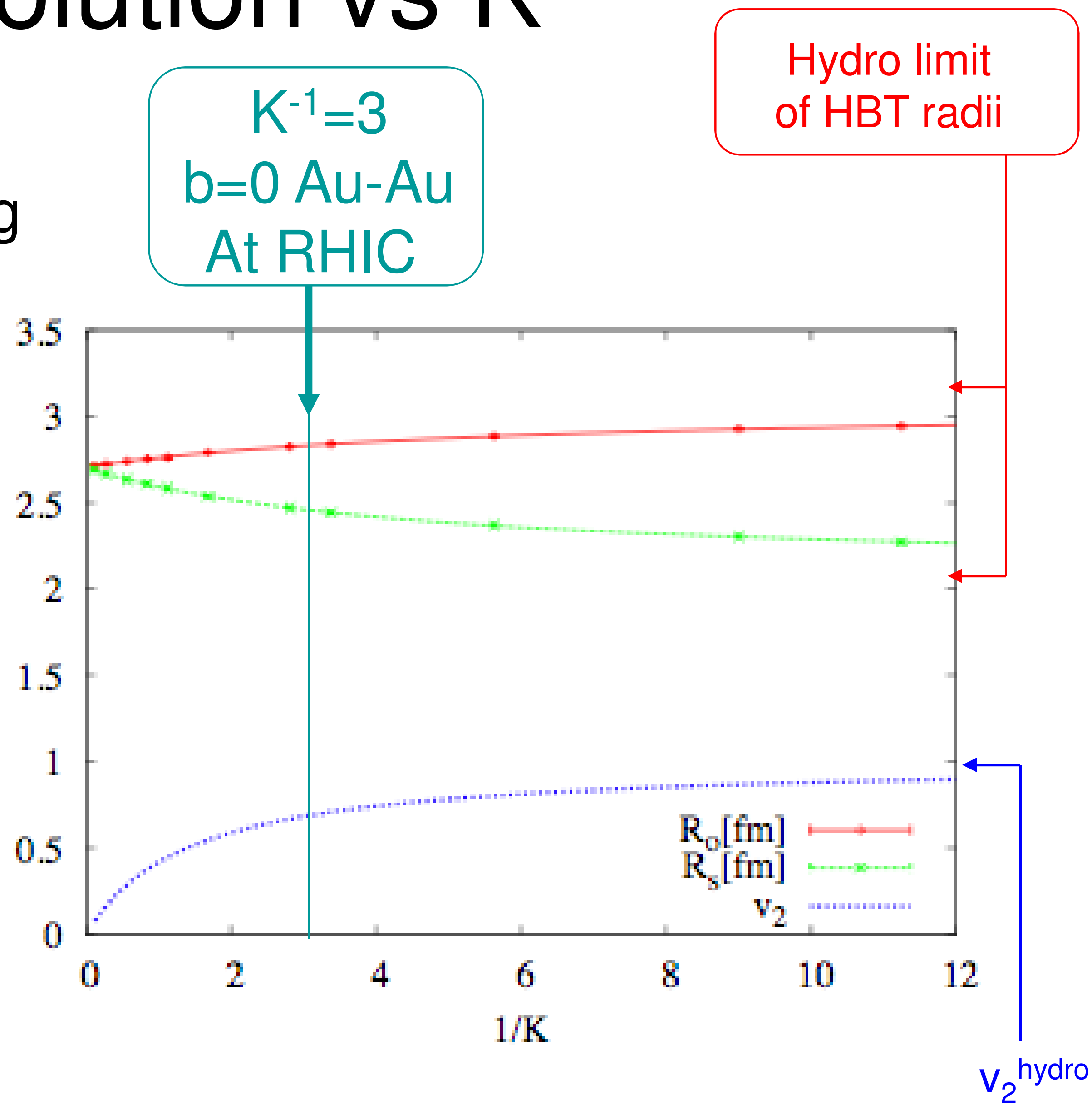
Note also that decreasing the mean free path in Boltzmann = Increasing the freeze-out time in ideal hydro

Evolution vs K^{-1}

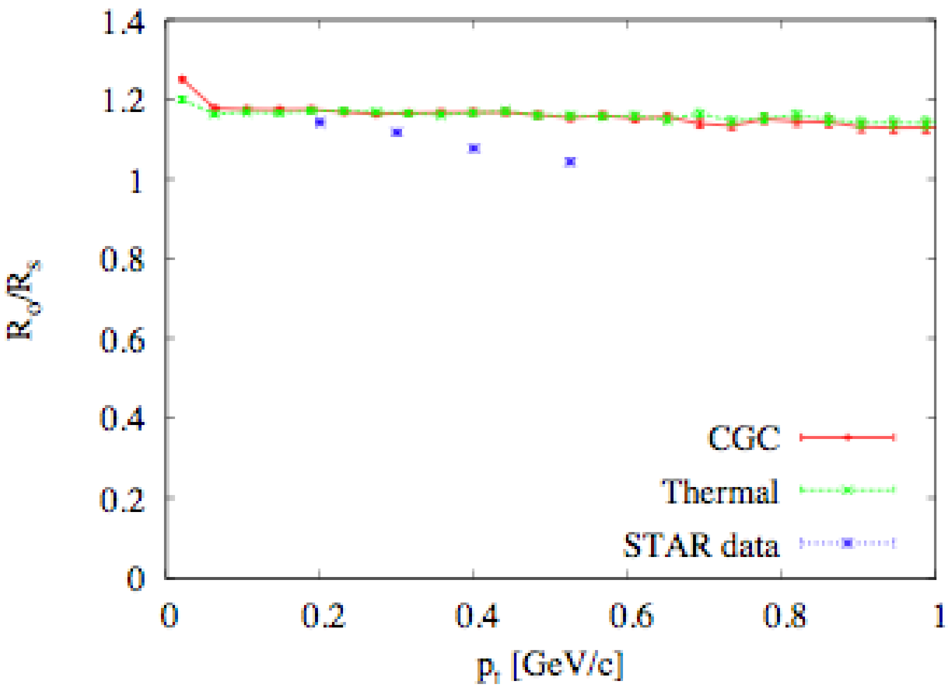
Solid lines are fits using
$F(K)=F0+F1/(1+F2*K)$

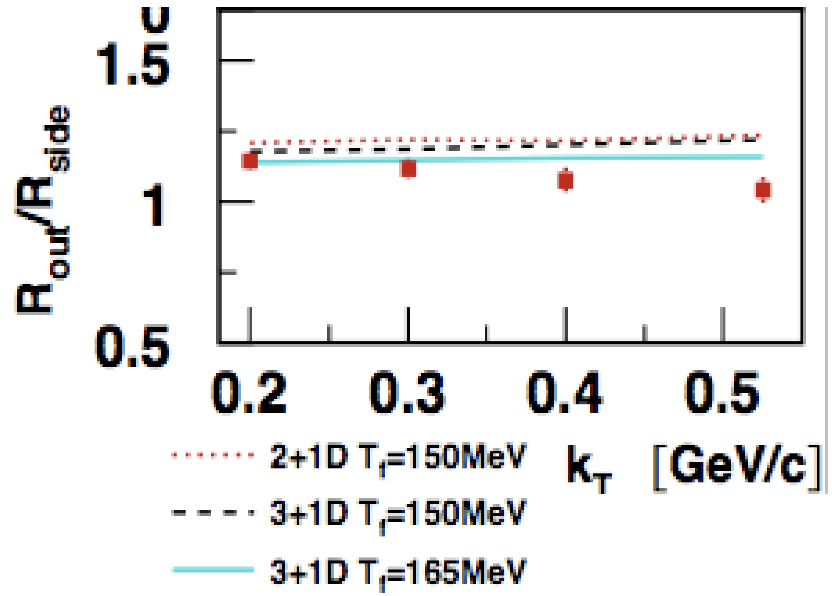
The larger F2, the slower the convergence to hydro ($K=0$ limit)

v_2 is known to converge slowly to hydro, but R_o and R_s converge even more slowly (by a factor ~3)



Partial solution of the HBT puzzle





Piotr Bozek & al arXiv:0902.4121v1

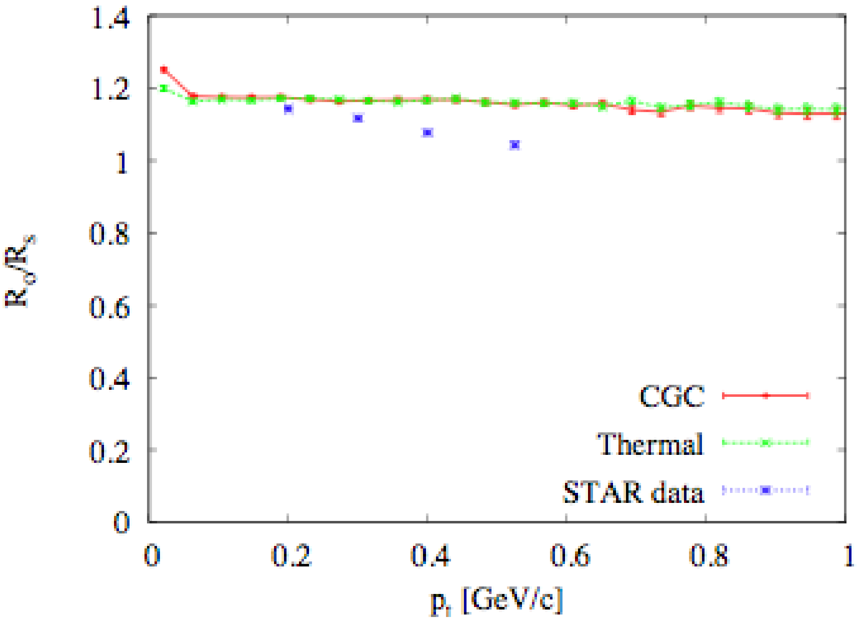
Partial thermalization (=few collisions per particles) explains most of the HBT Puzzle

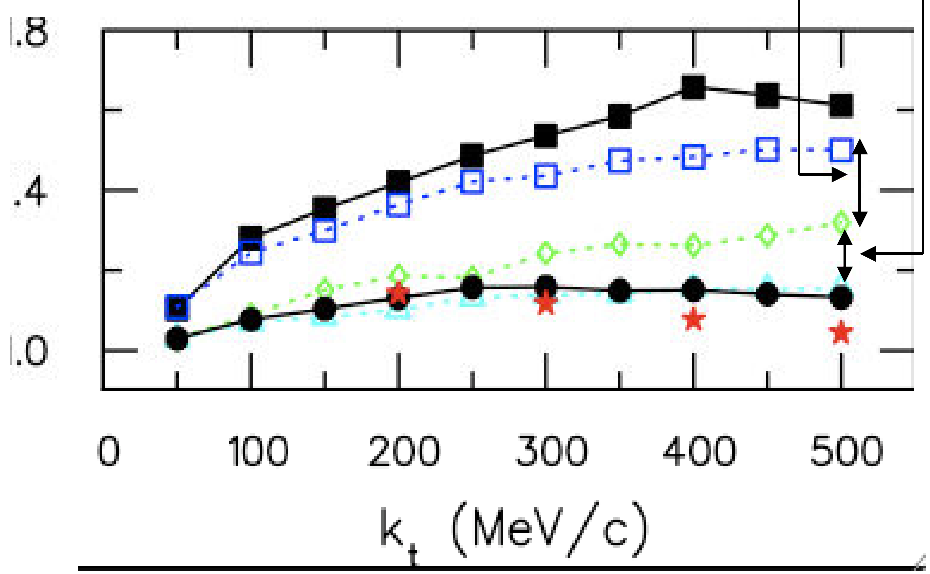
Note: similar results for Boltzmann with K=0.3 (inferred from the centrality dependence of v_2) and for the short lived ideal hydro of Bozek et al

Effect of the EOS

Viscosity⇔Partial thermalization

Realistic EOS





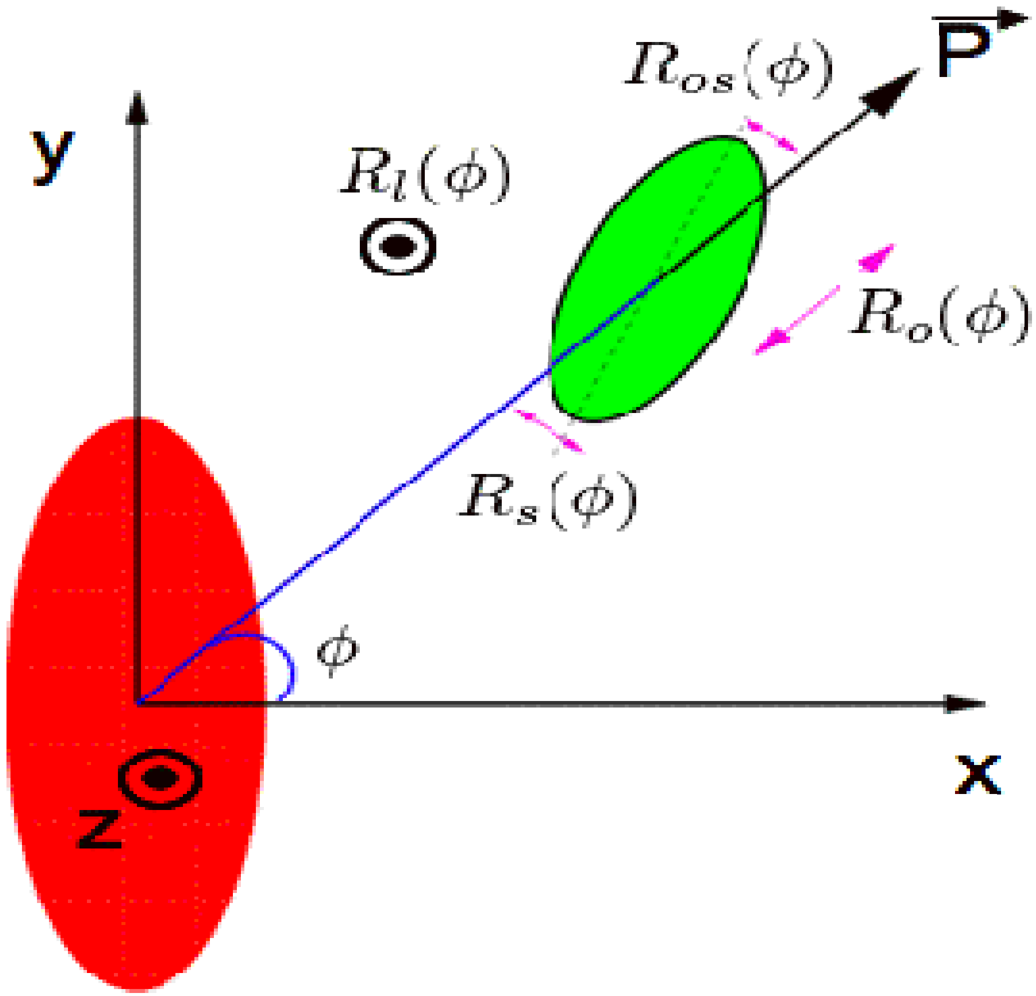
S. Pratt PRL102, 232301

Our Boltzmann equation implies Ideal gas EOS (ε=3P)

Pratt concludes that EOS is more important than viscosity

We find that viscosity (K=0.3) solves most of the puzzle

AzHBT Observables

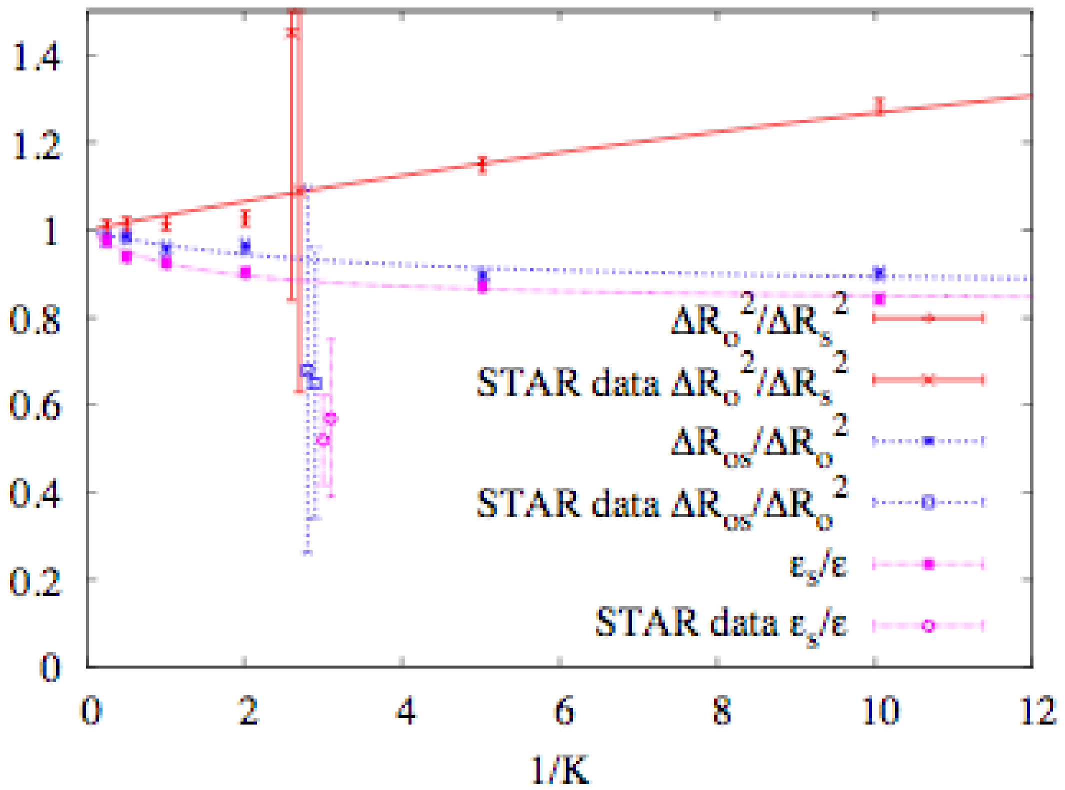


Define
Delta R=R(0)-R(pi/2) :
Magnitudes of azimuthal oscillations of HBT radii.

How do they evolve with the degree of thermalization?

How does the HBT eccentricity compare with the initial eccentricity?

Evolution vs K^{-1}



Our $\Delta R_o^2/\Delta R_s^2$ evolves in the same way as R_o/R_s. Data OK

Our ε_s remains close to the initial ε even in the hydro limit

But data show that $\varepsilon_s < \varepsilon$:is this an effect of the soft EOS?

Conclusions

- The pt dependence of HBT radii is not a signature of the hydro evolution
- The hydro prediction $R_o/R_s=1.5$ requires an unrealistically small viscosity
- Partial thermalization alone explains most of the "HBT Puzzle".
- The most striking feature of data: the eccentricity seen in HBT radii is twice smaller than the initial eccentricity. Not explained by collective flow alone.

Backup slides

Dimensionless numbers

- Parameters:
  - Transverse size R
  - Cross section sigma (~length in 2d!)
  - Number of particles N
- Other physical quantities
  - Particle density $n=N/R^2$
  - Mean free path lambda=1/(sigma*n)
  - Distance between particles $d=n^{-1/2}$
- Relevant dimensionless numbers:
  - Dilution parameter $D=d/\lambda=(\sigma/R)N^{-1/2}$
  - Knudsen number $Kn=\lambda/R=(R/\sigma)N^{-1}$

The hydrodynamic regime requires both D«1 and Kn«1.

Since $N=D^{-2}Kn^{-2}$,

a huge number of particles must be simulated.

(even worse in 3d)

The Boltzmann equation requires D«1

This is achieved by increasing N (parton subdivision)

Viscosity and partial thermalization

- Non relativistic kinetic theory

$$\frac{\eta}{\rho} \approx \lambda \upsilon_{therm}$$

- The Israel-Stewart theory of viscous hydro can be viewed as an expansion in powers of the Knudsen number

Implementation

- Initial conditions: Monte-Carlo sampling
  - Gaussian density profile (~ Glauber)
  - 2 models for momentum distribution:
    - *Thermal Boltzmann* (with $T=n^{1/2}$)

$$\frac{dN}{dp^2dx^2} = e^{-\frac{p}{T(x,y)}}$$

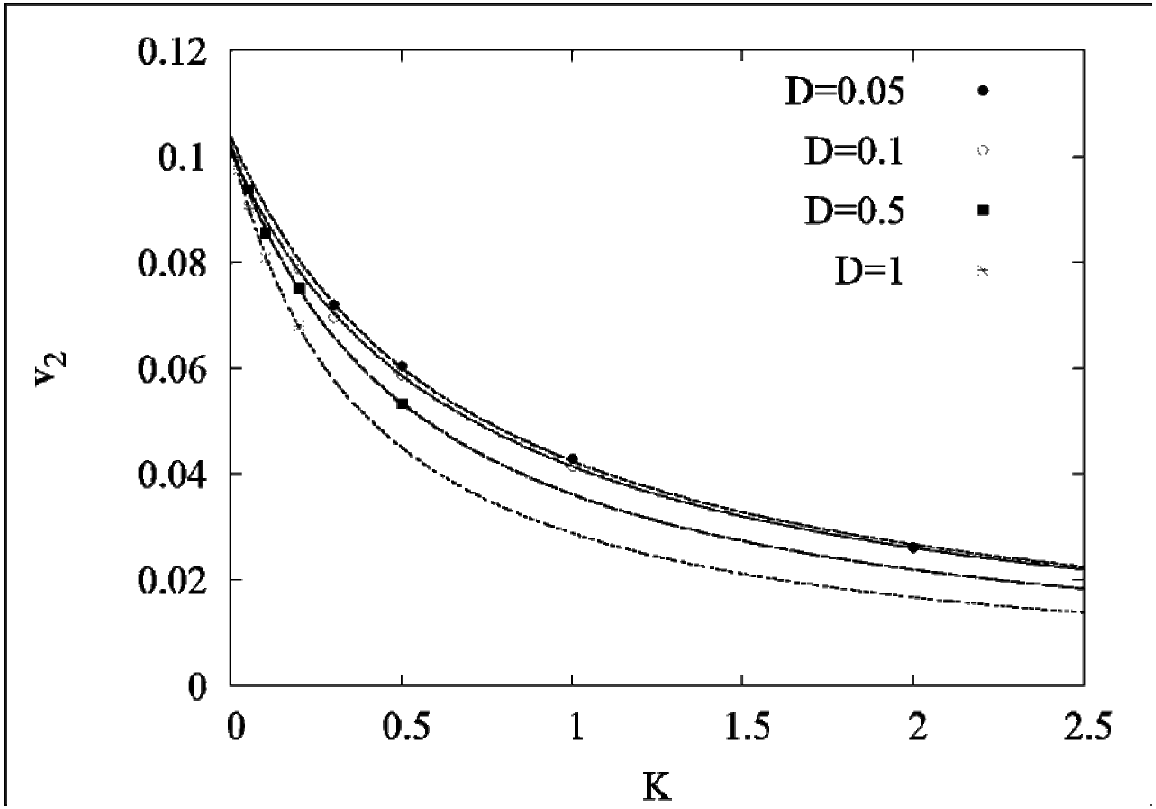
    - *CGC* *(*A. Krasnitz & al, Phys. Rev. Lett. **87** 19 (2001)*)*
      *(*T. Lappi Phys. Rev. C. **67** (2003) *)*

$$\frac{dN}{dp^2dx^2} = \begin{cases} a_1[e^{\frac{p}{bQs}} - 1]^{-1} & (p/Qs) < 1.5 \\ a_2 \log(4\pi p/Qs)(p/Qs)^{-4} & (p/Qs) > 1.5 \end{cases}$$

With a1=0.131, a2=0.087, b=0.465 and $Qs=n^{1/2}$

- Ideal gas EOS

Elliptic flow versus K



$$v_2 = v_2^{hydro}/(1+1.4\ K)$$

Smooth convergence to ideal hydro as K goes to 0

The centrality dependence of v_2 explained

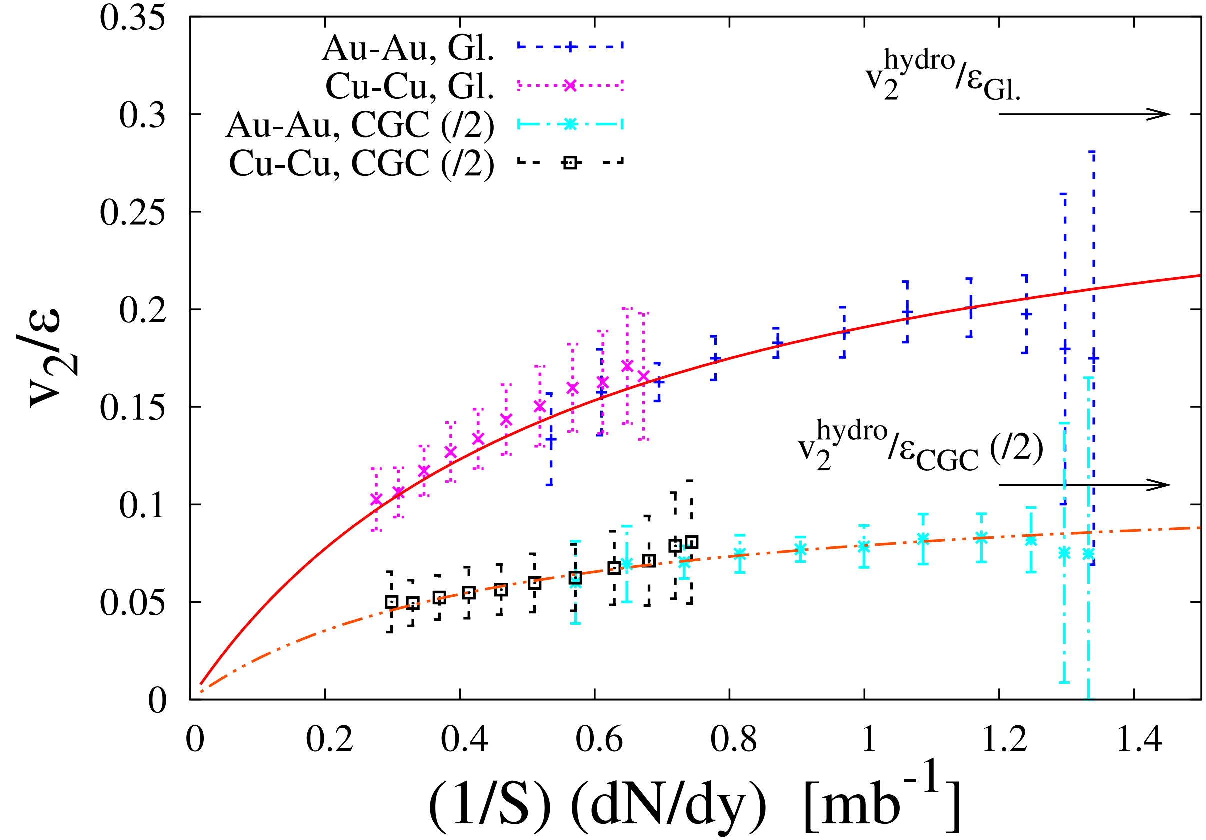
1. Phobos data for v_2
2. epsilon obtained using Glauber or CGC initial conditions +fluctuations
3. Fit with

$v_2 = v_2^{hydro}/(1+1.4\ K)$

assuming

$1/Kn = (alpha/S)(dN/dy)$

with the fit parameters alpha and v_2^{hydro}/epsilon

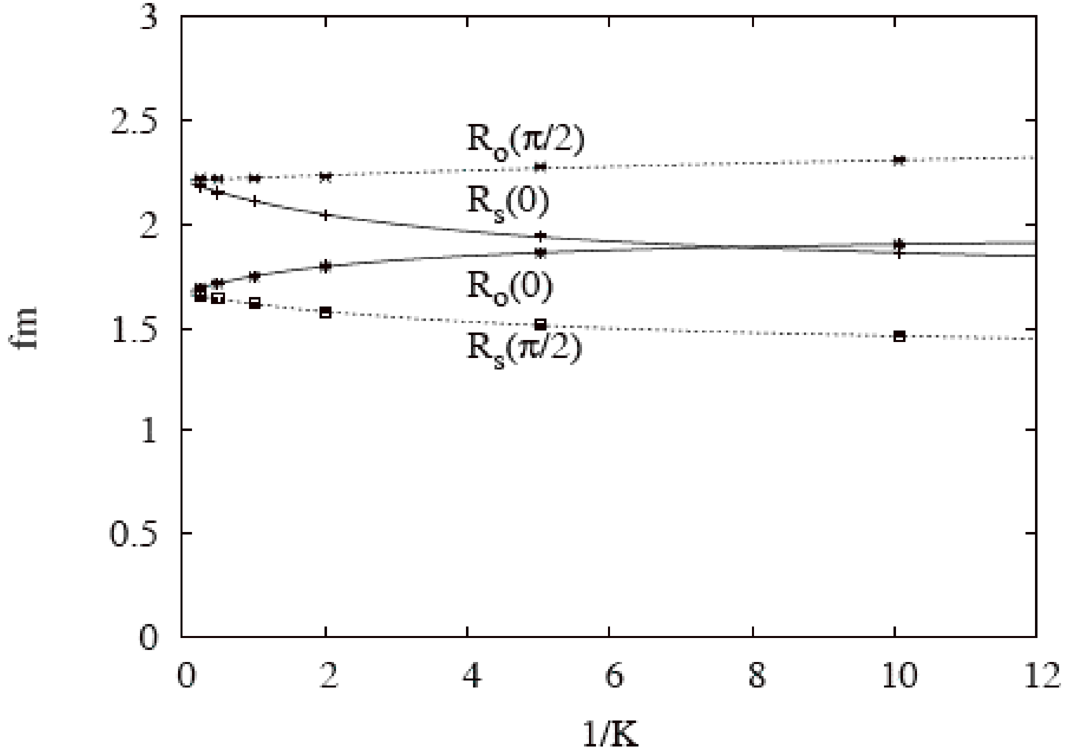


(Density in the transverse plane)

K~0.3 for central Au-Au collisions

v_2 : 30% below ideal hydro!

AzHBT radii evolution vs K^{-1}



Better convergence to hydro in the direction of the flow

EOS effects

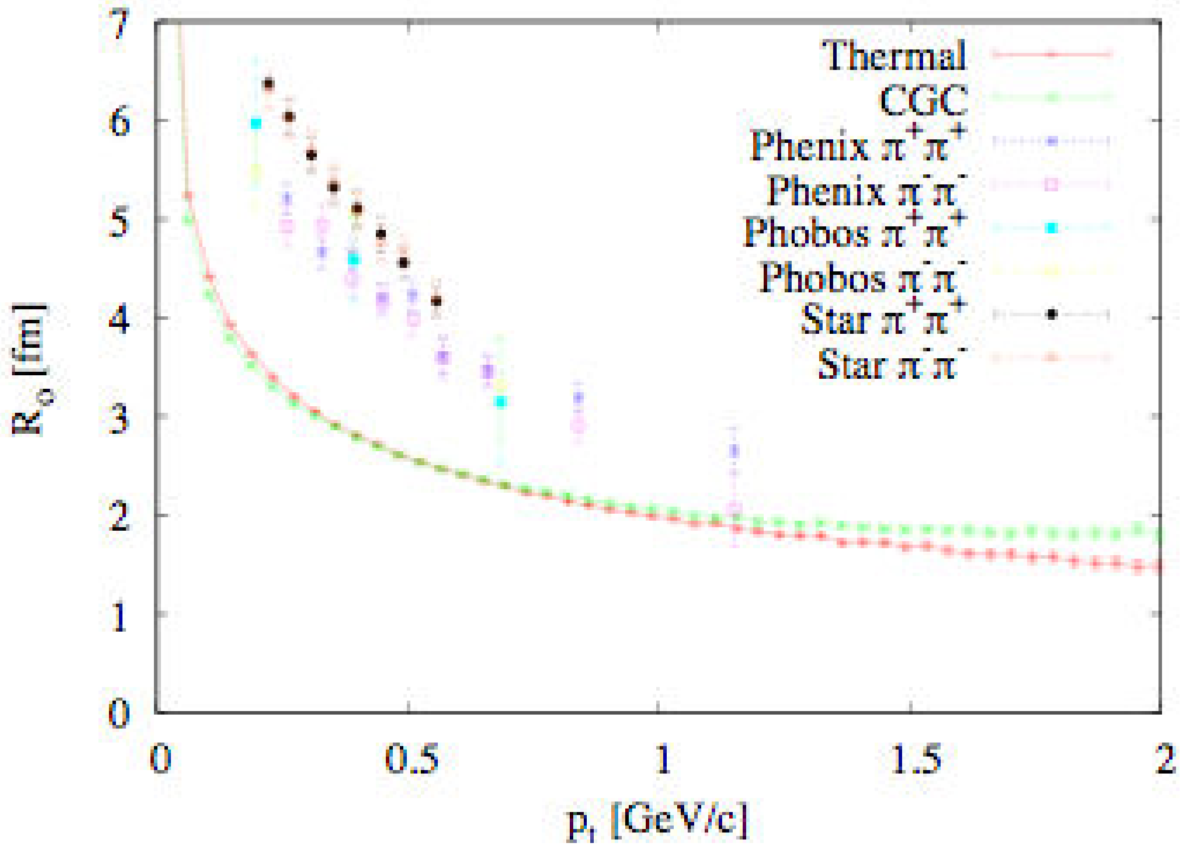
- Ideal gas
  - The HBT volume $R_o R_s R_l$ is conserved

S. V. Akkelin and Y. M. Sinyukov, Phys. Rev. C70, 064901 (2004)

- In hot QCD, we know that a dramatic change occurs near 170 MeV
  - Entropy density s decreases, but total entropy S constant at the transition (constant T)
  - This implies an increase of the volume V at constant T

Hadronization of QGP implies increase of HBT radii

HBT vs data



Thermal
CGC
Phenix π+π+
Phenix π-π-
Phobos π+π+
Phobos π-π-
Star π+π+
Star π-π-
R_o [fm]
p_t [GeV/c]
0
1
2
3
4
5
6
7
0
0.5
1
1.5
2

AzHBT vs data

Pt in [0.15,0.25] GeV 20-30%

	STAR data	our results	
		$K = 0.32$	$K = 0.51$
$\Delta R_o^2/\Delta R_s^2$	1.45 ± 0.61	1.08 ± 0.02	1.05 ± 0.02
$\Delta R_{os}/\Delta R_o^2$	0.68 ± 0.42	0.97 ± 0.03	0.99 ± 0.03
ϵ_s	0.080 ± 0.026	0.205 ± 0.003	0.213 ± 0.005

	STAR data	our results	
		$K = 0.31$	$K = 0.49$
$\Delta R_o^2/\Delta R_s^2$	1.09 ± 0.46	1.14 ± 0.02	1.06 ± 0.02
$\Delta R_{os}/\Delta R_o^2$	0.65 ± 0.31	0.90 ± 0.04	0.92 ± 0.04
ϵ_s	0.086 ± 0.017	0.172 ± 0.005	0.174 ± 0.005

Pt in [0.35,0.45] GeV 10-20%