HBT in Small Collisions

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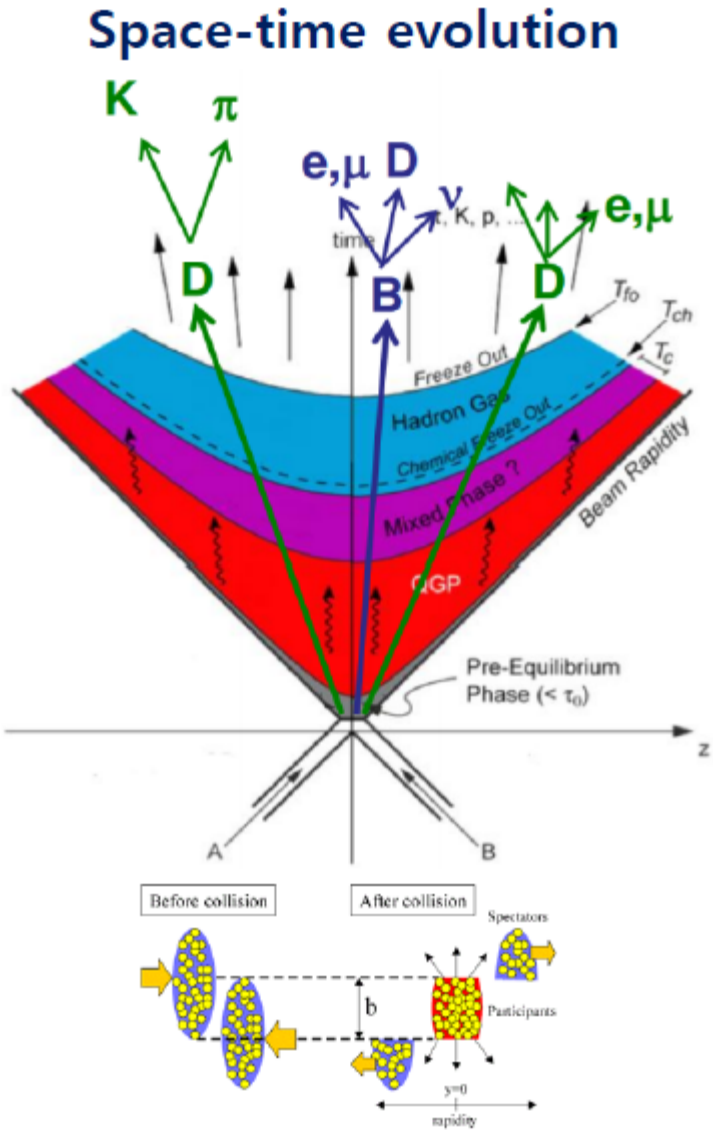
Outline

1. Background
2. ALICE Studies
3. STAR Studies
4. PHENIX Studies
5. Summary

Background



It is generally accepted that in relativistic A-A collisions a QGP medium is formed which signals its presence through long range correlations characteristic of collective flow.

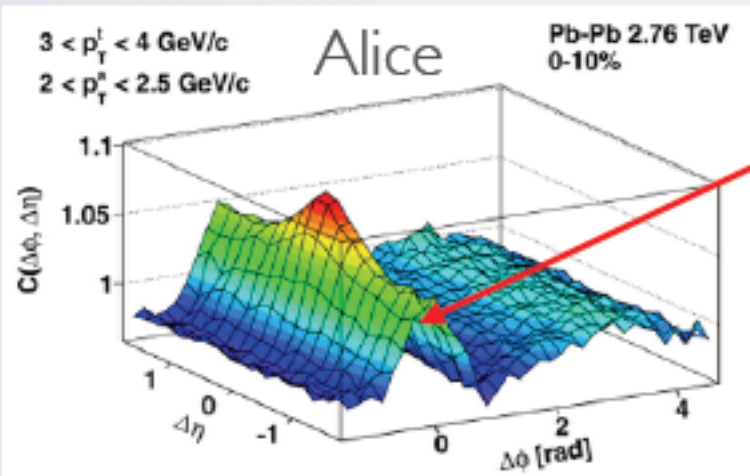
It has also been assumed a priori that p+p and (p,d)+A collisions are not capable of forming such a medium because of the small system size.

To test this assumption recent experiments have focused on looking at long range correlations in p+p and p+A systems.

A favored way of looking for collectivity has been to study long range azimuthal correlations

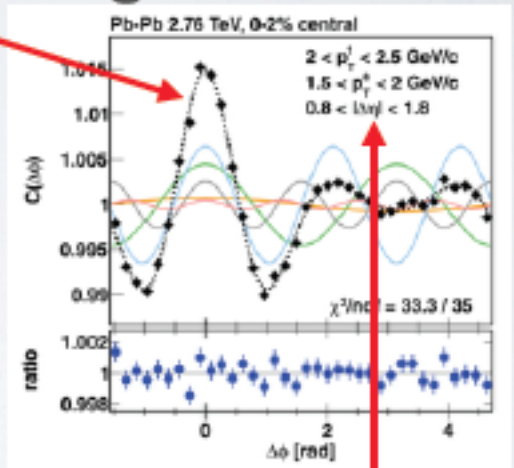
Find the **Δφ** and the **Δη** (the difference in the **azimuth** and the **pseudorapidity**) from each pair of particles measured from the collision

Near Side Ridge



Physics Letters B 708 (2012) 249–264

Fourier Transformation



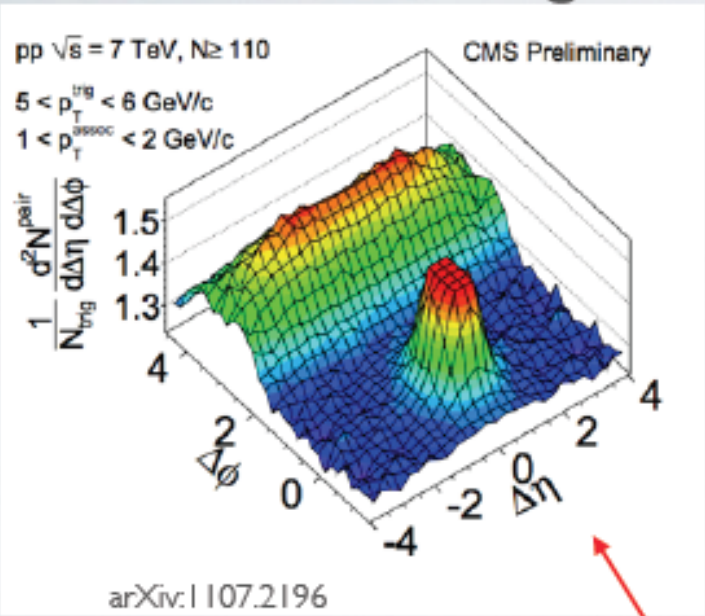
The detector acceptance must be subtracted out.

Cut away from the jet peak at $\Delta\eta = 0$

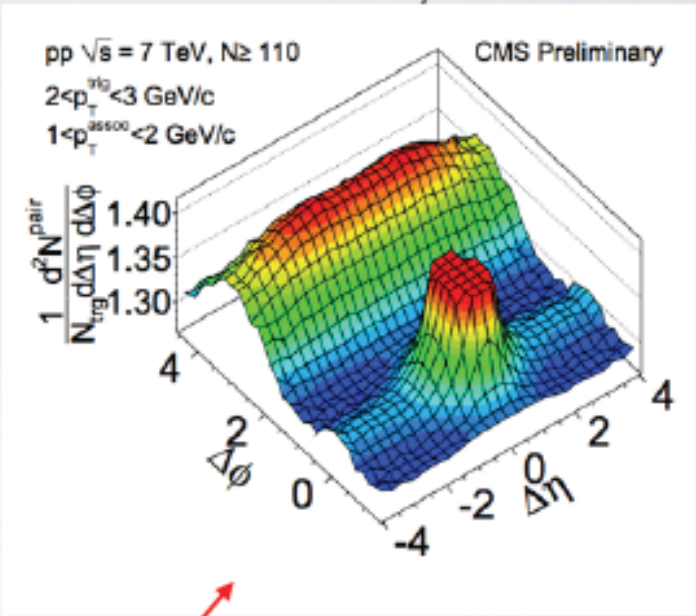
Observation of a near side ridge in central Pb-Pb at 2.76 TeV

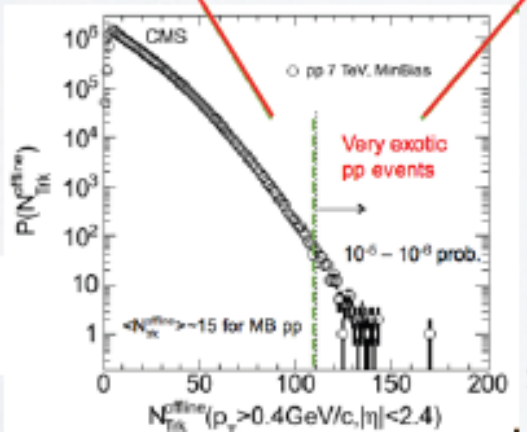
COLLECTIVITY IN P+P COLLISIONS?

Nearside Ridge: evidence of collectivity?



arXiv:1107.2196



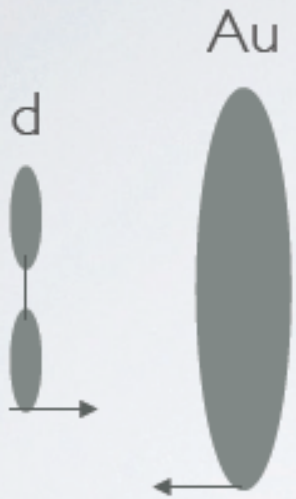


Only seen in rare ultra high multiplicity events

Slide from Wei Lei, Rice University

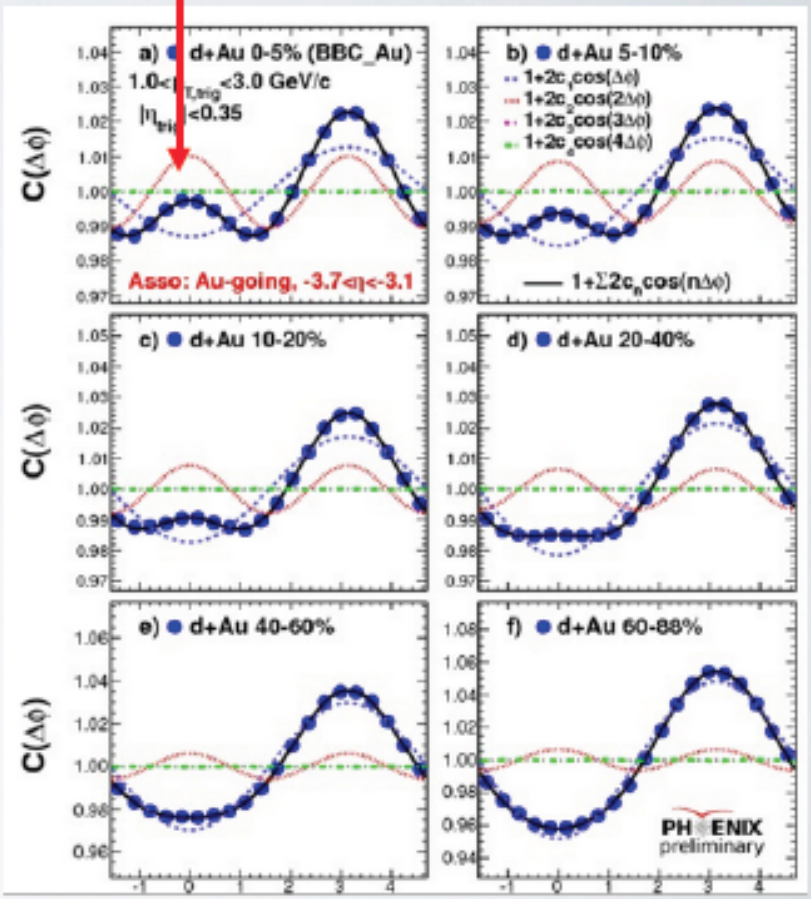
Observation of near side ridge in high multiplicity p-p at 7 TeV

D+AU CORRELATION



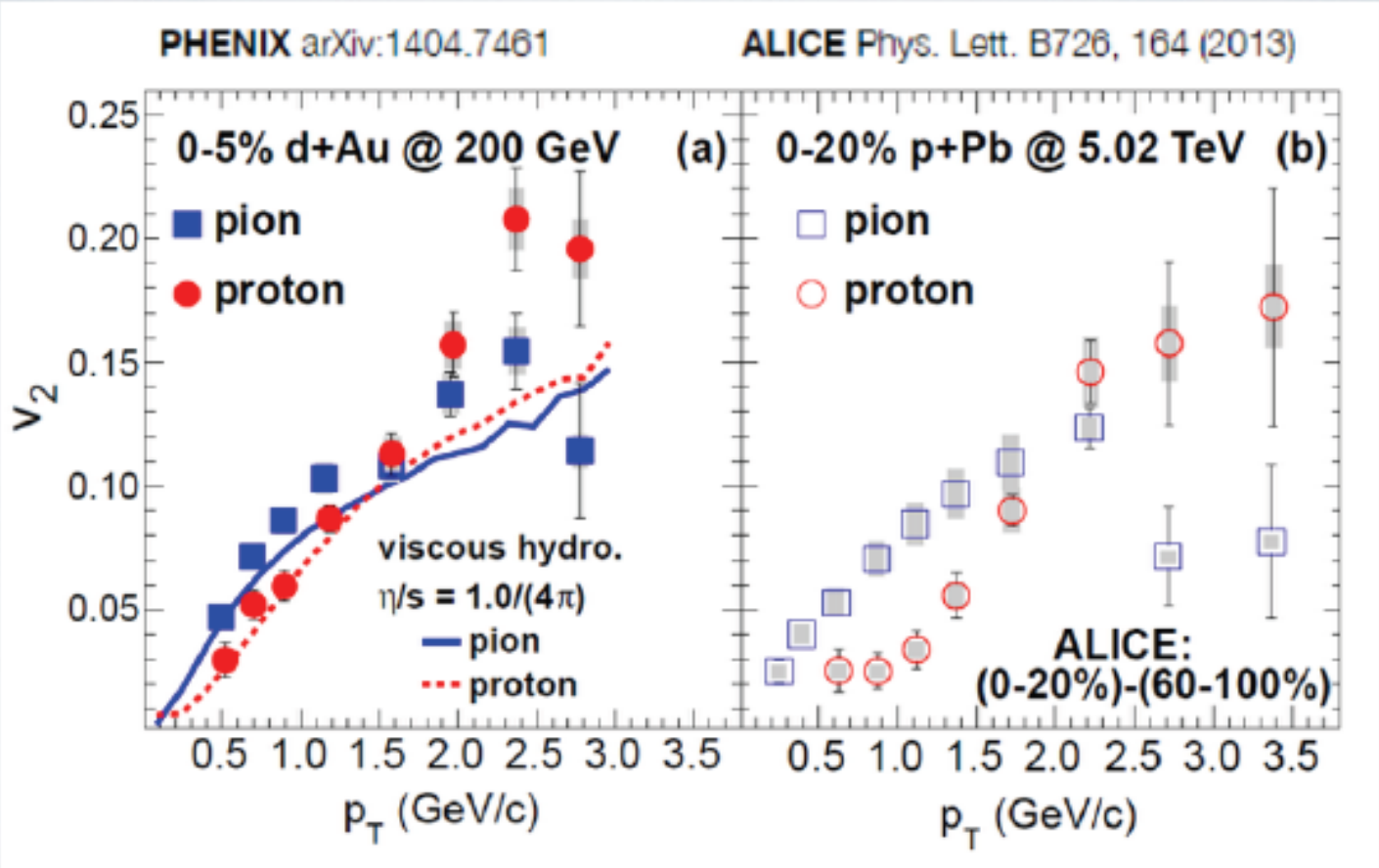
d+Au was thought of as the **control test** to measure cold nuclear matter effects.

Nearside Ridge



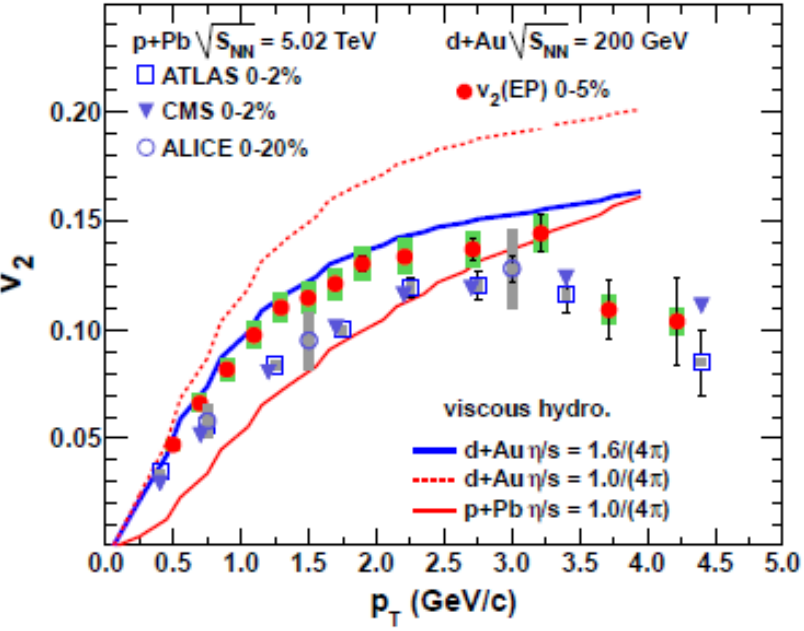
Observation of near side ridge in central 200 GeV d-Au

MASS ORDERING IN D+AU AND P+PB



v2 mass ordering in 200 GeV d+Au and 5.02 TeV p+Pb

Viscous hydro model vs data



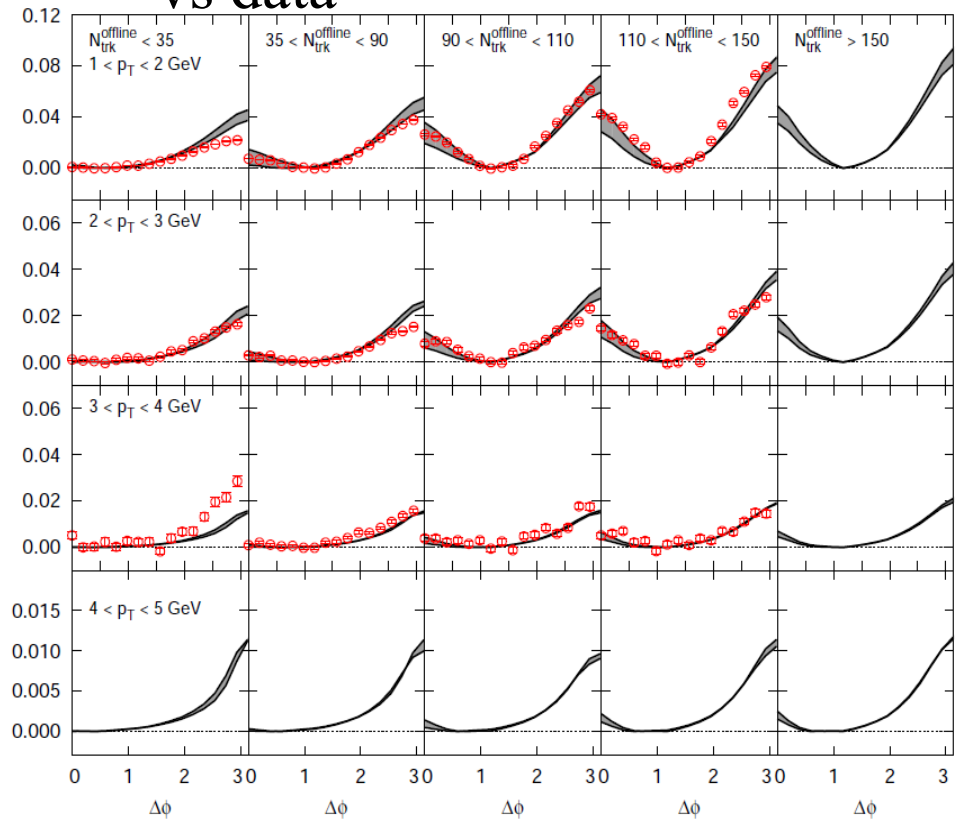
v2 of charged hadrons dAu(RHIC), pPb(LHC)

Data compared to Hydro model

Viscous hydro model: Observed collective effects due to fluctuations of initial state carried to final state through hydrodynamic evolution

CGC Initial State Model vs data

arXiv: 1302.7018



Long-range per-trigger-yields of charged hadrons p+Pb CMS: Data compared to CGC model

CGC framework: Observed two-ridge structure is a result of quantum interference effects between correlated gluons due to gluon saturation at small impact parameters

New results needed to see which is the driving factor
Initial state effects or hydro-like evolution ?

We have looked at large angle azimuthal correlations.

Next we shall look at small angle HBT correlations which carry information specifically about space-time extent of the system at freeze-out

Common trends in A+A and (p,d)+A systems in HBT measurements would be a strong indication of final-state effects

Freeze-out radii extracted from 3-pion cumulants in pp, p-Pb and Pb-Pb

ALICE

arXiv: 1404.1194

3-pion formalism from PRC 89 024911 (2014)

Isolation and fitting of 3-pion Bose-Einstein Cumulant

c_3 = 3-pion cumulant correlation

Isolated using:

- $N_3(p_1, p_2, p_3)$ — 3 pions from same event
- $N_2(p_1, p_2)N_1(p_3)$ — 2 pions from same event
- $N_1(p_1)N_1(p_2)N_1(p_3)$ — All pions from different events
- $K_3 = K_2^{12} * K_2^{13} * K_2^{23}$ — 3-body Final-State-Interaction

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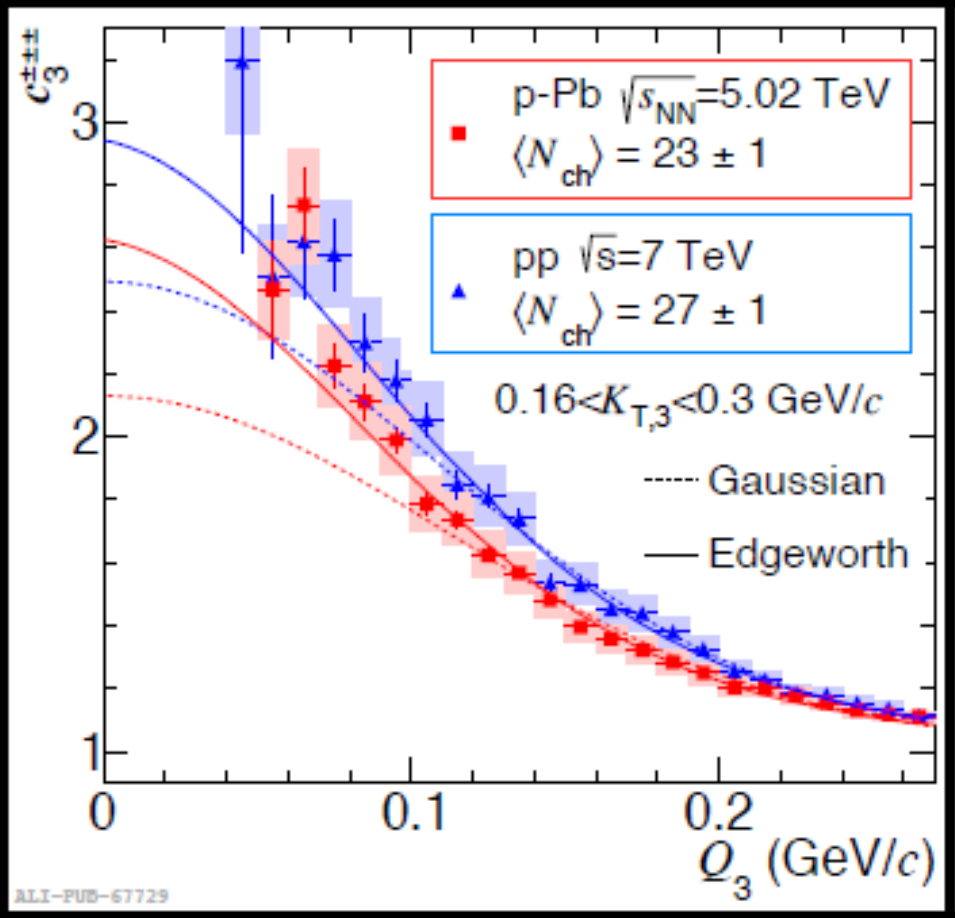
Cumulant fitting

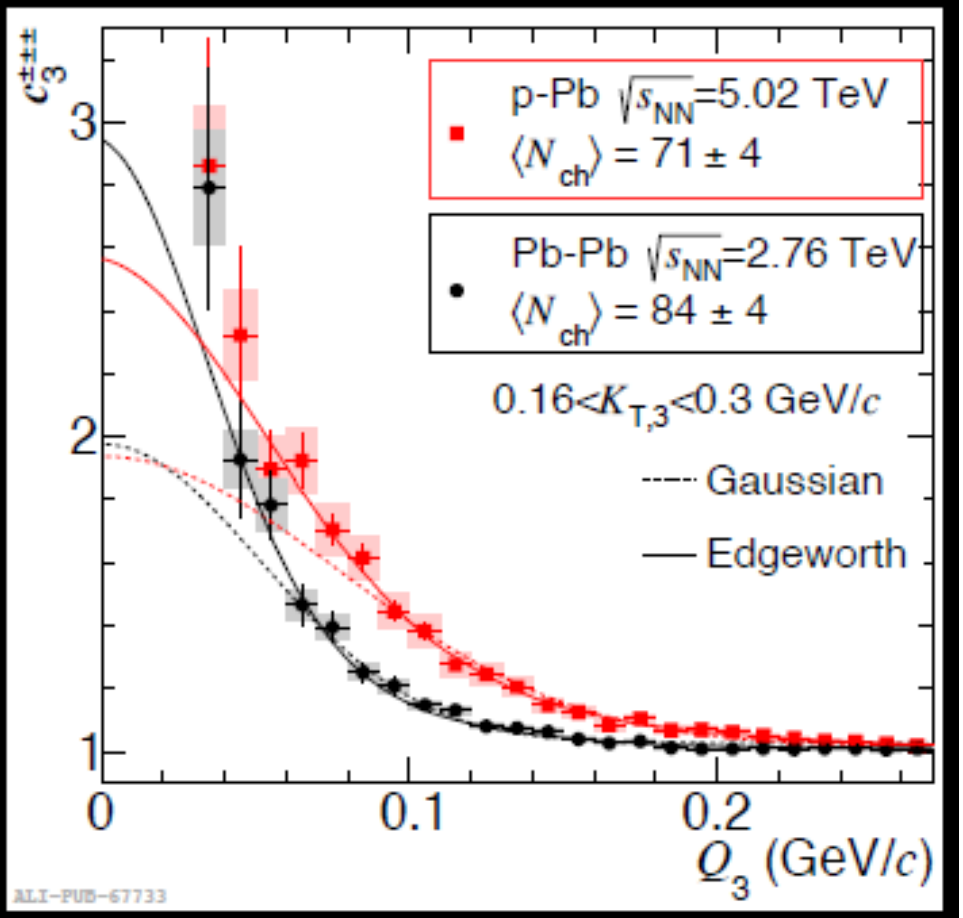
$$c_3(q_{12}, q_{31}, q_{23}) = 1 + \lambda_3 E_w(R_{inv,3}\, q_{12}) E_w(R_{inv,3}\, q_{31}) E_w(R_{inv,3}\, q_{23}) e^{-R_{inv,3}^2 Q_3^2/2}$$

3-pion suppression parameter

Edgeworth factors to account for non-Gaussian features

Comparison of c_3 at similar N_{ch}

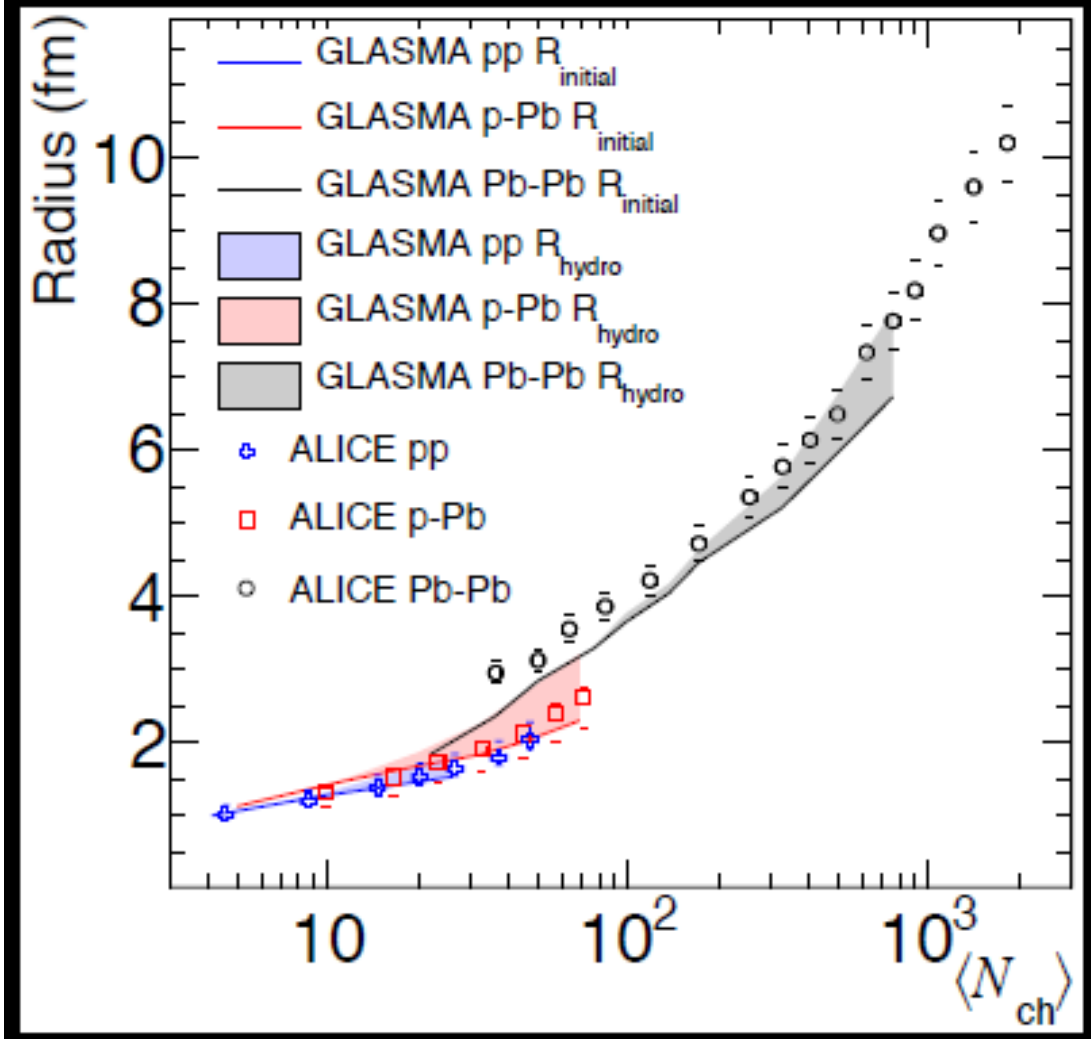




Correlation functions <u>similar</u>

Correlation functions <u>different</u>

Radii Comparison with IP-GLASMA



<u>Message:</u>
Similarity of ALICE radii in p-Pb and pp can be reproduced with GLASMA initial conditions alone.

They can also be reproduced with a hydrodynamic phase in p-Pb.

Schenke & Venugopalan
arXiv:1405.3605

- GLASMA points are first scaled such that the calculations in pp match the ALICE pp data. Scale = 1.15. GLASMA calculations have uncertainty due to infrared cutoff (m=0.1 GeV).

Conclusions

- p-Pb radii 5-15% larger than pp radii, at similar multiplicity.
  - The possibility of large initial radii in p-Pb radii is excluded.
  - There may or may not be hydrodynamic expansion in p-Pb.
  - If it is there, it must be similar in pp at the same dN/dy.
- Pb-Pb radii 35-55% larger than p-Pb, at similar multiplicity.

Charged kaon Bose-Einstein correlations in p+p collisions at STAR

Fitting procedures

- Correlation functions were fitted by a standard parameterization assuming the gaussian space-time distribution:

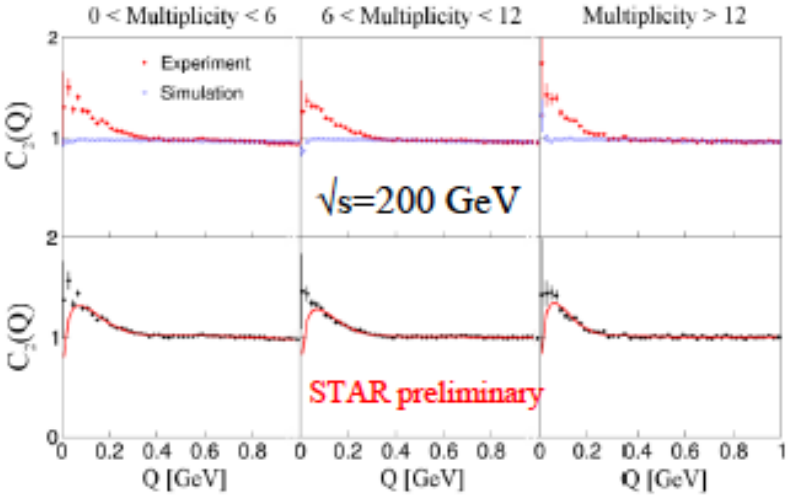
$$C_2(Q) = N\left(1 - \lambda + \lambda K(Q) e^{-R^2 Q^2}\right) B(Q)$$

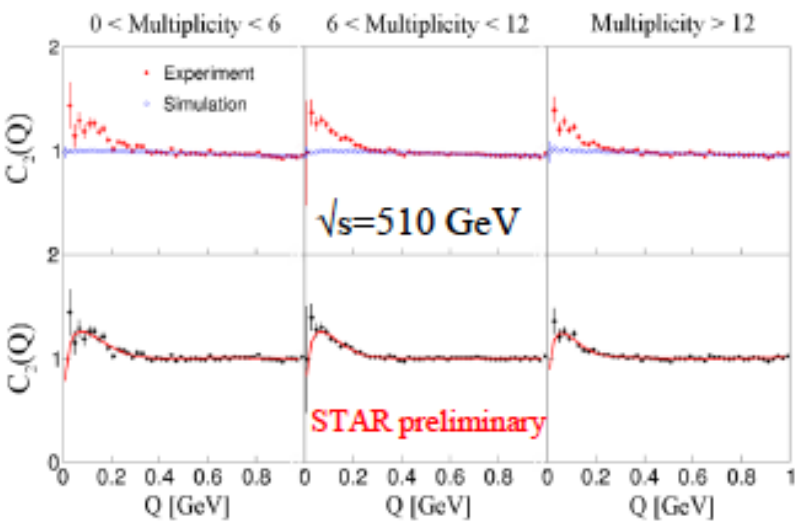
  - N – normalization factor
  - λ – correlation strength
  - *K(Q)* – Coulomb function integrated over a spherical source of 1 fm
  - *B(Q)* – baseline function, that takes into account non-femtoscopic correlations

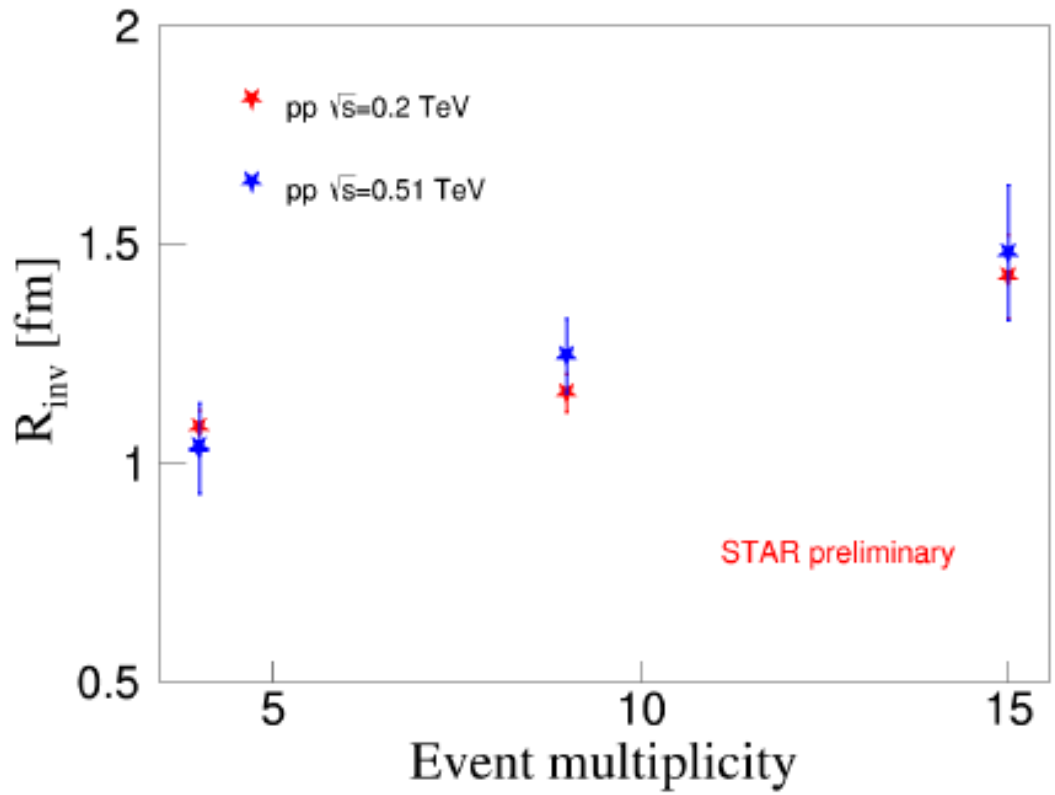
- In order to take into account non-femtoscopic correlations Monte Carlo generator PYTHIA-6.4.27 with Perugia 2010 Tune was used

T. Sjostrand, S. Mrenna, P. Z. Skands, JHEP 05:026, 2006
P. Z. Skands, Phys. Rev. D 82:074018, 2010

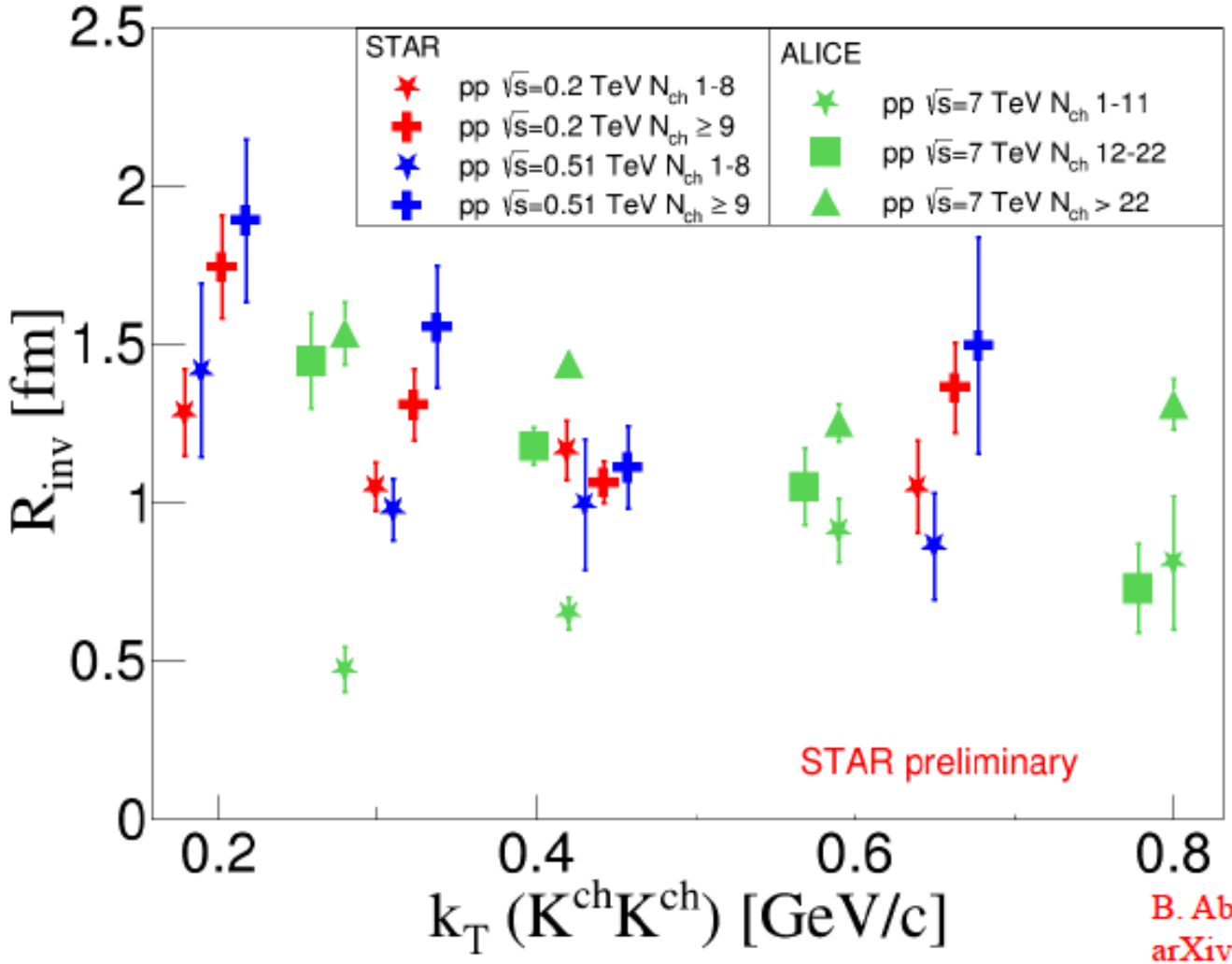
Event multiplicity and energy dependencies







The source radius weakly (does not?) depends on the collision energy and increases with event multiplicity



The source radii decrease with pair transverse momentum for both event multiplicities. Small difference in the measured emitting source radii between RHIC and LHC energies.

B. Abelev et al, (The ALICE collaboration), arXiv:1212.5958 [hep-ex]

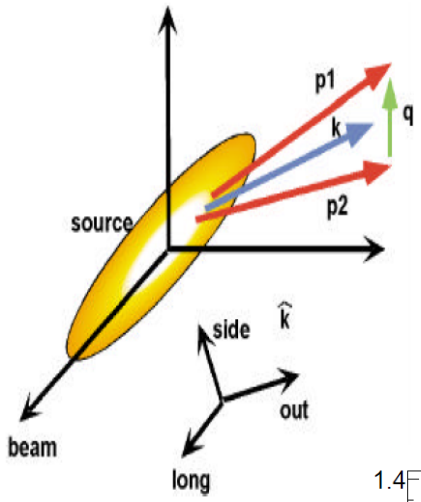
Conclusions

- The emitting source radii increase with event multiplicity and weakly depend from on the incident energies

- The extracted source radii for two multiplicity and four pair transverse momentum ranges slightly decrease with k_T for both multiplicities and incident energies that may reflect bulk collective flow

Pion HBT in d+Au and Au+Au Collision Systems at PHENIX

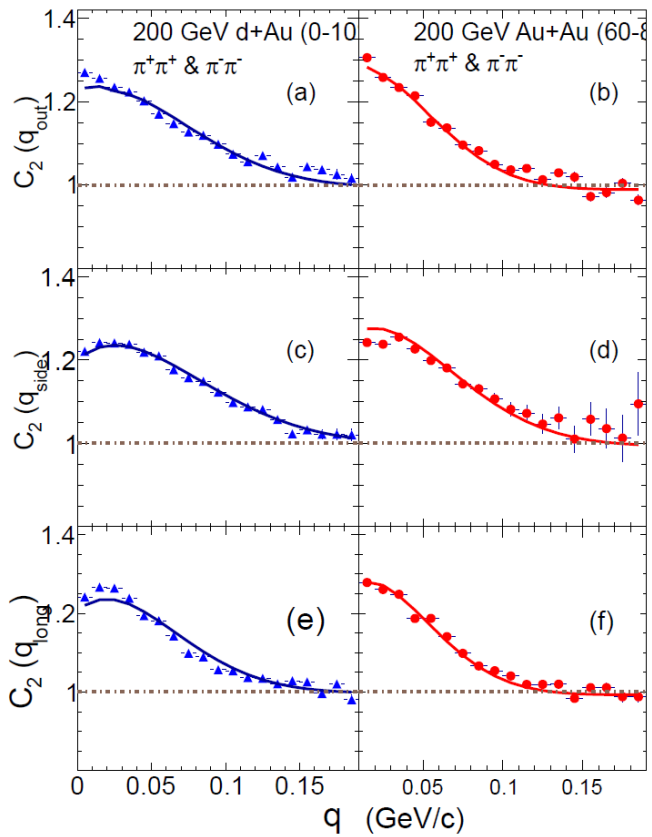
3D HBT



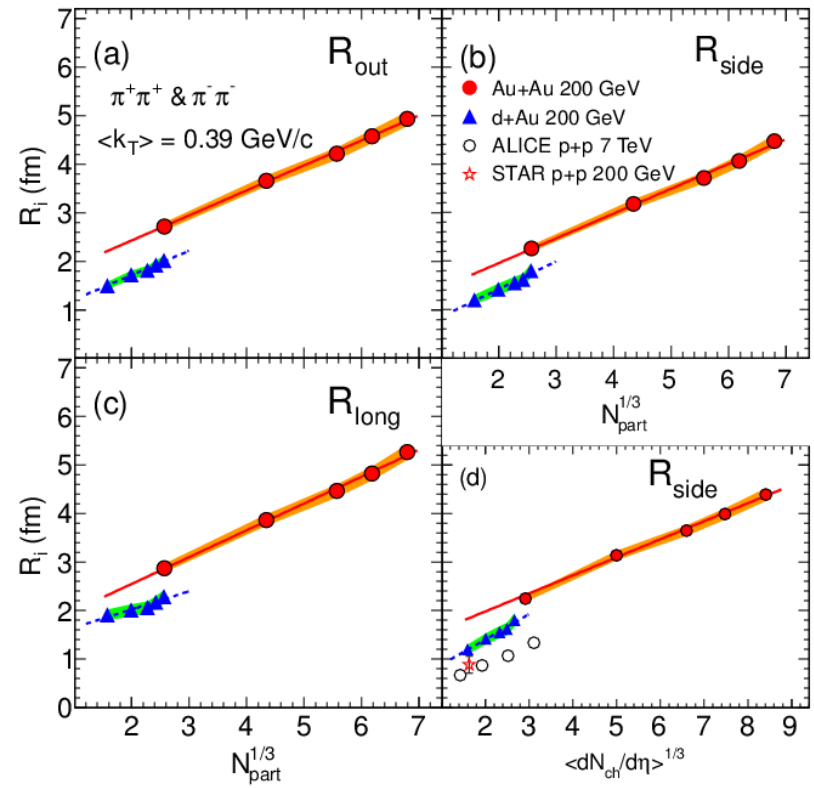
$$C(q_{side}, q_{out}, q_{long}) = (1-\lambda) + \lambda(1+G)Fc\,,$$

Fc=Coulomb Correction

$$G = \exp\left(-R_{side}^2 q_{side}^2 - R_{out}^2 q_{out}^2 - R_{long}^2 q_{long}^2\right)$$



d+Au and Au+Au HBT correlations at similar Npart and kT

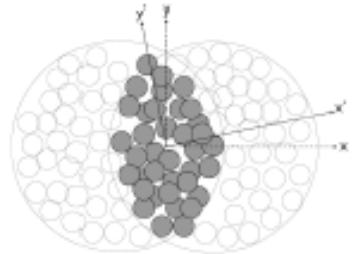


Pion HBT radii for d+Au and Au+Au do NOT scale together

Hydro models associate a larger expansion time with a larger initial size
Does it make $\bar{R}$ a good scaling parameter ?

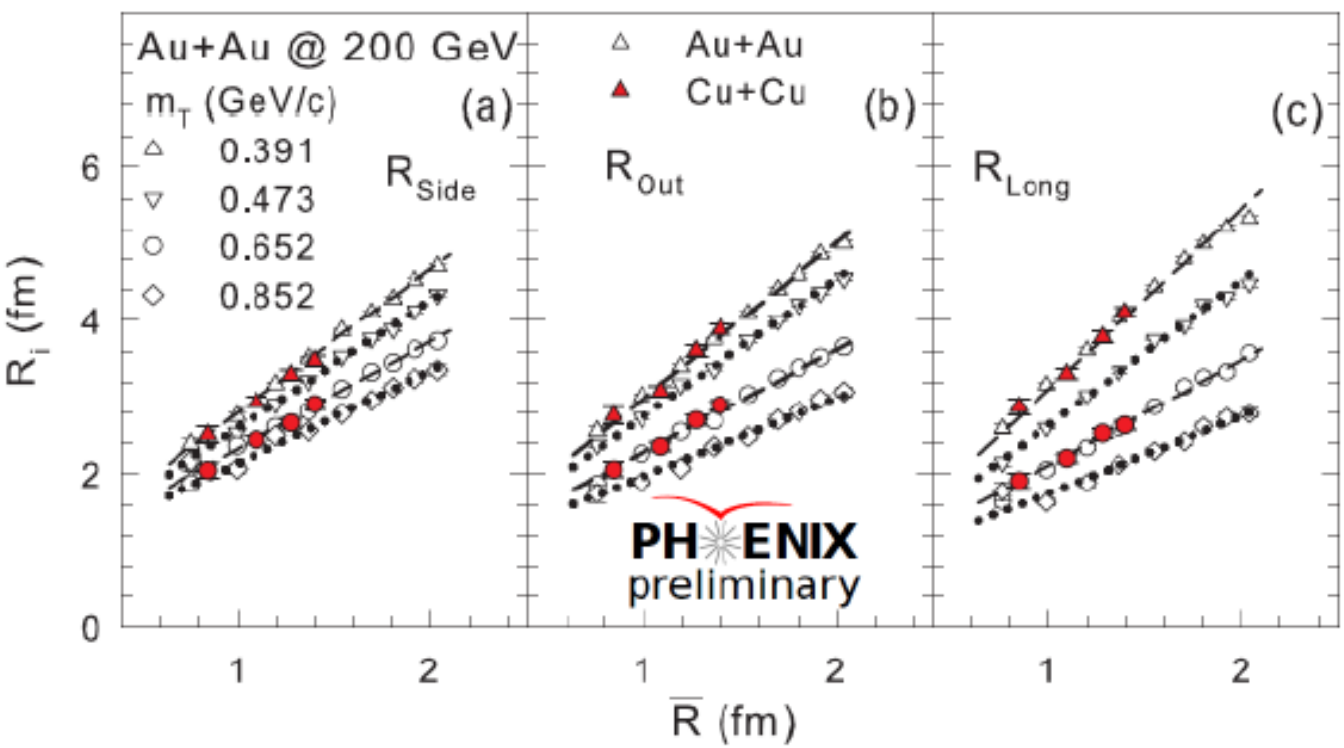
Use Glauber model to get

$N_{part}^{1/3}$ ***vs*** ***initial size*** $\bar{R}$



$$\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$$

σ_x & σ_y → *RMS widths of density distribution*

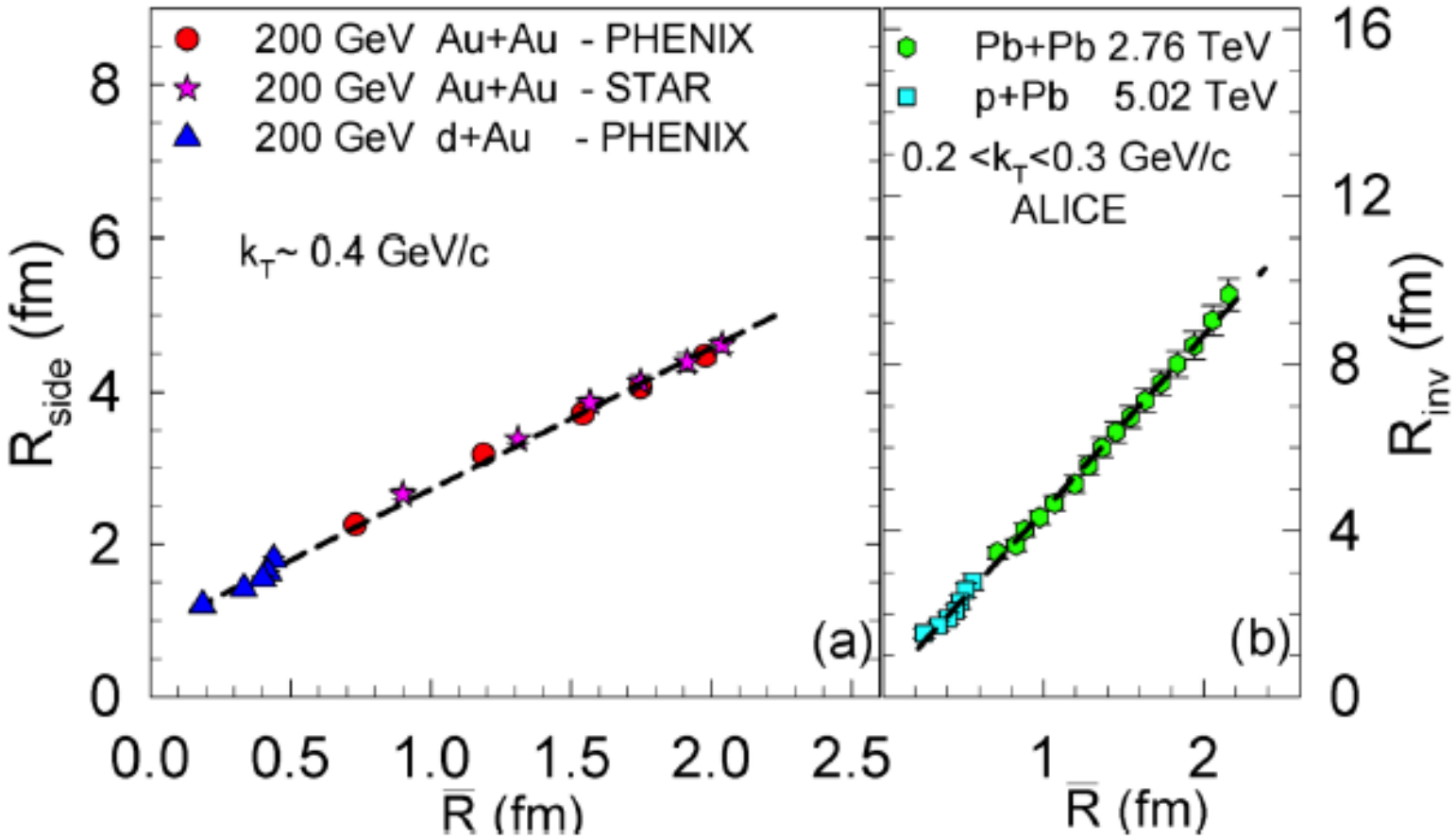


Pion HBT radii scale with $\bar{R}$

Linear dependence of transverse expansion on initial geometry

Application of $\bar{R}$ scaling to d+Au and p+Pb

arXiv:1404.4946



Linear dependence and good scaling seen between p/d+A and A+A systems Implies radial expansion in d+Au collisions

dAu HBT

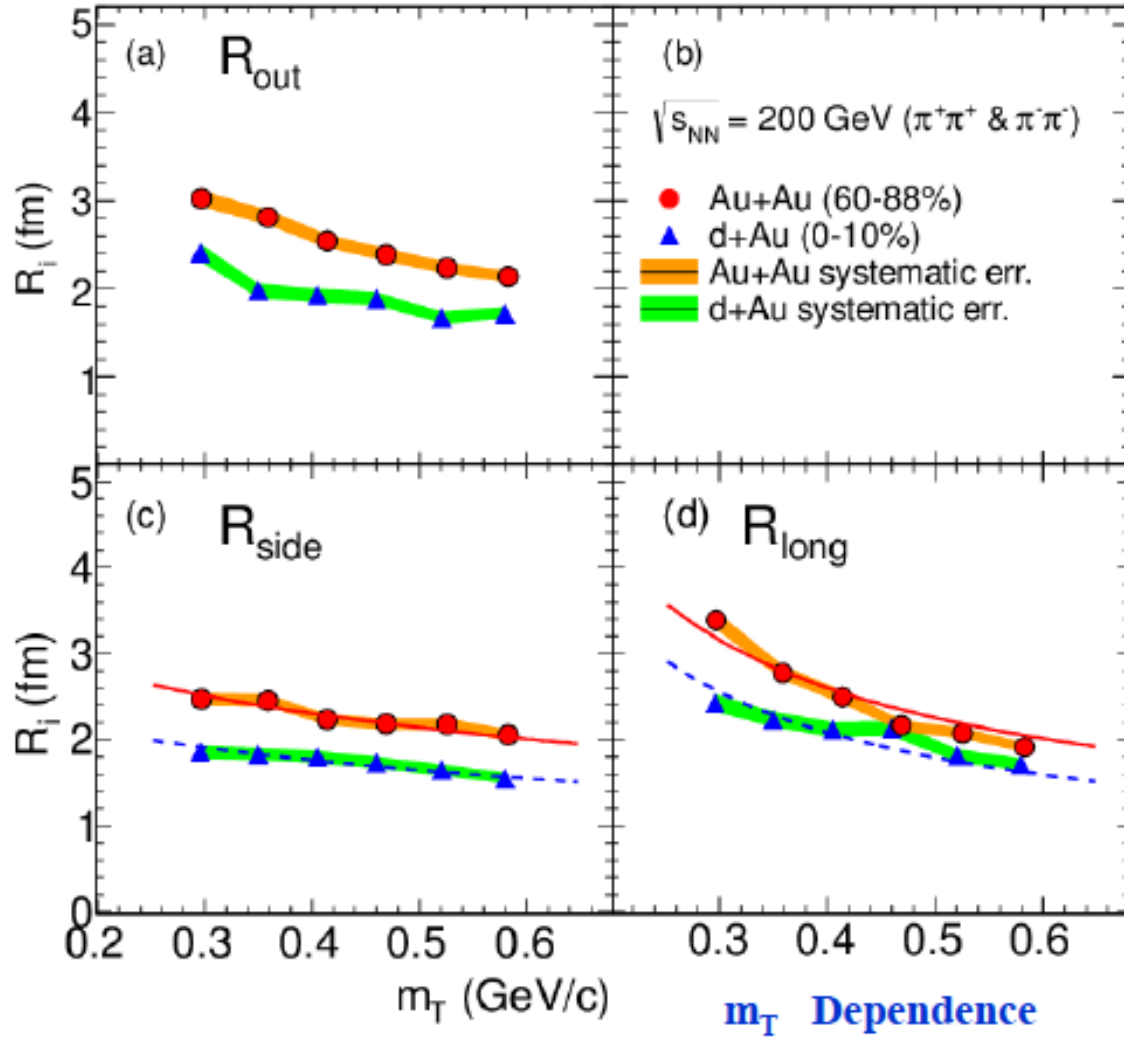
arXiv:1404.4946

Similar m_T dependence observed in d+Au and Au+Au

As expected from space momentum correlations Introduced by hydrodynamic expansion

Blast Wave Fit defined by expansion velocity and temperature at freeze-out

Smaller size for d+Au



m_T Dependence

$$R_{side} = R_{geom} / \sqrt{(1 + \beta^2 (m_T / T))},$$

$$R_{long} = \tau_0 \sqrt{(T / m_T)[(K_2(m_T / T)) / (K_1(m_T / T))]},$$

TABLE I. Fit parameters

	d+Au	Au+Au
τ_0 (fm/c)	3.2 ± 0.04 ± 0.4 (syst)	3.8 ± 0.04 ± 0.3 (syst)
χ^2/ndf	26/5	24/5
R_{geom} (fm)	2.2 ± 0.03 ± 0.2 (syst)	2.8 ± 0.03 ± 0.2 (syst)
χ^2/ndf	6/5	4/5

Conclusions

m_T dependence of HBT radii are similar for d+Au and Au+Au

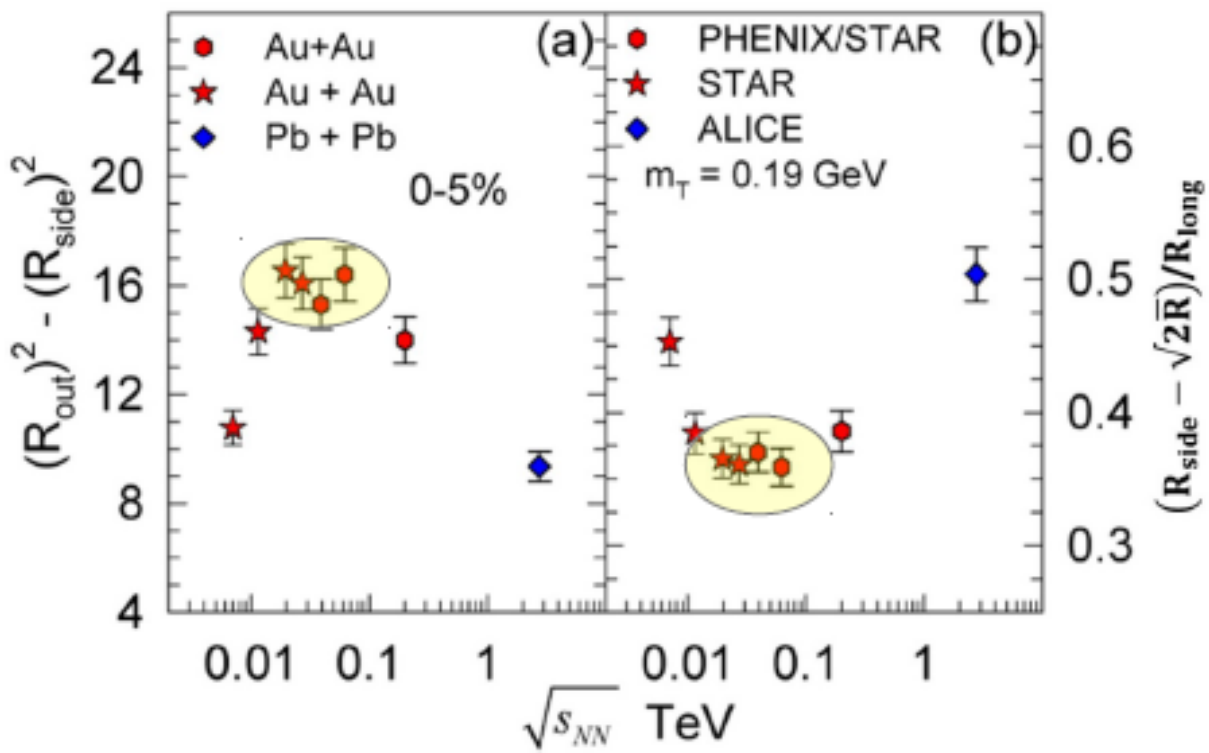
Implies similar expansion dynamics

HBT radii scale with $\overline{R}$ across systems

Results suggest radial expansion in d+Au collisions as seen in hydro-dynamic evolution with final state scattering

Expansion dynamics in HBT: $R^2_{out} - R^2_{side}$ and $(R_{side} - 2\overline{R})/R_{long}$

$$R^2_{out} = \frac{R^2_{geom}}{1+\frac{m_T}{T}\upsilon^2} + \frac{1}{2}\left(\frac{T}{m_T}\right)^2 \beta_T^2 \tau_0^2 \qquad R^2_{side} = \frac{R^2_{geom}}{1+\frac{m_T}{T}\upsilon^2} \qquad R^2_{long} = \tau^2 \frac{T}{m_T}\frac{K_2(m_T/T)}{K_1(m_T/T)}$$



- A maximum is observed in (a) $R^2_{out} - R^2_{side}$ dependence on beam energy ($\sqrt{s_{NN}}$) with complimentary minimum in (b) $(R_{side} - 2\overline{R})/R_{long}$ dependence on $\sqrt{s_{NN}}$
- Nonmonotonic behavior over small range in $\sqrt{s_{NN}}$ may point to a change in the reaction dynamics over this range
- Additional energy scans over the range of interest (BES II) needed

Summary of observations and inferences for Small Collisions

They exhibit near side ridge in long range azimuthal correlations

V2(pT) shows mass ordering

Pion femtoscopy at ALICE shows that at similar multiplicity freeze-out radii in Pb+Pb 35-55% greater than in p+Pb which is 5-15% greater than in p+p
Maybe evidence for hydrodynamic expansion.

Kaon femtoscopy at STAR in p+p shows source size grows with particle mulitplicity. Weak beam energy dependence. May reflect bulk collective flow.

Pion femtoscopy at PHENIX shows m_T dependence of HBT radii are similar for d+Au and Au+Au and scale with initial size suggesting hydro-dynamic evolution