Collectivity as a signature of Quark Gluon Plasma

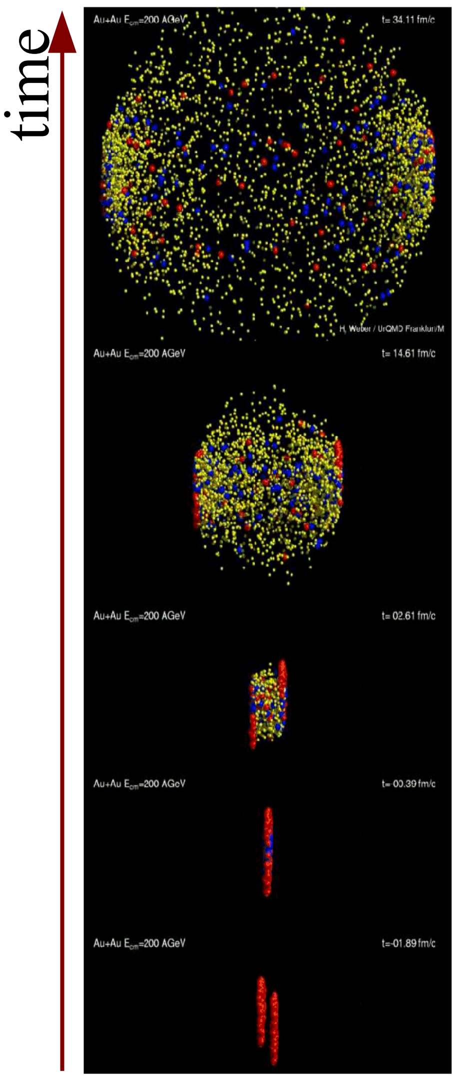
EMMI Symposium on Perspectives in
Quark-Gluon Plasma Physics

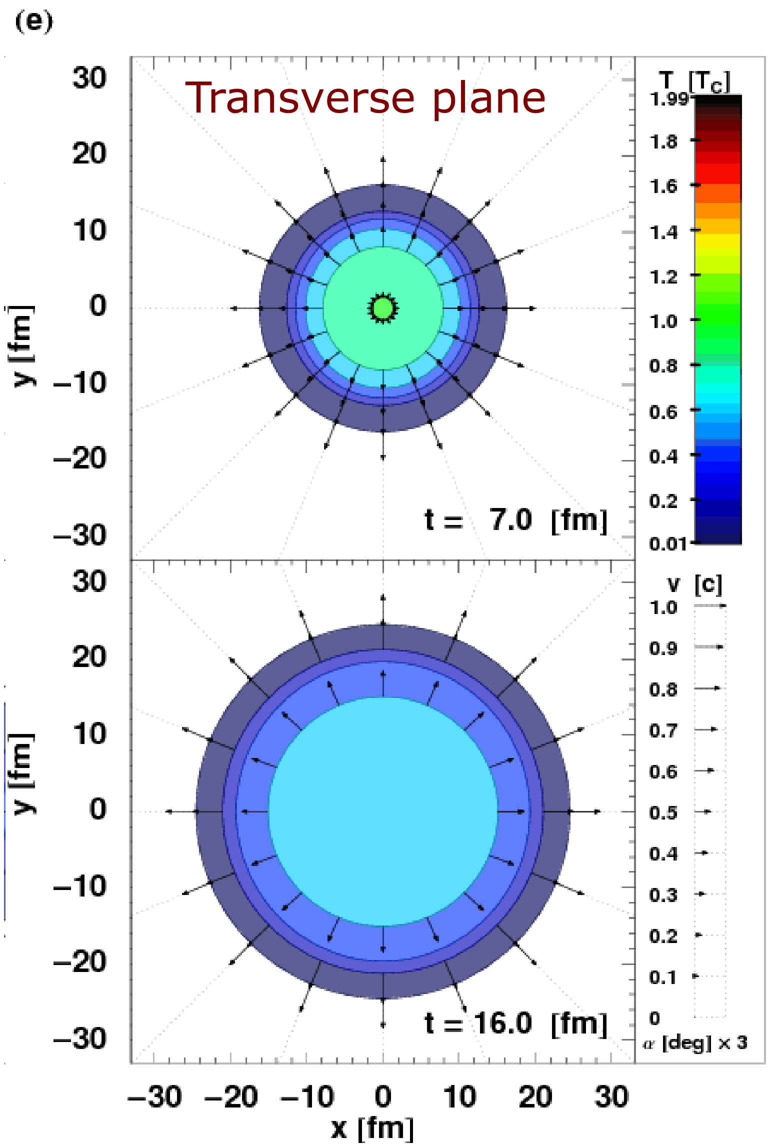
Adam Kisiel
CERN

Outline

- Physics motivation
  - Collectivity as QGP signature
  - Femtoscopy: part of the two-particle correlation program
- Physics results
  - Identical particle femtoscopy
  - Femtoscopy vs. reaction plane orientation
  - Non-identical particle correlations
- First results at the LHC

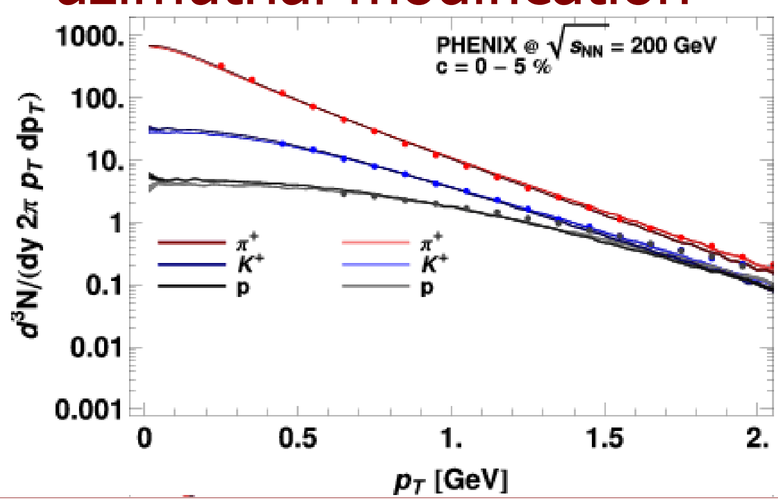
Heavy Ion collision evolution



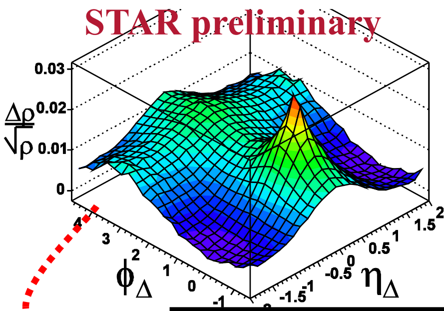


M. Chojnacki, W. Florkowski,
PRC 74 (2006) 034905

- HIC is expected to go through a QGP phase, where matter is strongly interacting – resulting in the development of collective motion
- Radial flow dominates, with elliptic flow as azimuthal modification



p-p 200 GeV

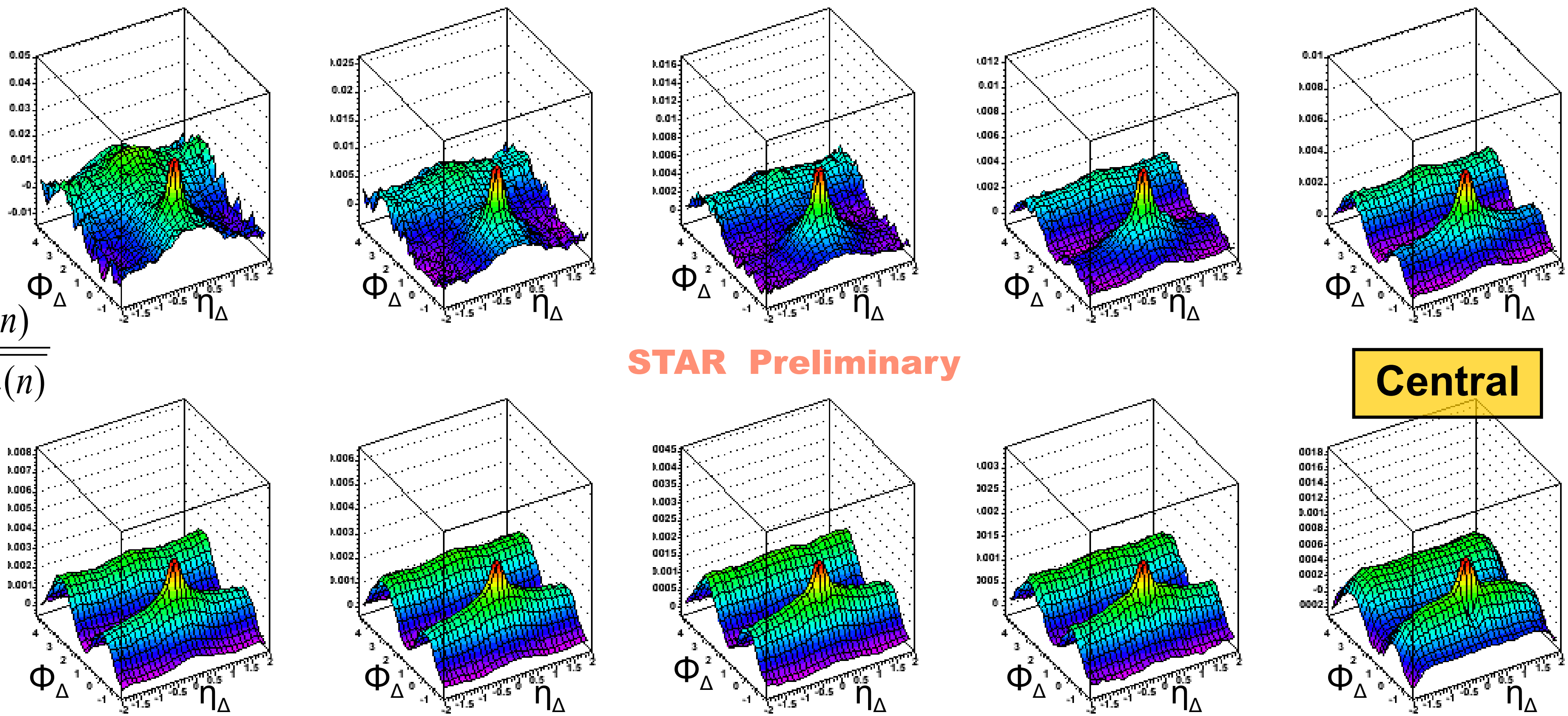


Event structure via correlations

0.15 < p_t<2 GeV/c
|η|<1.0, full ϕ=2π
merging & HBT cuts applied

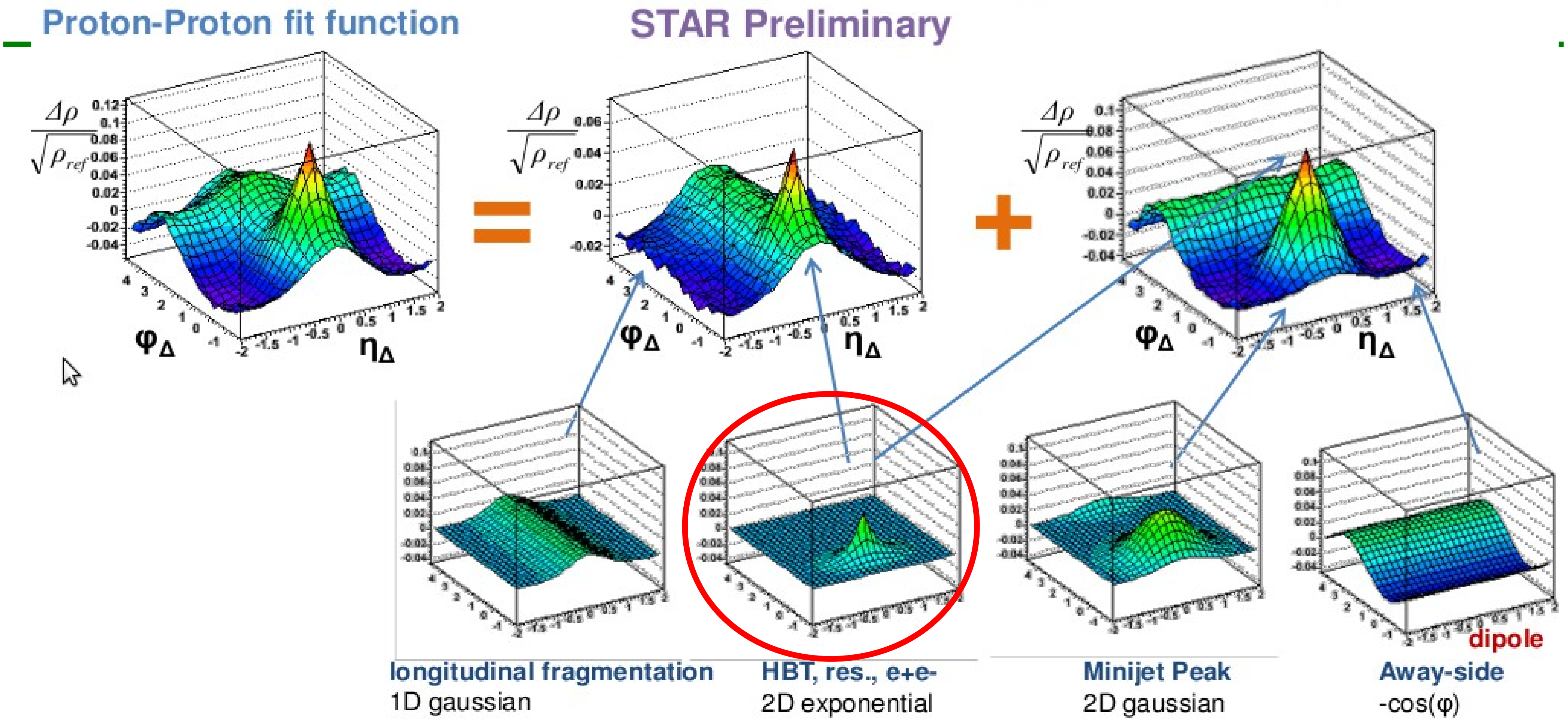
Peripheral

$$\frac{\Delta\rho(n)}{\sqrt{\rho_{ref}(n)}}$$

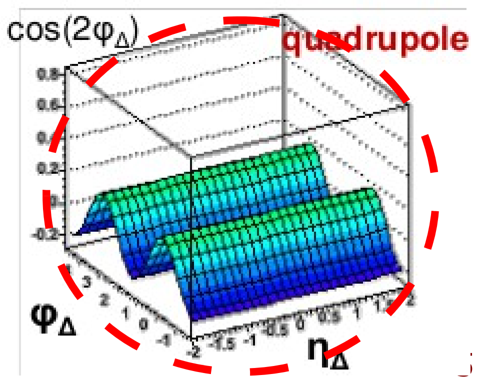


STAR – Lanny Ray – QM2005

Focusing on collectivity measurements

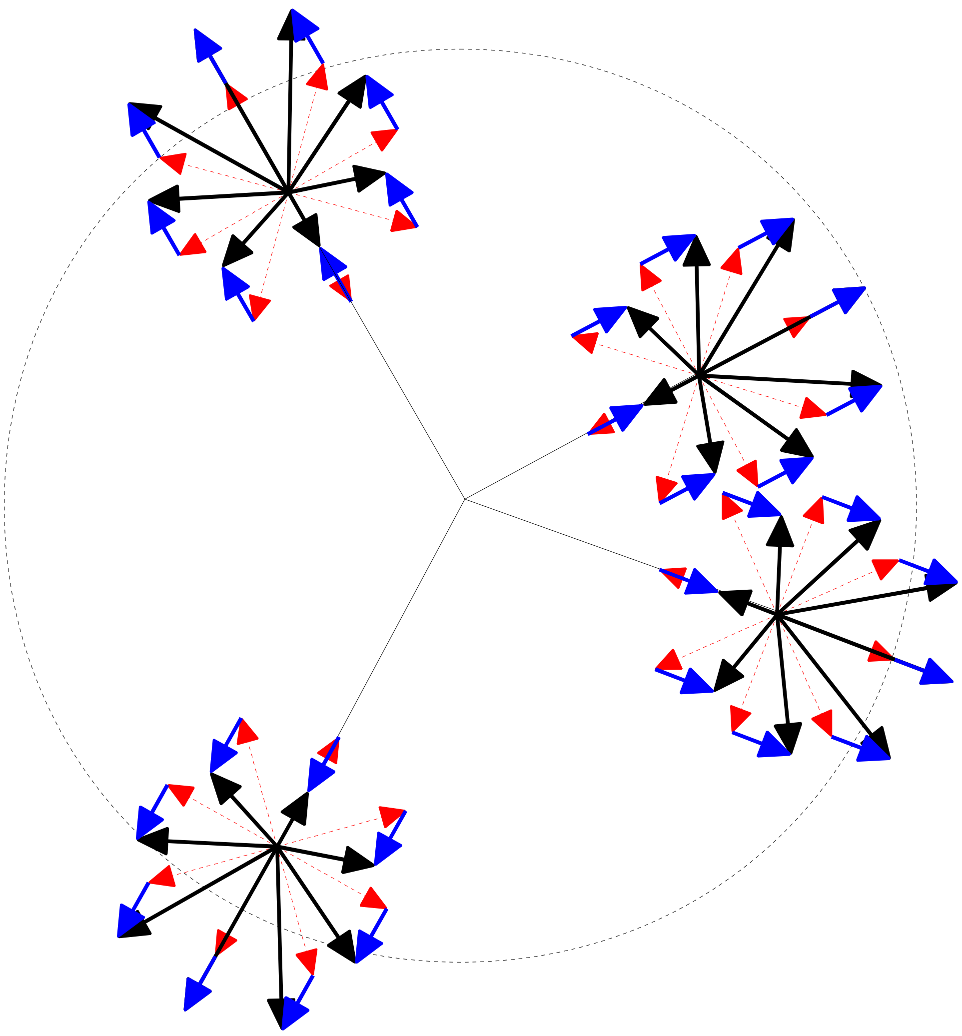


- Many effects, presumably from different physics mechanisms, all combine to create a single correlation structure.



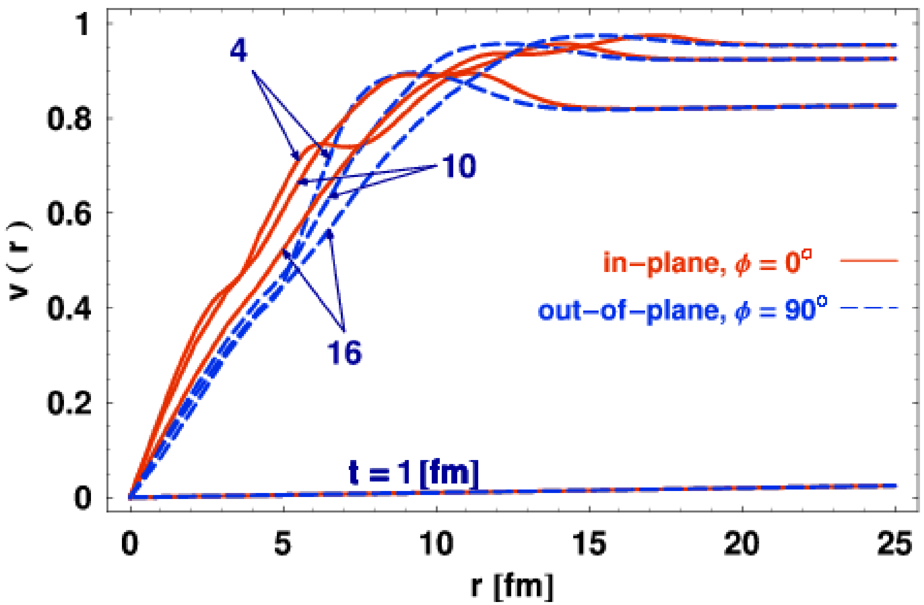
Michael Daugherity Quark Matter 2008:

Which collectivity do we seek?



- A collective component is a "common" velocity for all particles emitted close to each other
- To that one adds "thermal" (random) velocity
- We expect specific "common" velocity – radial direction, pointing outwards from the center

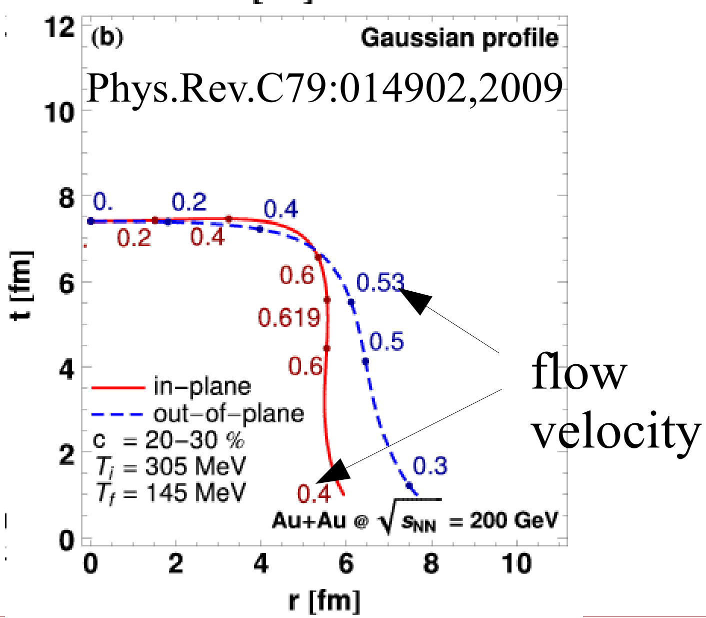
Quantifying collectivity



Chojnacki M., Florkowski W.
nucl-th/0603065, Phys. Rev. C74: 034905 (2006)

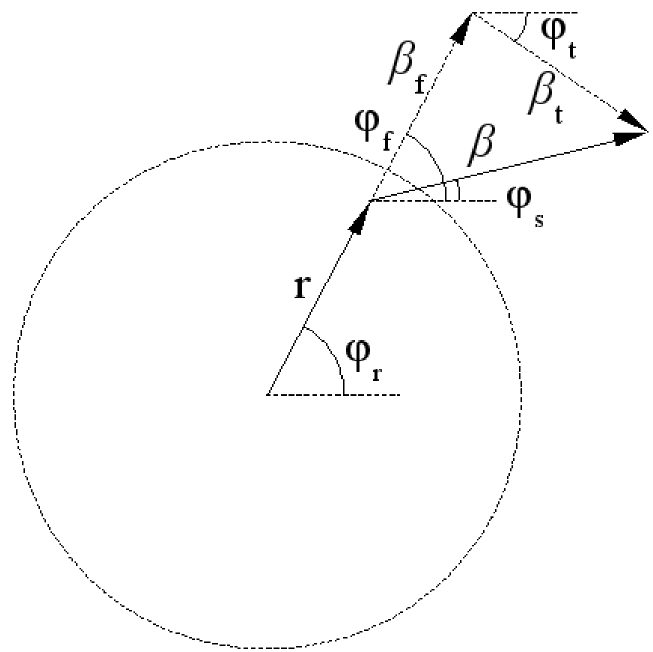
- Hydrodynamics produces collective flow: common velocity of all particles

$$\langle v_{out} \rangle = \left\langle \frac{\vec{v}_T \vec{r}_T}{|\vec{r}_T|} \right\rangle \quad \langle v_{side} \rangle = \left\langle \frac{\vec{v}_T \times \vec{r}_T}{|\vec{r}_T|} \right\rangle = 0$$

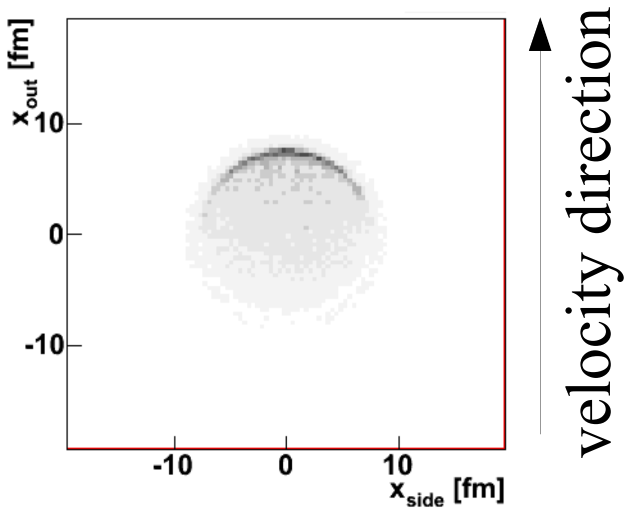


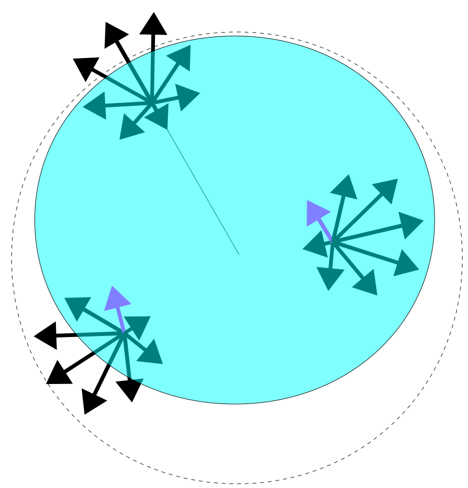
- The process drives the space-time evolution of the system
- For non-central collisions differences between in-plane and out-of plane velocities arise
- Space and time azimuthal evolution closely connected.

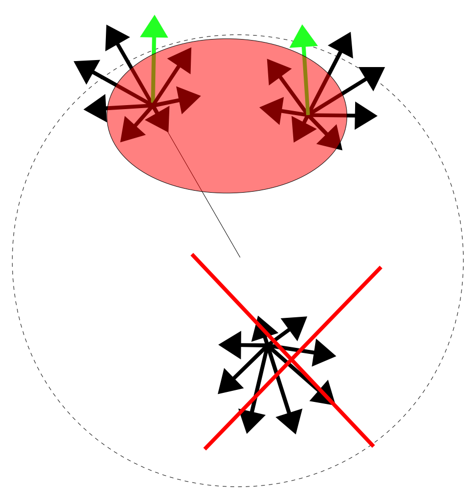
Thermal emission from collective medium



- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where such particles can be emitted gets smaller and shifted to the outside of the source

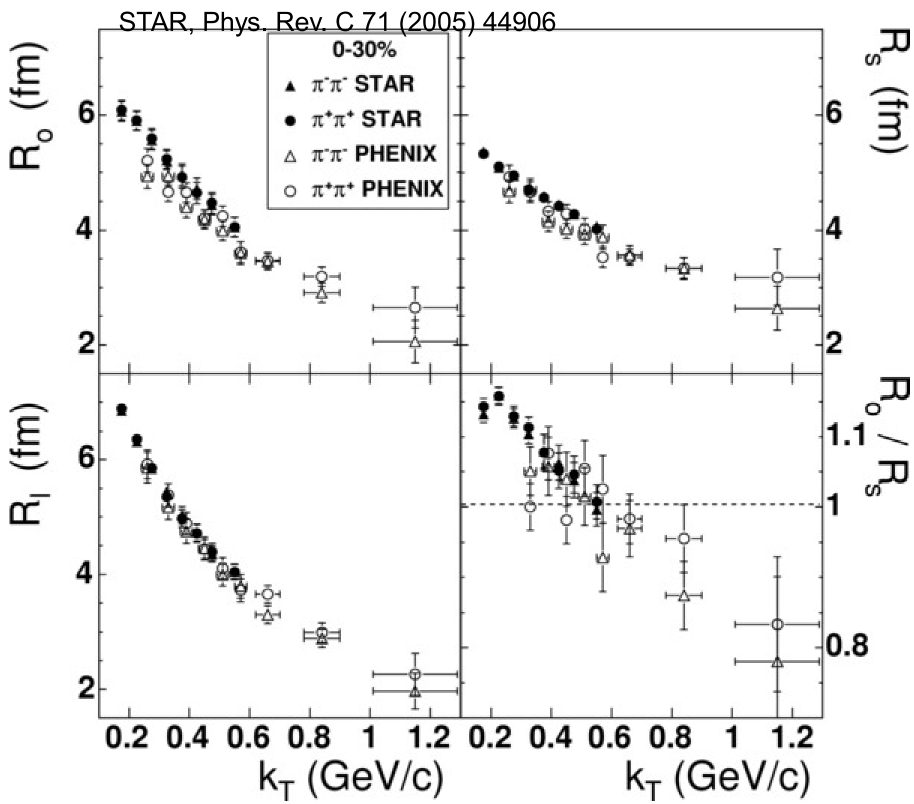


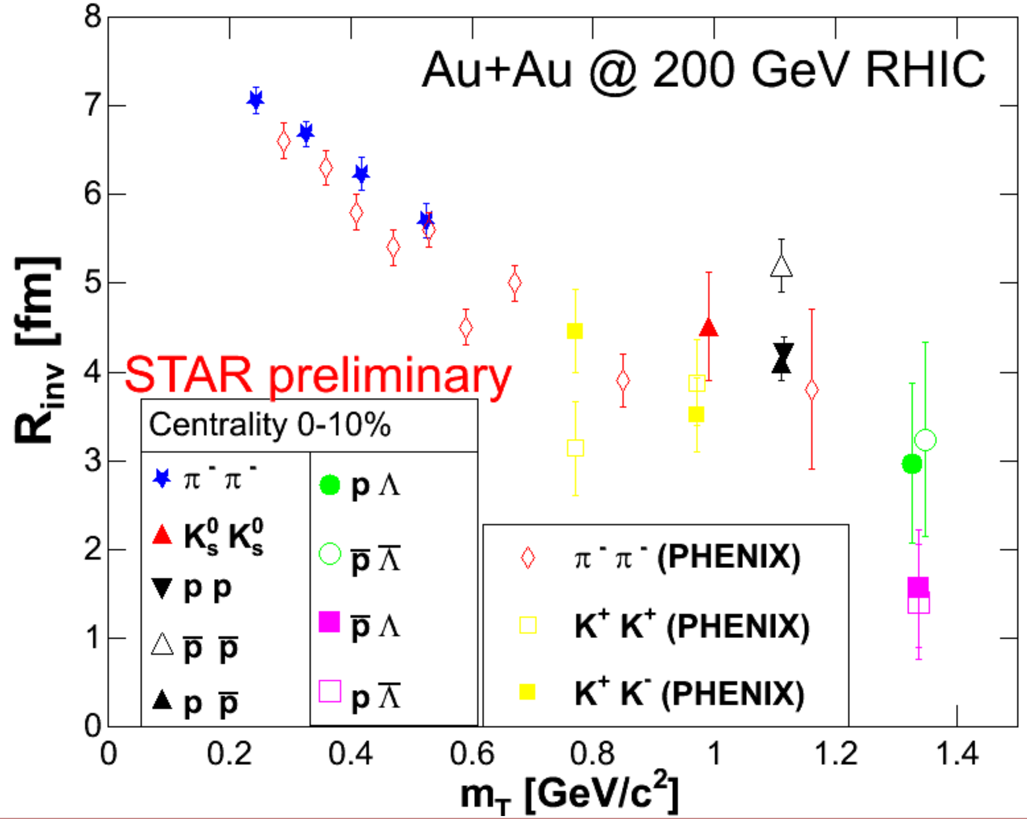




m_T dependence at RHIC

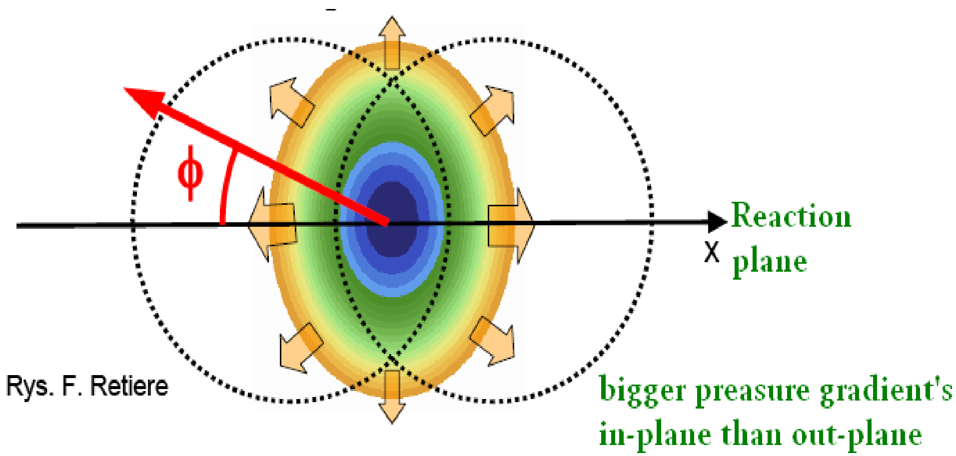
- A clear m_T dependence is observed, for all femtoscopic radii and for all particle types: but is it hydrodynamic like? And can we tell?



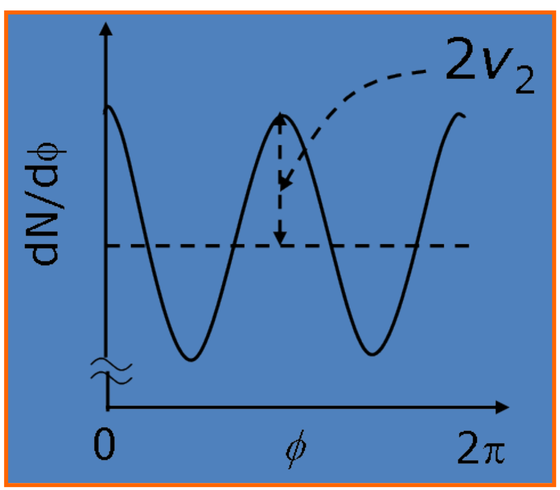


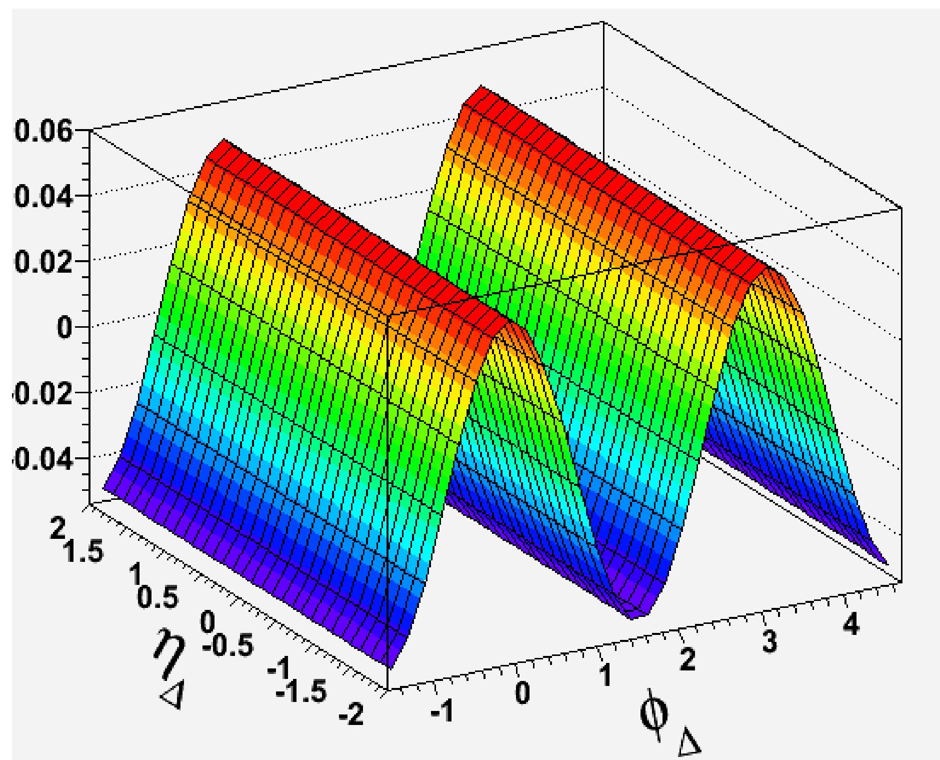
Non-central collisions = elliptic flow

Elliptic flow is a sensitive probe of early dynamics – used as a primary evidence for hydrodynamics-like flows at RHIC.

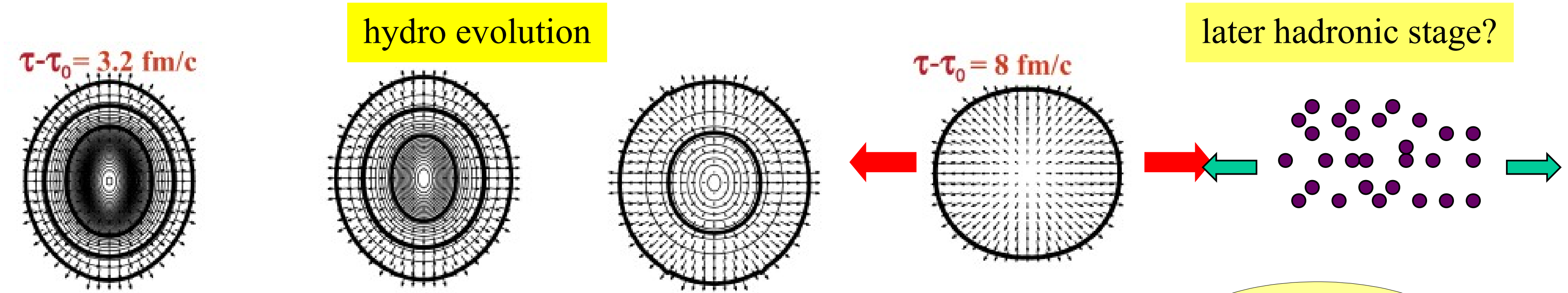


$$v_2 = \langle \cos 2\phi \rangle$$





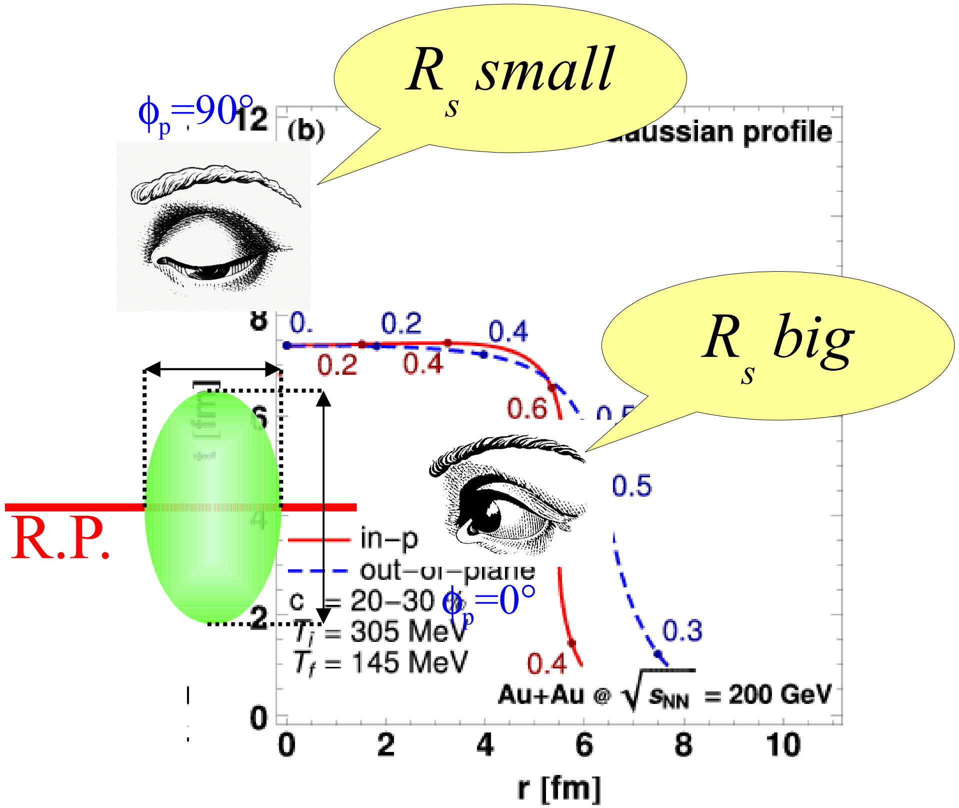
Non-central collisions: azimuthal modulation of collectivity



Kolb & Heinz

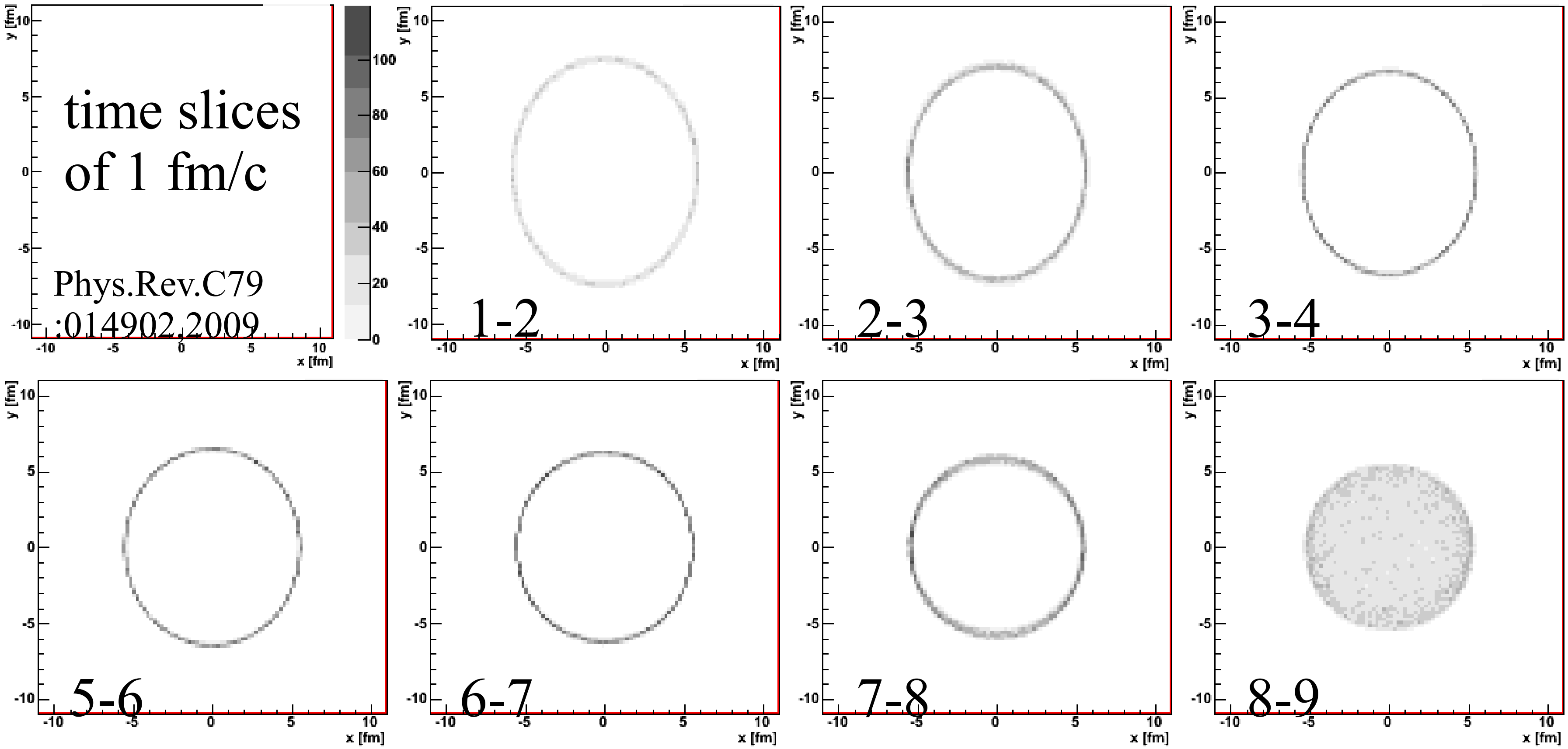
anisotropic pressure gradients

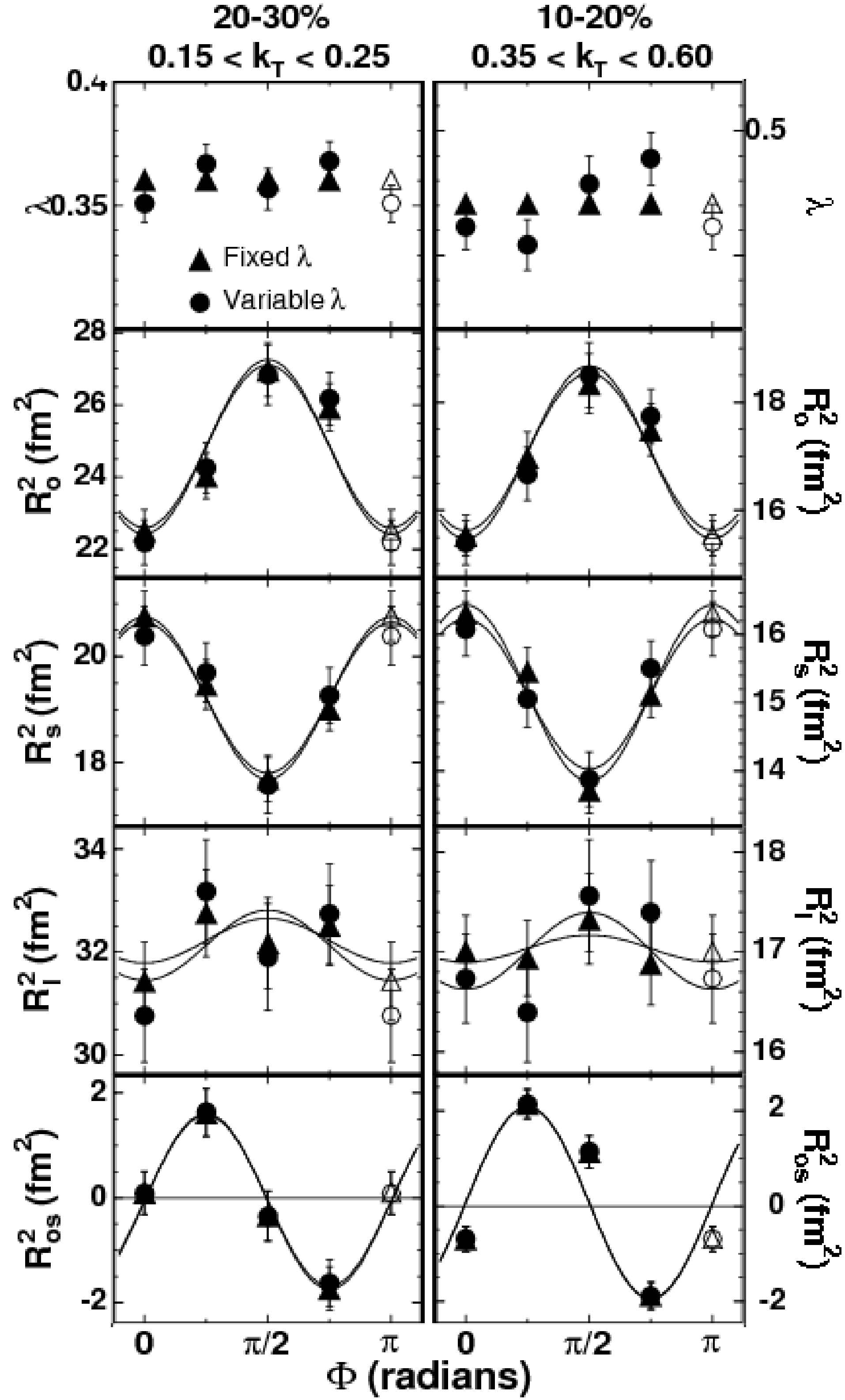
- drives the emergence of elliptic flow (v_2)
- Space-time and momentum anisotropy connected: can they be described at the same time?
- Azimuthally sensitive femtoscopy measures the space-time asymmetry by measuring radii vs. reaction plane
- Specific oscillations are expected



Emission from the source vs. time

- Azimuthal anisotropy is self-quenching – evolving towards a spherical shape
- Observed shape is a multipicity-weighted average





Radii vs. reaction plane orientation

- Separate CFs are constructed for each orientations of pair k_T vs. reaction plane
- Radii are extracted vs this angle, total dependence can be characterized by 7 parameters:

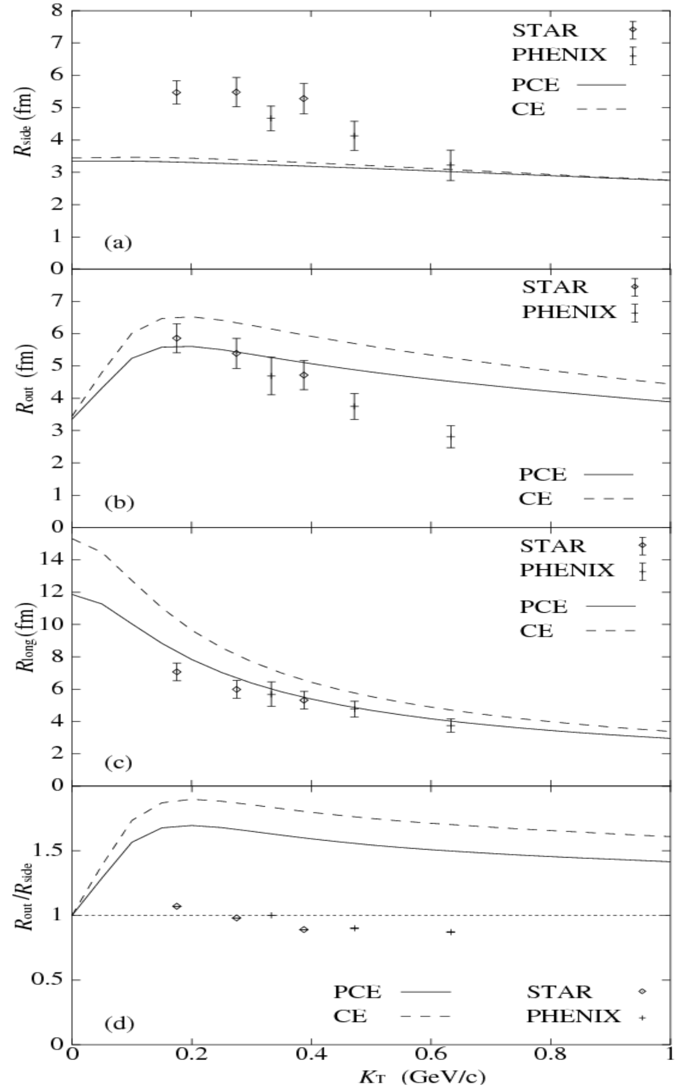
$$R^2_{out} = R^2_{out,0} + 2R^2_{out,2}\cos(2\phi_p)$$
$$R^2_{side} = R^2_{side,0} + 2R^2_{side,2}\cos(2\phi_p)$$
$$R^2_{long} = R^2_{long,0} + 2R^2_{long,2}\cos(2\phi_p)$$
$$R_{out-side} = 2R_{side-out,2}\sin(2\phi_p)$$

- Experiment clearly sees an anisotropic source shape

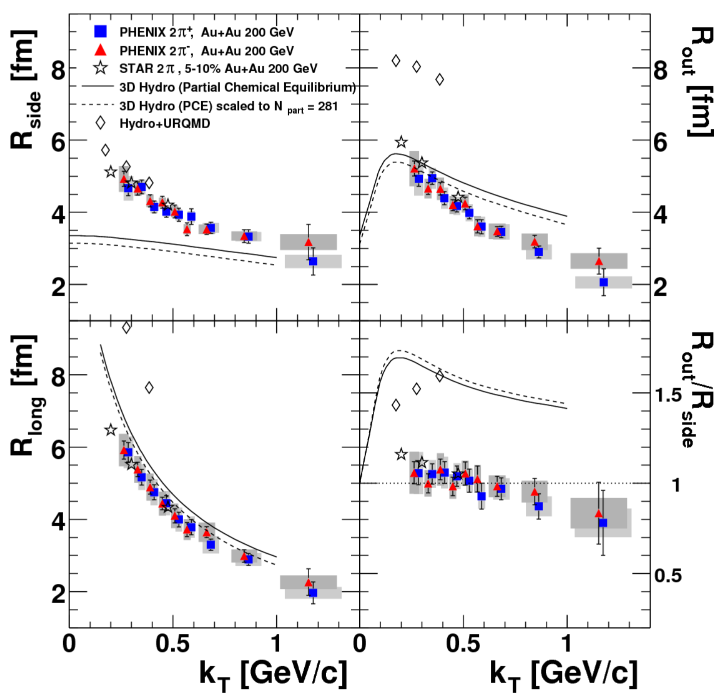
STAR, Phys. Rev. Lett. 93 (2004) 12301
e-Print Archives (nucl-ex/0312009)

RHIC Hydro-HBT puzzle

T. Hirano, K. Tsuda, nucl-th/0205043
Phys.Rev.C66:054905,2002.



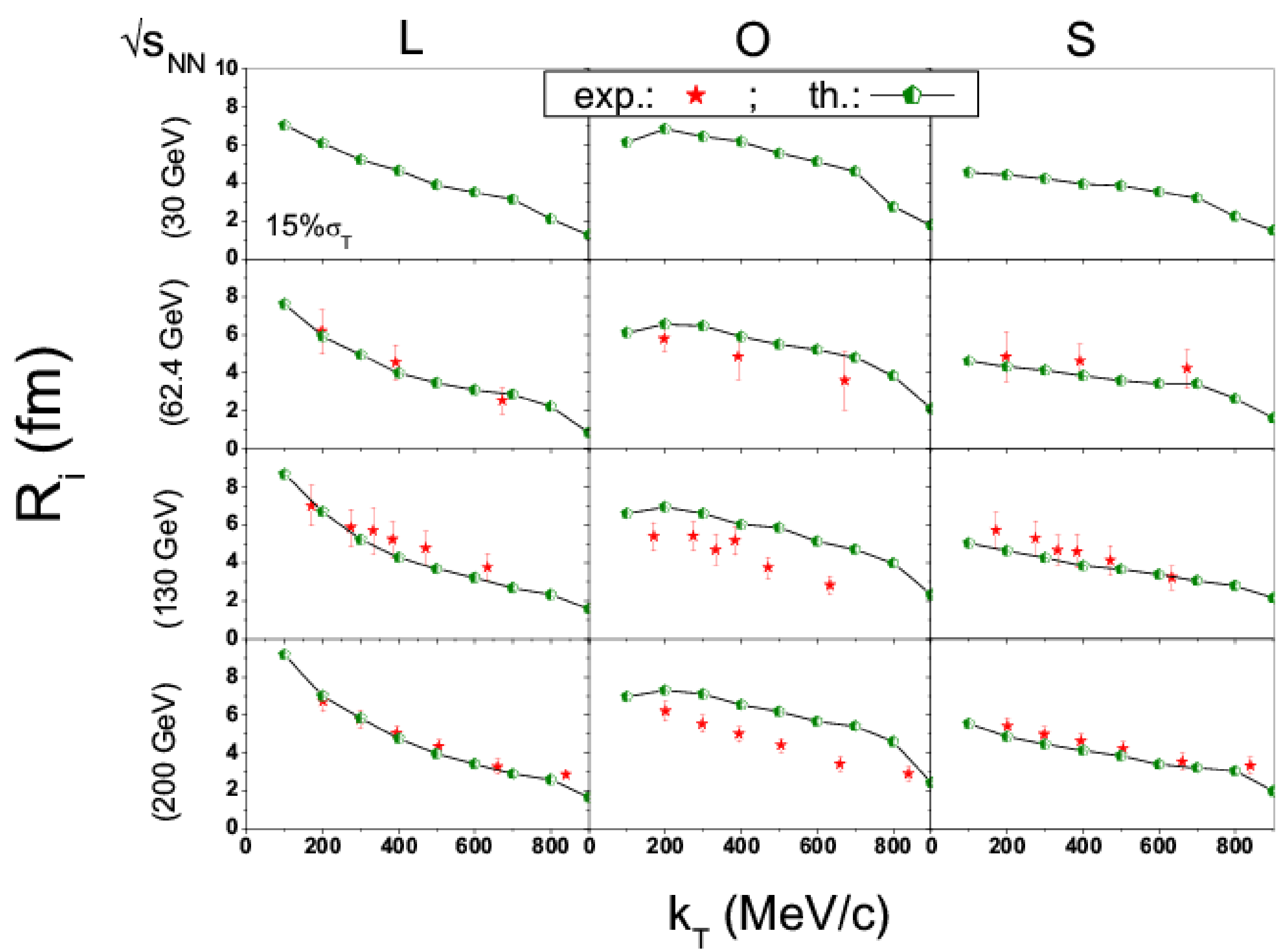
- First hydro calculations struggle to describe femtoscopic data: predicted too small R_{side} , too large R_{out} – too long emission duration
- No evidence of first order phase tr.



U. Heinz, P. Kolb,
hep-ph/0204061
Phys. Rev. Lett. 93, 152302 (2004)

How about rescattering models?

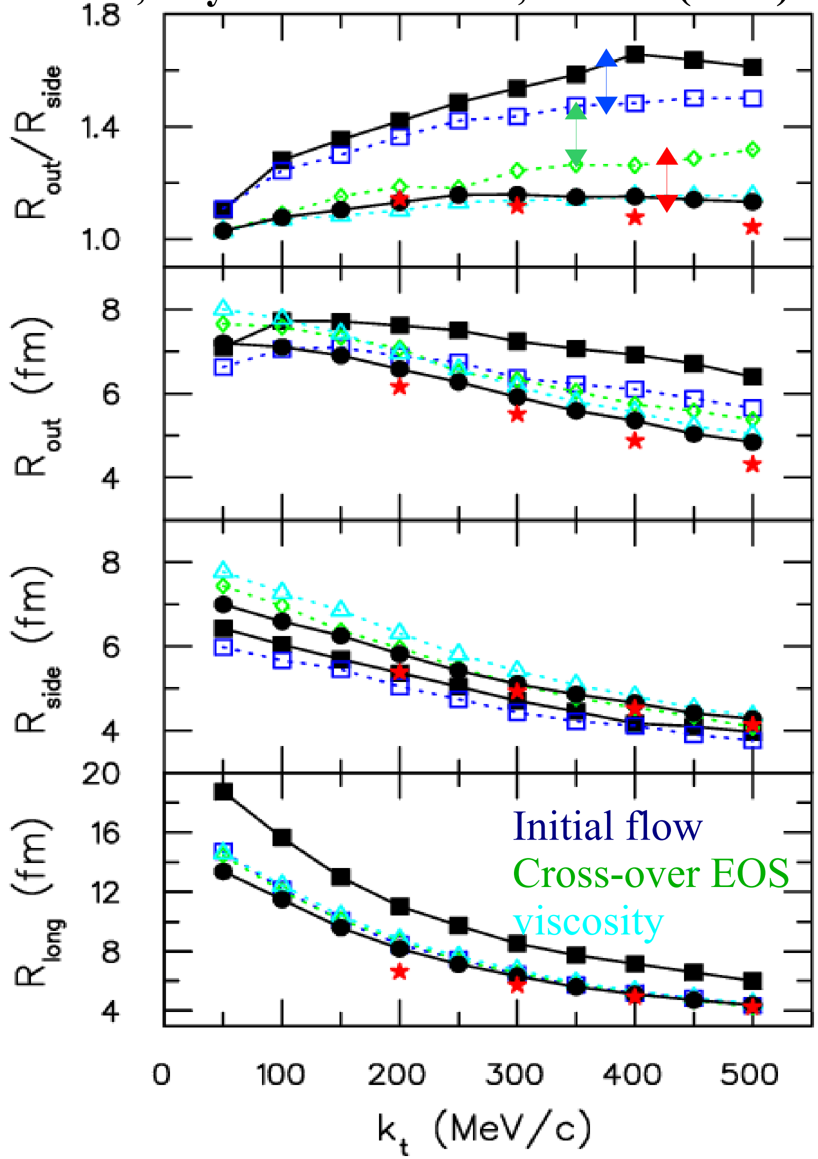
- Rescattering models also struggle to describe the femtoscopic data
- Problems similar to hydro: R_{side} too small (but with correct slope), R_{out} too large



Bleicher et al., nucl-th/0602032

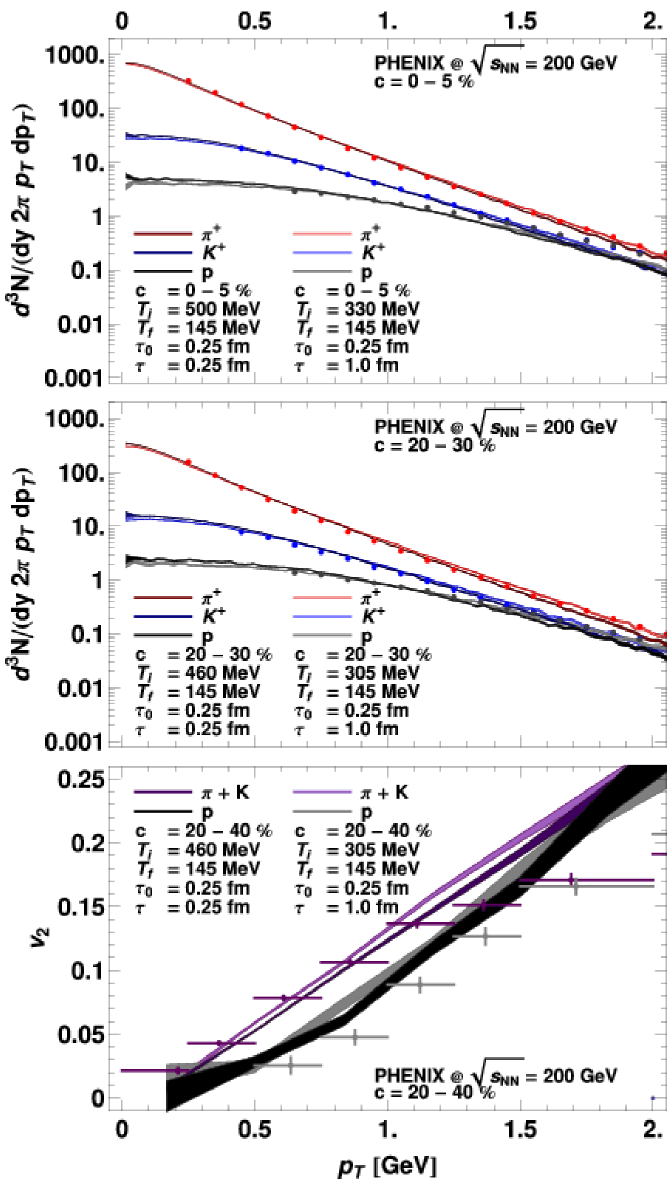
Revisiting hydrodynamics assumptions

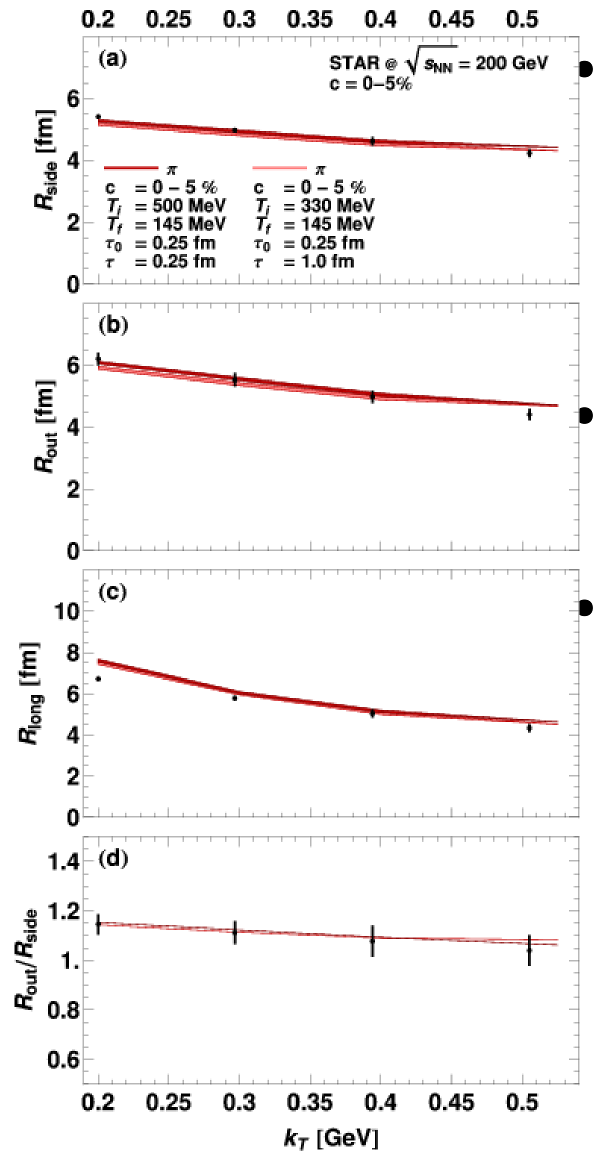
S. Pratt, Phys. Rev. Lett. 102, 232301 (2009)



- Data in the momentum sector (p_T spectra, elliptic flow) well described by hydrodynamics, why not in space-time?
- Usually initial conditions do not have initial flow at the start of hydrodynamics (~1 fm/c) – they should.
- Femtoscopy data rules out first order phase transition – smooth cross-over is needed
- Resonance propagation and decay as well as particle rescattering after freeze-out need to be taken into account: similar in effects to viscosity

Lhyquid+Therminator at RHIC

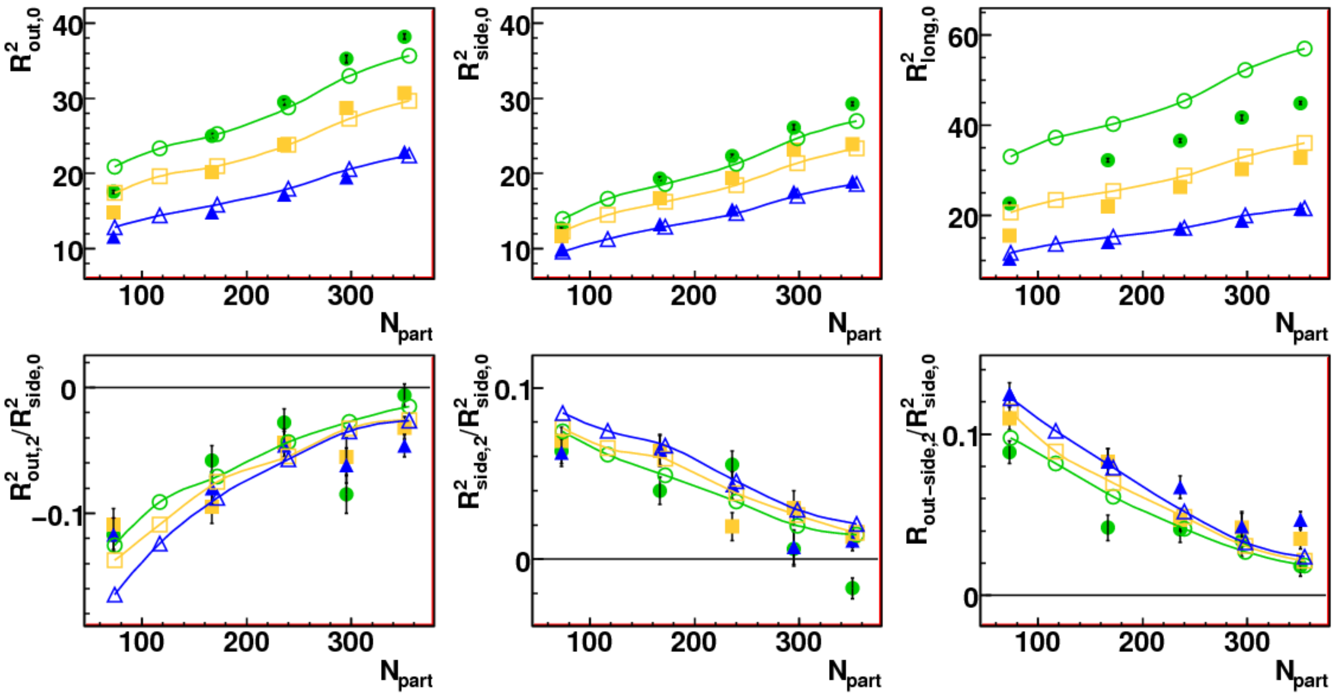




- Dynamical model with hydrodynamical evolution, propagation of strong resonances
- Reproduces spectra, elliptic flow and HBT
- Initial flow, smooth cross-over phase transition, resonance treatment are naturally included

W.Broniowski, W.Florkowski, M.Chojnacki, AK
nucl-th/0801.4361; nucl-th/0710.5731

Therminator: centrality vs. k_T vs. reaction plane



Filled points: STAR data from:

Phys. Rev. Lett. 93 (2004) 012301

e-Print Archives (nucl-ex/0312009)

Colors: different kt bins

Open points: Lhyquid+Therminator

Phys.Rev.C79:014902,2009.

Phys.Rev.C78:014905,2008.

- Full centrality vs. pair transverse momentum vs. reaction plane orientation dependence of HBT radii is reproduced.
- Collectivity at RHIC consistent with hydro-like behavior, with QGP-like equation of state.
- But is it unique?

Does femotscopy probe collectivity?

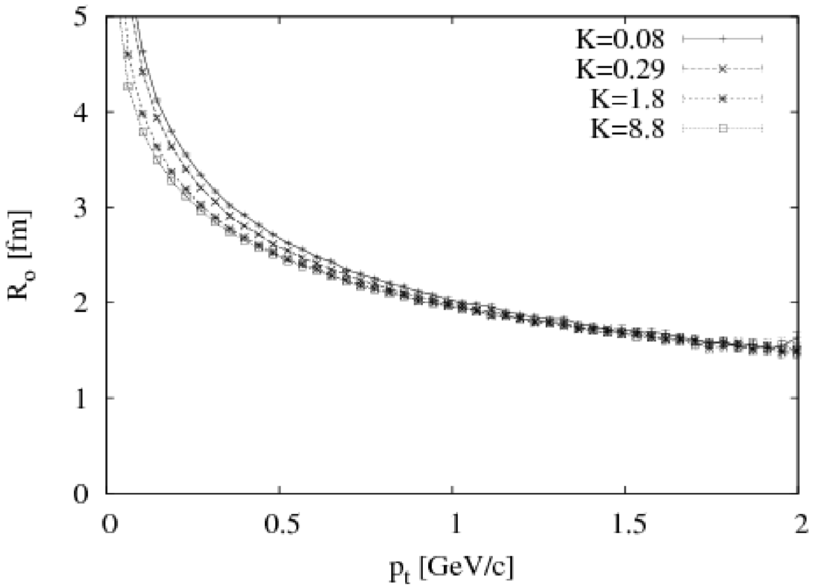


FIG. 1: HBT radius R_o versus transverse momentum p_t of particles in the transport calculation. The curves are labeled by the value of the Knudsen number K.

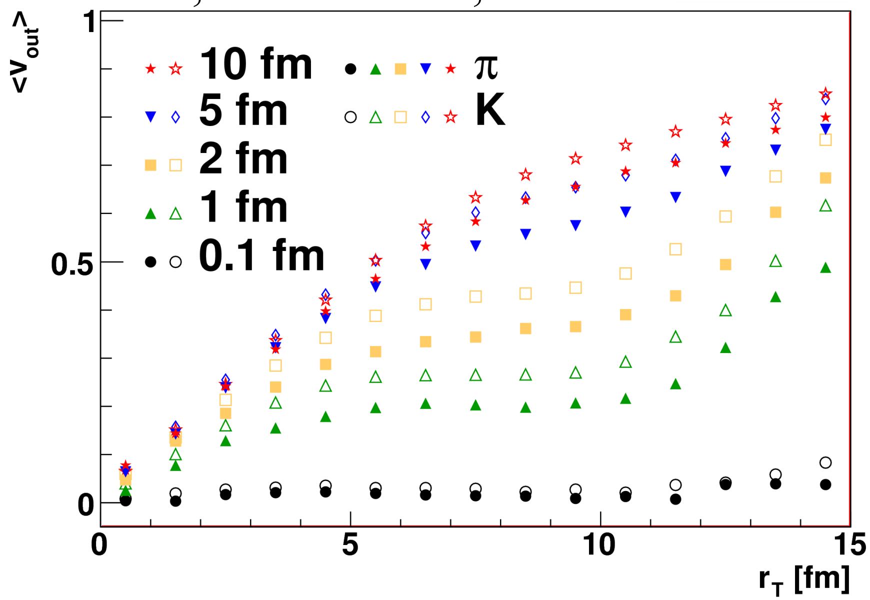
Gombeaud C., Lappi T., Ollitrault J., Phys.Rev.C79:054914,2009. arXiv:0901.4908 [nucl-th]

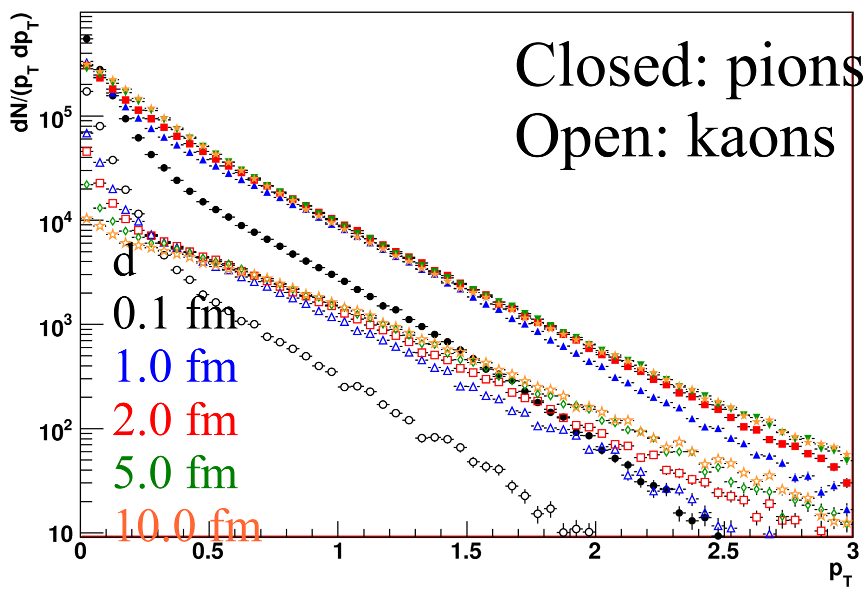
- Ideal hydrodynamics: strong assumptions about the system (zero mean free path, local thermalization, "large" system)
- Relaxing assumptions seems not to affect m_T scaling of radii for massless particles – is femtoscopy really probing the collectivity (and hence thermalization) of the system?

Relaxing hydro assumptions – rescattering test

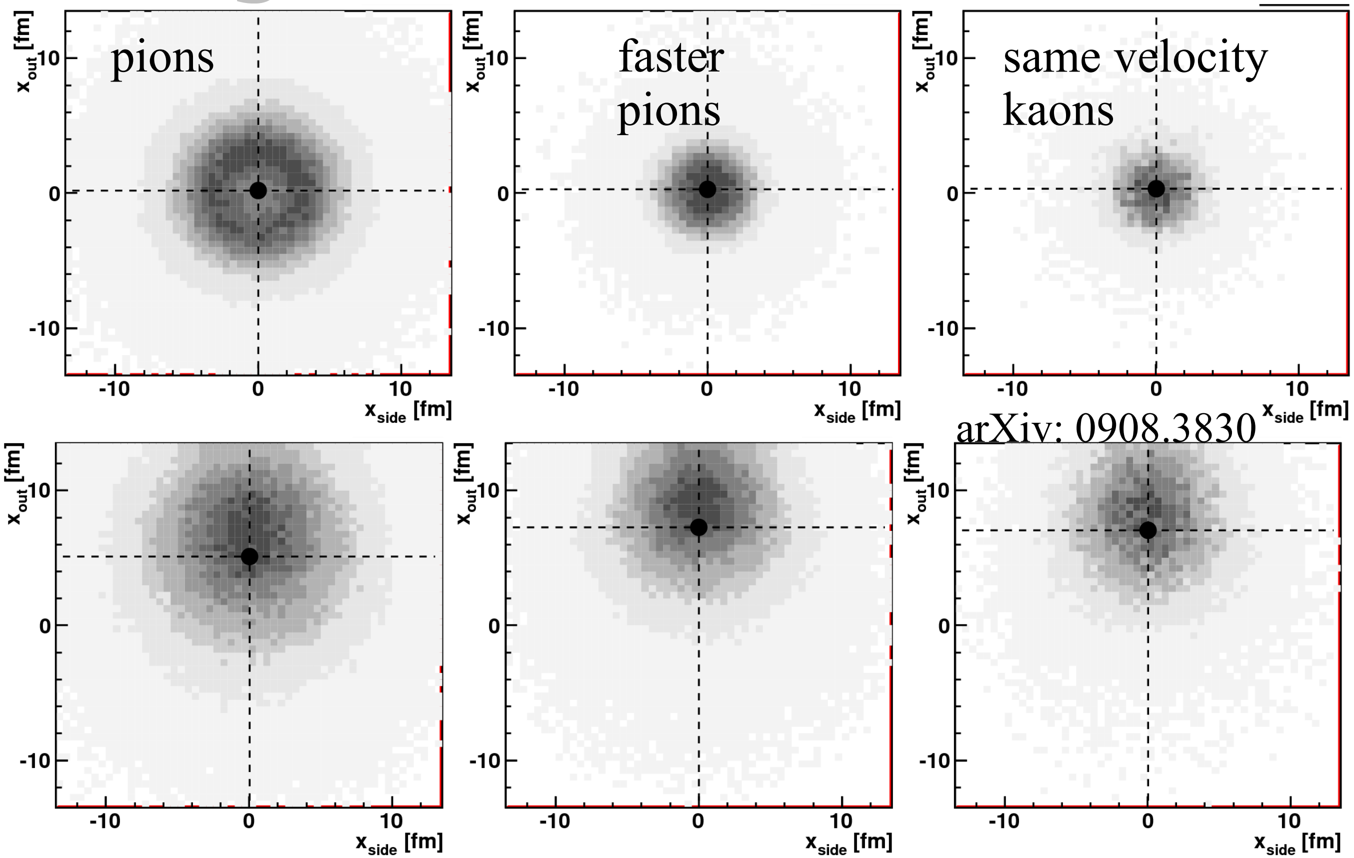
- Simple model: two types of particles ("pions" and "kaons"), rescattering with cross-section d^2.
- Initial state: no collectivity. Two scenarios: uniform temperature or temperature gradient.
- d increases: spectra evolve to thermal, collectivity develops

AK, T.J. Humanic, 0908.3830





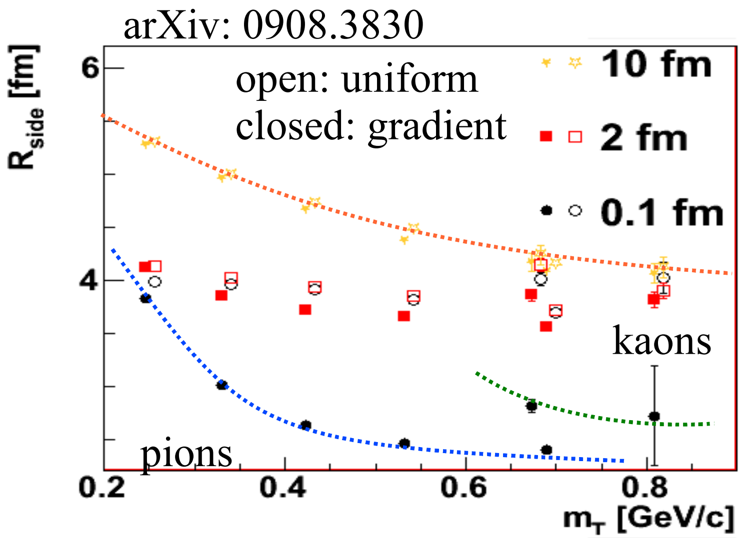
Is "gradient" and "collectivity" the same?

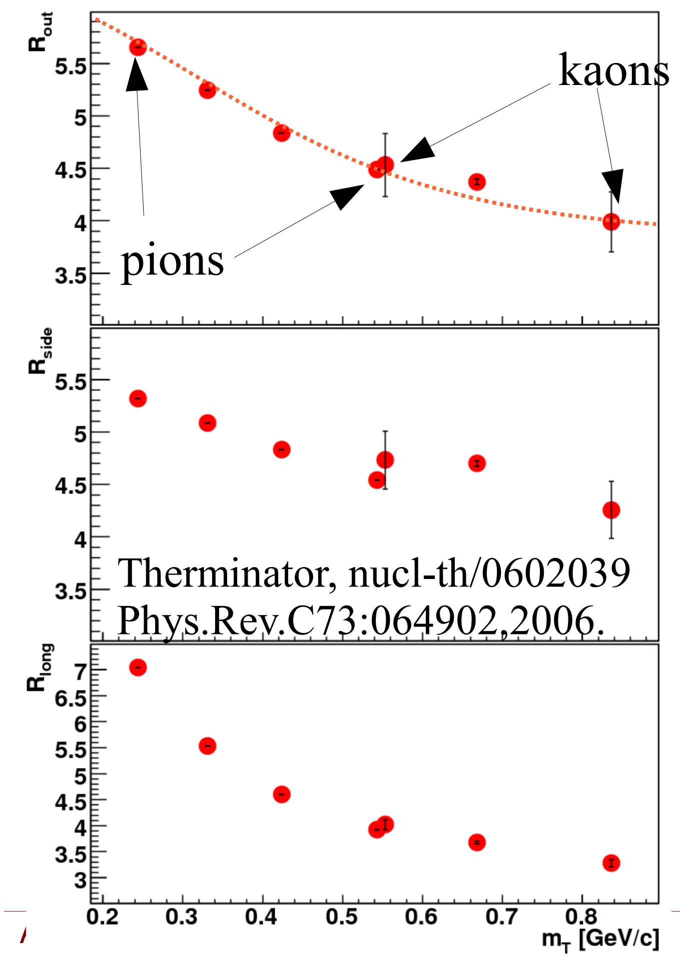


Gradient case
No interactions
Size decreases
No shift

Gradient case
With interactions
Size decreases
Mean emission point shifted

- m_T scaling of radii can be produced both by temperature gradients and "collectivity"
- Additional effect of collectivity: the source is shifted

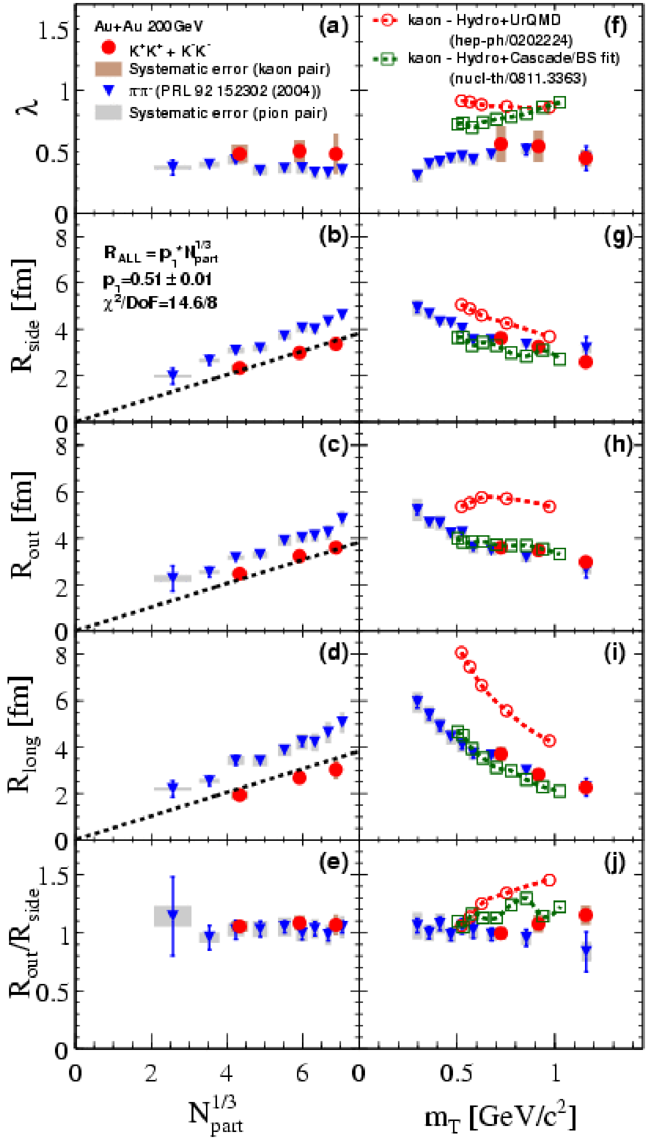




m_T scaling = collectivity?

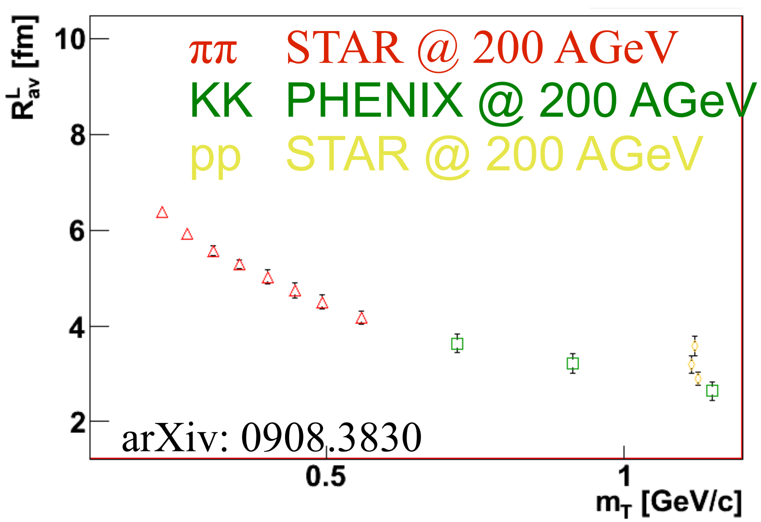
- "Gradient" case with no interactions shows m_T dependence – scenario alternative to collectivity? But ...
- Kaons do not follow the trend
- Simulations with interactions also show m_T dependence, but now kaons follow the same trend as pions
- Predictions from hydro (with resonance propagation) also show common m_T scaling

m_T scaling for kaons and protons

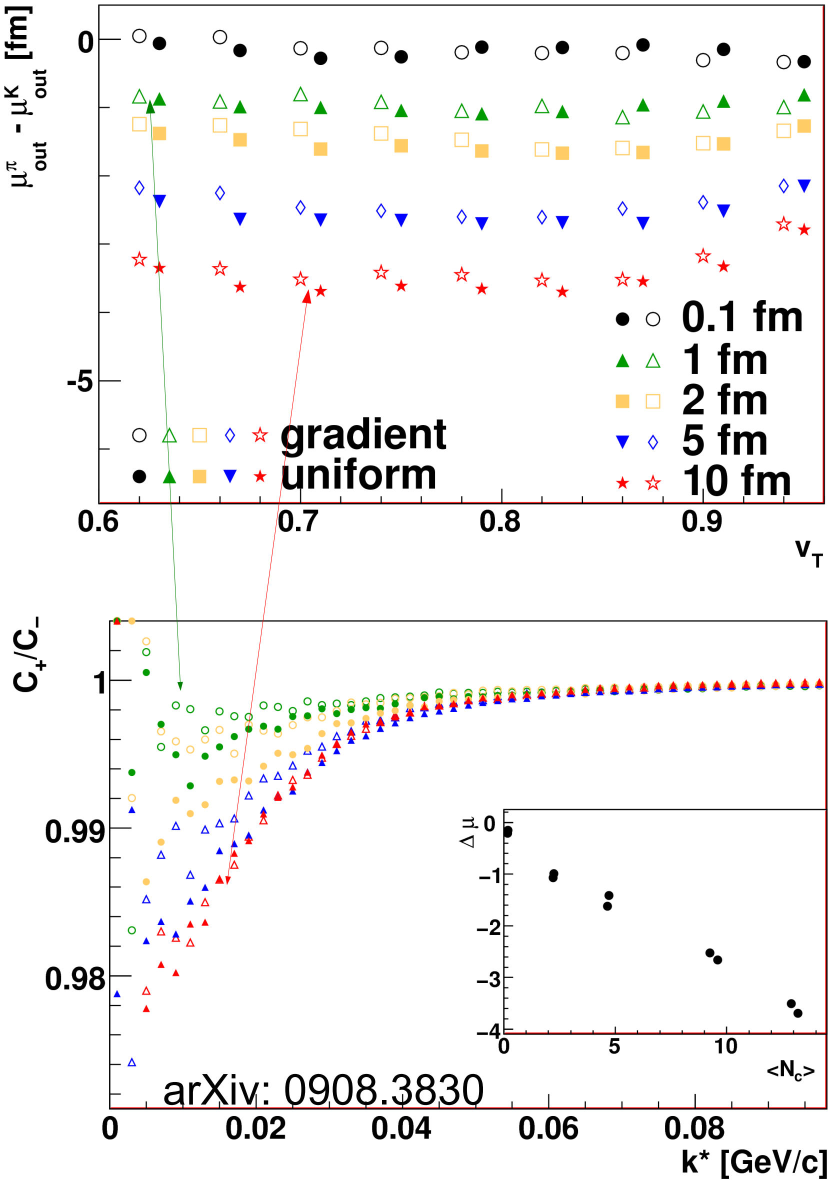


PHENIX, Phys. Rev. Lett. 103, 142301 (2009)

- m_T scaling, coming both from p_T and from mass, is observed in data for pions, kaons, protons
- It is consistent with collective flow, inconsistent with temperature gradients with no collectivity

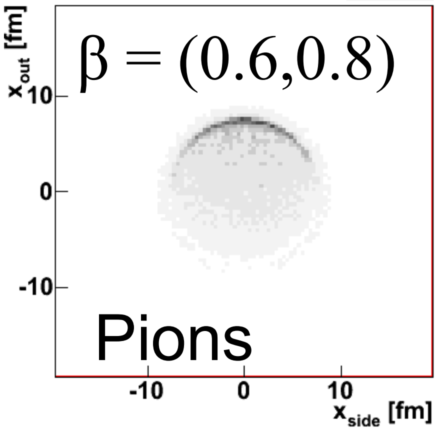


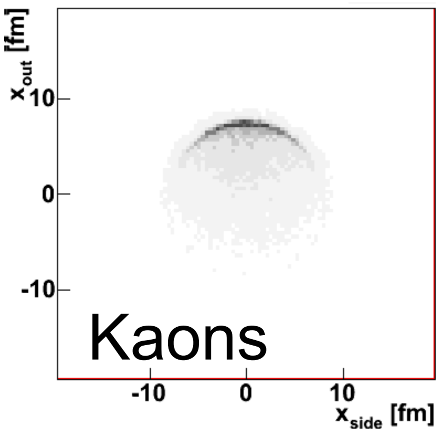
Mean emission point difference: clean signal of collectivity

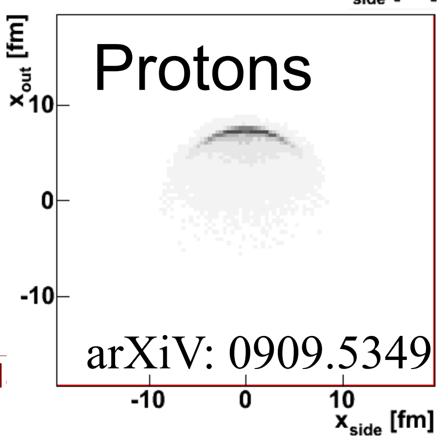


- Mean emission point difference $\mu_{out}^{\pi K} = \langle x_{out}^{\pi} \rangle - \langle x_{out}^{K} \rangle$ between pions and kaons increases linearly with number of collisions per particle – clean and unambigous signature of collectivity
- Initial temperature gradients do not matter – asymmetry depends only on collectivity
- Can be measured by non-identical particle femtoscopy

Collectivity and emission asymmetry







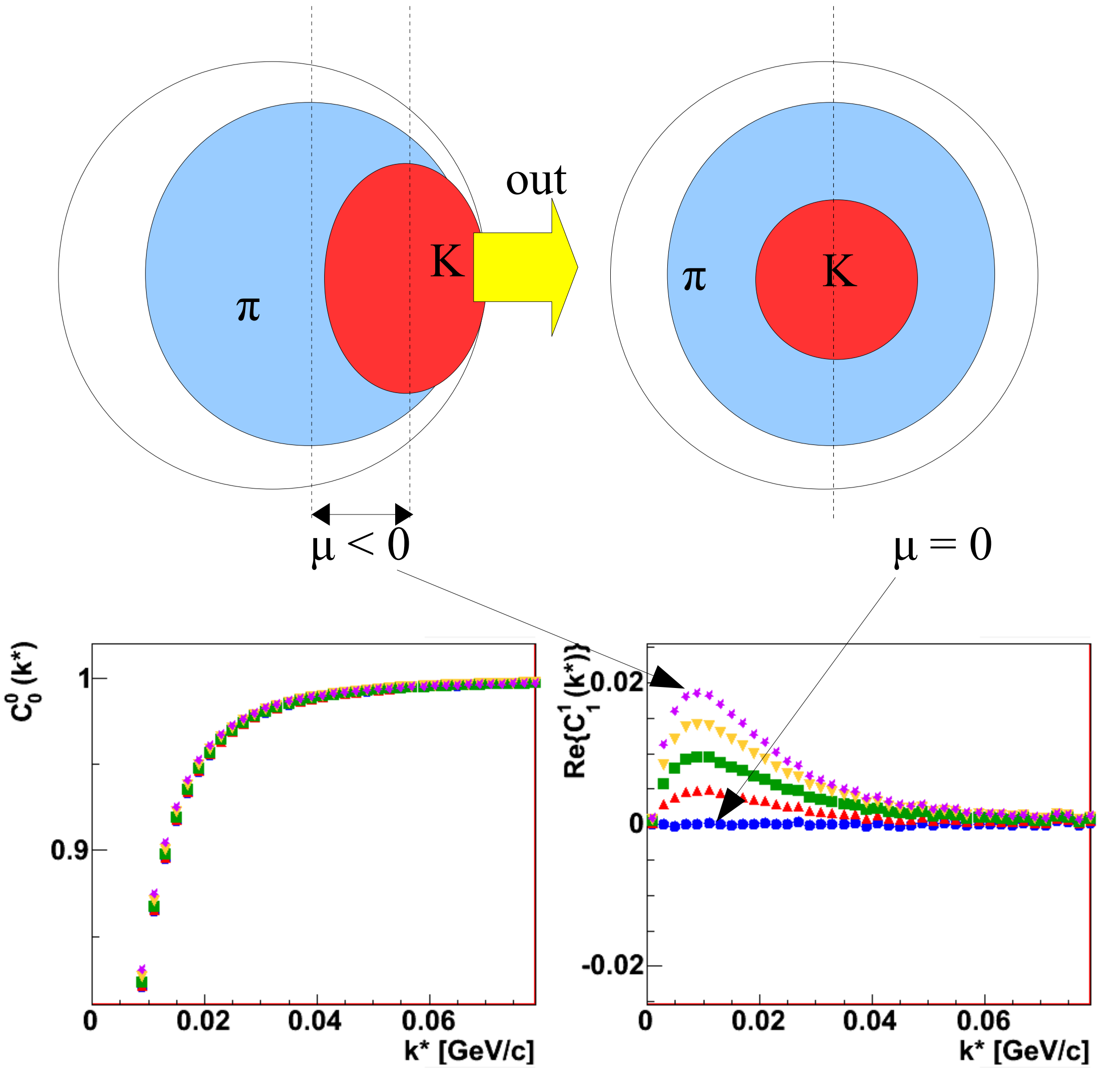
- As particle mass (or p_T) grows, average emission point moves more "outwards" - origin of the effect the same as m_T scaling
- Average emission points for particles with same velocity but different mass:

Pions $<x^{\pi}_{\alpha t}>$	Kaons $<x^{K}_{\alpha t}>$	Protons $<x^{p}_{\alpha t}>$
2.83 fm	4.47 fm	5.61 fm

$$\text{Asymmetry: } \langle r^{\pi K}_{out} \rangle \approx \langle x^{\pi}_{out} \rangle - \langle x^{K}_{out} \rangle$$

- Similar asymmetry can come from time difference (e.g. from resonance products) but detailed simulation shows it is less than 1/3 of the total effect.

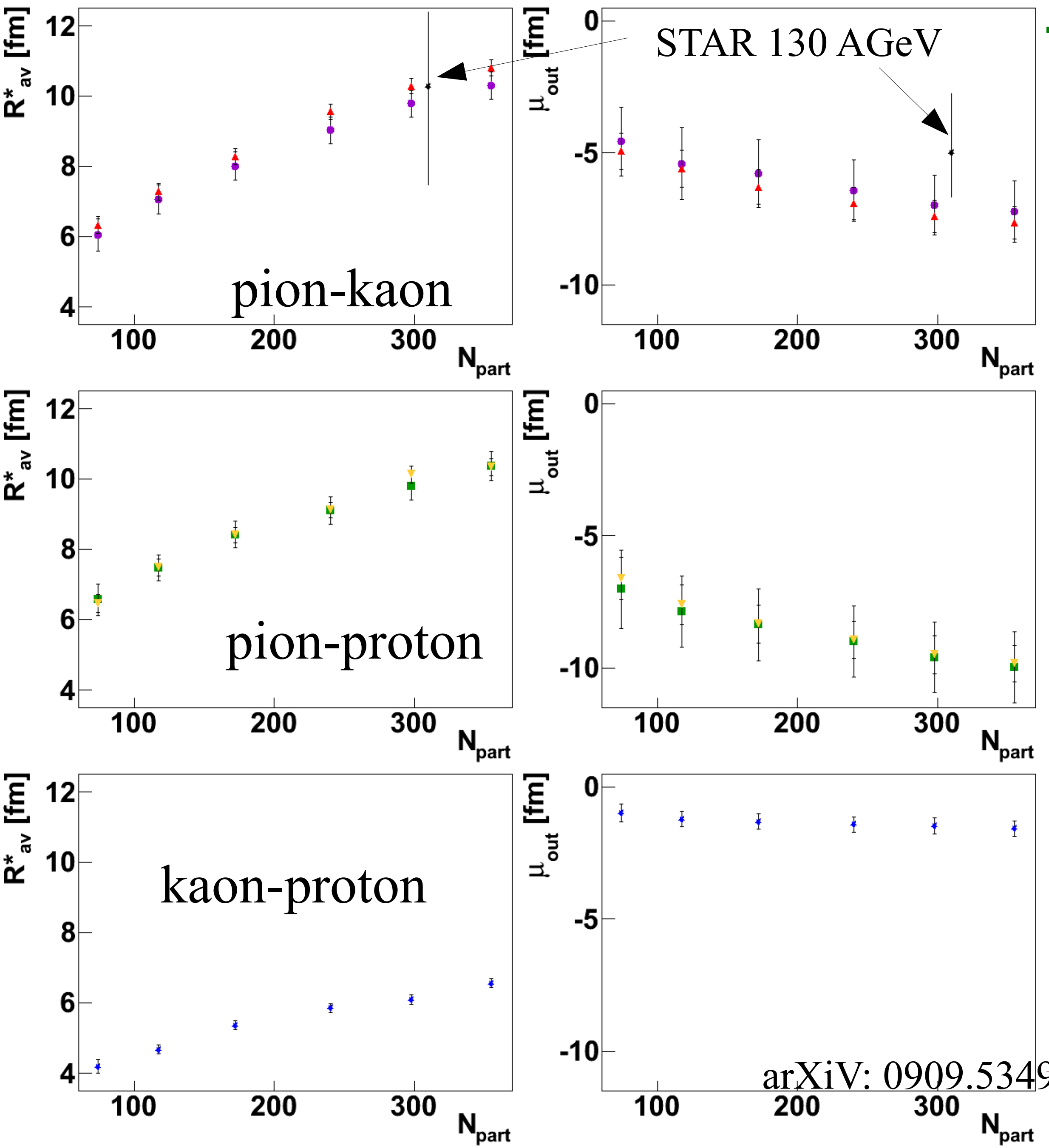
Accessing emission asymmetries



$$\Re\{C_1^1\} \sim \int C(\phi, \cos(\theta)) \cos(\phi)\, d\phi\, d\cos(\theta)$$

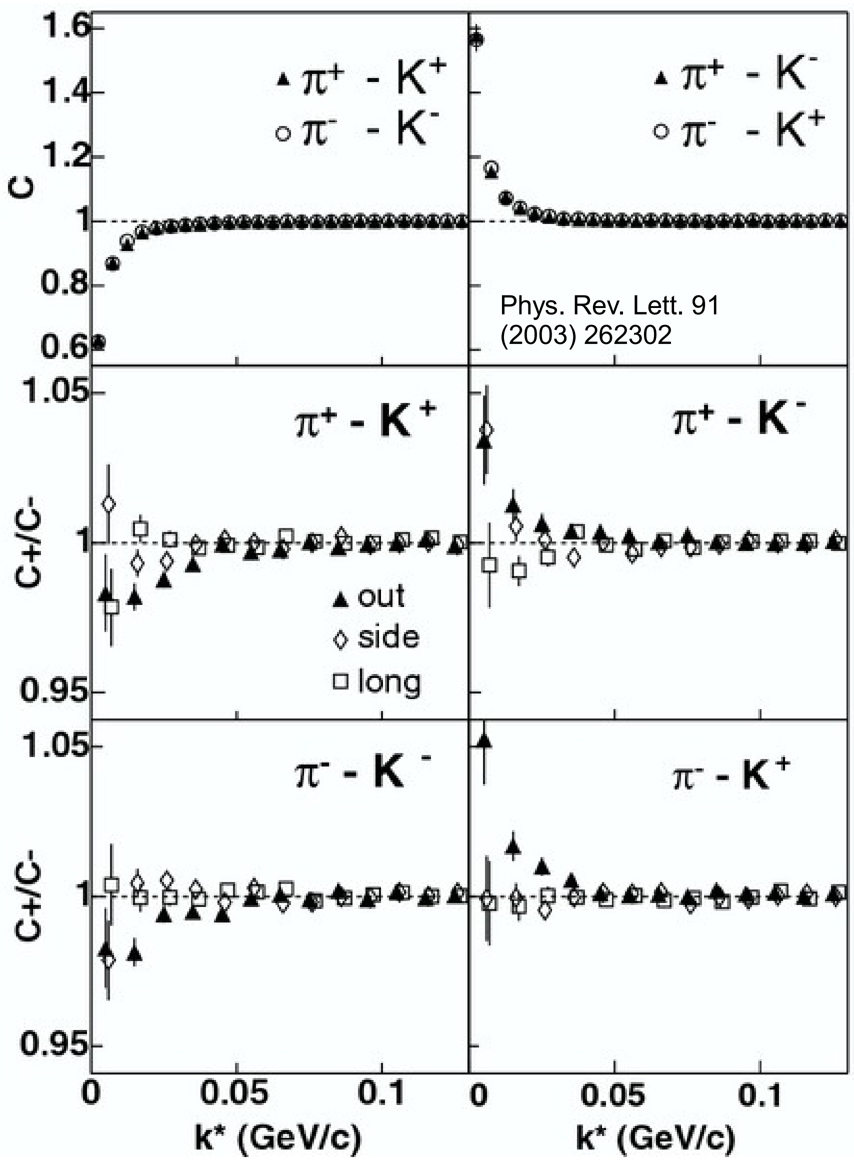
- Non-identical particle femtoscopy is sensitive to differences in average emission points:
  - If a faster pion is emitted closer to the center, after emission it stays close to the kaon longer – building a stronger correlation.
  - $\mathrm{Re}\{C_1^1\}$ measures the difference in correlation strength between the “faster pion” and “faster kaon” configurations.

Predictions from Therminator+Lhyquid



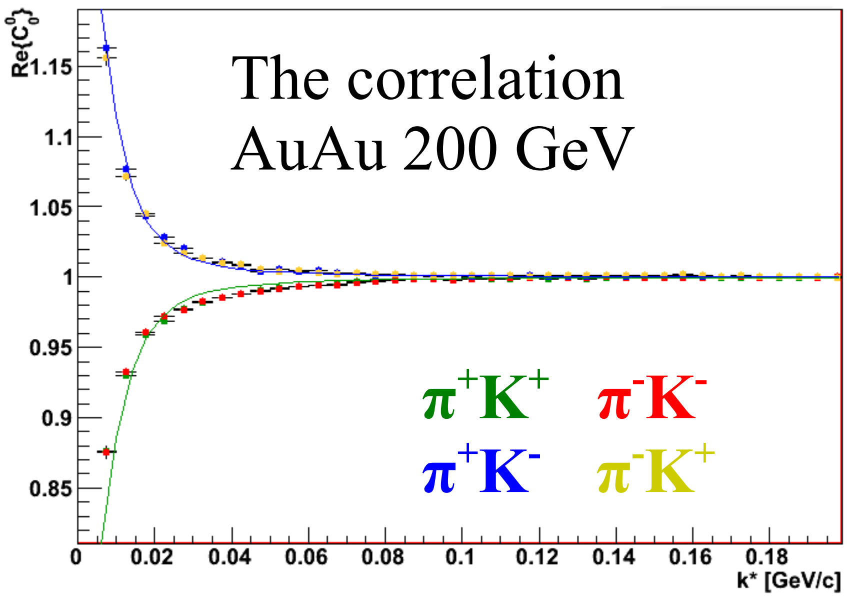
- Expected centrality trend: size grows, asymmetry grows
- Expected size and asymmetry ordering for three pair types
- Sizeable asymmetry predicted for pion-kaon and pion-proton pairs, dominated by collectivity induced

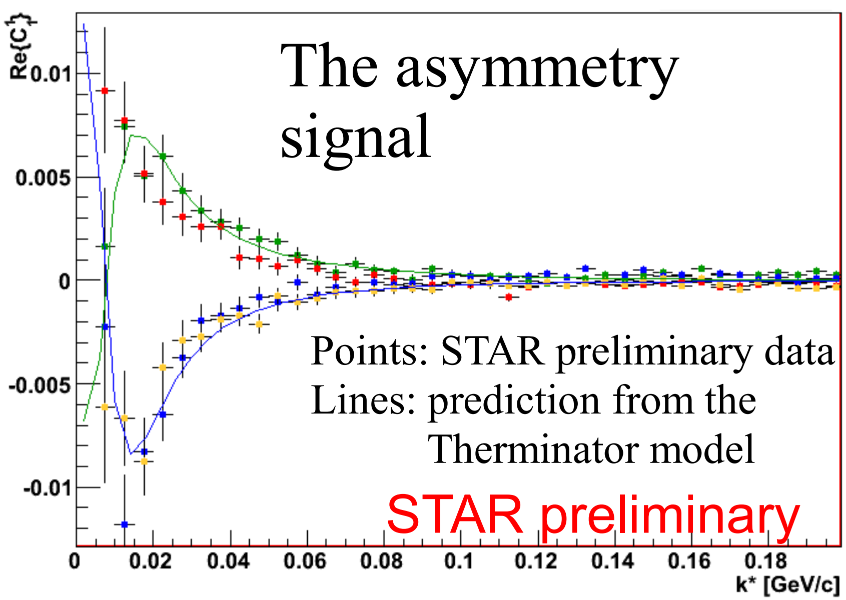
Pion – Kaon correlations at 130 AGeV



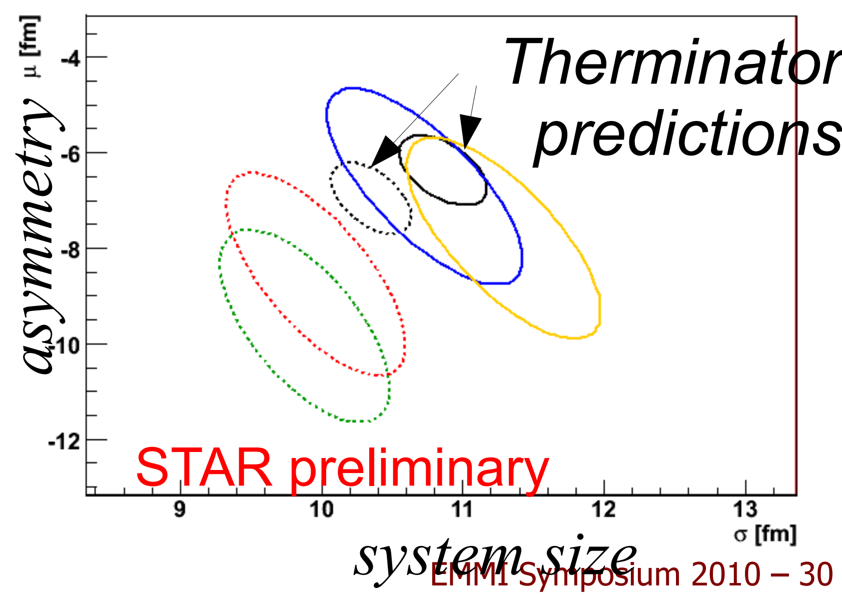
- Clear asymmetry in the "out" direction is seen for all pairs.
- Asymmetry direction consistent with hydrodynamic predictions: pions are emitted closer to the center and/or later than kaons with the same velocity
- Strict validity test for models of dynamical source evolution.

Pion-Kaon correlations at 200 AGeV

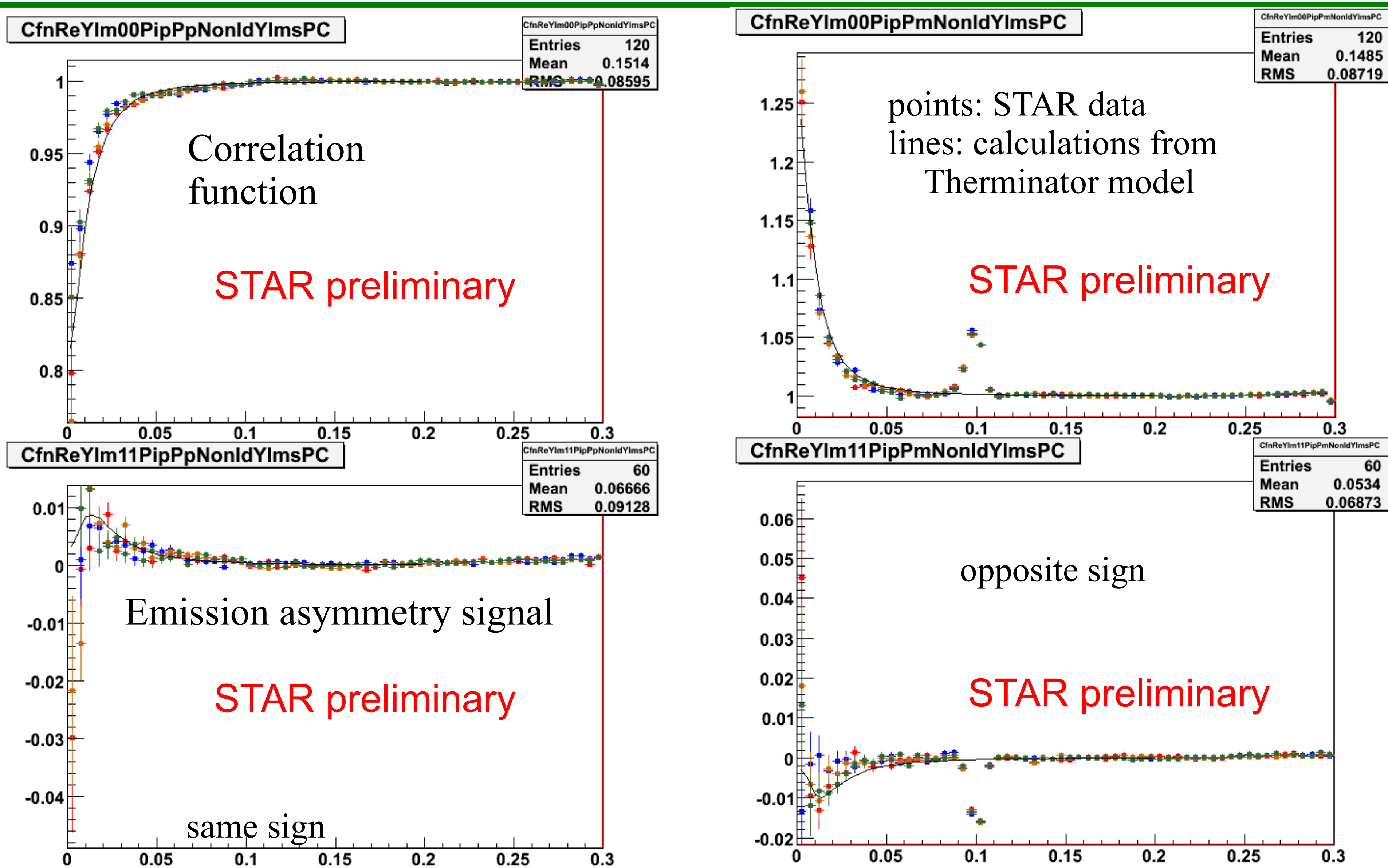




- Data show clear asymmetry: pions are emitted closer to the center and/or later than kaons
- Consistent with hydrodynamic model predictions, strong evidence against competing explanations



Pion-proton – STAR vs. Therminator

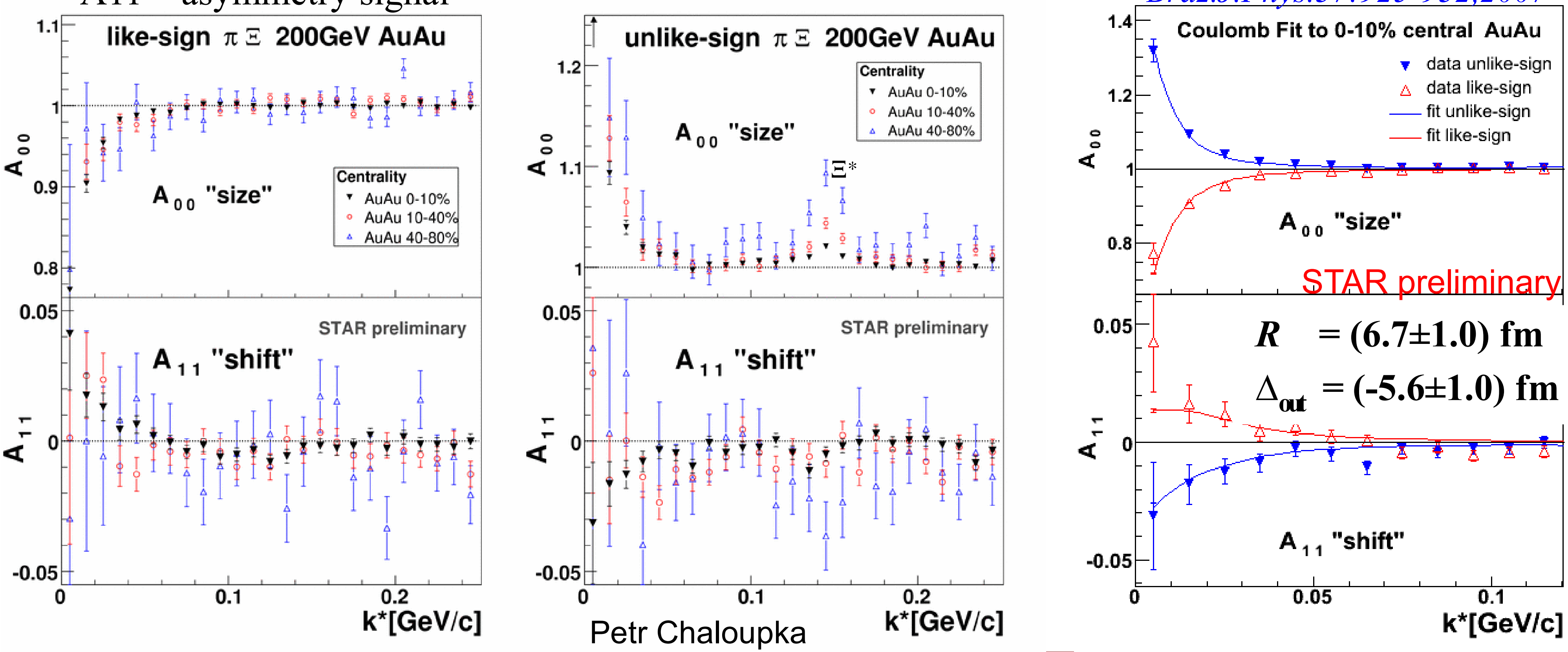


Femtoscopy with exotic systems

- Pion-Xi correlations show robust asymmetry signal: the Xi is emitted earlier or more on the outside of the system – even the heavy and weakly interacting Xi flows

A00 - Correlation function
A11 – asymmetry signal

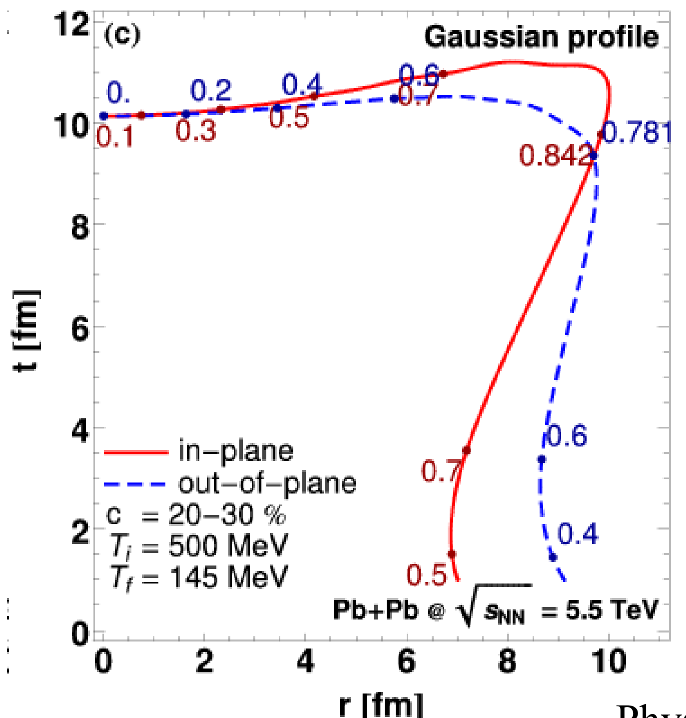
Braz.J.Phys.37:925-932,2007

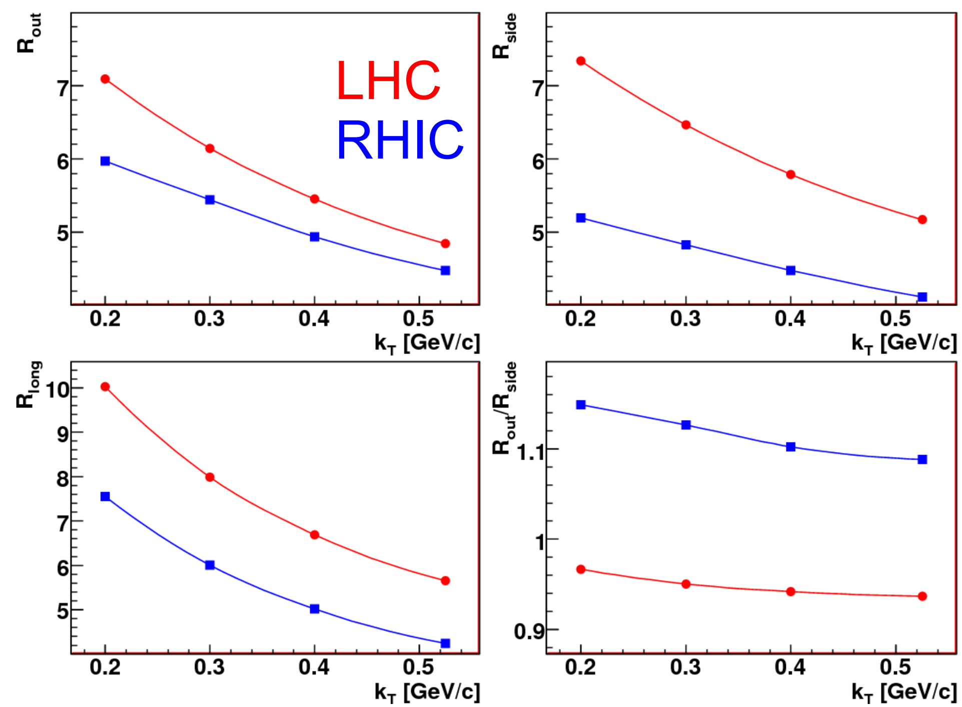


Petr Chaloupka

Predictions for collectivity at LHC

- Specific predictions for LHC: steeper m_T dependence from larger flow, longer evolution gives larger size and the reversal of the azimuthal anisotropy in space-time. The decrease of R_{out}/R_{side} ratio is even larger than at RHIC.

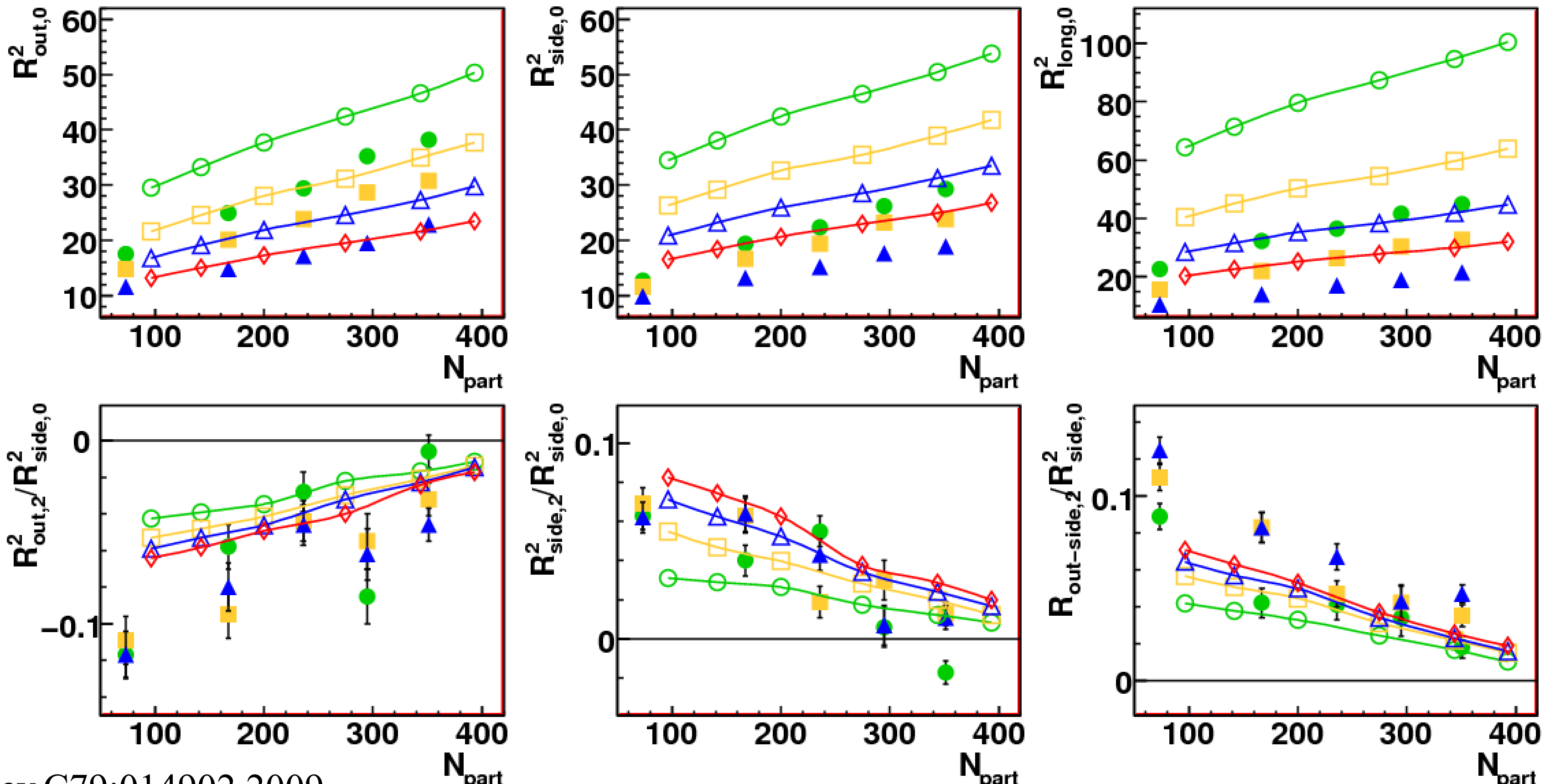




Phys.Rev.C79:014902,2009

Azimuthal oscillations at the LHC

- At the LHC longer evolution makes the shape in-plane extended at the end. The averaged shape is still out-of-plane extended, but with smaller oscillations



Phys.Rev.C79:014902,2009

Comparing pp and ions at STAR

R(pT) taken as strong space-time evidence of flow in Au+Au

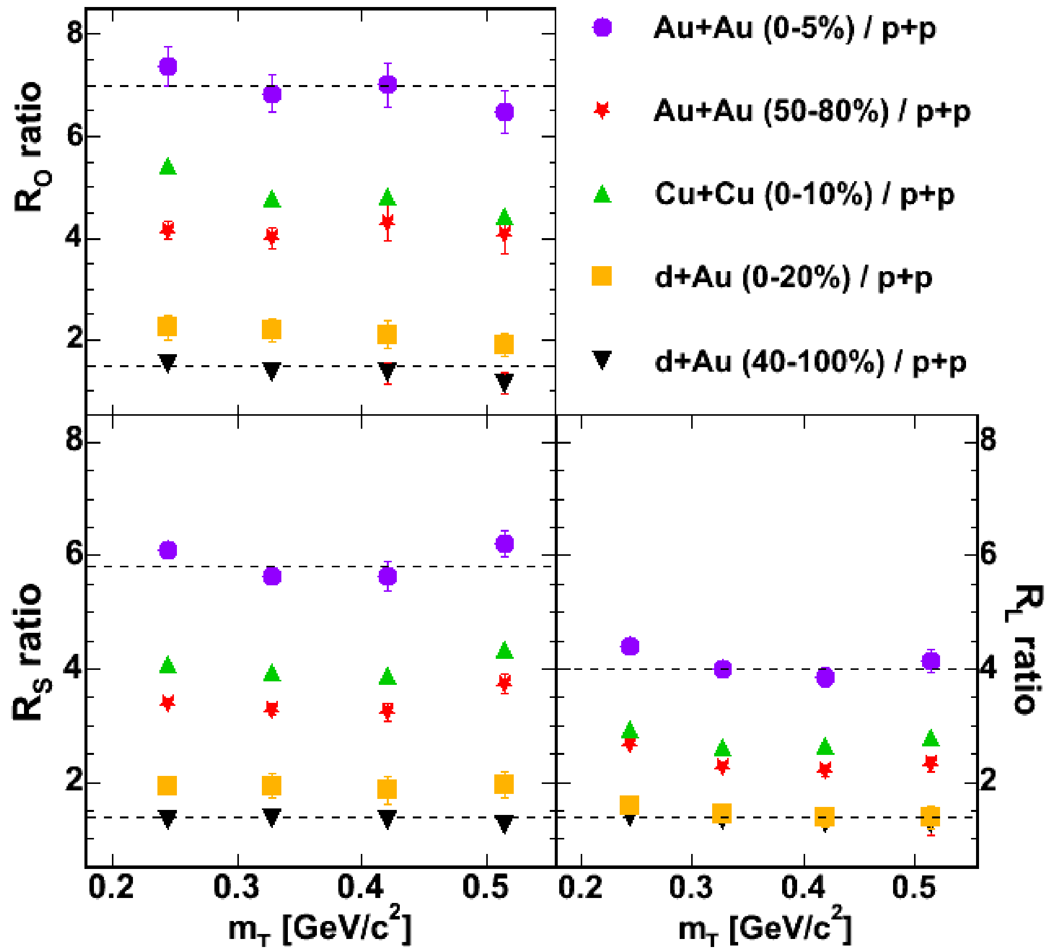
- clear, quantitative consistency predictions of BlastWave

"Identical" signal seen in p+p

- cannot be of "identical" origin? (other than we "know it cannot"...)

- Systematic effects from low multiplicity important in pp and peripheral AuAu

Ratio of (AuAu, CuCu, dAu) HBT radii by pp



pp, dAu, CuCu - STAR preliminary

Z. Chajecki, QM05

M.A. Lisa - Radial Flow in p+p Collisions - CERN Theory Phenomenology Seminar - 16 Oct 2009

Correlations from low-multiplicity

- At low multiplicity correlations from Energy and Momentum Conservation (EMCICs) constraints become important.
- A 3D correlation structure shows clear non-femtoscopic effects
- Analytical formalism was developed to account for these:

$$\Omega(p_1, p_2) = 1 - M_1 \overline{\{\vec{p}_{1,T}\, \vec{p}_{2,T}\}} - M_2 \overline{\{p_{1,Z}\, p_{2,Z}\}} - M_3 \overline{\{E_1 E_2\}} + M_4 \overline{\{E_1 + E_2\}} - M_4^2 / M_3$$

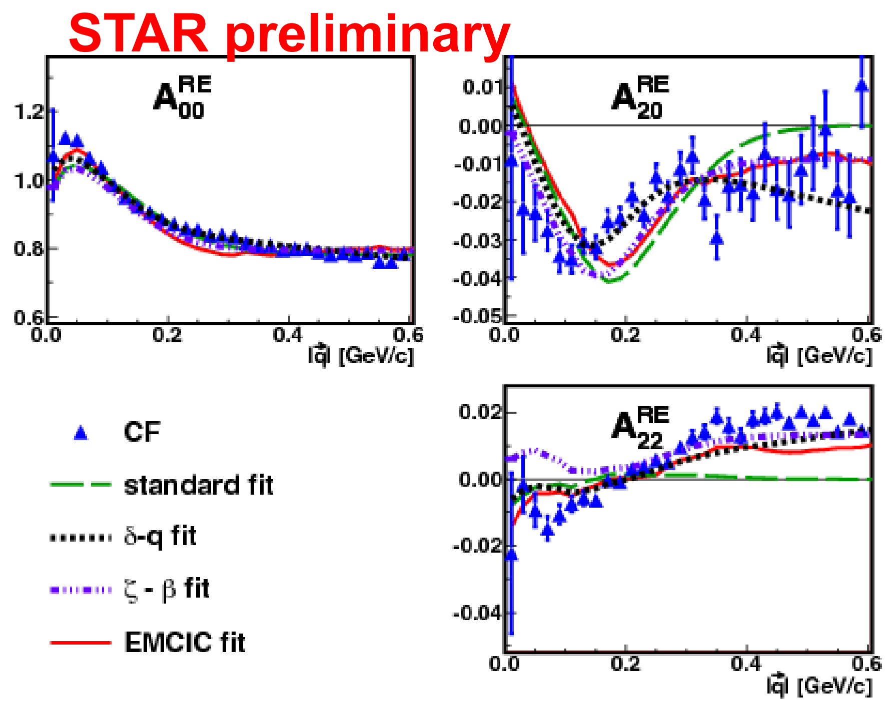
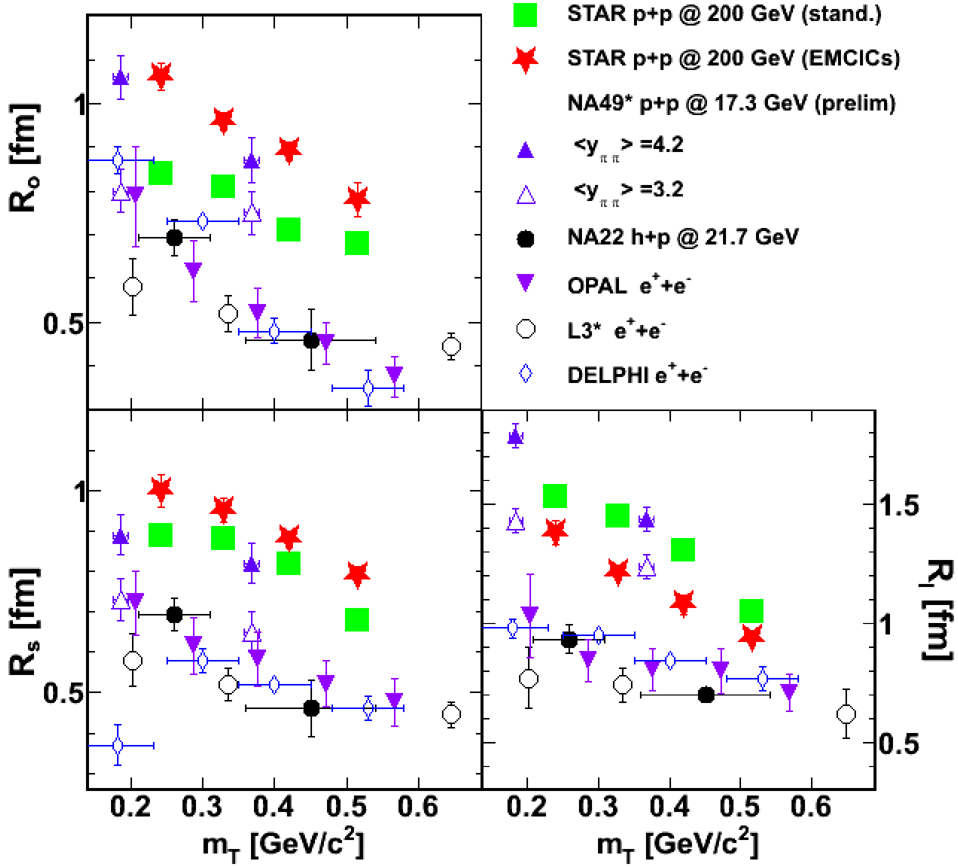
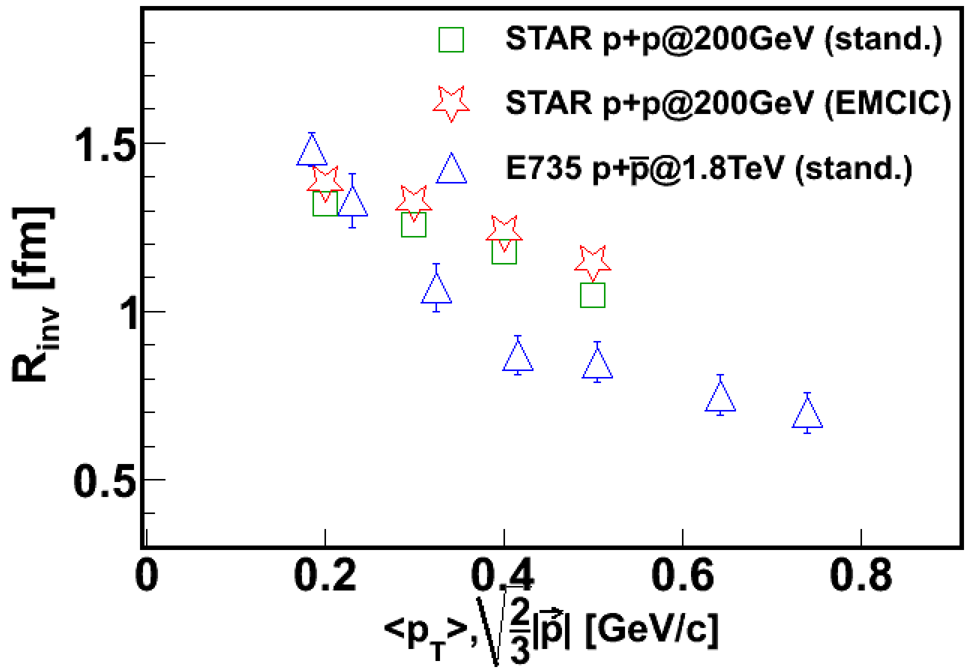


FIG. 2: (Color online) The first three non-vanishing moments of the spherical harmonic decomposition of the correlation function from $p+p$ collisions at $\sqrt{s}$=200 GeV, for $k_T = [0.15, 0.25]$ GeV/c. Femtoscopic effects are parameterized with the form in Eq. 11; different curves represent various parameterizations of non-femtoscopic correlations used in the fit and described in detail in Sec. II B.

STAR m_T dependence in pp

- Clear m_T dependence is seen, both in 1D and 3D, with standard fits (flat background).
- Fits with EMCICs differ in magnitude but trends the same.





Summary

- Collectivity is one of the defining features of the complicated systems created in heavy-ion collisions
- Hydrodynamic-like behavior, also seen in rescattering simulations, produces specific patterns in femtoscopic observables: m_{T} scaling of radii for particles of all masses, oscillation of radii vs. reaction plane orientation and mean emission point differences
- All effects observed in data, but modifications in original assumptions of hydrodynamics needed to describe them exactly: femtoscopy provides important constraints on the physics assumptions
- Results from pp bring questions about the nature of (high-multiplicity) collisions there: a "non-QGP baseline" or "mini-QGP"?