Measuring the size and dynamics of heavy-ion collisions with femtoscopy

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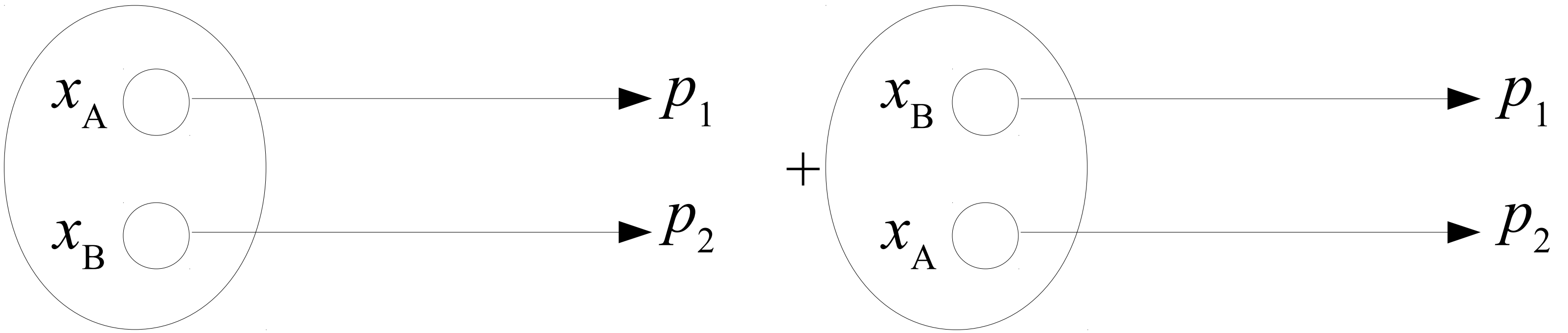
Overview

- What is femtoscopy and what does it measure
- Femtoscopy and collectivity
- Pion femtoscopy of the p-p, p-Pb and Pb-Pb collisions
  - Lessons from RHIC
  - Pb-Pb results from the LHC
  - Azimuthally sensitive femtoscopy
  - Comparison pp, PbPb and world systematics
  - P-Pb results vs. p-p and Pb-Pb data
  - Pion coherent emission from 3-pion correlations
- Femtoscopy of heavier particles
  - What more can we learn from baryon correlations
  - Baryon-baryon and baryon-antibaryon results at the LHC

Correlation – identical particles



$q = p_1 - p_2$

$r = x_A - x_B$

- Quantum interference of indistinguishable scenarios
  - We detect a pair of particles with (p_1, p_2), knowing that they have been emitted somewhere from the source (x_A, x_B)

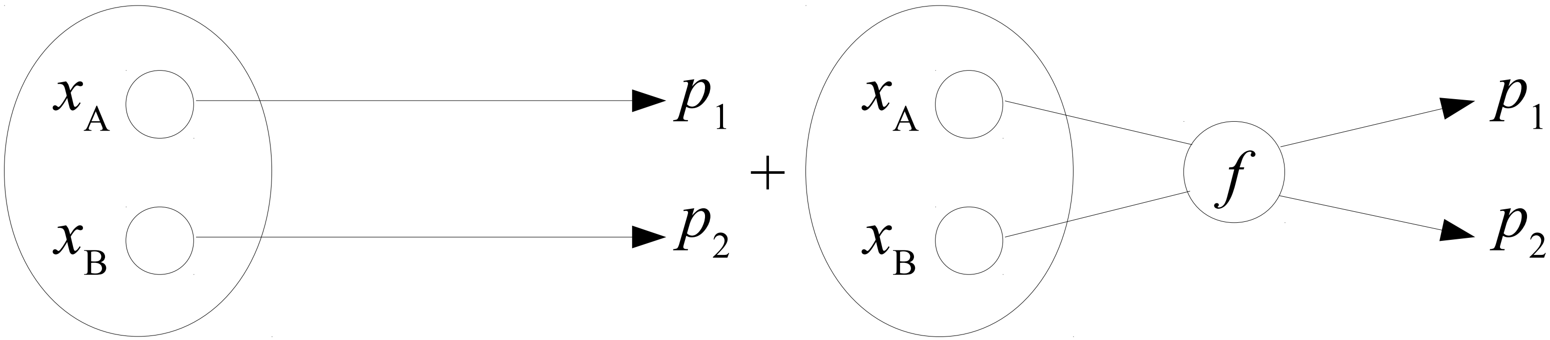
$$\Psi = \frac{1}{\sqrt{2}}\left[\exp(-i\,p_1 x_A - i\,p_2 x_B) + \exp(-i\,p_1 x_B - i\,p_2 x_A)\right]$$

$$|\Psi|^2 = 1 + \frac{1}{2}\left[\exp(-i\,p_1 x_A - i\,p_2 x_B + i\,p_1 x_B + i\,p_2 x_A) + \exp(-i\,p_1 x_B - i\,p_2 x_A + i\,p_1 x_A + i\,p_2 x_B)\right]$$

$$= 1 + \frac{1}{2}\left\{\exp[-i(x_A - x_B)(p_1 - p_2)] + \exp[i(x_A - x_B)(p_1 - p_2)]\right\}$$

$$= 1 + \cos(q\,r)$$

Correlation – hadrons



$q = 2k^* = p_1 - p_2$

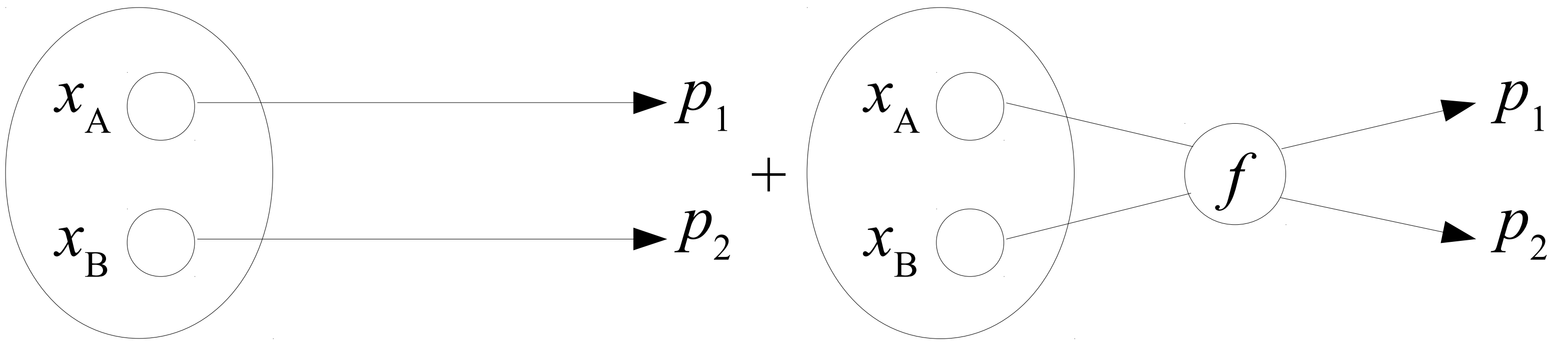
$r = x_A - x_B$

- Two hadrons interact via the strong interaction after their last scattering (emission)
  - The wave function is the Bethe-Salpeter amplitude, corresponding to the standard quantum scattering problem, taken with the inverse time direction
  - For identical hadrons it must also be properly (anti-)symmetrized

$$\Psi = \exp(-i\vec{k}^*\vec{r}) + f\,\frac{\exp(ik^*r)}{r}$$

$$f^{-1} = \frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - ik^*$$

Correlation – charged particles



$$q = 2k^* = p_1 - p_2$$
$$r = x_A - x_B$$

- Two charged particles interact via Coulomb after their last scattering
  - This gives the final form of the wave-function, which must also be properly (anti-)symmetrized for identical particles

$$\Psi_{-\boldsymbol{k}^*}(\boldsymbol{r}^*) = e^{i\delta_c}\sqrt{A_c(\eta)}\left[e^{-i\boldsymbol{k}^*\boldsymbol{r}^*}F(-i\eta,1,i\xi) + f_c(k^*)\tilde{G}(\rho,\eta)/r^*\right]$$

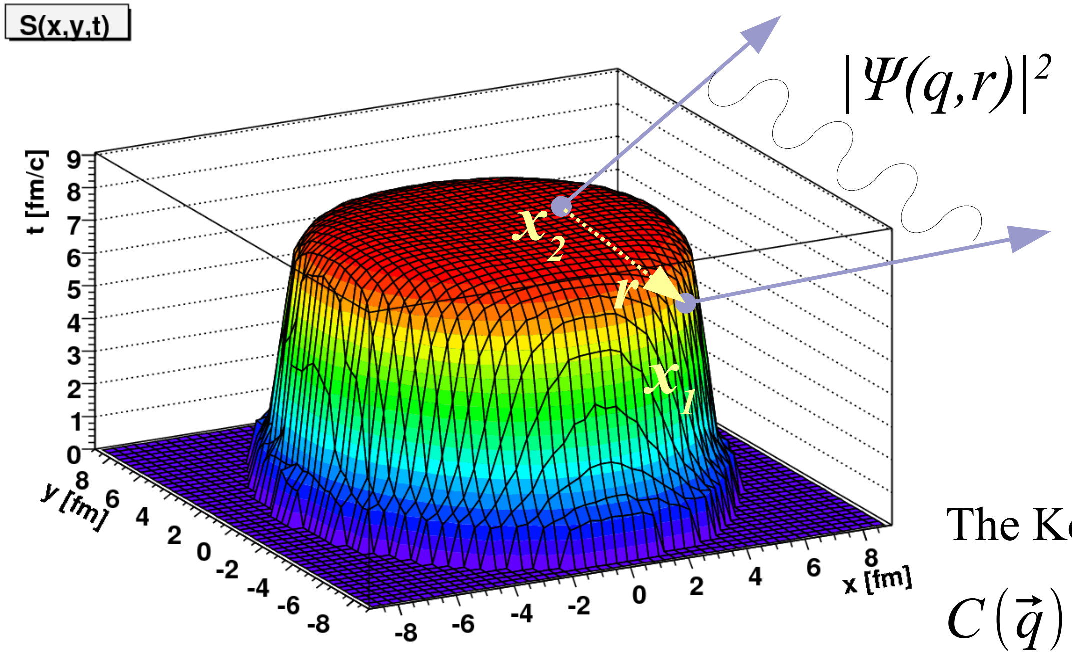
Gamow factor — Coulomb part — Strong+Coulomb part

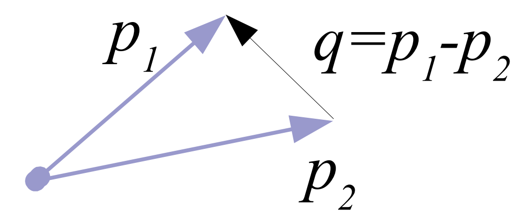
$$\xi = \boldsymbol{k}^*\boldsymbol{r}^* + k^*r^* \equiv \rho(1+\cos(\theta^*)),\quad \rho = k^*r^*,\quad \eta = (k^*a)^{-1},\quad a = (\mu z_1 z_2 e^2)^{-1}$$

$$F(k^*,r^*,\theta^*) = 1 + r^*(1+\cos\theta^*)/a + (r^*(1+\cos\theta^*)/a)^2 + ik^*r^{*2}(1+\cos\theta^*)^2/a + \ldots$$

θ^* is an angle between separation r^* and relative momentum k^*

Measuring space-time extent: femtoscopy





The Koonin-Pratt Equation

$$C(\vec{q}) = \int S(\boldsymbol{r}) |\Psi(\vec{q}, \boldsymbol{r})|^2 d^4 r = \langle |\Psi(\vec{q}, \boldsymbol{r})|^2 \rangle_{pairs}$$

- Use two-particle correlation, coming from the interaction Ψ
- Can be quantum statistics (HBT), coulomb and strong
- Try to invert the Koonin-Pratt eq. to learn S from known Ψ and measured C

What "size" do we measure?

- Source is described by S, which is usually taken as Gaussian:

$$S(\boldsymbol{x}) \sim \exp\left(-\frac{x_o^2}{2R_o^2} - \frac{x_s^2}{2R_s^2} - \frac{x_l^2}{2R_l^2}\right)$$

- But the Koonin-Pratt (KP) equation takes the pair separations:

$$S(\boldsymbol{r}) = \int S(\boldsymbol{x_1}) S(\boldsymbol{r} - \boldsymbol{x_1})\, d\boldsymbol{x_1} \sim \exp\left(-\frac{r_o^2}{4R_o^2} - \frac{r_s^2}{4R_s^2} - \frac{r_l^2}{4R_l^2}\right)$$

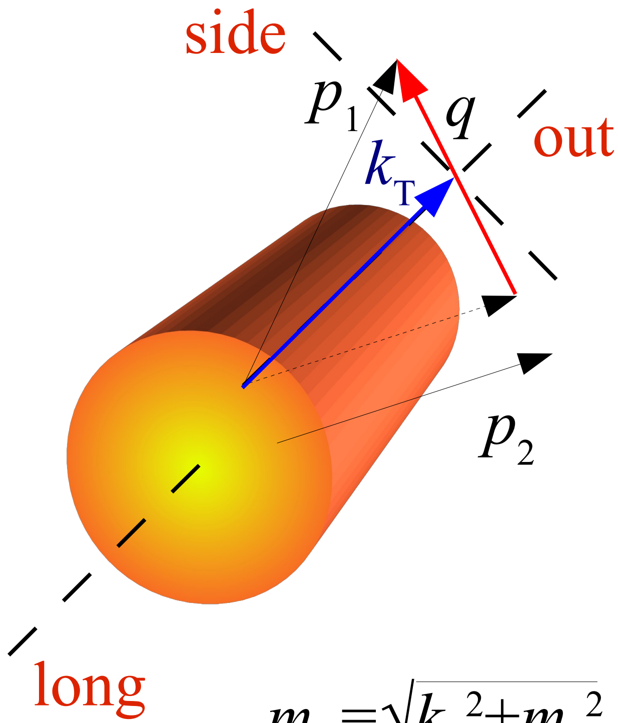
- For identical pions coulomb factor K is factorized out, Ψ is then $1+\cos(qr)$. Then KP gives the femtoscopic part of CF:

$$C_f = (1-\lambda) + \lambda K \left(1 + \exp(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2)\right) B(q)$$

both R and q can be evaluated in several reference frames.

- The size R measured in this way is a variance of single-particle emission function (emission probability distribution)

Refernce frames



$$m_T = \sqrt{k_T^2 + m_\pi^2}$$

Longitudinally Co-Moving System (LCMS):

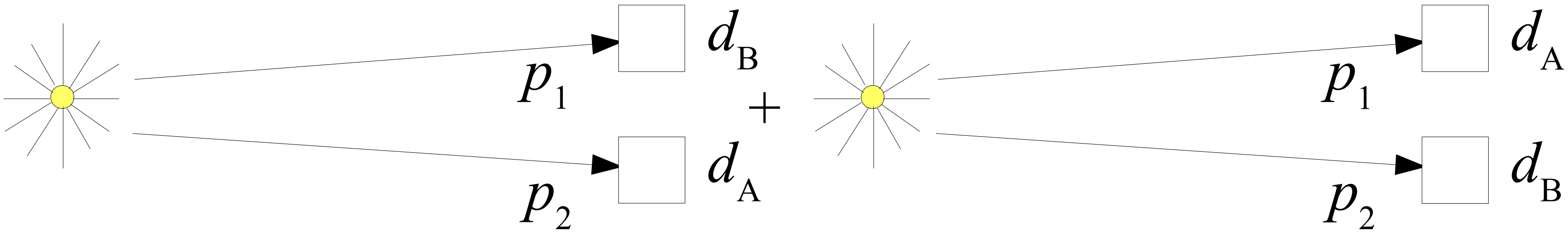
$$p_{1,long} = -p_{2,long}$$

The Koonin-Pratt Equation:

$$C(\vec{q}) = \int S(\boldsymbol{r}) |\Psi(\vec{q}, \boldsymbol{r})|^2 d^4 r$$

- If statistics is sufficient (charged pions ...) the measurement can be done in 3 dimensions, giving 3 independent sizes
- The Longitudinally Co-Moving System is used
- The Bertsch-Pratt decomposition of q:
  - Long along the beam: sensitive to longitudinal dynamics and evolution time
  - Out along k_T: sensitive to geometrical size, emission time and space-time correlation
  - Side perpendicular to Long and Out: sensitive to geometrical size
- For analyses which are statistically challenged, the measurement is done in one dimension (giving only one size) in Pair Rest Frame

Why is it called "HBT" ?



$q = p_1 - p_2$

$d = d_A - d_B$

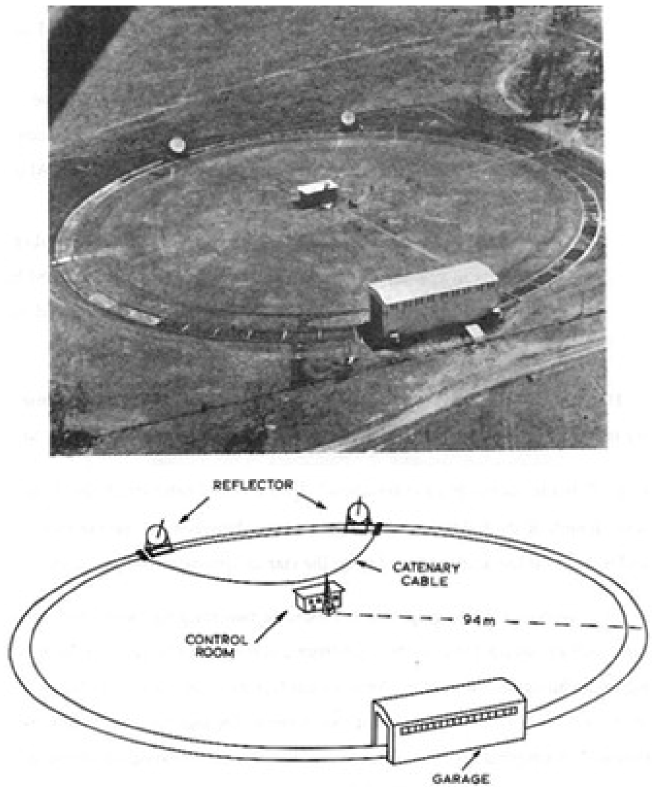


Figure 1. Aerial photo and illustration of the original HBT apparatus. They have been extracted from Ref.[1].

- In astronomy angular size of the star is measured via photon correlation vs. spatial separation of detectors
- The momentum spread can be inferred, which is transformed into angular size of the star
- The mathematical formalism is similar
- The first measurement was done by Hanbury-Brown and Twiss – HBT !

Experimental procedure

- In experiment one measures the standard correlation function for pairs of **identified particles,** as a function of pair **relative momentum**:

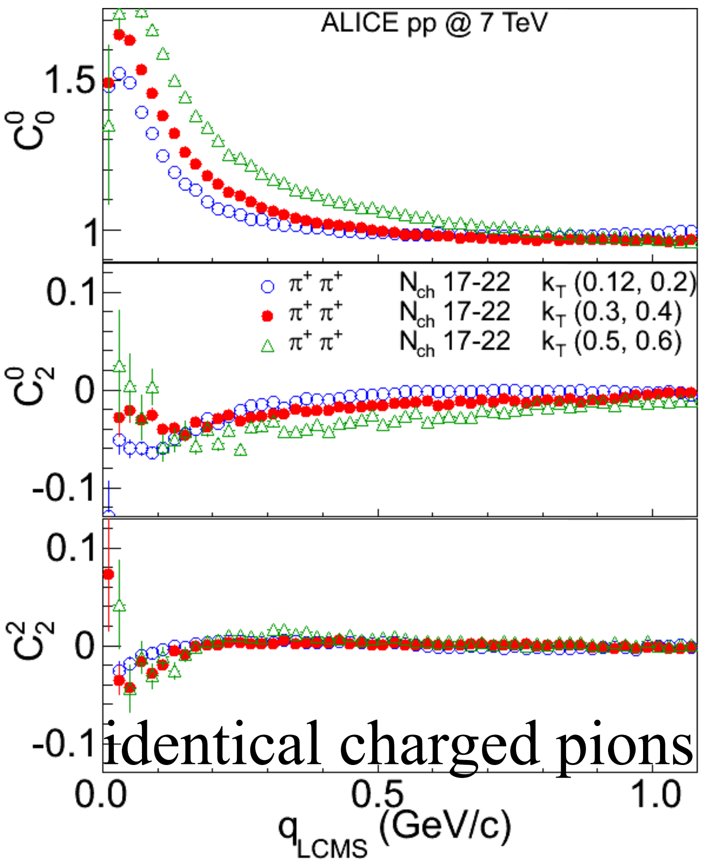
$$C_e(\vec{q}) = S(\vec{q}) / B(\vec{q})$$

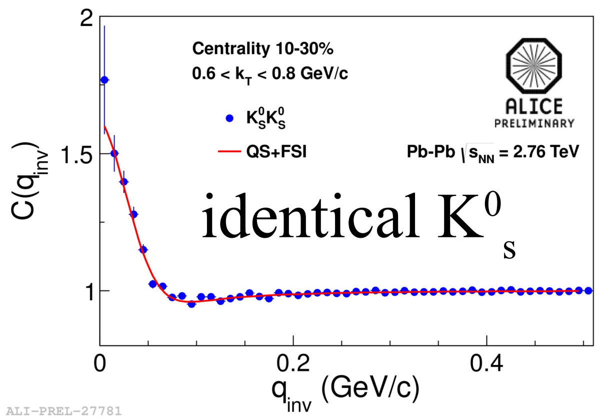
- The "Signal" **S** is a distribution of pairs where both particles come from **the same event**, "background" **B** can be constructed in many ways. Most common is "event mixing" where the two particles come from **two different events**, similar in terms of single-particle acceptance.
- However a single "source size" is not very interesting, what really matters is the source **size dependence** on many variables: **collision system**, event **centrality**, collision **energy** and pair **transverse momentum**

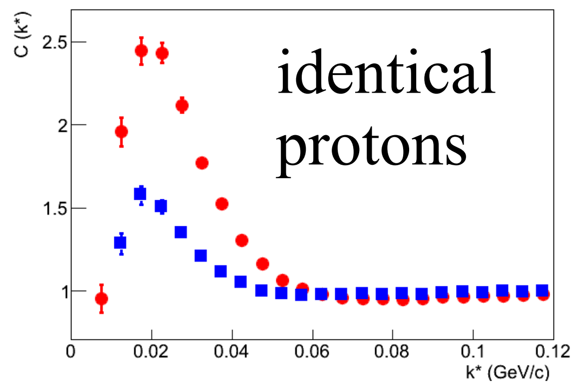
How does it look like?

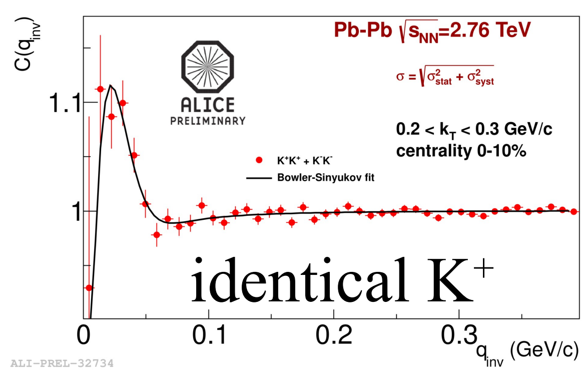
- Various shapes and momentum scales, depending on the pair type (interactions involved), collision system and energy, pair transverse momentum, etc.

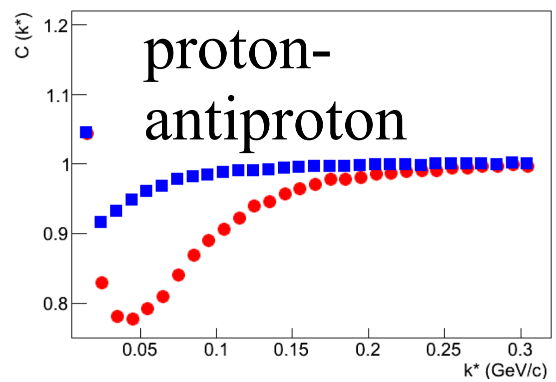
$$e.g: \quad C_e(\vec{q})=(1-\lambda)+\lambda K(q)[1+\exp(-R^2 q^2)]$$



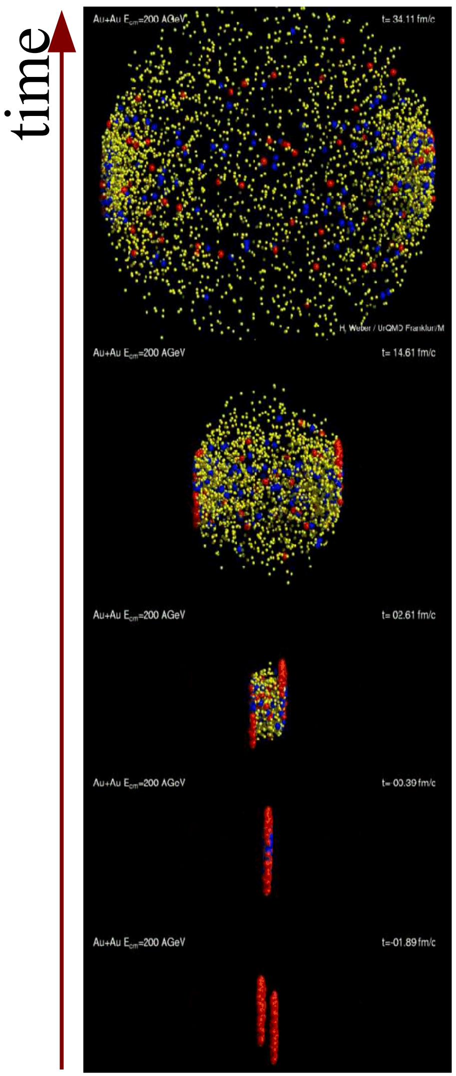


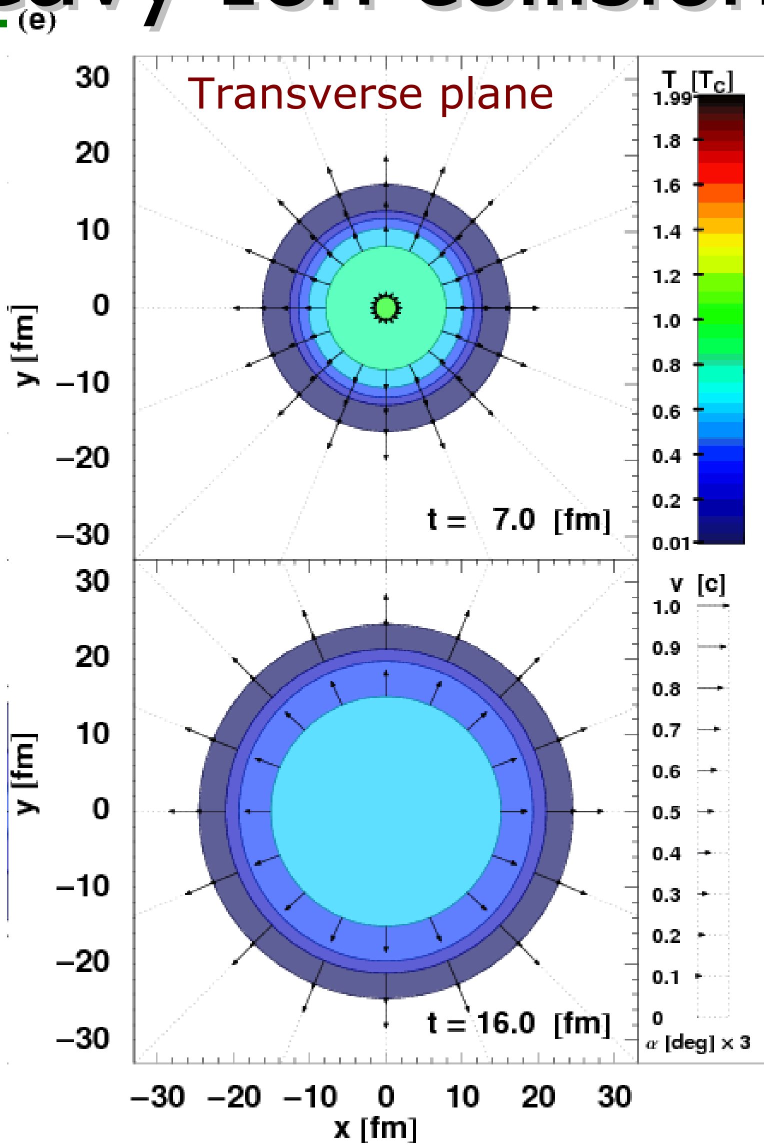






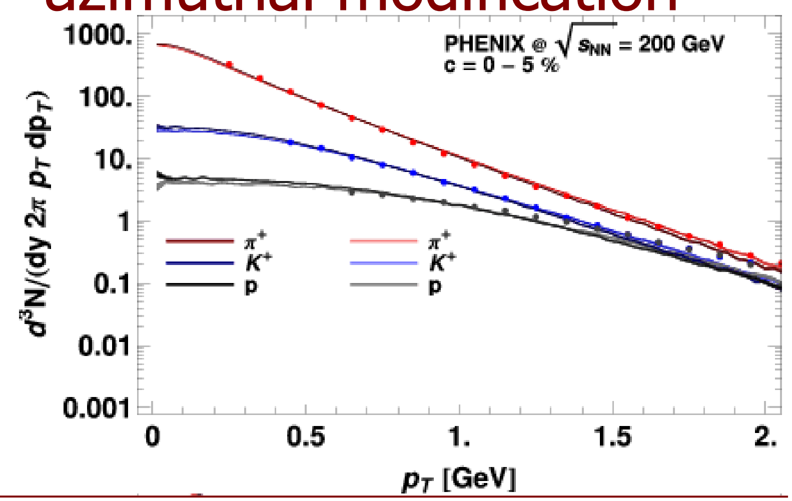
Heavy Ion collision evolution



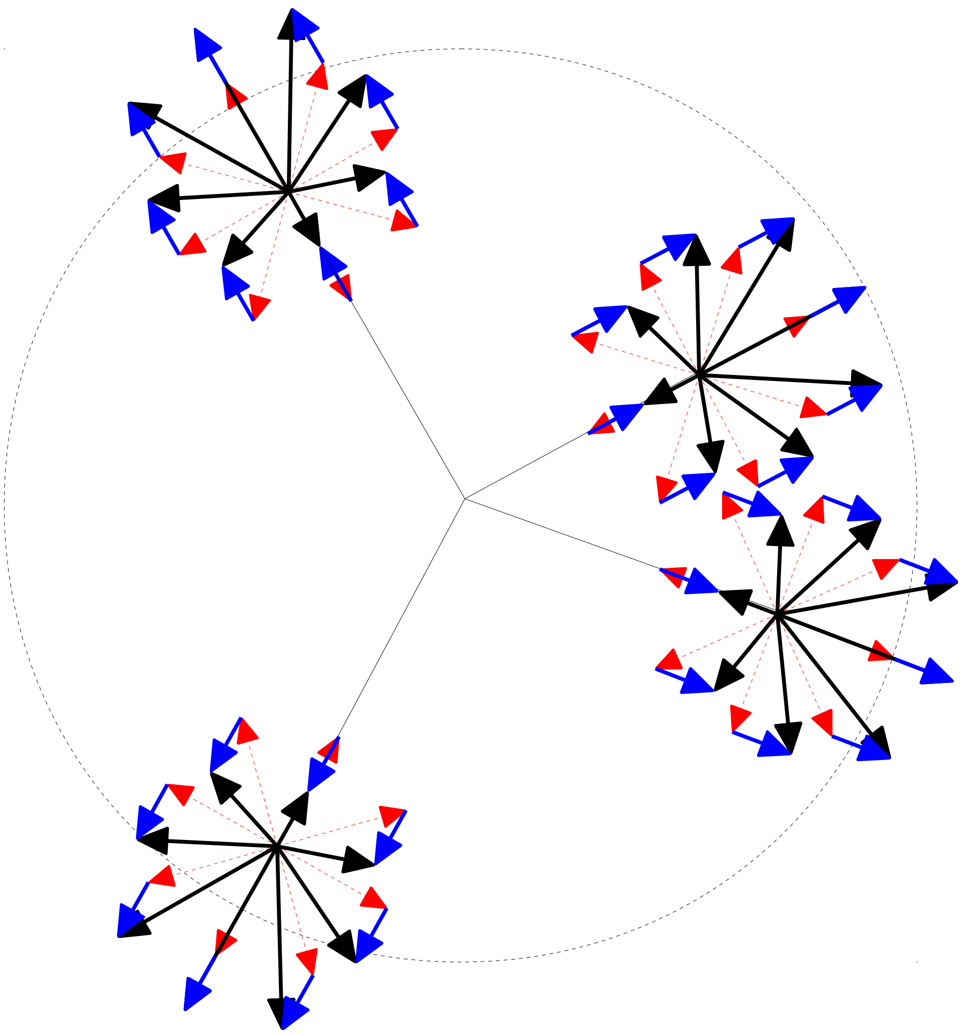


M. Chojnacki, W. Florkowski,
PRC 74 (2006) 034905

- 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

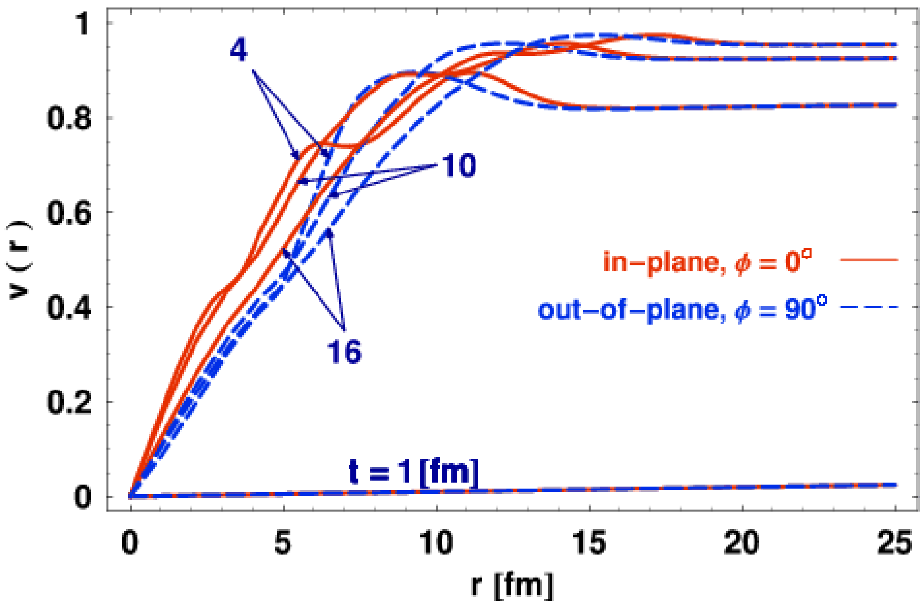


Which collectivity do we seek?



- 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

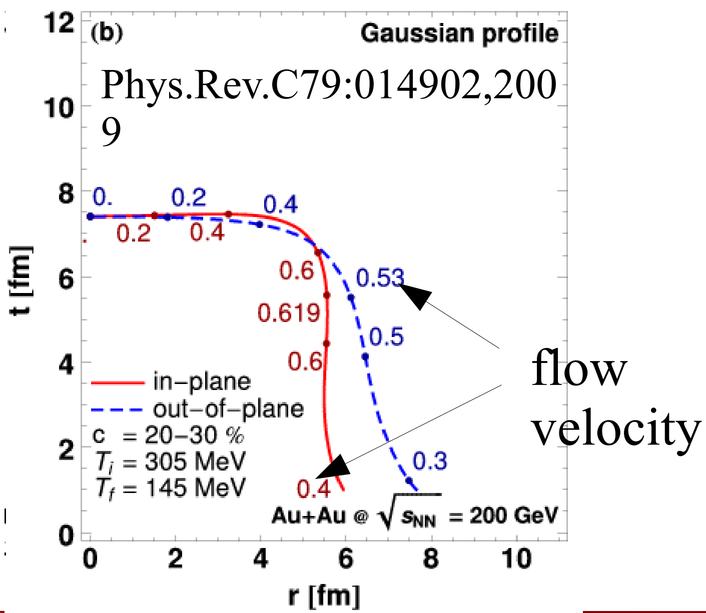


Chojnacki M., Florkowski W.
nucl-th/0603065, Phys. Rev. C74: 034905 (2006)

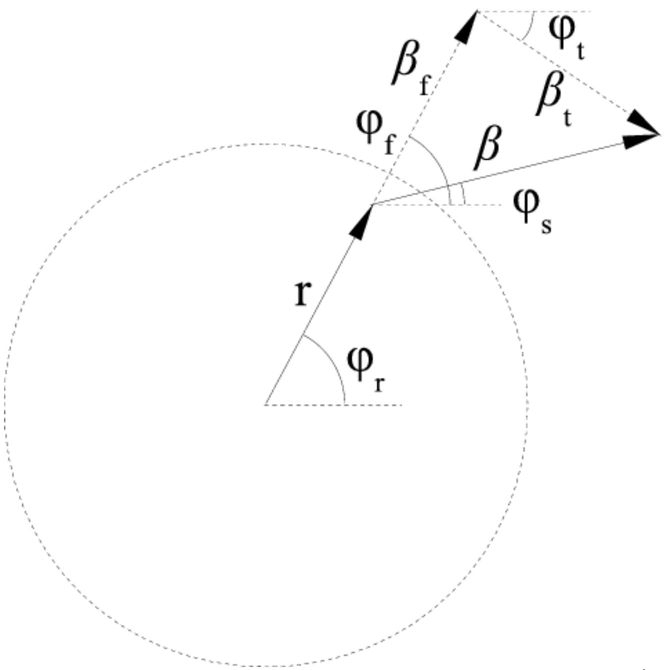
- Hydrodynamics produces collective flow: common velocity of all particles

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

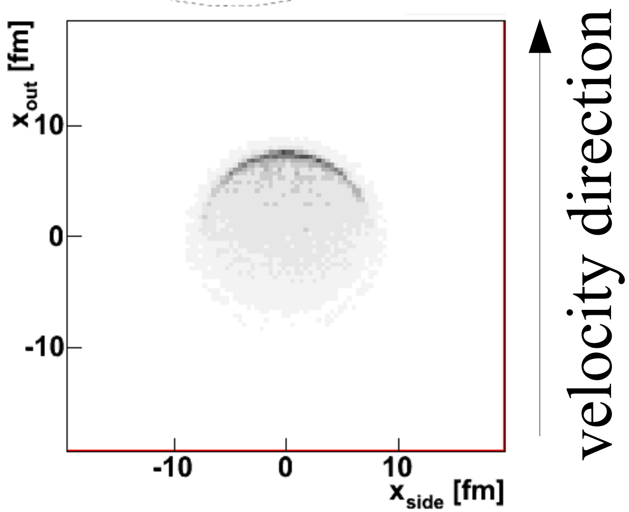
- The process drives the space-time evolution of the system
- For non-central collisions differences between in-plane and out-of plane velocities arise
- Space and time azimuthal evolution closely connected.

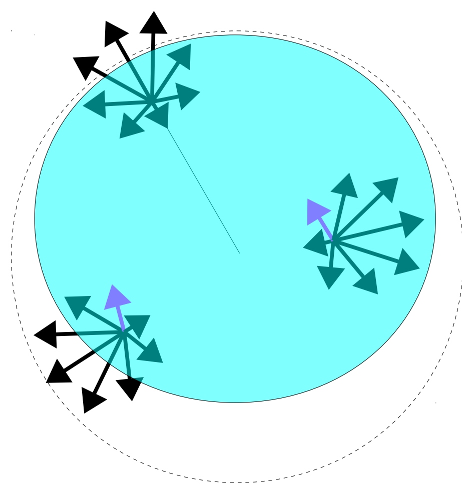


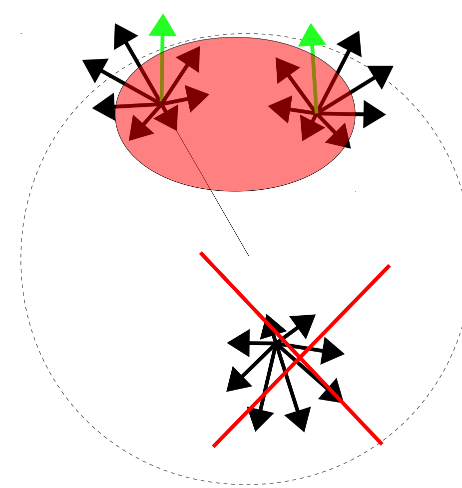
Thermal emission from collective medium



- 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



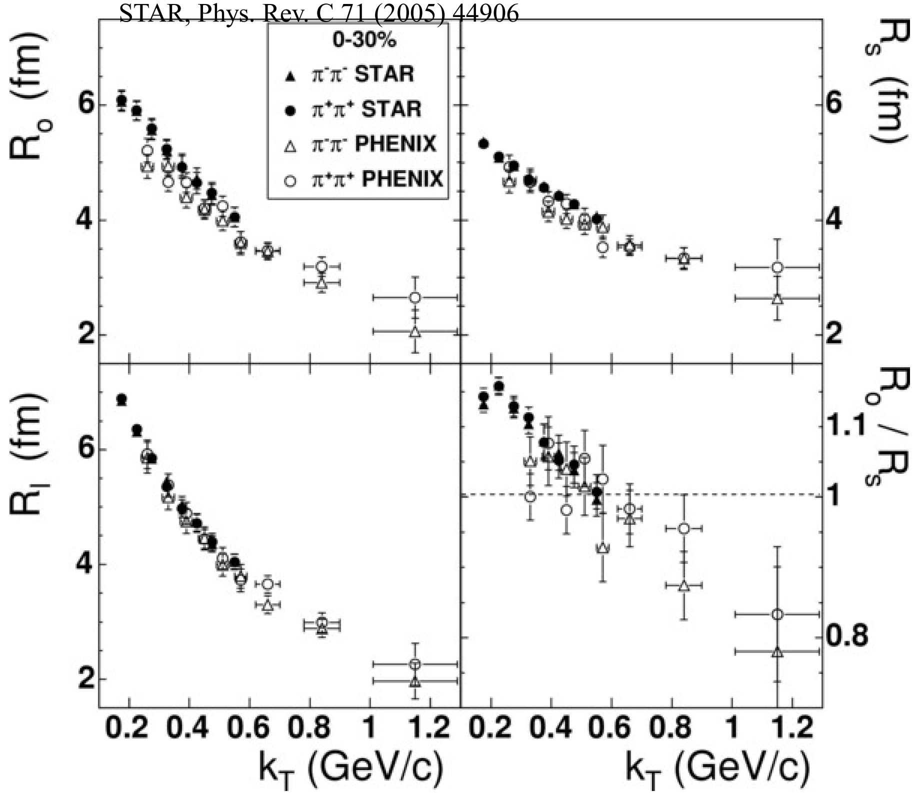


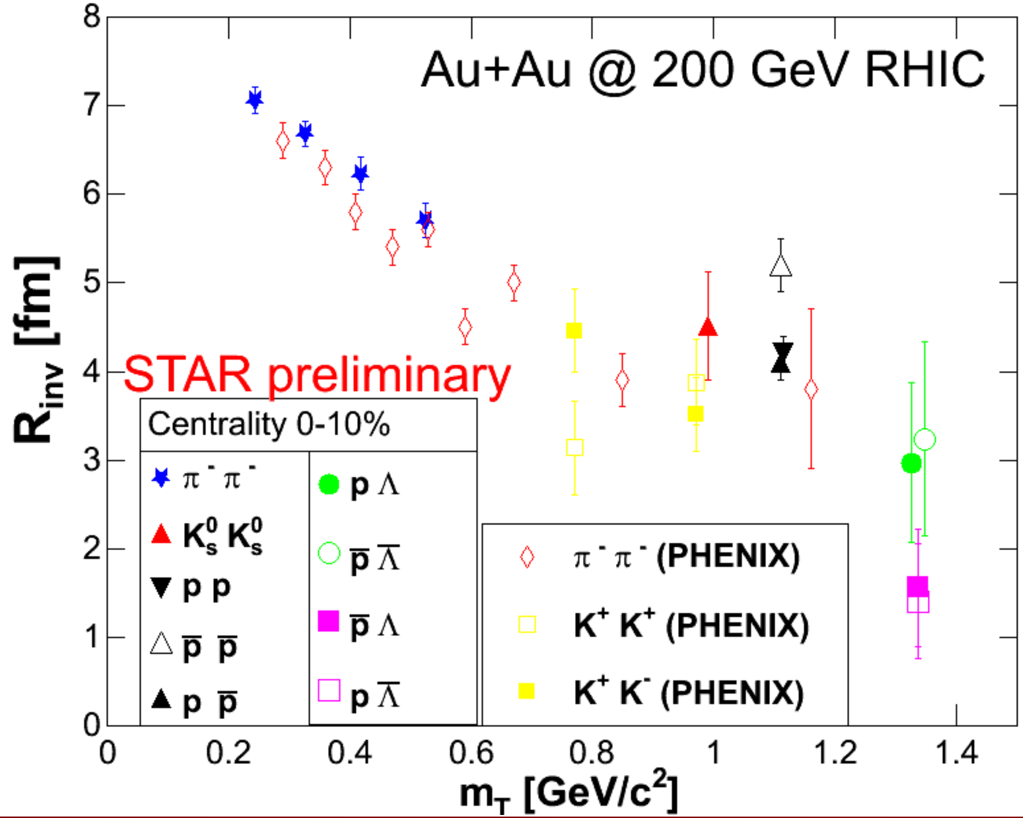


m_T dependence at RHIC

- 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?

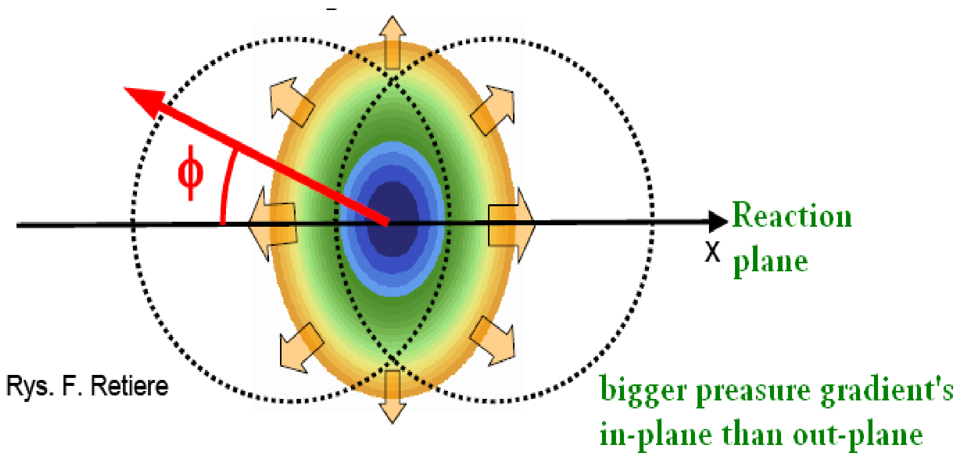
STAR, Phys. Rev. C 71 (2005) 44906

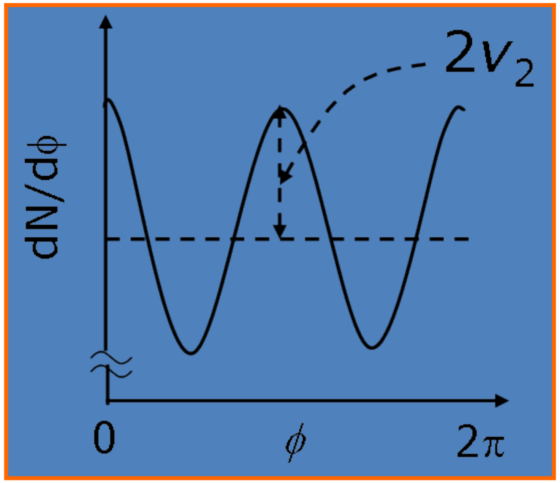




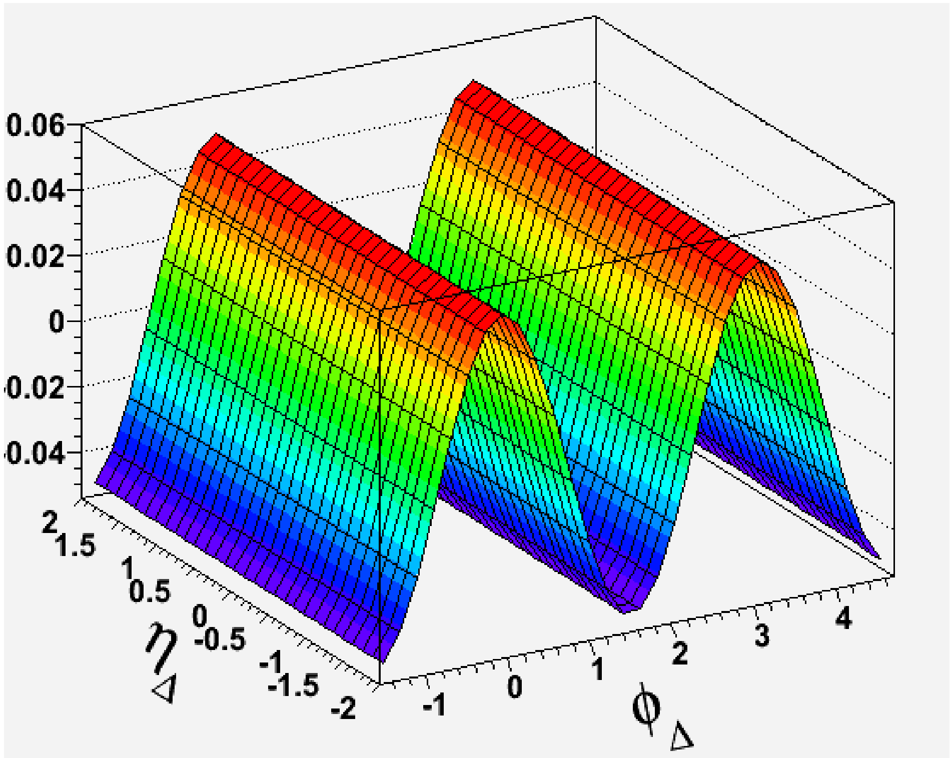
Non-central collisions = elliptic flow

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

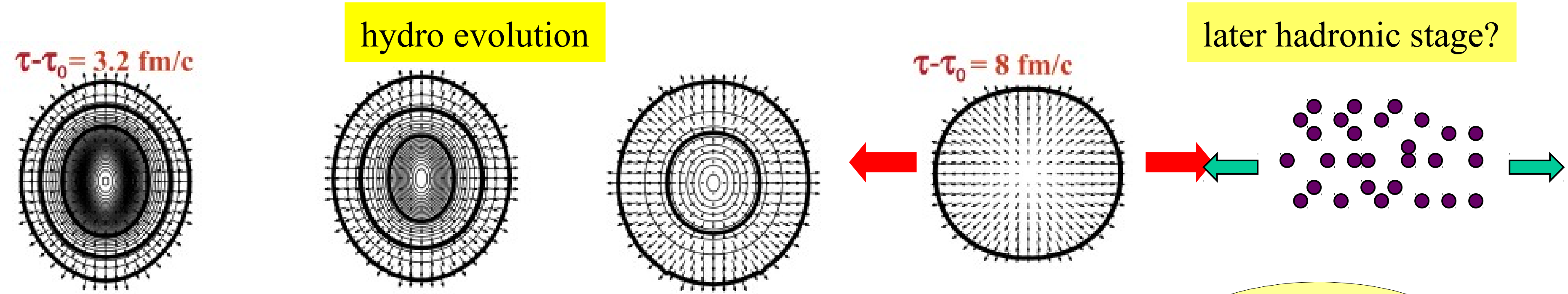




$$v_2 = \langle \cos 2\phi \rangle$$



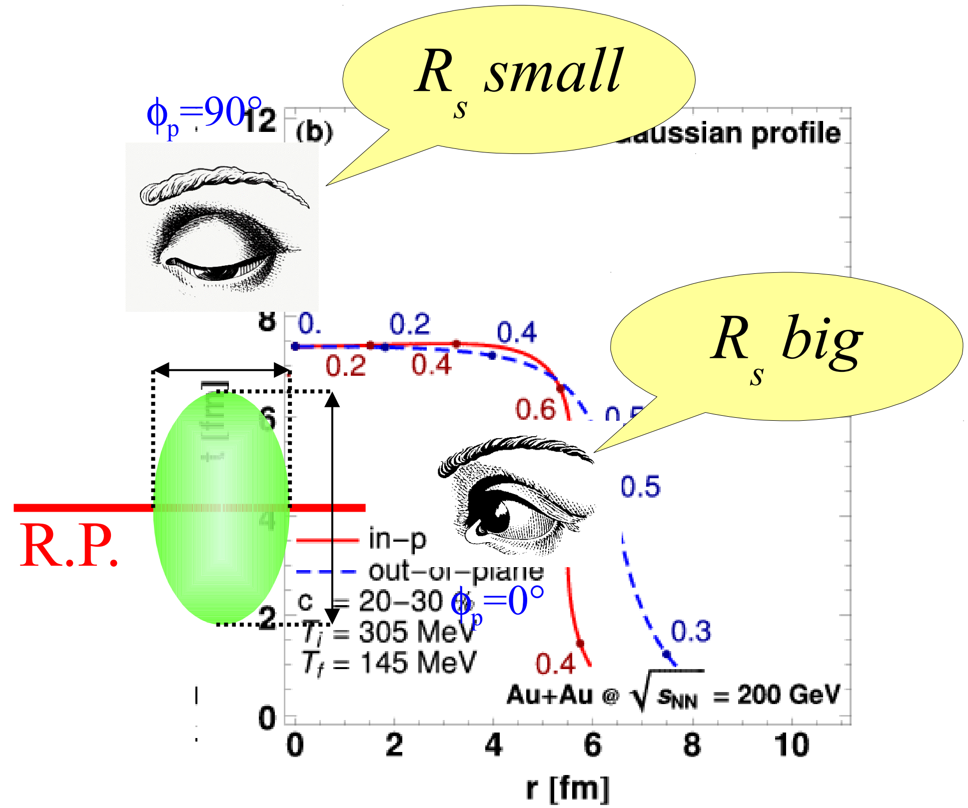
Non-central collisions: azimuthal modulation of collectivity



Kolb & Heinz

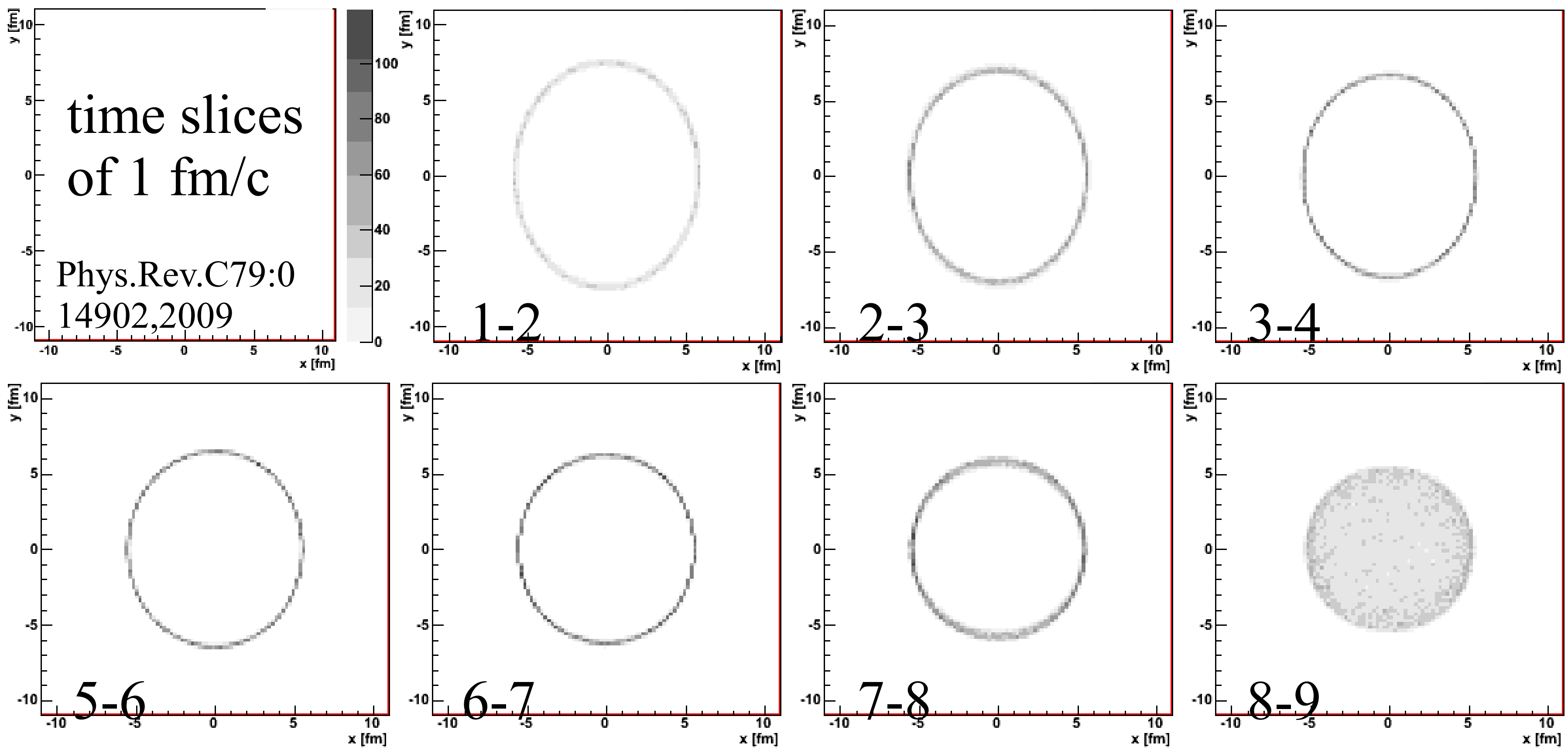
anisotropic pressure gradients

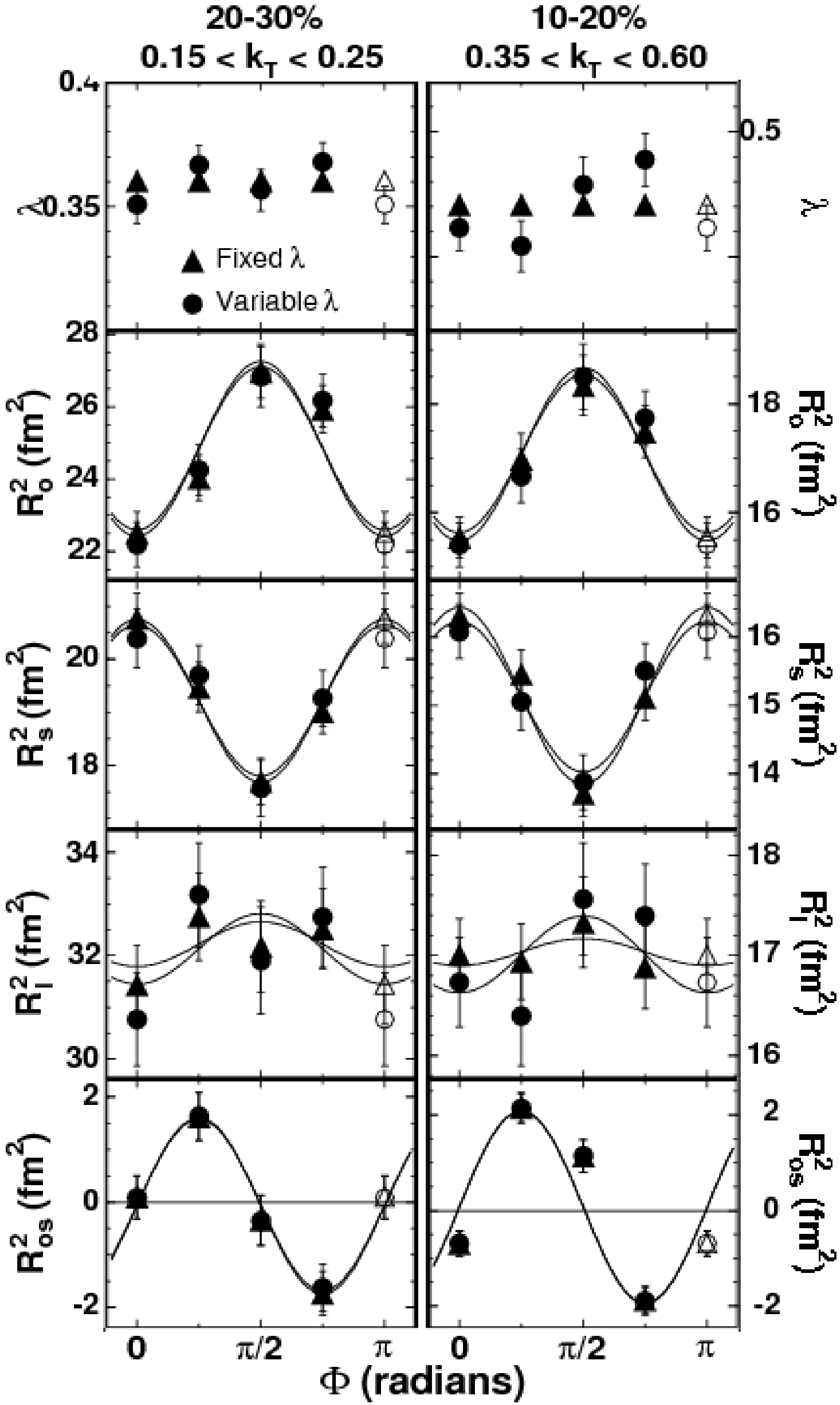
- drives the emergence of elliptic flow (v_2)
- Space-time and momentum anisotropy connected: can they be described at the same time?
- Azimuthally sensitive femtoscopy measures the space-time asymmetry by measuring radii vs. reaction plane
- Specific oscillations are expected



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:

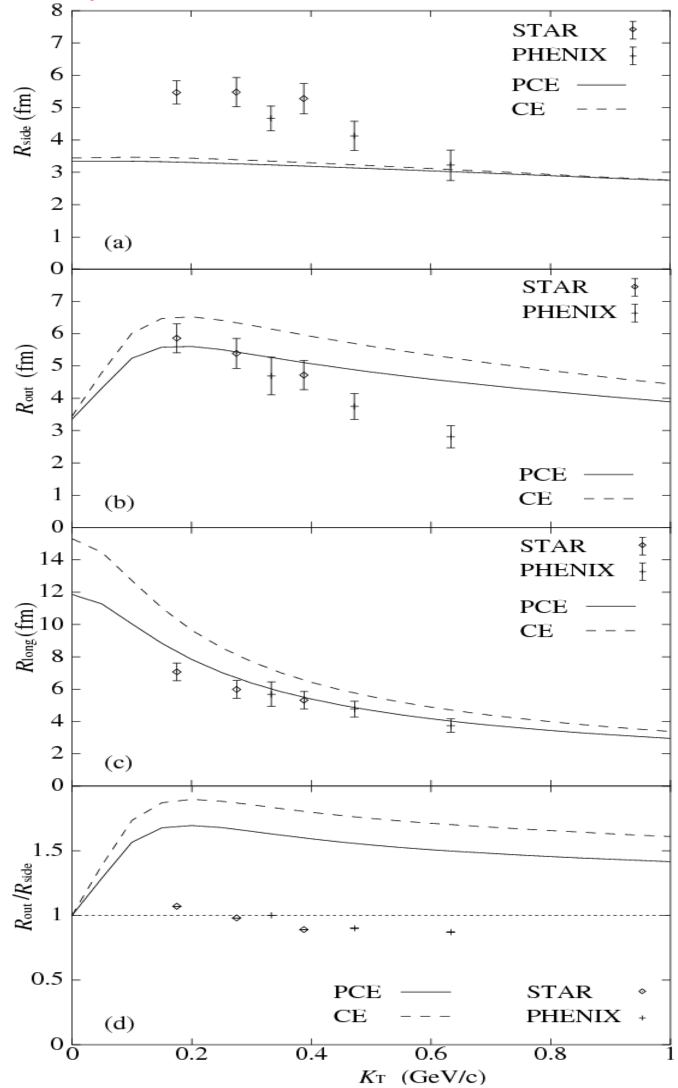
$$R^2_{out} = R^2_{out,0} + 2R^2_{out,2}\cos(2\phi_p)$$
$$R^2_{side} = R^2_{side,0} + 2R^2_{side,2}\cos(2\phi_p)$$
$$R^2_{long} = R^2_{long,0} + 2R^2_{long,2}\cos(2\phi_p)$$
$$R_{out-side} = 2R_{side-out,2}\sin(2\phi_p)$$

- Experiment clearly sees an anisotropic source shape

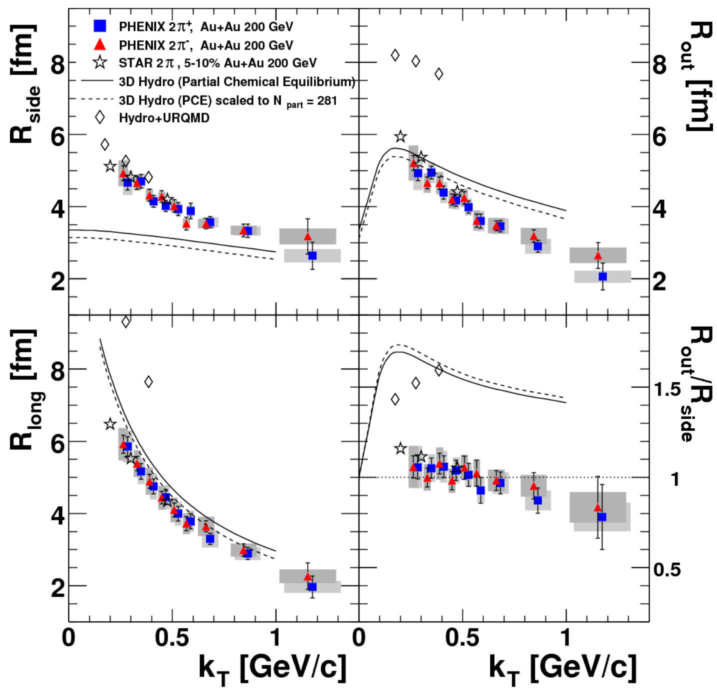
STAR, Phys. Rev. Lett. 93 (2004) 12301
e-Print Archives (nucl-ex/0312009)

RHIC Hydro-HBT puzzle

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



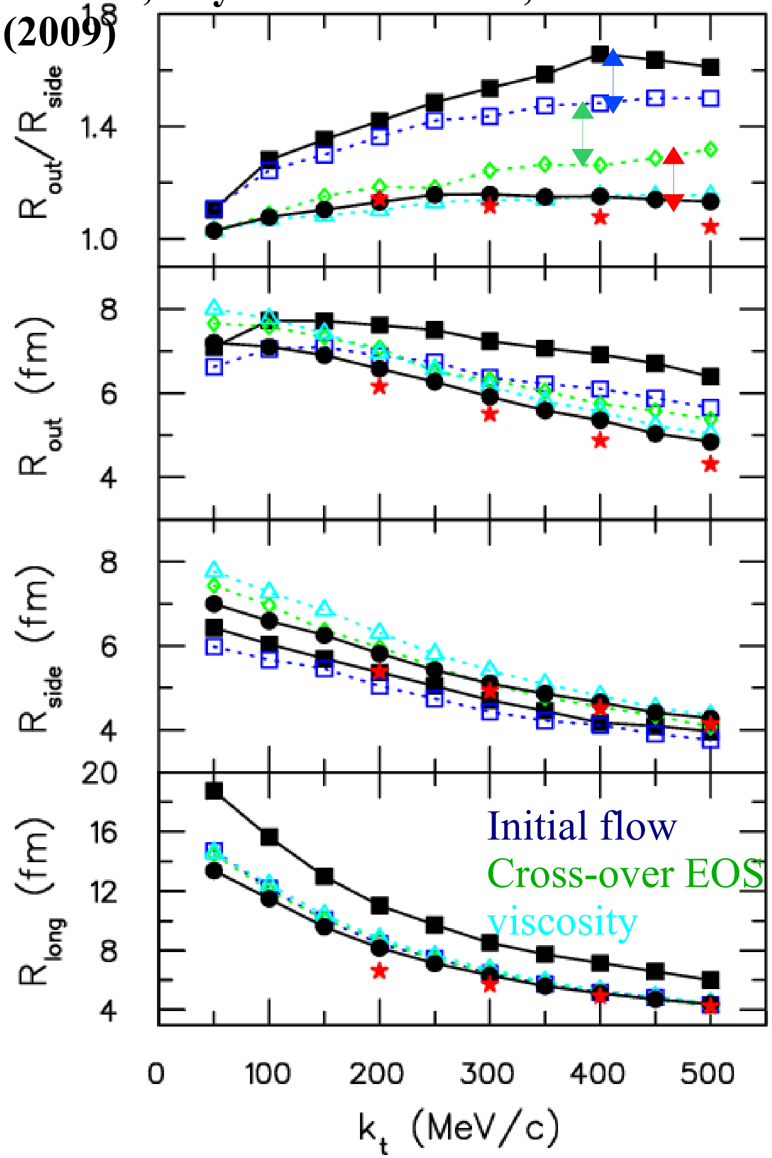
- First hydro calculations struggled to describe femtoscopic data: predicted too small R_{side}, too large R_{out} – too long emission duration
- No evidence of first order phase tr.



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

Revisiting hydrodynamics assumptions

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

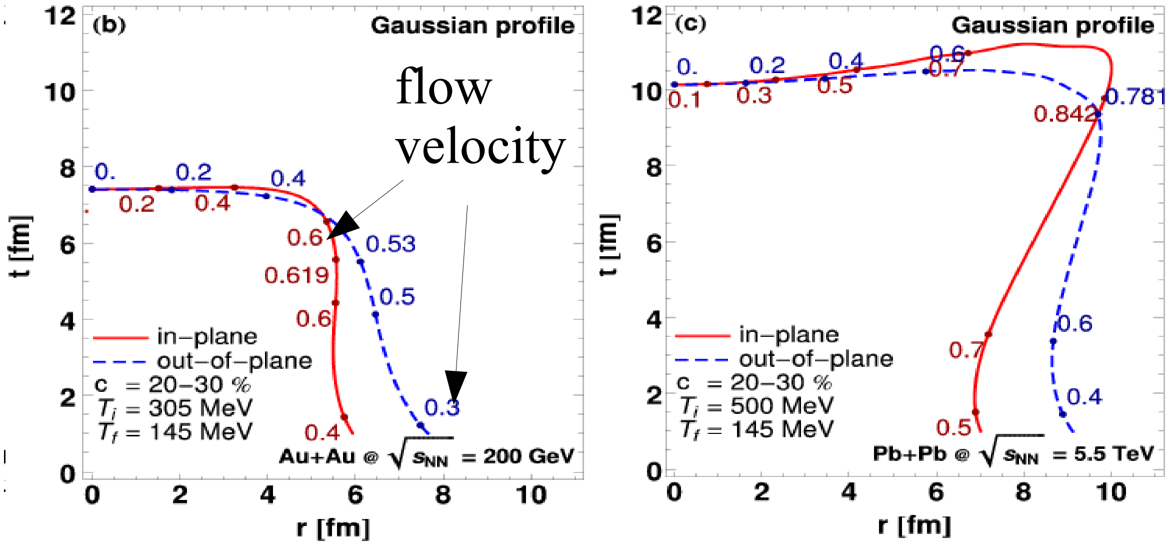


- Data in the momentum sector (p_T spectra, elliptic flow) well described by hydrodynamics, why not in space-time?
- Usually initial conditions do not have initial flow at the start of hydrodynamics (~1 fm/c) – they should.
- Femtoscopy data rules out first order phase transition – smooth cross-over 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

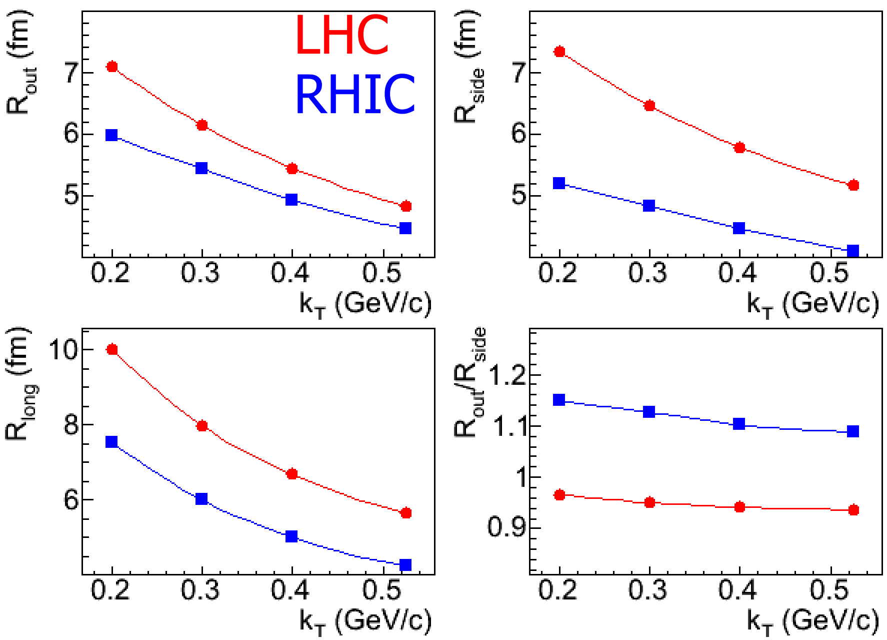
Expectations for the LHC

- Lessons from RHIC:
  - "Pre-thermal flow": strong flows already at τ_0=1 fm/c
  - EOS with no first-order phase transition
  - Careful treatment of resonances important
- Extrapolating to the LHC:
  - Longer evolution gives larger system → all of the 3D radii grow
  - Stronger radial flow → steeper k_T radii dependence
  - Change of freeze-out shape → lower R_{out}/R_{side} ratio

RHIC → LHC



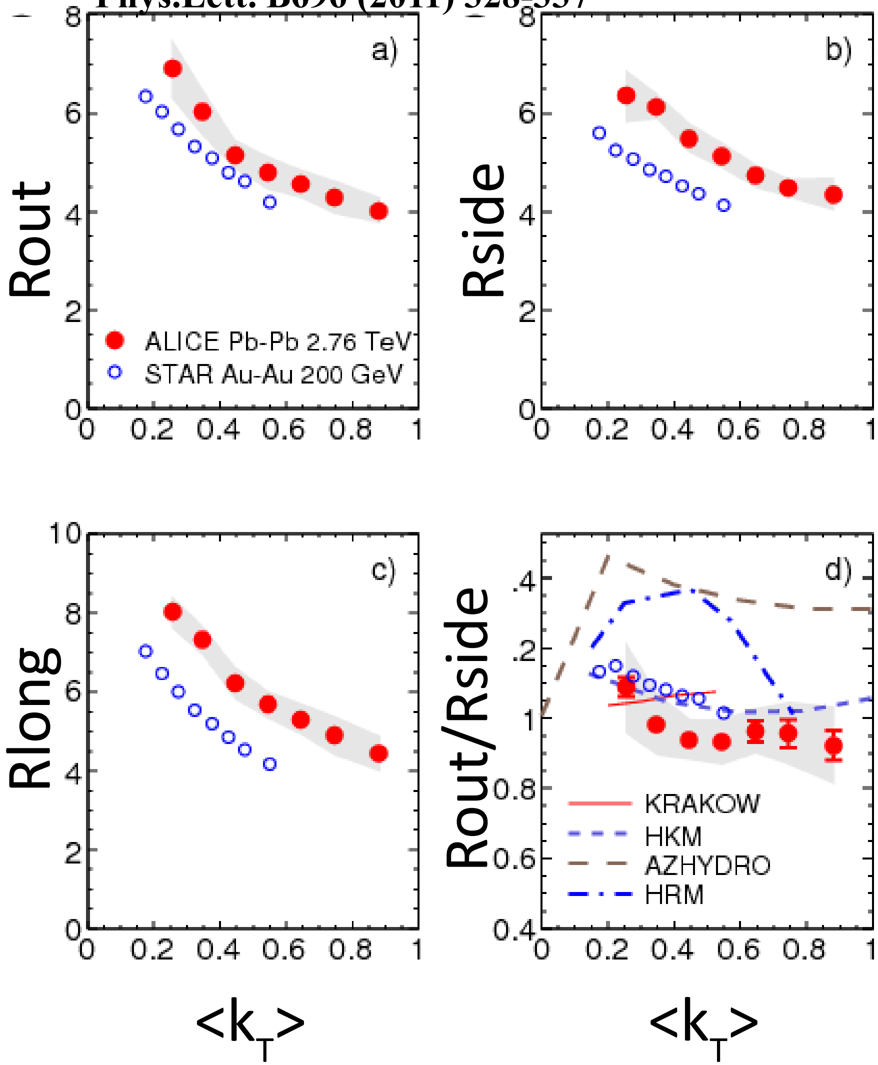
Phys.Rev.C79:014902,2009



Comparing LHC to RHIC

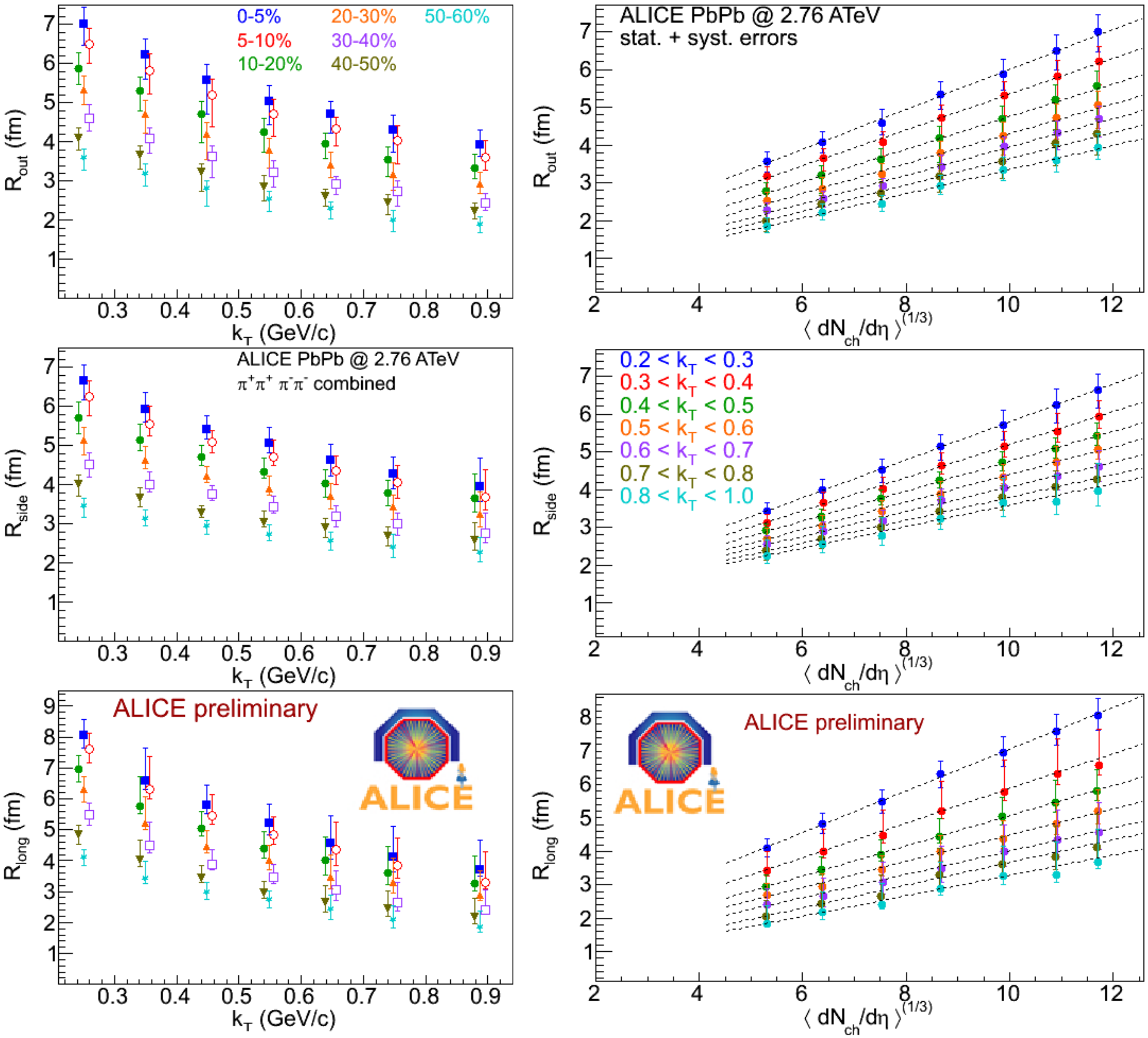
ALICE Pb-Pb

Phys.Lett. B696 (2011) 328-337



- 30% increase in homogeneity lengths between most central RHIC and LHC
- Strong dependence of all radii on pair momentum, consistent with strong collective radial and longitudinal flow
- The R_{out}/R_{side} ratio comparable or smaller than at RHIC: gives discriminating power to challenge models
- Only models tuned to reproduce RHIC data continue to work at the LHC
- All features expected from hydrodynamics extrapolation observed

Radii vs. centrality and k_T



Femtoscopic radii vs. k_T for 7 centrality bins

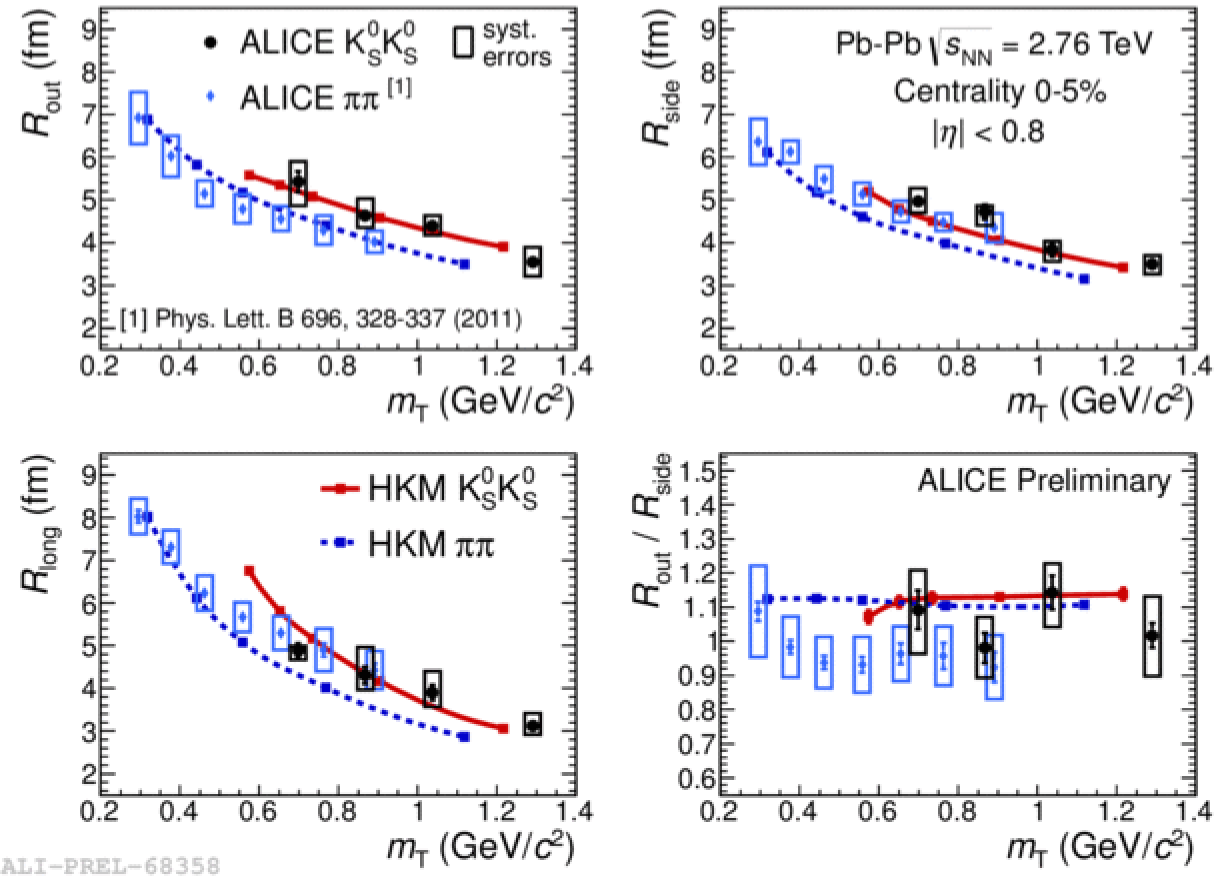
Radii scaling factorizes into linear in multiplicity and power-law in k_T

Both dependencies in agreement with predictions from collective models (hydrodynamics)

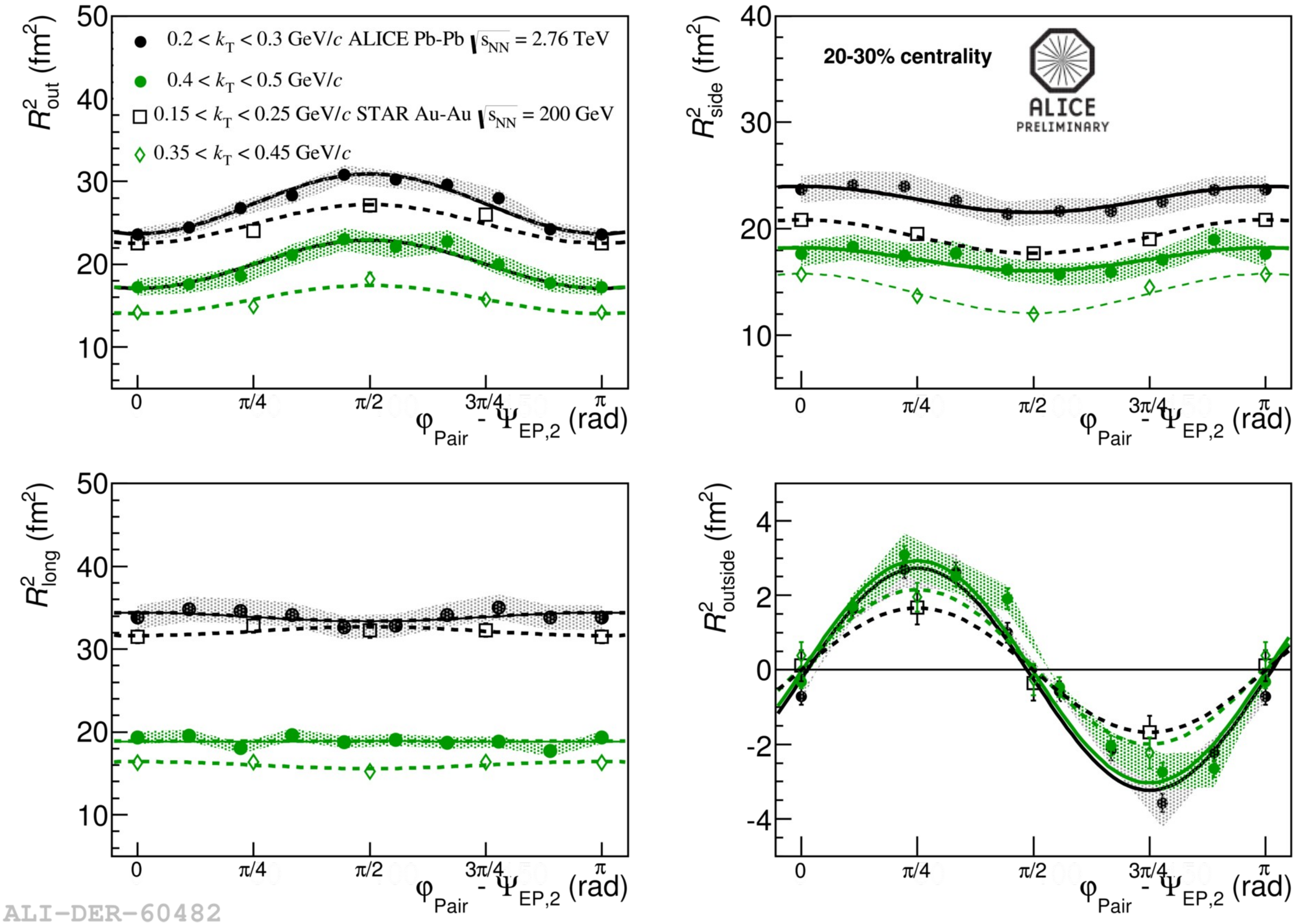
Scaling similar to this seen at lower energies

Collectivity with heavier particles

- The k_{T} dependence should be equally valid for heavier particles
- The 3D K^0_s results in central Pb-Pb consistent with collectivity (hydro) expectations

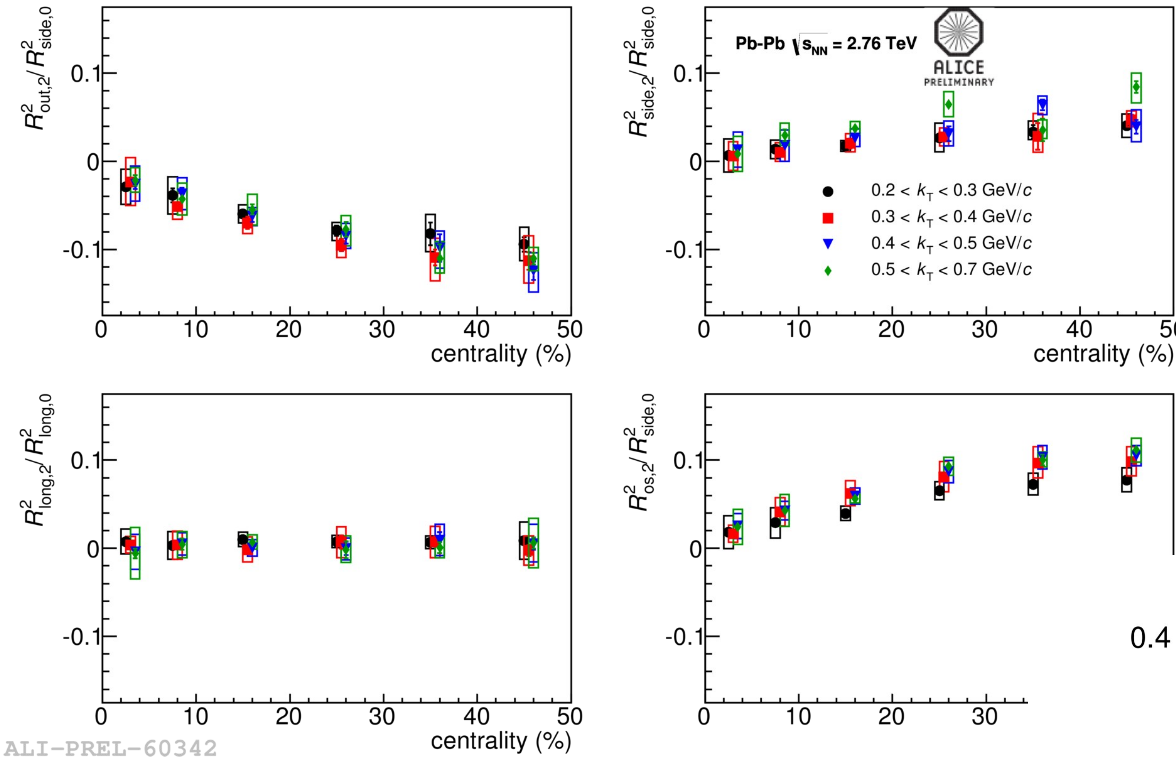


Azimuthally sensitive HBT

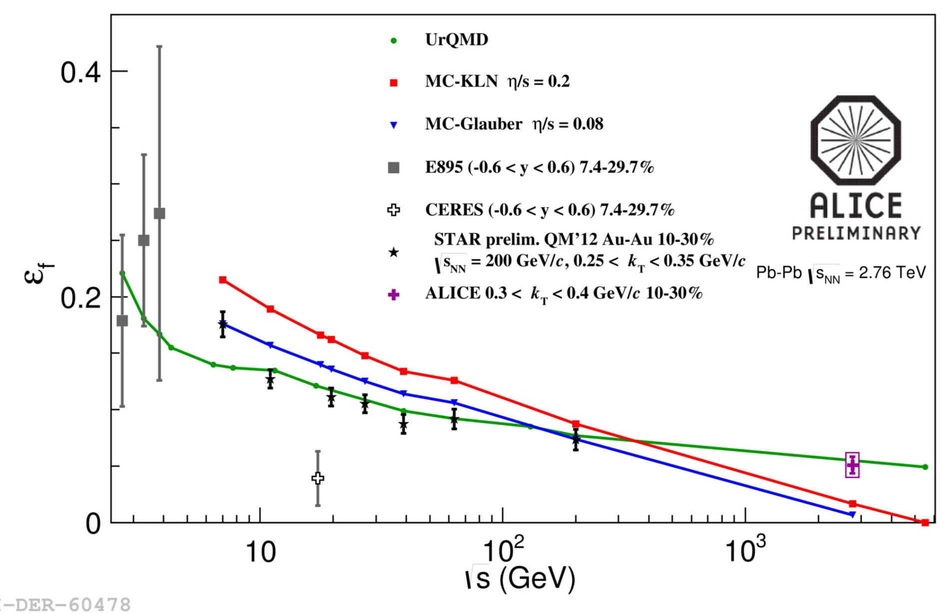


- Measurement of pion radii vs. reaction plane orientation – important cross-check of azimuthal evolution. Directly comparable to STAR.

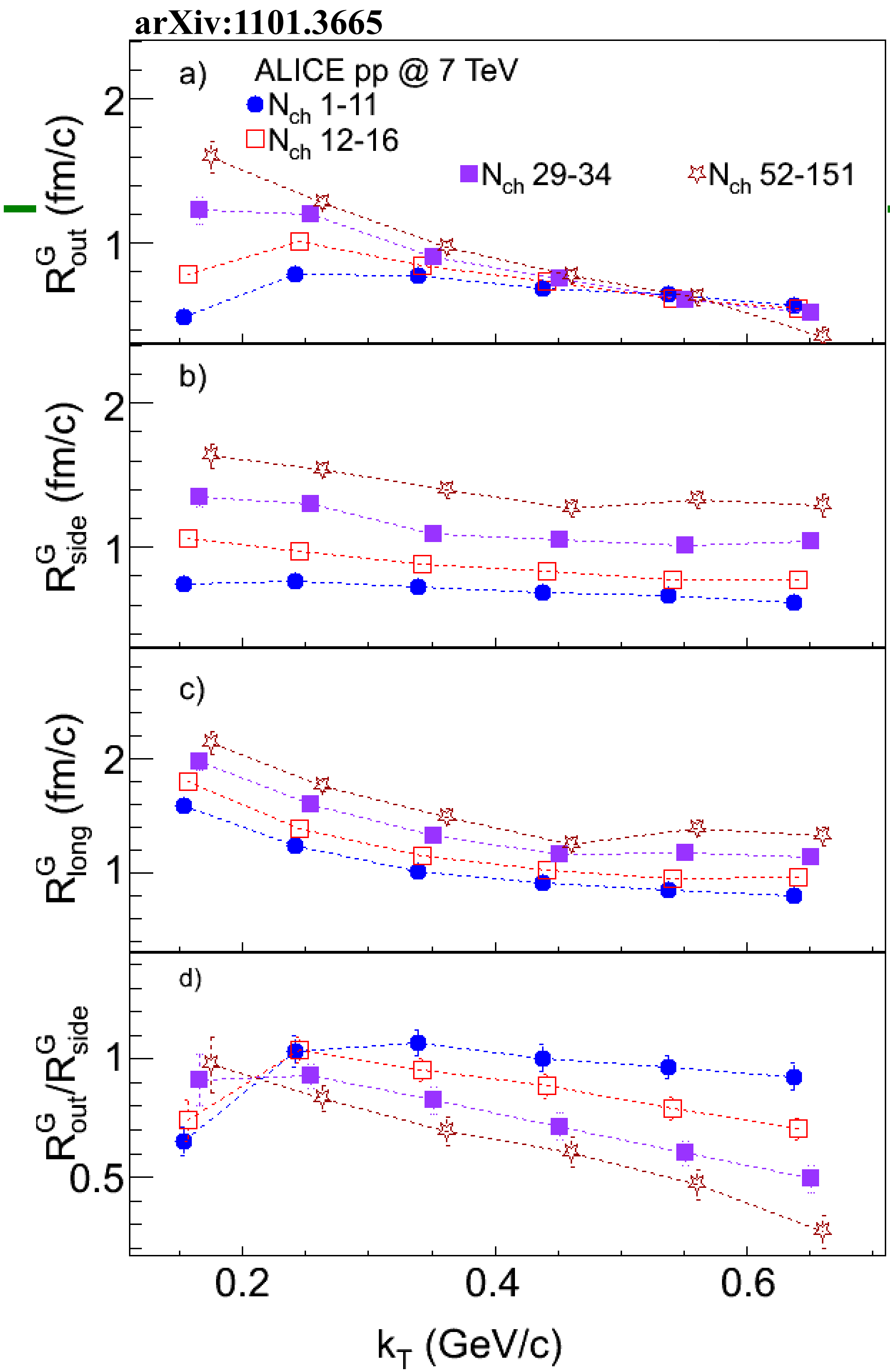
Clocking the evolution



- Final eccentricity comparable but smaller than at RHIC, as expected for longer evolution duration
- Qualitatively confirms hydro



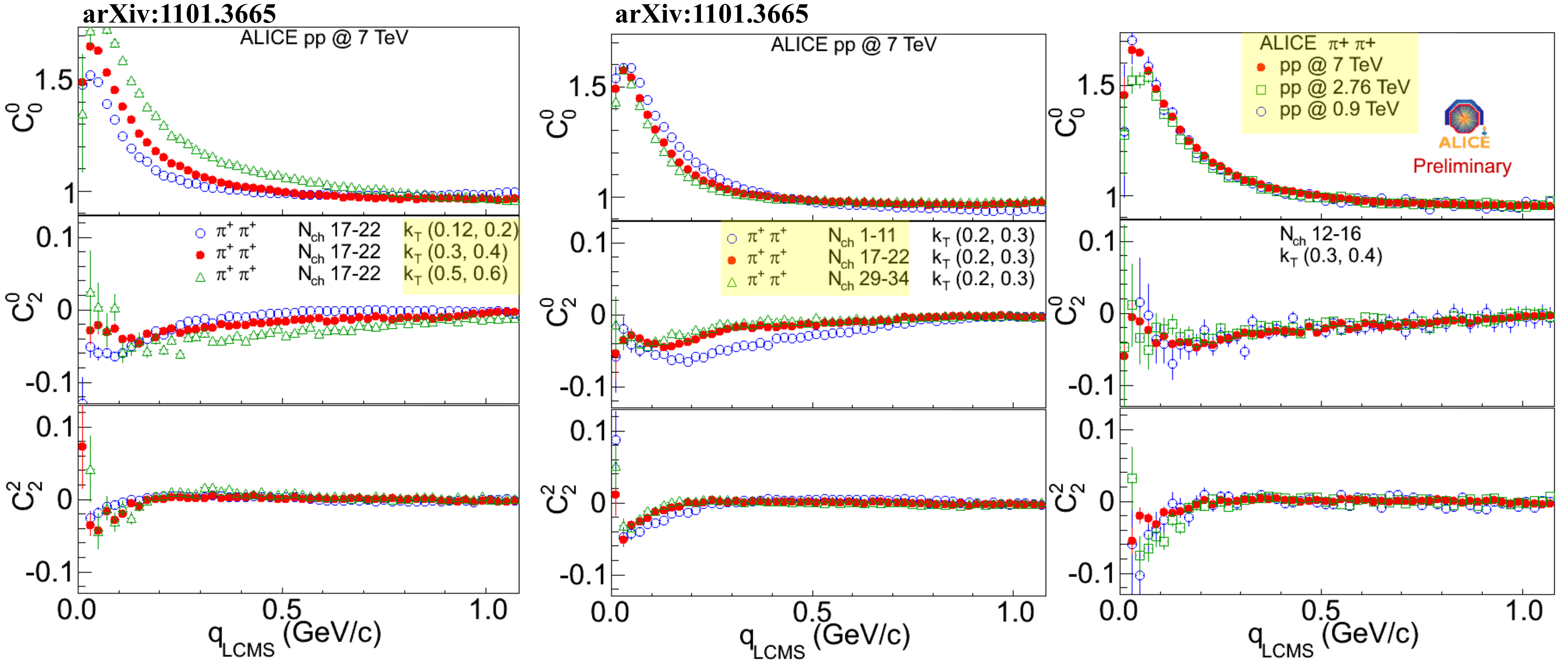
pp collisions: radii vs. k_T



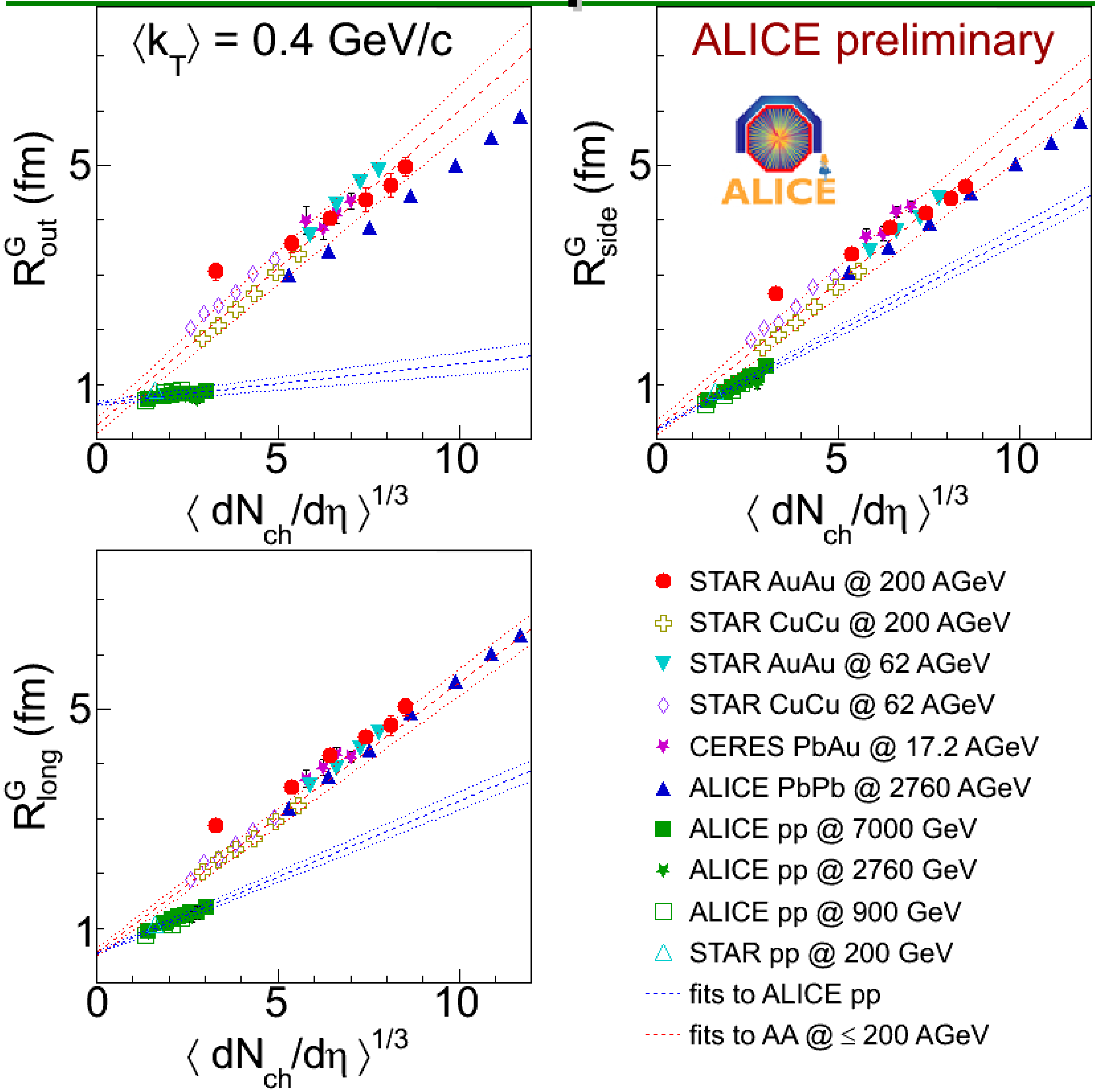
- R_{long} falls with k_T for all multiplicities
- R_{side} flat with k_T at lowest mult, develops dependence as mult increases
- R_{out} dependence on k_T evolves strongly with multiplicity and is steeply falling at top mult
- R_{out}/R_{side} falls with multiplicity, goes significantly below 1.0
- Behavior in heavy-ions is not a simple scaling of pp, as suggested at RHIC

Looking for scaling variables

- 3D LCMS correlation decomposed into Spherical Harmonics, first 3 non-vanishing components shown
- Correlations vary with $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ and k_{T}, independent of $\sqrt{s}$



Comparison LHC vs. world

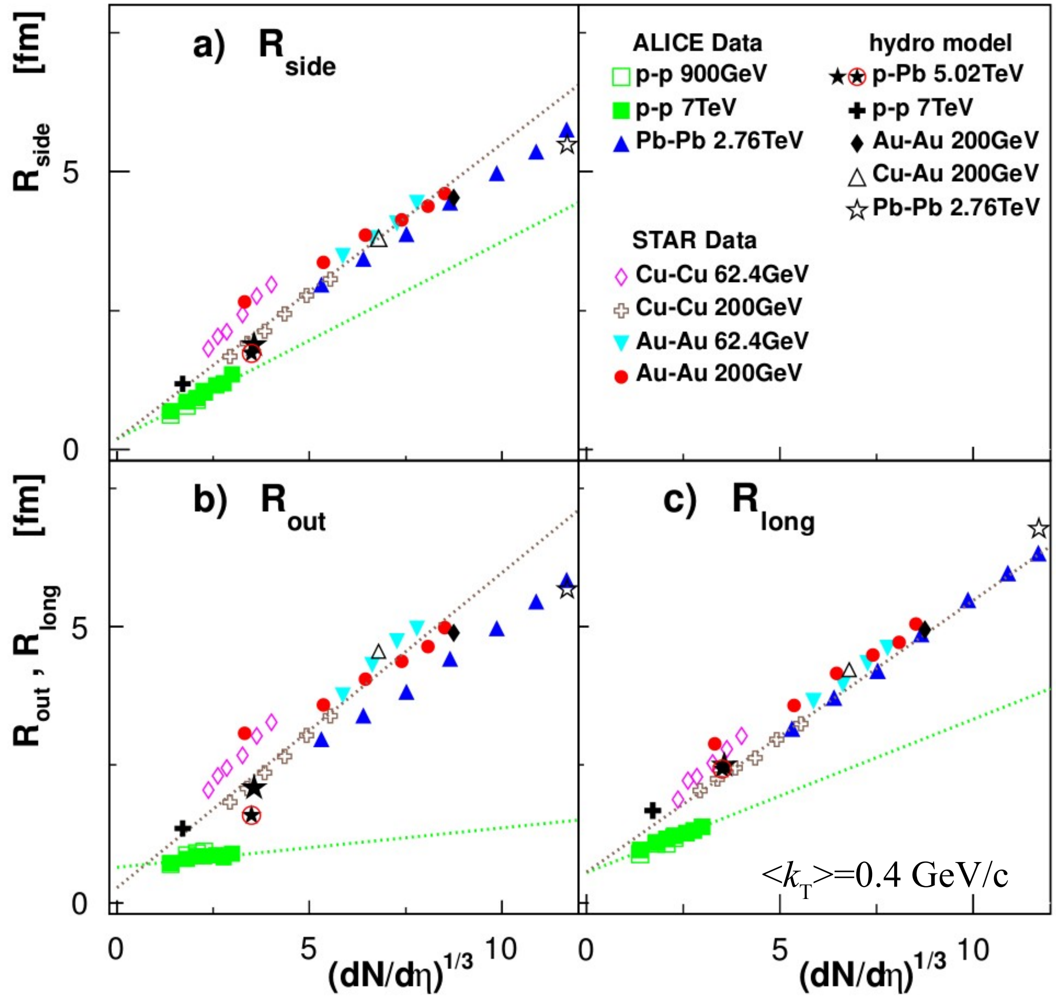


- pp and AA linear scaling clearly different, no simple pp/AA scaling
- ALICE PbPb R_{long} in perfect agreement with world data
- ALICE PbPb R_{side} in reasonable agreement with world data
- ALICE R_{out} clearly below the linear scaling
- Behavior of all 3 radii in PbPb @ 2.76 TeV in qualitative agreement with hydrodynamical model expectations.

p-Pb like pp or PbPb?

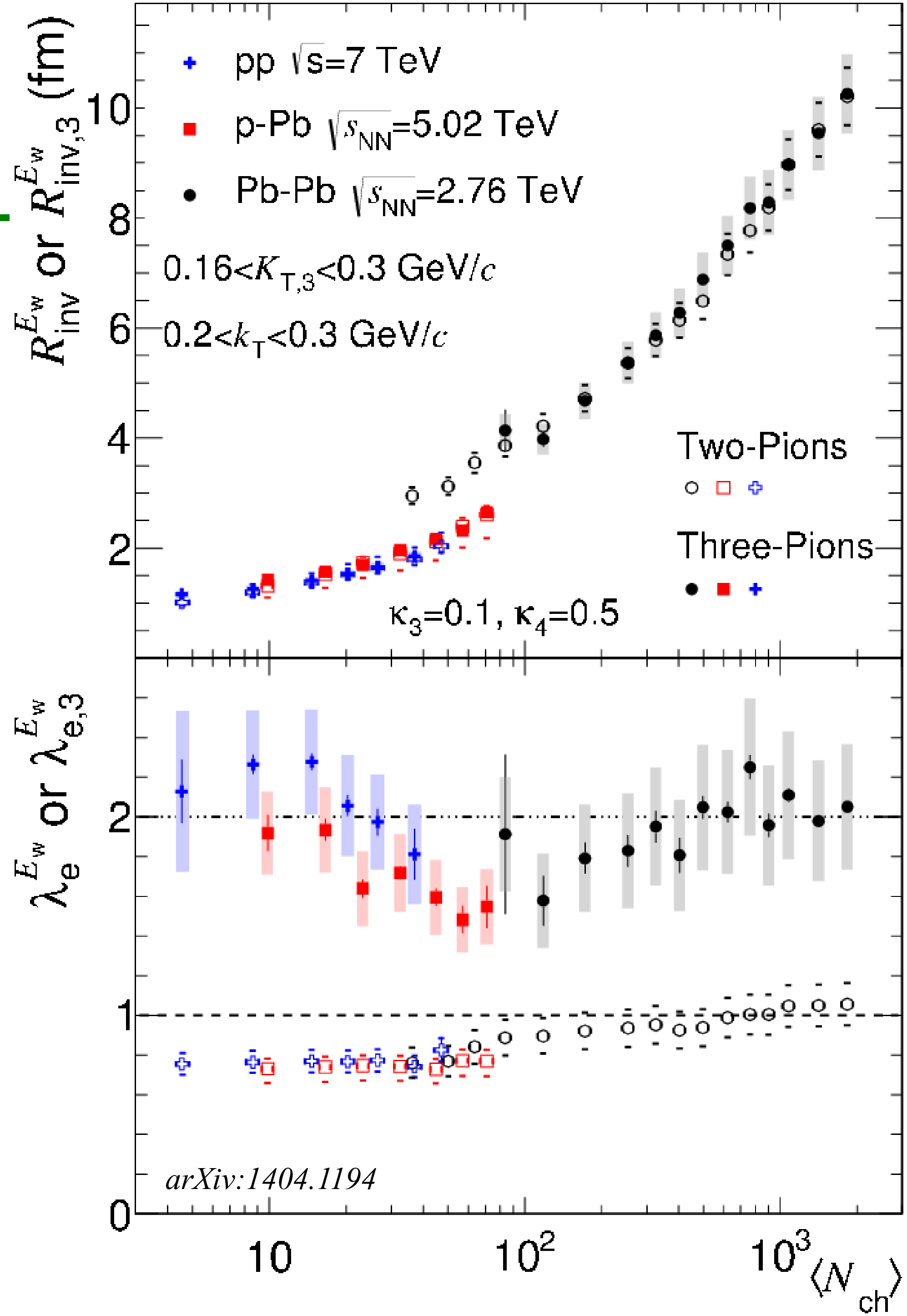
Phys. Lett. B720 (2013) 250
arXiv:1301.3314

- Hydrodynamics predicts that radii for pPb are consistent with PbPb scaling
- Important to compare the pp, pPb and PbPb results at similar multiplicity
- The GCG-type calculations predict size in pPb generally similar to that observed in pp



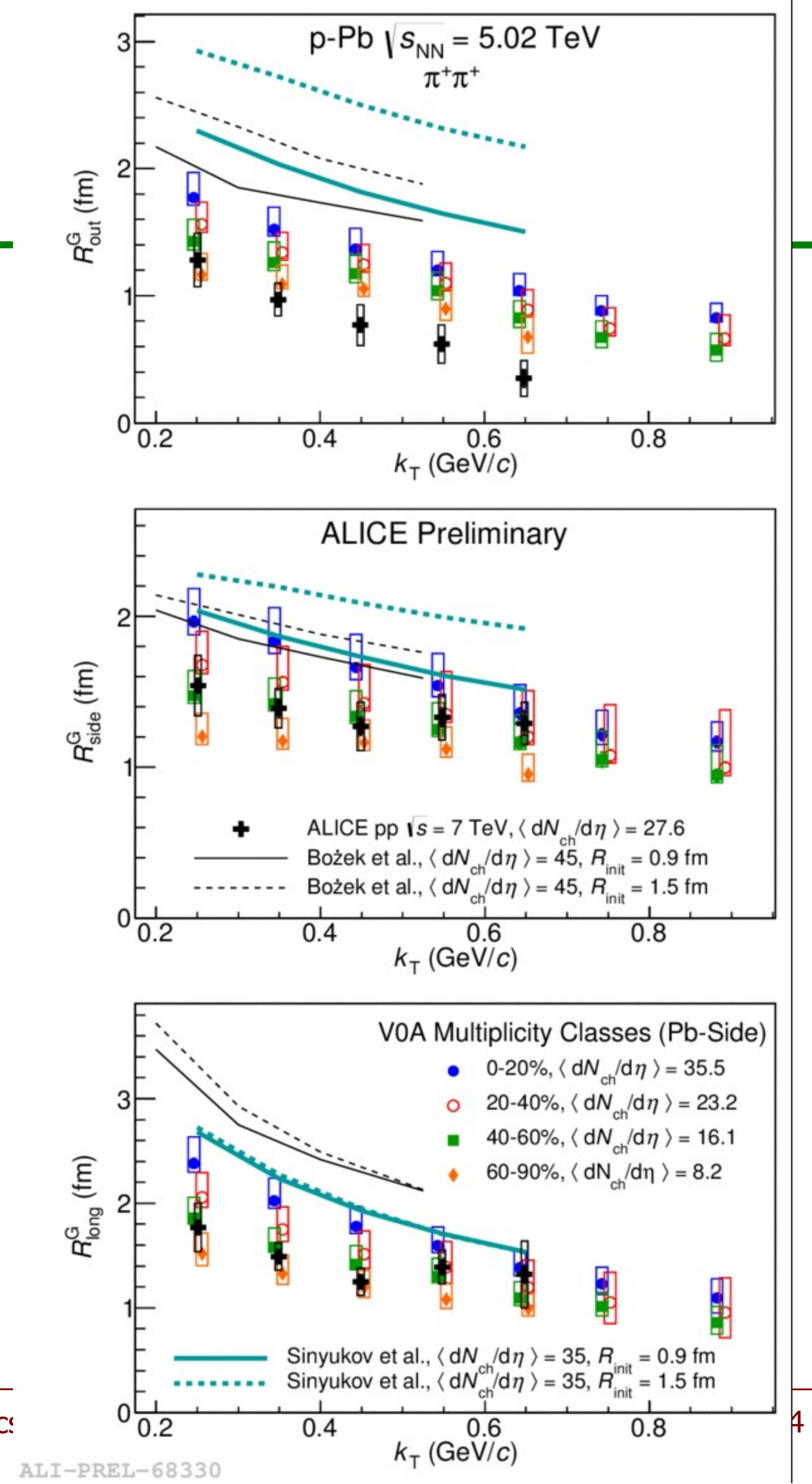
1D pPb from ALICE

- 1D analysis performed for pp, pPb and PbPb
- Uses 2-pion and 3-pion formalism, with different sensitivity to backgrounds
- pPb results approximately 10% higher than pp at similar multiplicity, up to 40% smaller than PbPb
- Comparing only LHC results, not “AA line” from lower energies
- No k_T dependence, so hard to conclude on collectivity

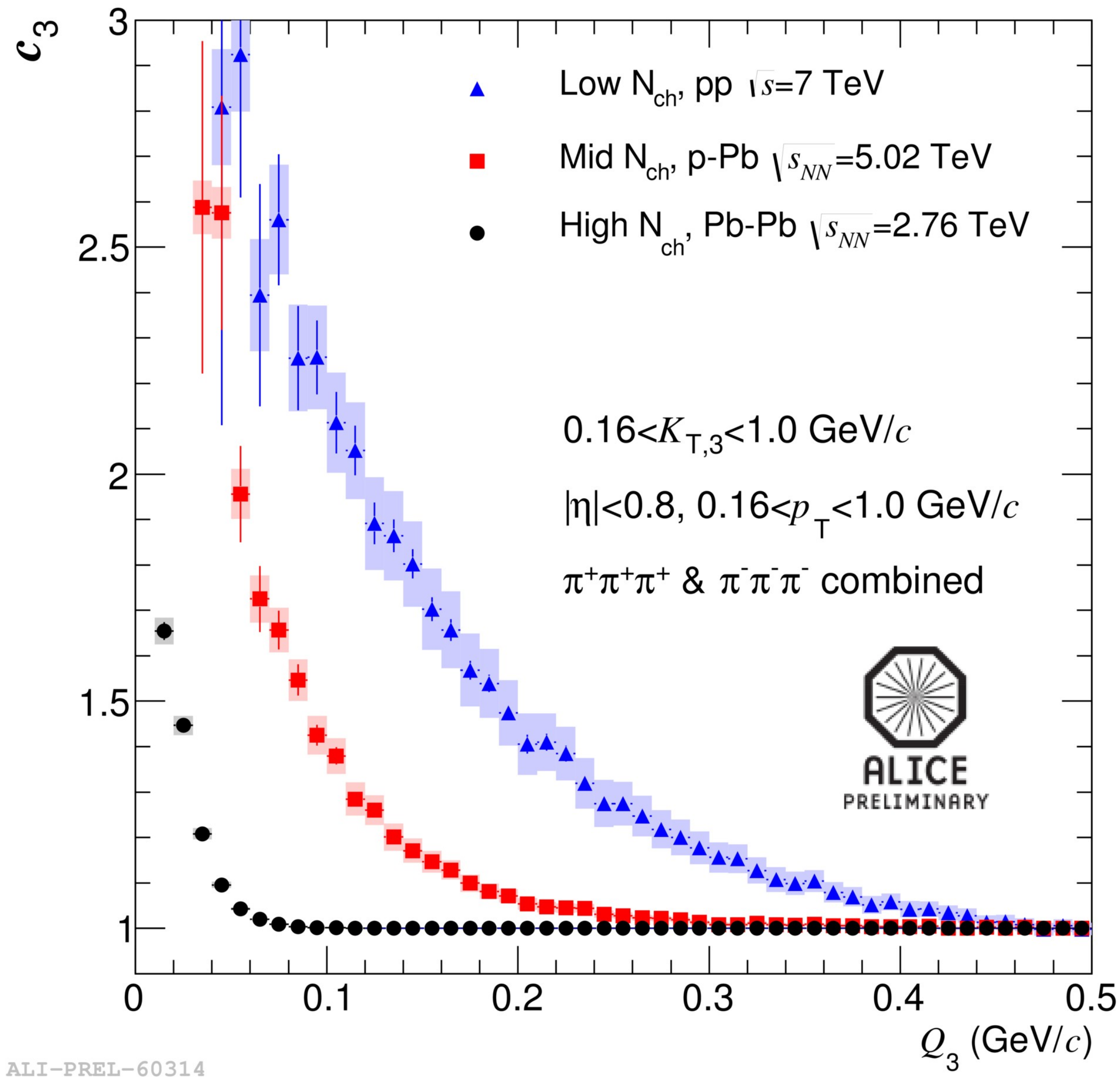


3D pPb in ALICE

- Analysis in 3D is also sensitive to collectivity signatures
- pPb radii are 10% larger than pp at similar multiplicity in Side and Long, Out shows larger difference
- Hydro predictions are comparable to high-multiplicity pPb in Side and Long and overestimate Out
- k_{T} dependence similar in models and data

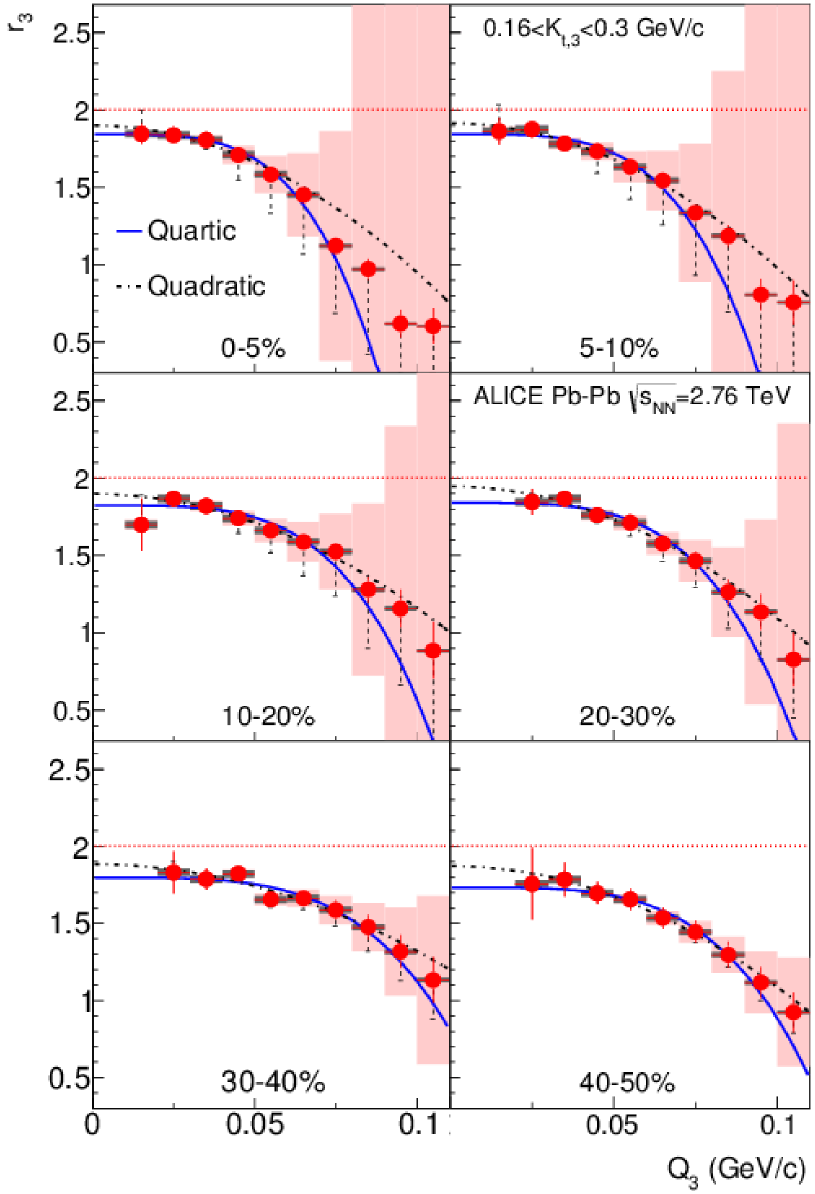


3-pion correlations



- 3-pion cumulant extracts the genuine 3-particle correlation
- Has higher signal/background ratio
- Is sensitive to source size
- Is much more sensitive to coherent pion production than the 2-pion correlation

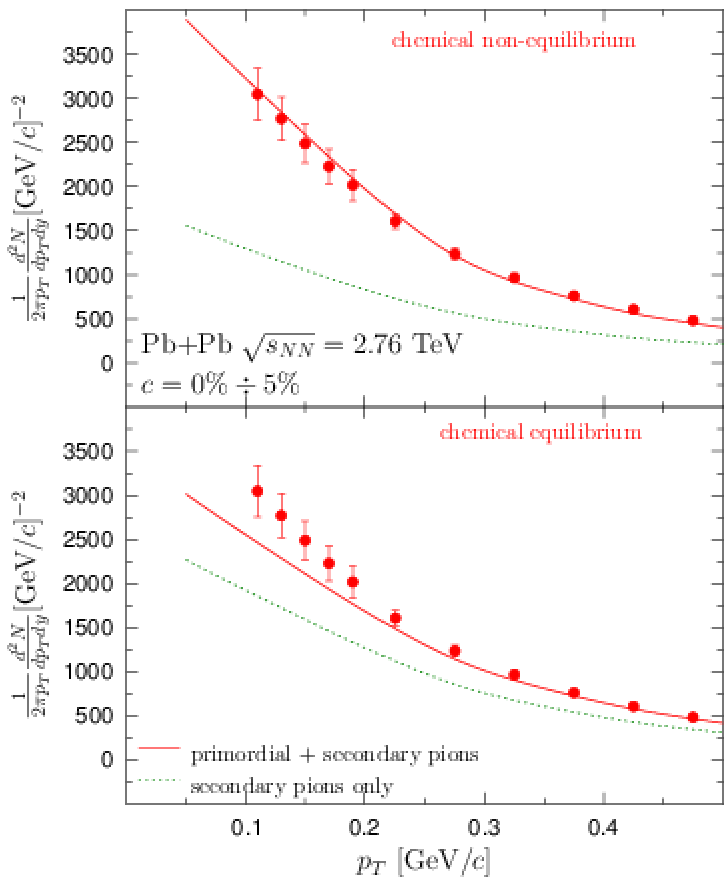
Extracting coherent fraction



- The r_3 variable should approach 2 for Q_3 -> 0 for fully chaotic emission
- At low triplet momentum the extrapolated intercept is below 2, does not depend strongly on centrality
- At high triplet momentum the intercept is consistent with 2
- Deviation from theoretical limit of 2 consistent with up to 20% coherent pion production

Interpretation of 3-particle results

Biegun, Florkowski, Rybczyński; arXiv:1312.1487



- Other possible effect of coherent pion production: increase of pion multiplicity at low momentum
- Preliminary model calculations show intriguing effects in the low-p_T region
- Are the two effects consistent and/or connected?

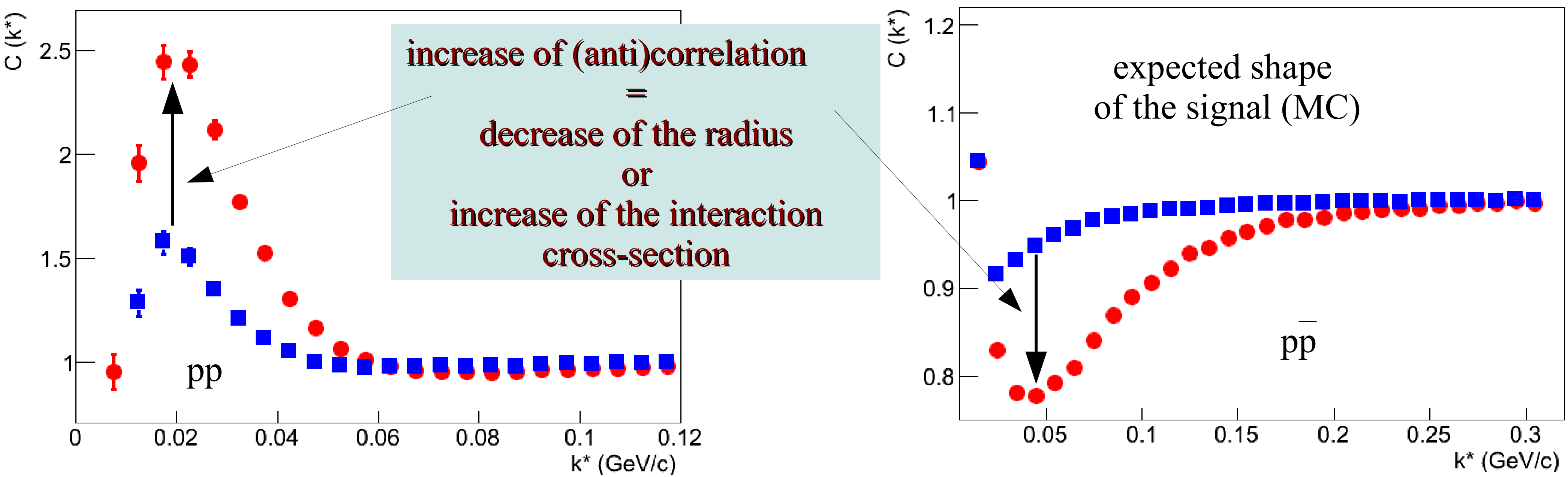
Baryon femtoscopy

$$C(\vec{q}) = \int S(\vec{r})\,|\Psi(\vec{q},\vec{r})|^2\, d^4 r$$

measured correlation

emission function (radius)

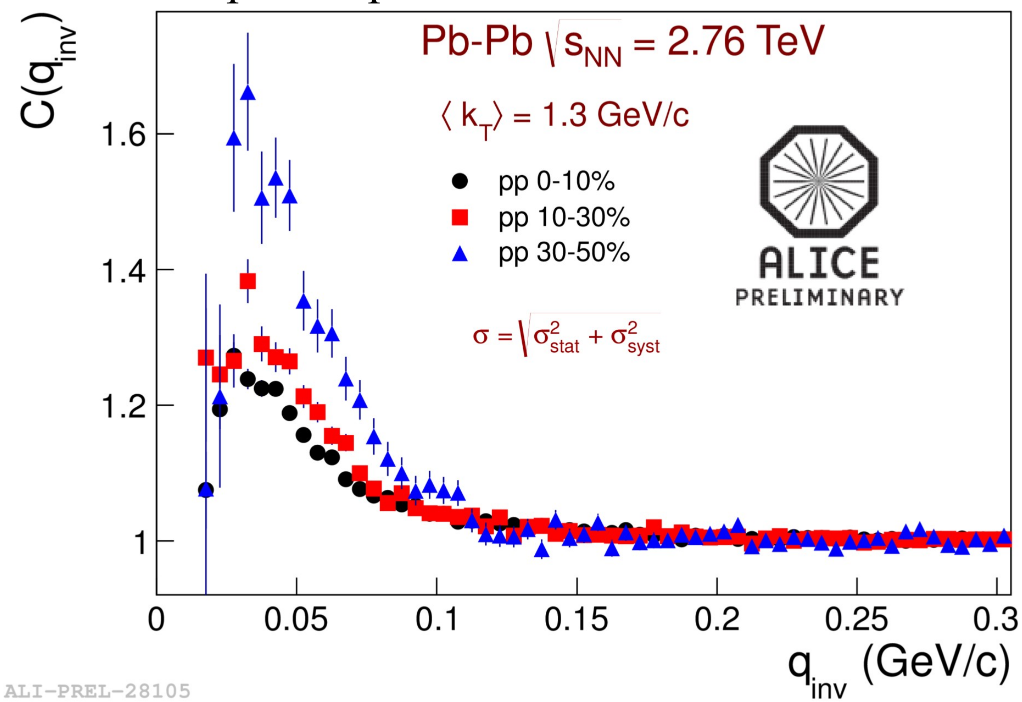
cross-section



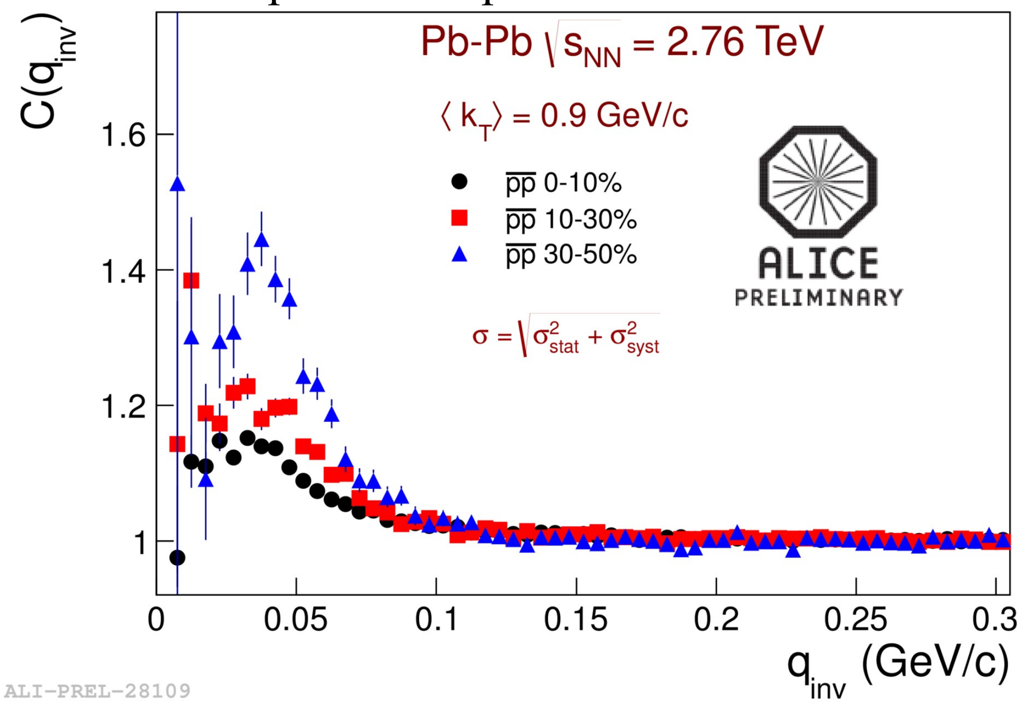
- For protons, cross-sections known, only radius can change
- For other (e.g. pΛ, ΛΛ), the radius and the cross-section not known (or known with large uncertainties) → only one can be a free parameter

pp and $\overline{pp}$ correlation functions

proton-proton

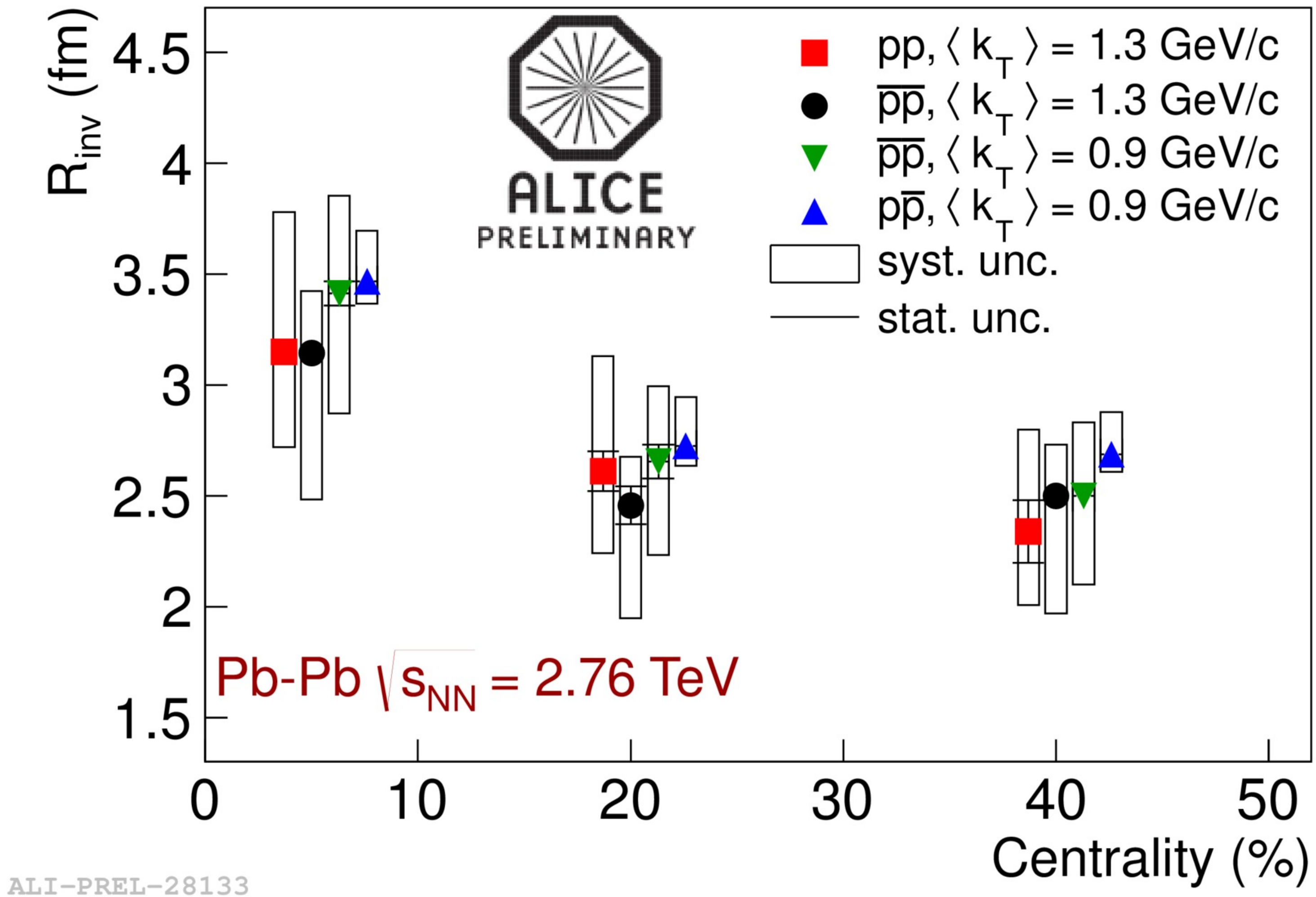


antiproton-antiproton



- Correlation effect increases for more peripheral events - size decreases with decreasing multiplicity
- QS, Coulomb and Strong FSI – all contribute to measured correlations
- Possible to extract the source radius for heavy particles

R_{inv} from proton femtoscopy



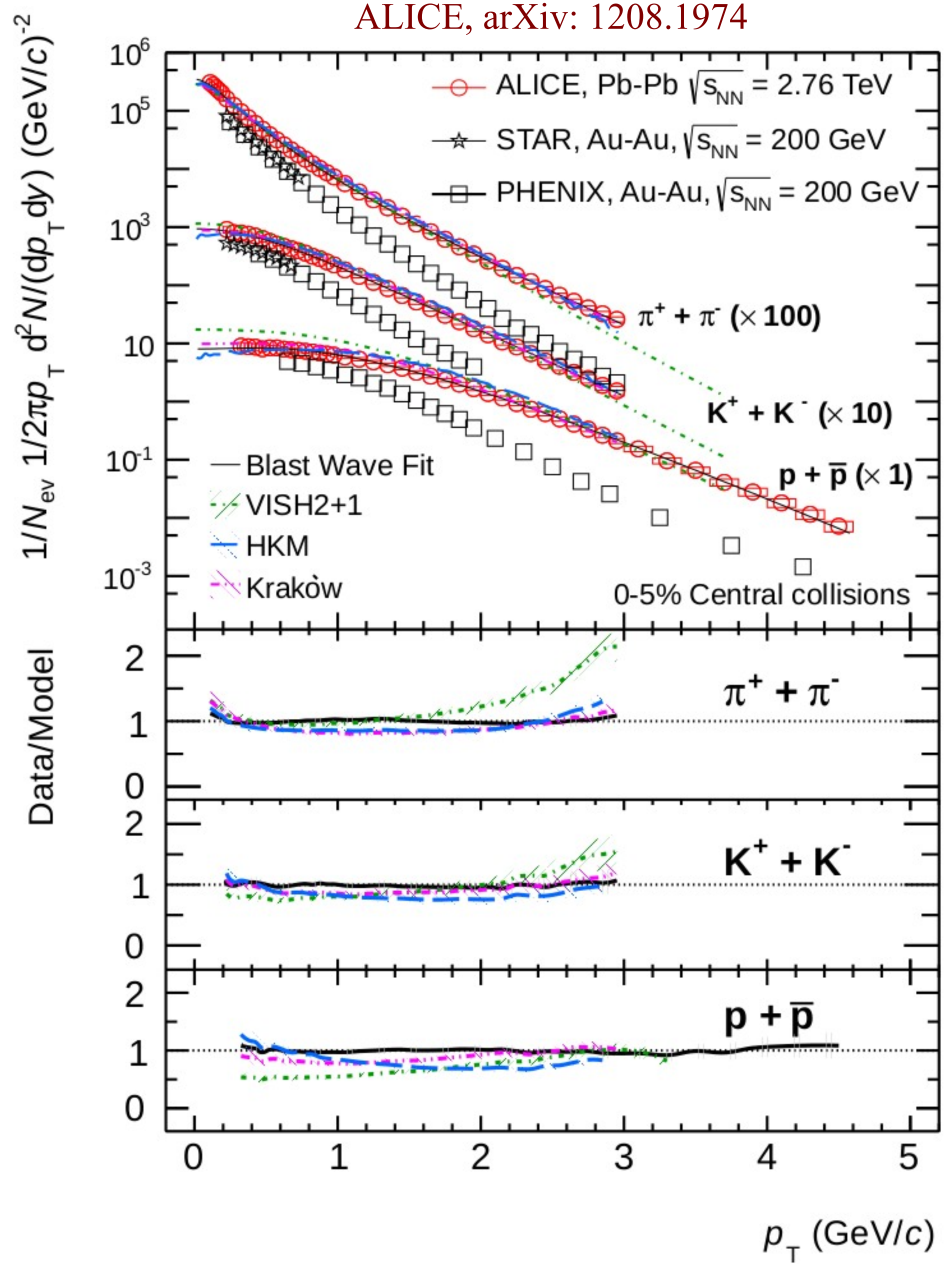
- Radii increase with multiplicity, higher k_T gives smaller radii, consistent with hydro collectivity

Annihilation in baryon-antibaryon correlations

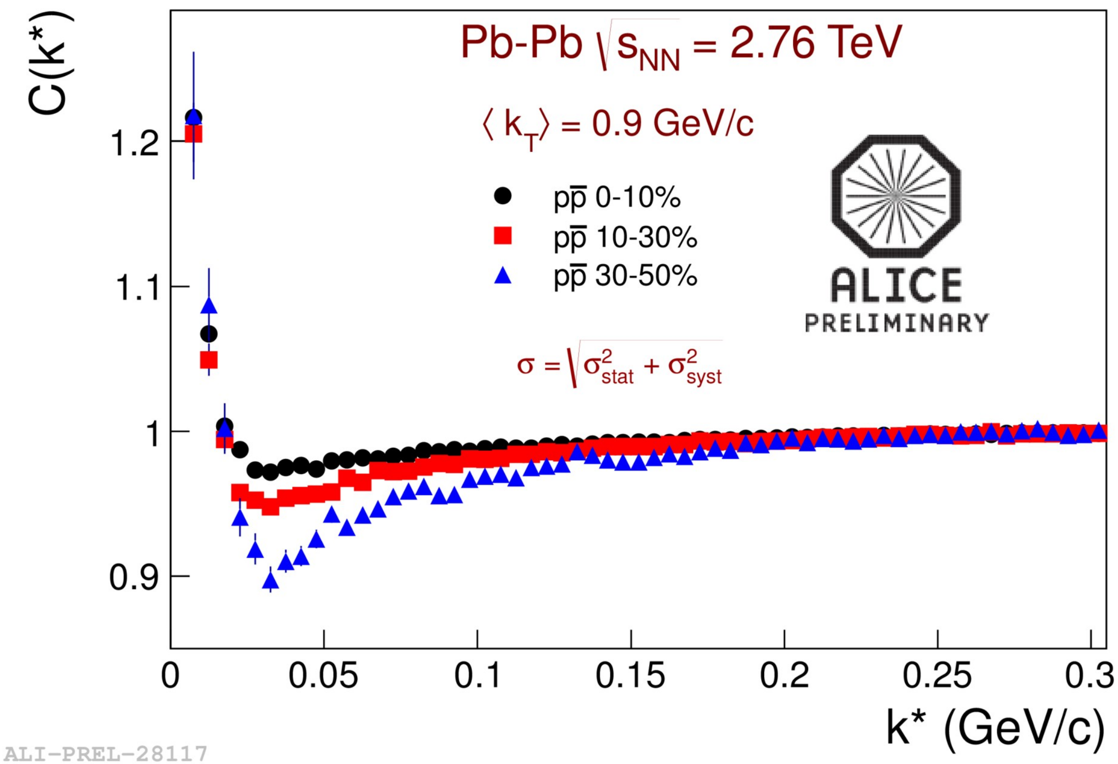
- Deviation of proton yields from chemical models expectations
  - "rescattering" phase should be taken into account while determining yields
    - Steinheimer, Aichelin, Bleicher; arXiv:1203.5302
    - Werner et al.; Phys.Rev. C85 (2012) 064907
    - Karpenko, Sinyukov, Werner; arXiv:1204.5351
  - If true, annihilation must be seen in baryon-antibaryon correlations

(...)switching $B\bar{B}$-annihilation on suppresses baryon yields, in the same time increases pion yield, thus lowering p/π ratio to the value 0.052, which is quite close to the one measured by ALICE(...)

ALICE, arXiv: 1208.1974

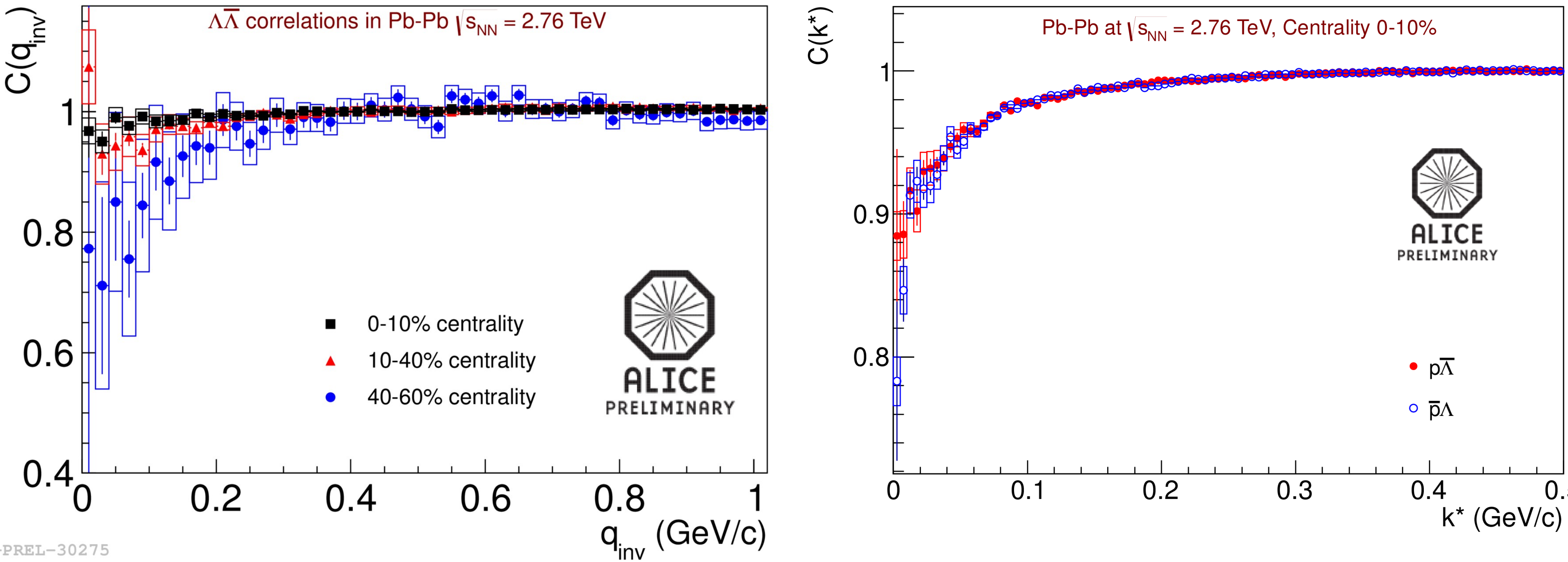


$p\bar{p}$ correlation functions



- Shape dominated by Coulomb and Strong FSI
- Wide negative correlation consistent with annihilation in the strong FSI
- Femtoscopic effect very wide, better statistical handle on the system size (compared to pp)

$\Lambda\overline{\Lambda}$ and $p\overline{\Lambda}$ correlation functions



- Wide negative correlation observed, consistent with annihilation in the strong FSI
- Annihilation not limited to particle-antiparticle systems!
- Correlation strength increases with decreasing multiplicity (consistent with decrease of the system size)
- Quantitative analysis requires careful consideration of the residual correlations (feed-up from $p\overline{p}$, correlations with $\overline{\Sigma}^0$ and others)

Summary

- Femtoscopy is sensitive to system size (lengths of homogeneity) and collision dynamics
- Femtoscopy provides important constraints on system dynamics and Equation of State at RHIC and at the LHC
- Pion femtoscopy at the LHC consistent with predictions from hydrodynamics, constrained by RHIC data
- Radii in pp scale linearly with multiplicity, depend on momentum in non-trivial way, do not depend on energy, are different from PbPb
- Radii in pPb more similar to pp rather than PbPb, transverse momentum dependence similar to hydro
- Significant annihilation for $B\bar{B}$ systems observed (not limited to particle-antiparticle!), should provide better data on cross-sections for the rescattering codes and other fields

End