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System size from SPS and RHIC BES to LHC

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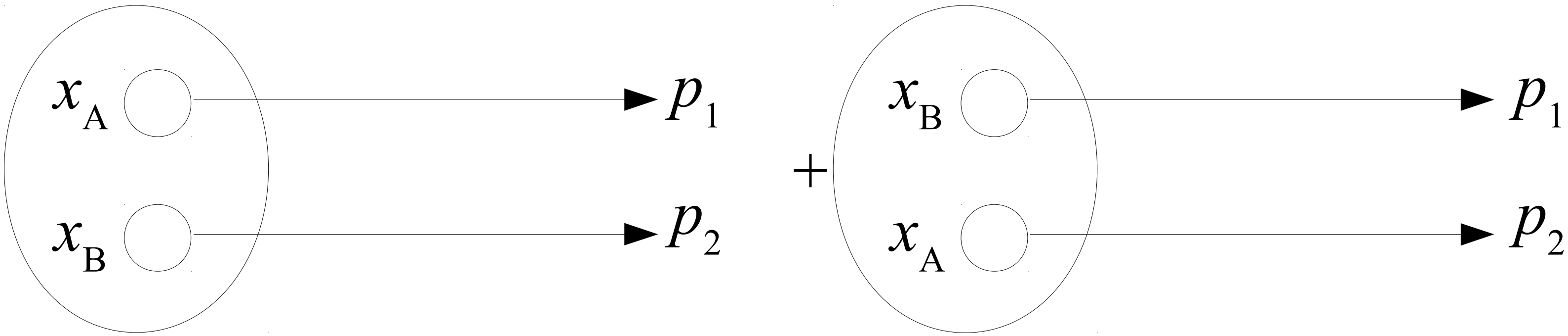
Overview

- What is femtoscopy and what does it measure
- Measuring the size from SPS to LHC
- Femtoscopy and collectivity
  - Lessons from RHIC
  - Validation of hydro predictions for the LHC
  - Femtoscopy with heavy particles
  - Azimuthally sensitive femtoscopy
- Femtoscopy in small systems
  - Differences and similarities to heavy-ion collisions
  - Understanding source evolution in elementary collisions

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)

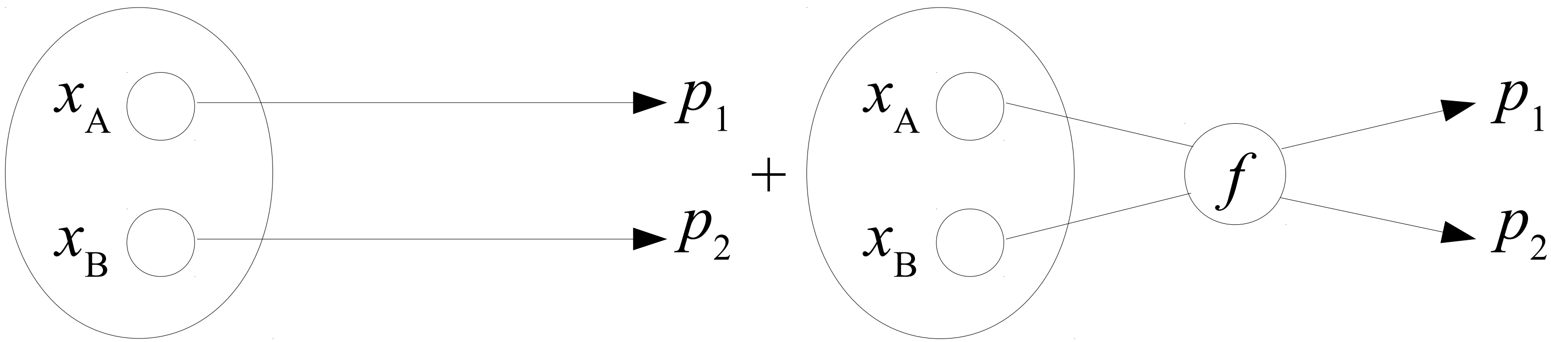
$$\Psi = \frac{1}{\sqrt{2}}\left[\exp\left(-i\,p_1 x_A - i\,p_2 x_B\right) + \exp\left(-i\,p_1 x_B - i\,p_2 x_A\right)\right]$$

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

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

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

Correlation – hadrons



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

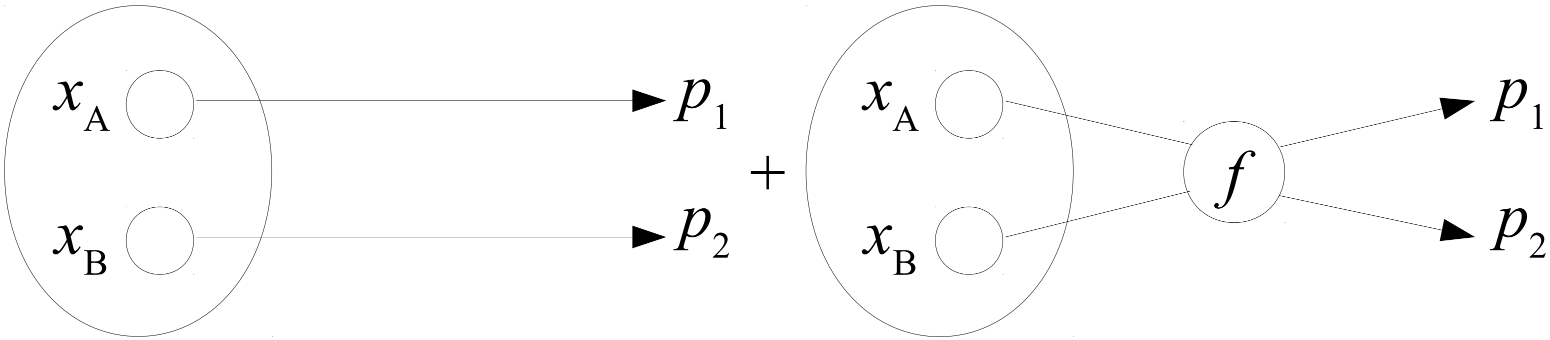
$$r = x_A - x_B$$

- Two hadrons interact via the strong force after their last scattering (emission)
  - Ψ 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

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

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

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

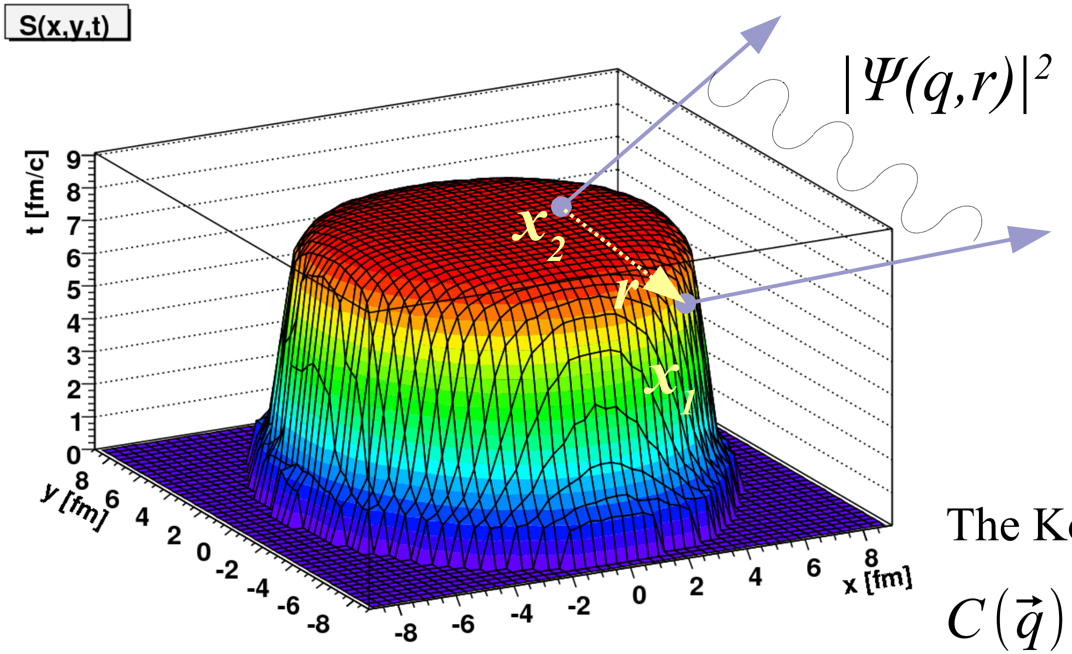
$$\Psi_{-\mathbf{k}^*}(\mathbf{r}^*) = e^{i\delta_c}\sqrt{A_c(\eta)}\left[e^{-i\mathbf{k}^*\mathbf{r}^*}F(-i\eta,1,i\xi) + f_c(k^*)\tilde{G}(\rho,\eta)/r^*\right]$$

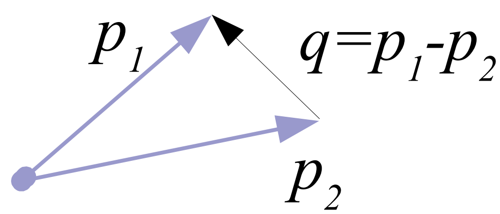
$$\xi = \mathbf{k}^*\mathbf{r}^* + k^*r^* \equiv \rho(1+\cos(\theta^*)),\ \ \rho = k^*r^*,\ \ \eta = (k^*a)^{-1},\ \ a = (\mu z_1 z_2 e^2)^{-1}$$

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

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

Measuring space-time extent: femtoscopy





The Koonin-Pratt (KP) 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?

- Particle source is given by S, 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 KP equation takes the pair separations:

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

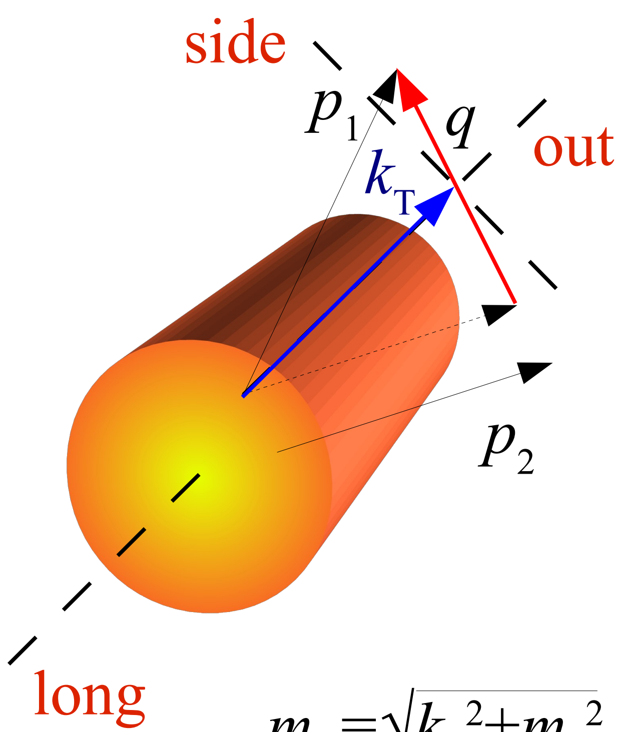
- For identical pions coulomb factor K is factorized out, Ψ is then $1+\cos(qr)$. Then KP gives the femtoscopic part of CF:

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

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:

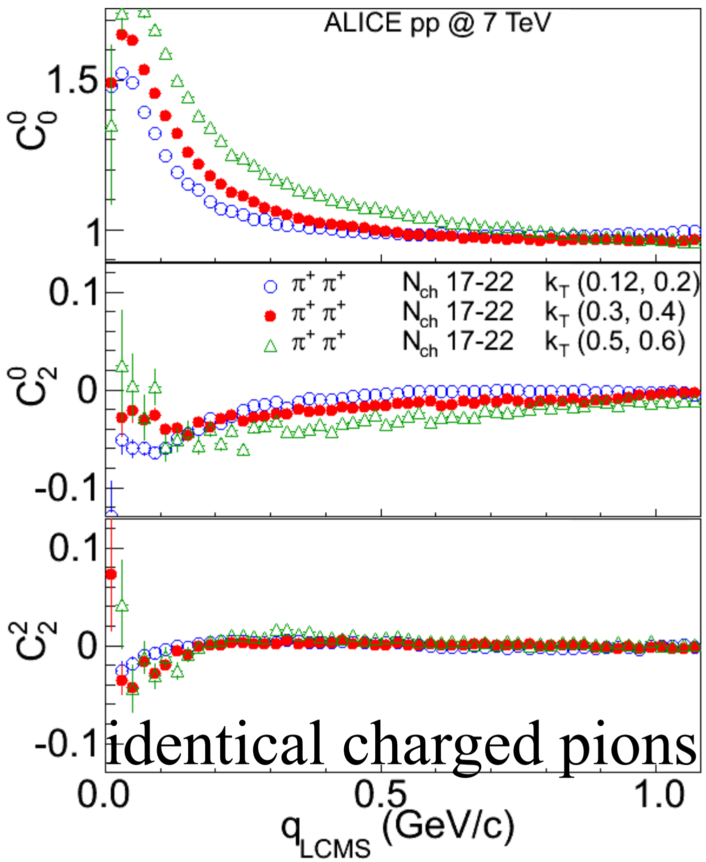
$$C(\vec{q}) = \int S(\boldsymbol{r}) |\Psi(\vec{q}, \boldsymbol{r})|^2 d^4 r$$

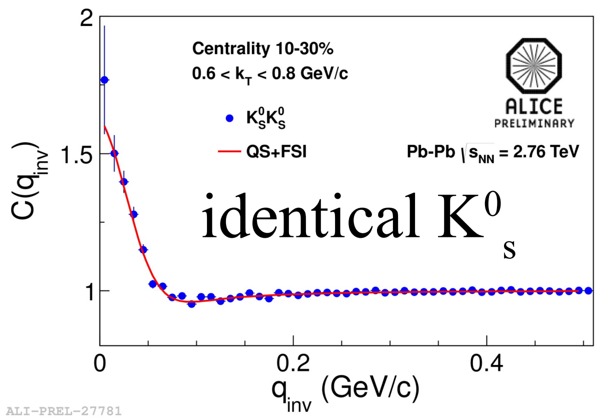
- If statistics is sufficient (charged pions ...) the measurement is in 3 dimensions, giving 3 independent sizes
- The Longitudinally Co-Moving System is used
- The Bertsch-Pratt decomposition of q:
  - Long along the beam: sensitive to longitudinal dynamics and evolution time
  - Out along k_T: sensitive 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

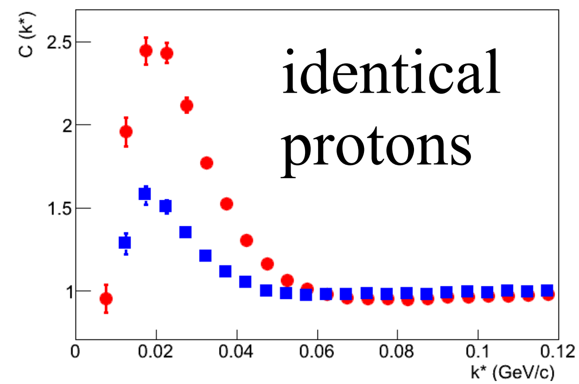
How does it look like?

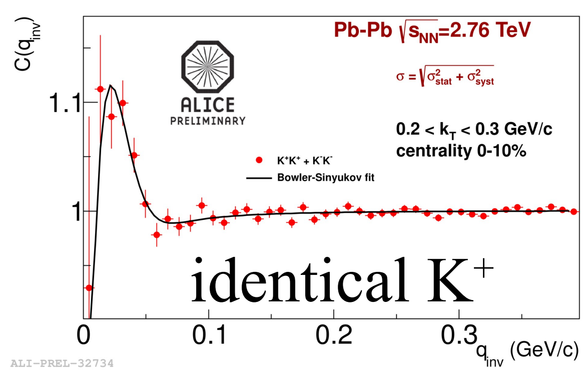
- Various shapes and momentum scales, depending on the pair type (interactions involved), collision system and energy, pair transverse momentum, etc.

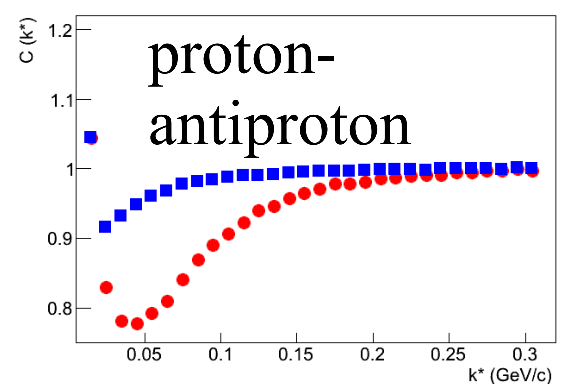
$$e.g: \quad C_e(\vec{q}) = (1-\lambda) + \lambda K(q)[1+\exp(-R^2 q^2)]$$



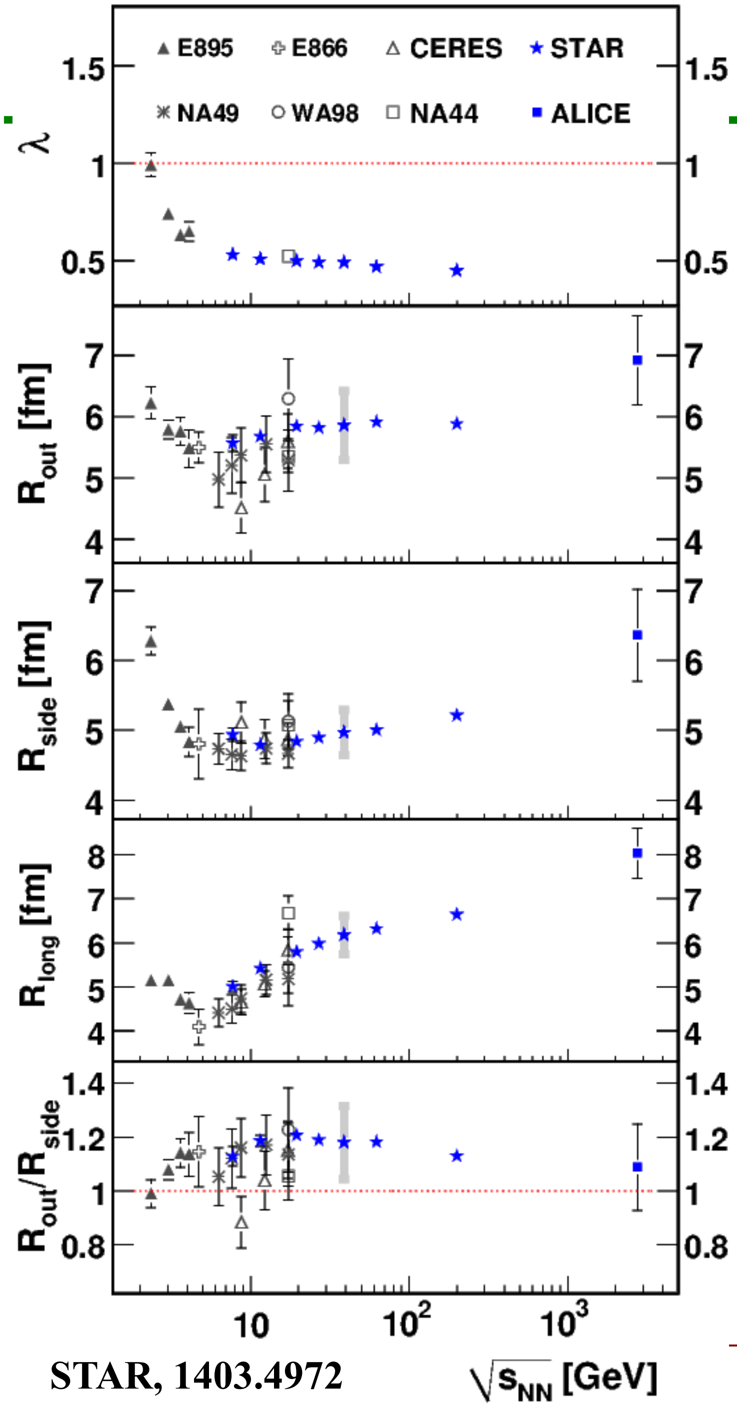




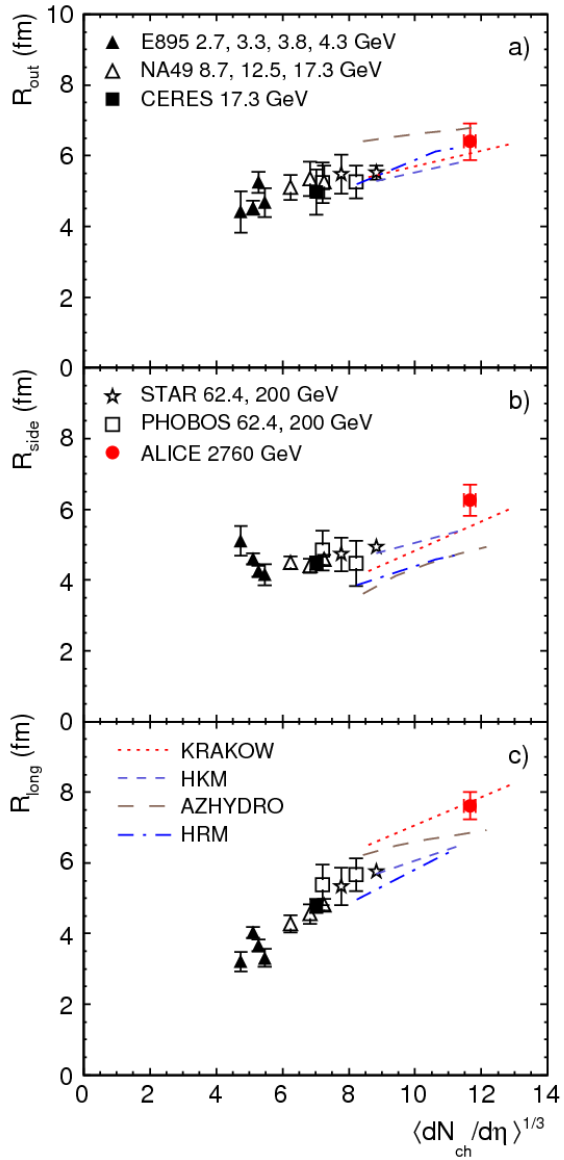




Size evolution



STAR, 1403.4972

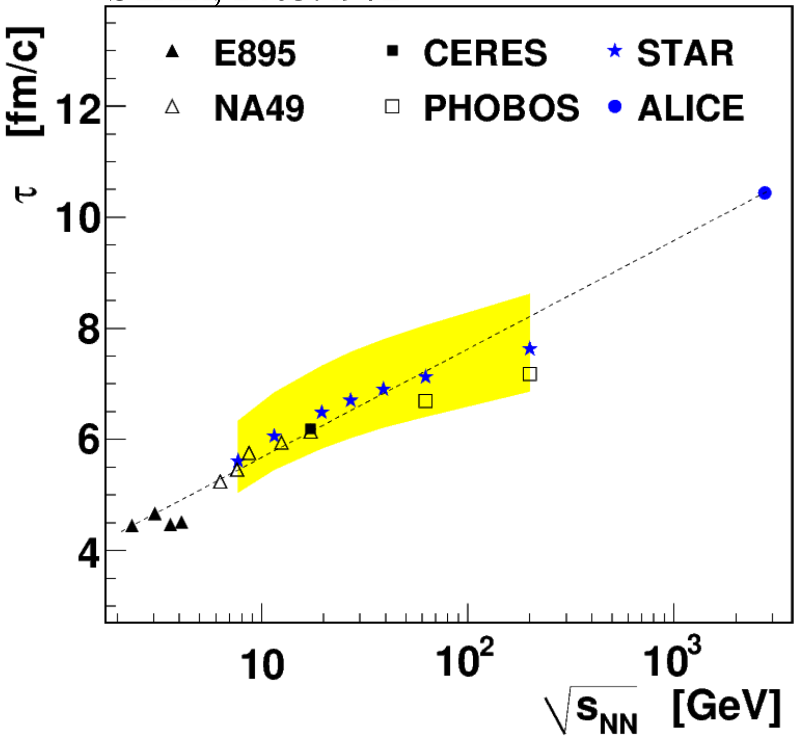


- Non-trivial size evolution at few GeV $\sqrt{s_{NN}}$, interpreted as a change to pion dominated system
- Later a smooth transition with energy
- At LHC the sizes visibly larger, growing with multiplicity
- Qualitatively consistent with hydro

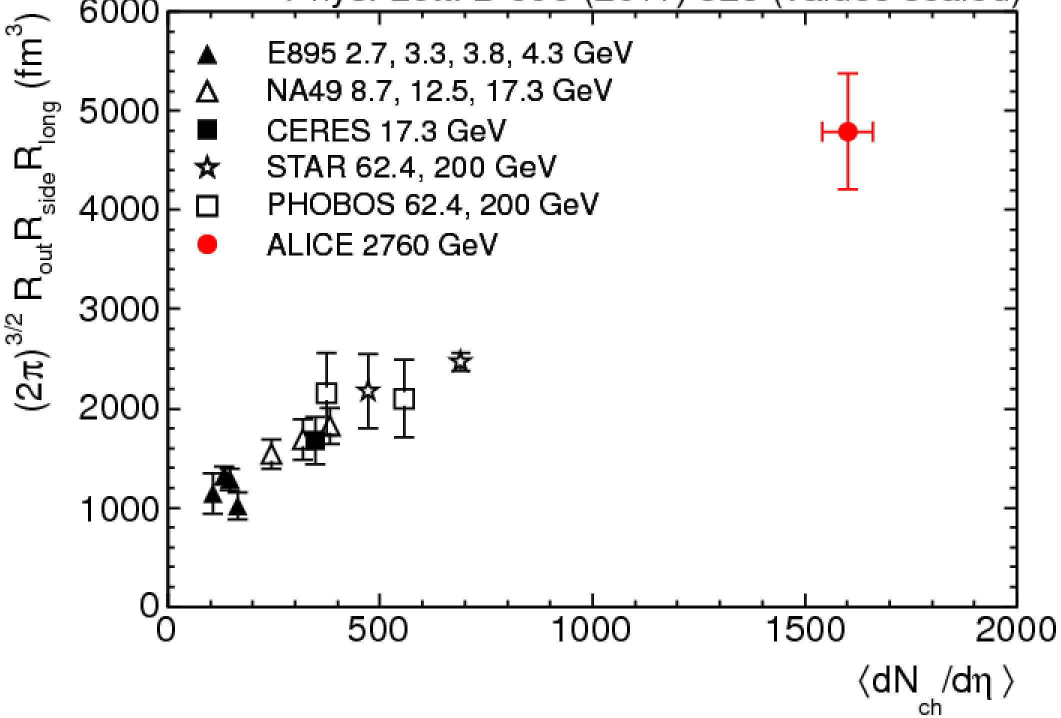
Measuring system lifetime

- Lifetime can be estimated from the longitudinal radius
- Clear increase of system volume and lifetime with collision energy, at LHC system twice as large and living 30% longer than at top RHIC energy (good conditions for QGP studies)

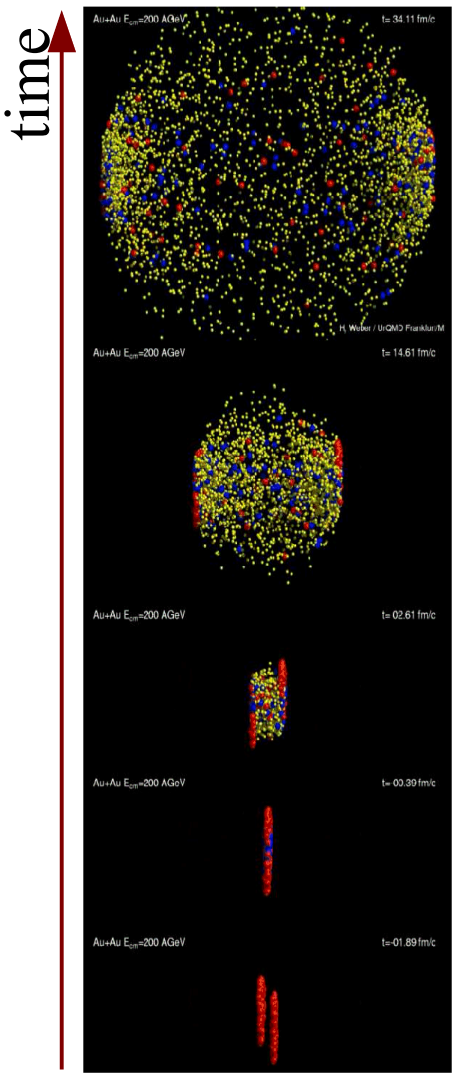
STAR, 1403.4972

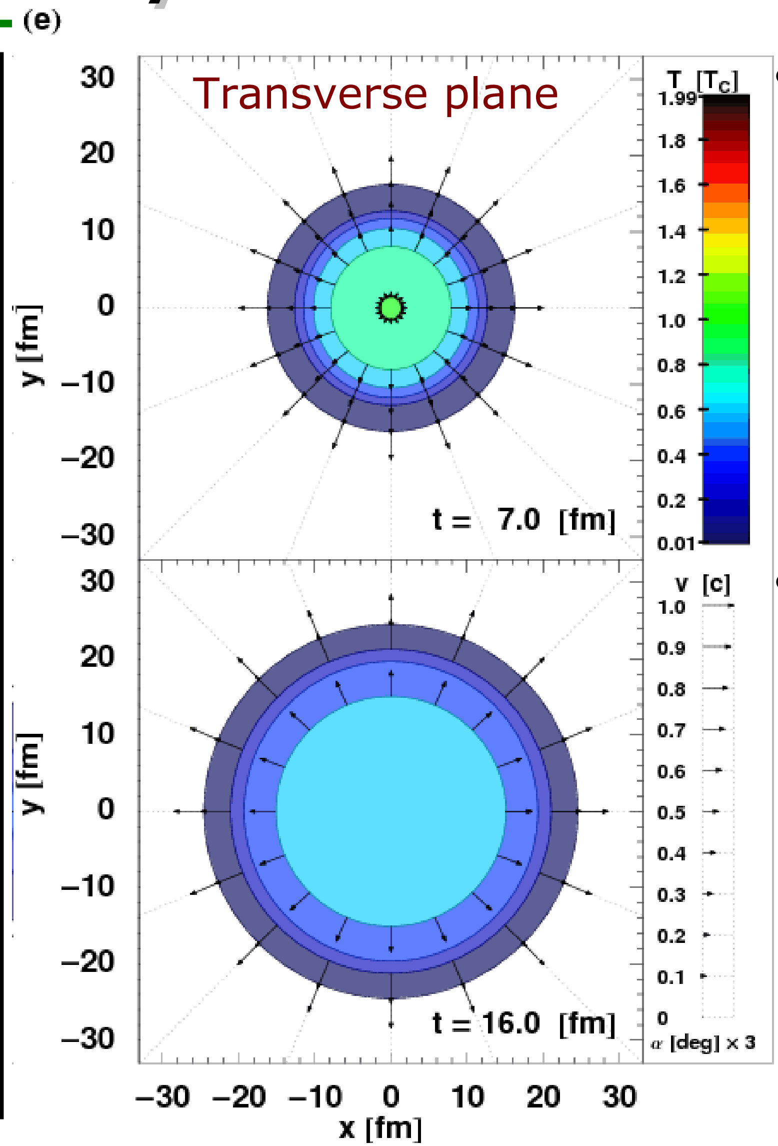


Phys. Lett. B 696 (2011) 328 (values scaled)



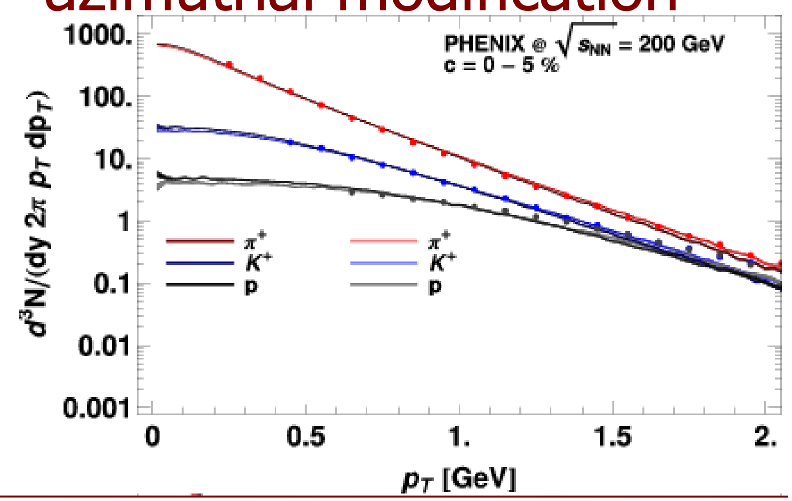
Heavy Ion collision evolution



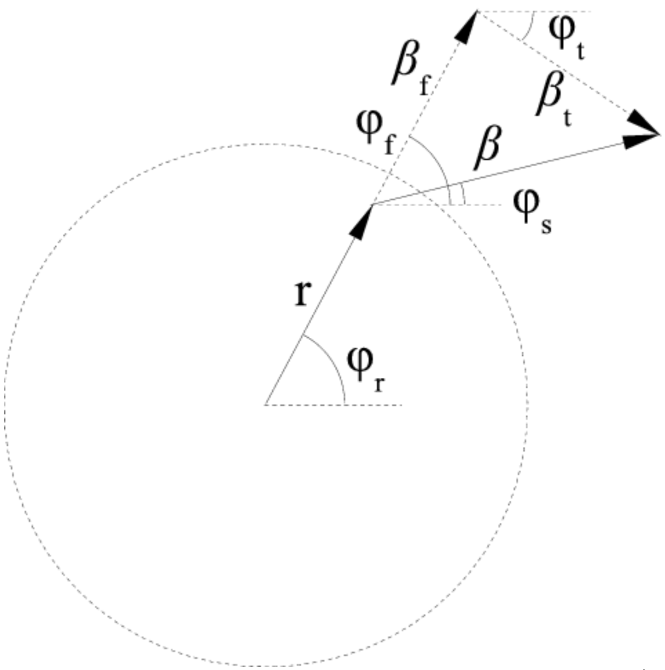


M. Chojnacki, W. Florkowski, PRC 74 (2006) 034905

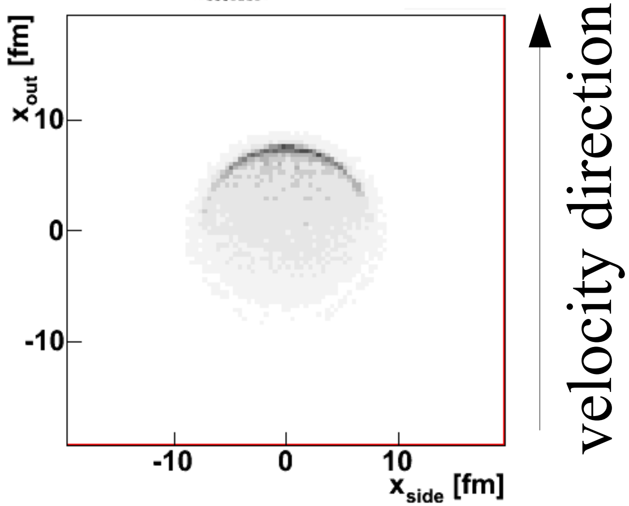
- HIC is expected to go through a QGP phase, where matter is strongly interacting – resulting in the development of collective motion
- Radial flow dominates, with elliptic flow as azimuthal modification

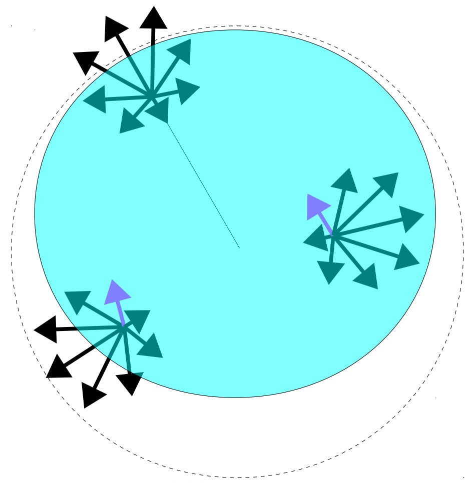


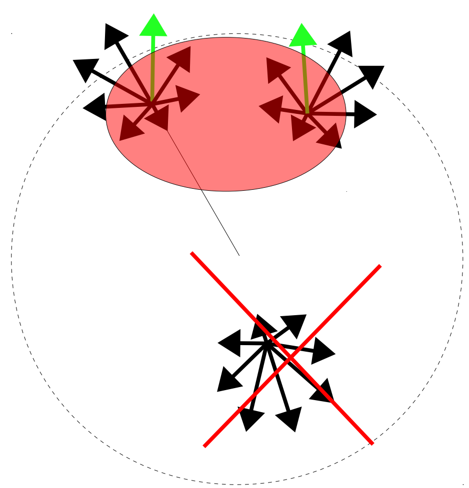
Thermal emission from collective medium



- 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 pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source



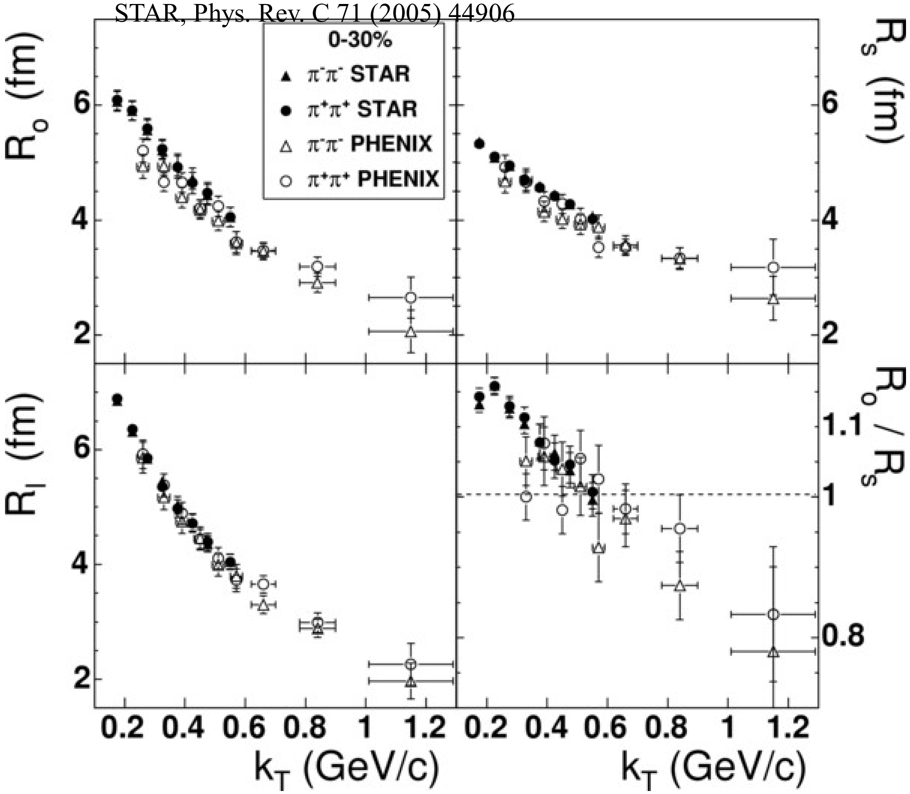


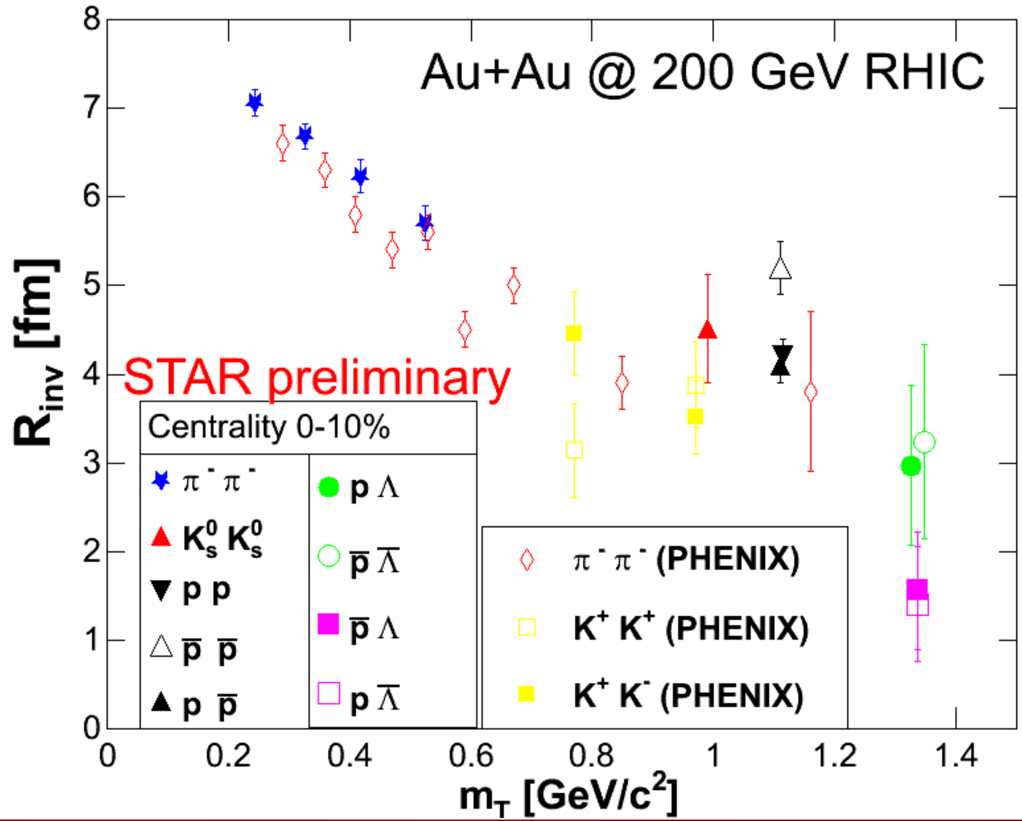


m_T dependence at RHIC

- 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?

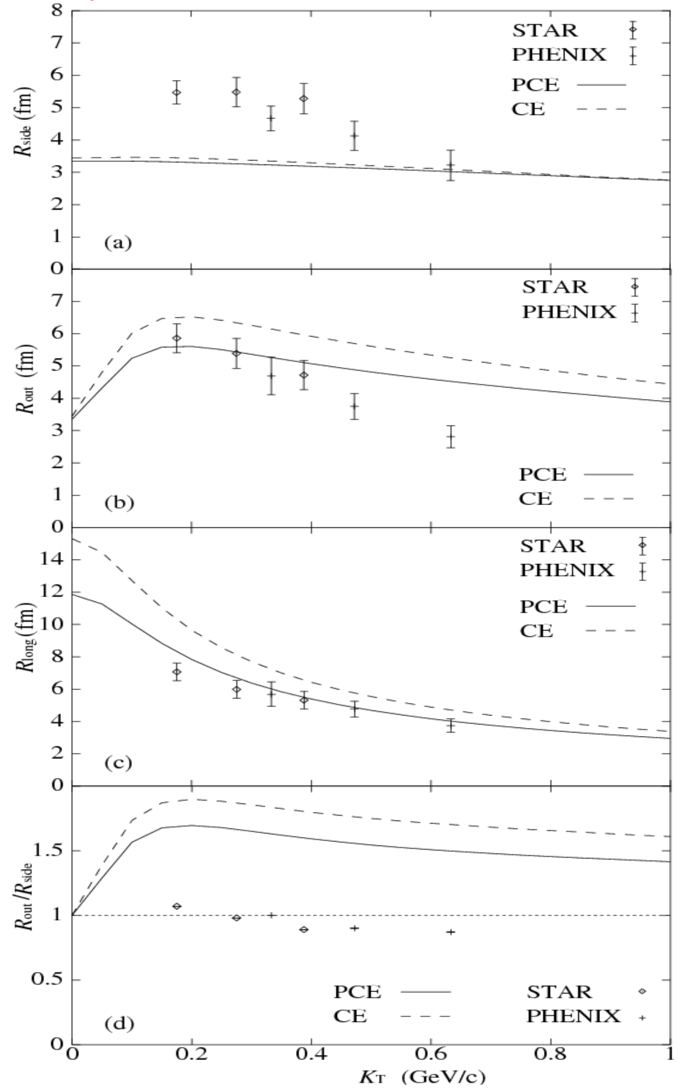
STAR, Phys. Rev. C 71 (2005) 44906



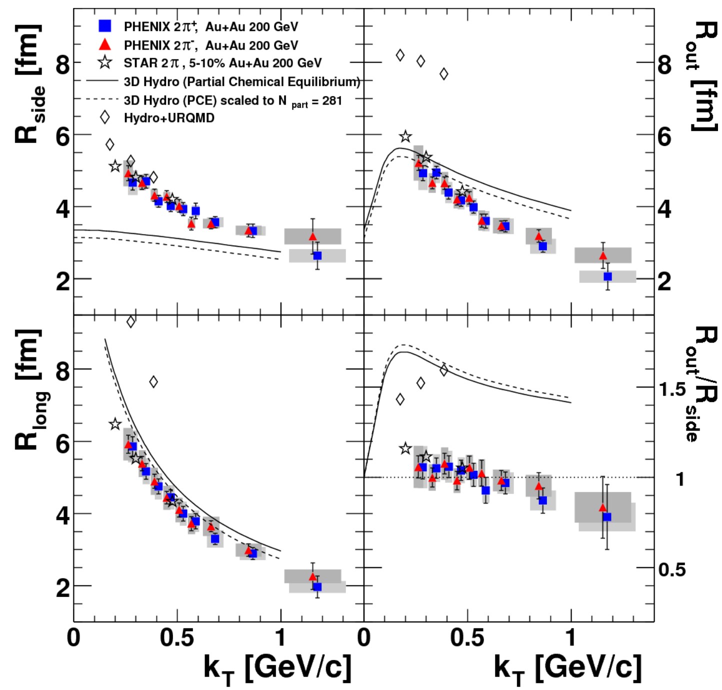


RHIC Hydro-HBT puzzle

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



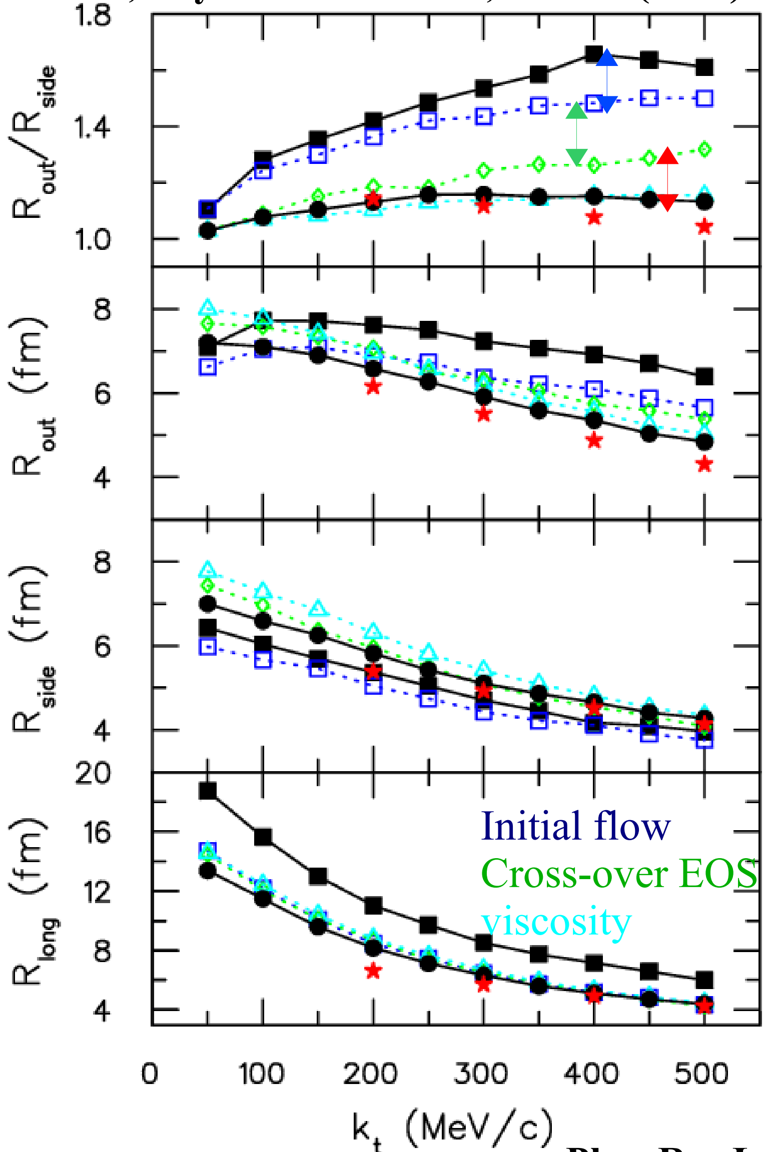
- First hydro calculations struggled to describe femtoscopic data: predicted too small R_{side}, too large R_{out} – too long emission duration
- R_{out}/R_{side} sensitive to emission duration, which is large for first order phase tr.



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

Revisiting hydrodynamics assumptions

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



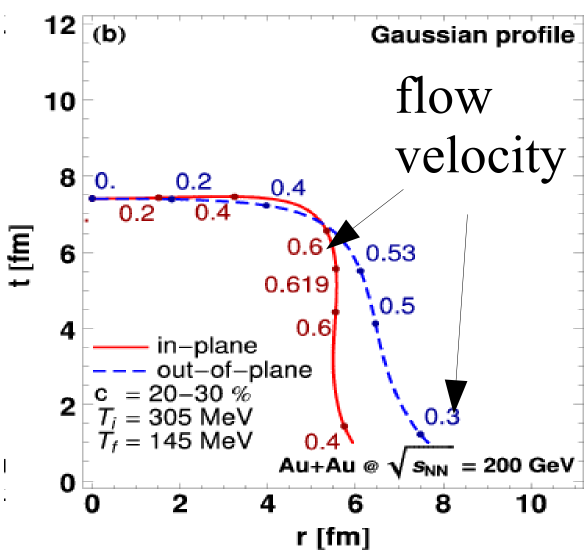
Phys.Rev.Lett. 101 (2008) 022301

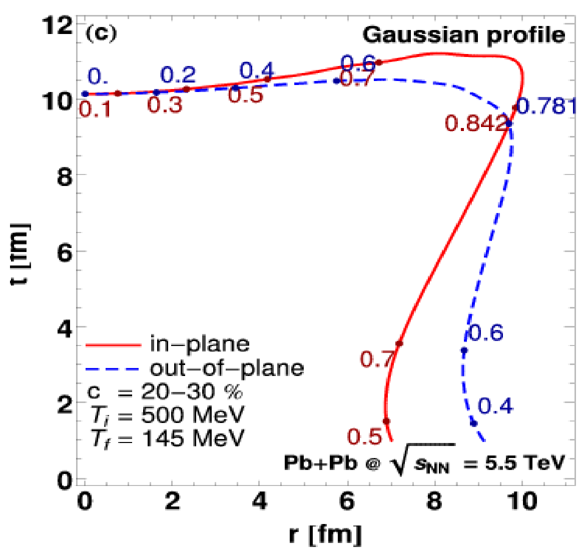
- Data in the momentum sector (p_T spectra, elliptic flow) well described by hydrodynamics, why not in space-time?
- Usually initial conditions do not have initial flow at the start of hydrodynamics (~1 fm/c) – they should.
- Femtoscopy data rules out first order phase transition – smooth cross-over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

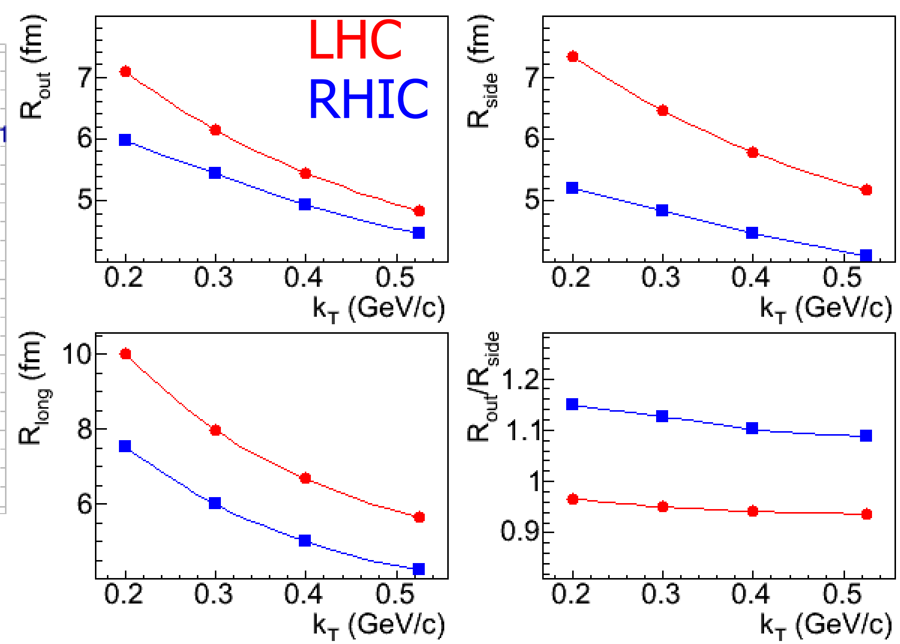
- Lessons from RHIC:
  - "Pre-thermal flow": strong flows already at τ_0=1 fm/c
  - EOS with no first-order phase transition
  - Careful treatment of resonances important
- Extrapolating to the LHC:
  - Longer evolution gives larger system → all of the 3D radii grow
  - Stronger radial flow → steeper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

RHIC → LHC

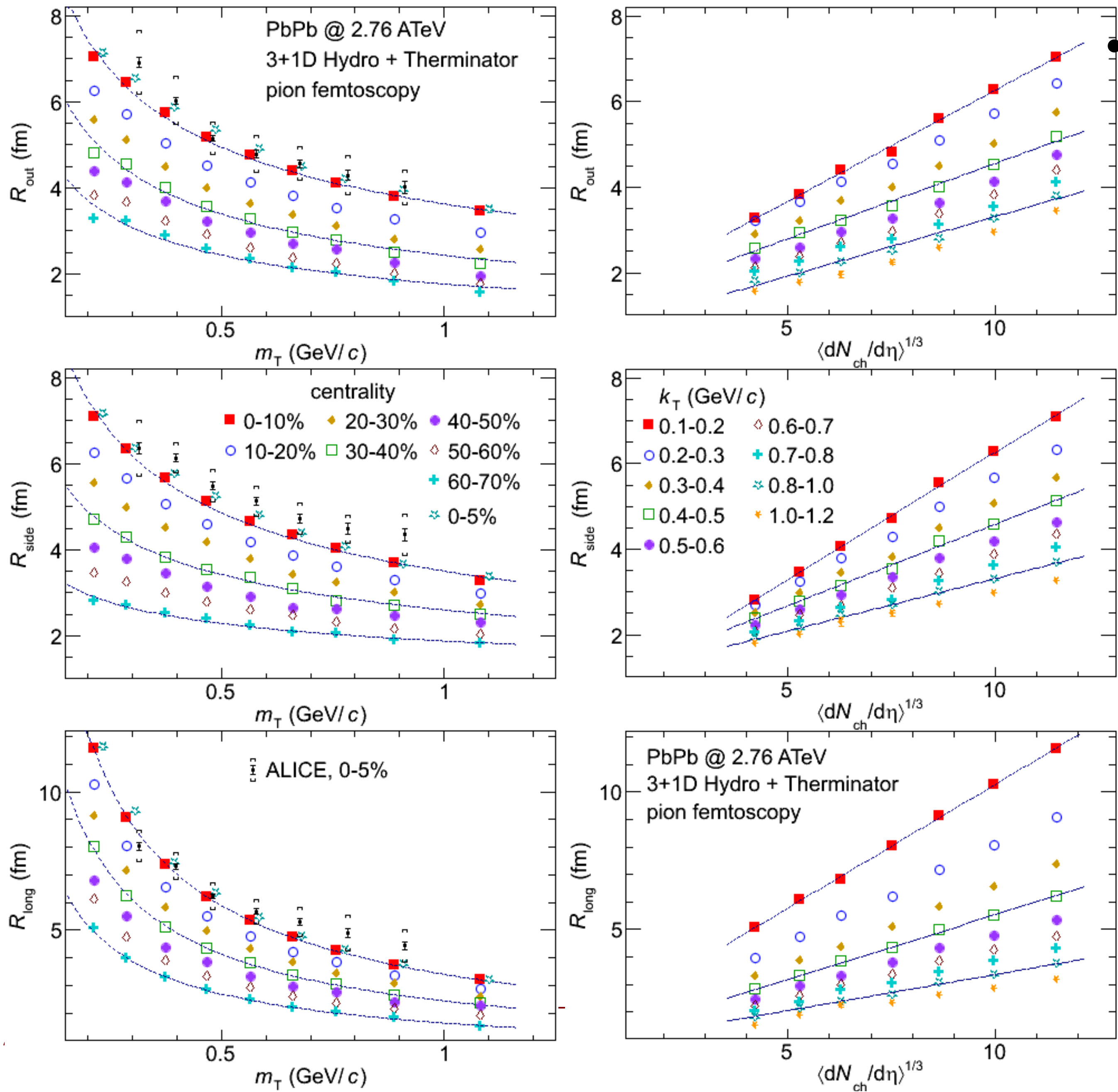




Phys.Rev.C79:014902,2009



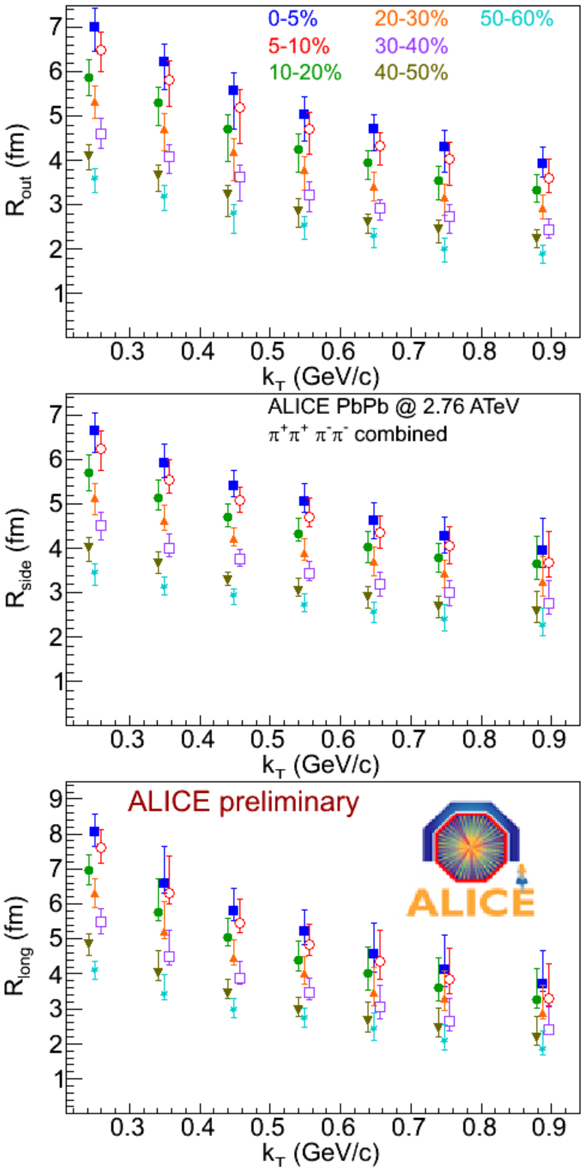
Model multiplicity and m_T dependence



- For high multiplicity A+A collisions where hydro is applicable:
  - Strong flows result in clear m_T dependence (power-law)
  - Dependence is most steep in *long*
  - All radii scale linearly with final state multiplicity

A.Kisiel, M.Gałażyn, P.Bożek; arXiv:1409.4571

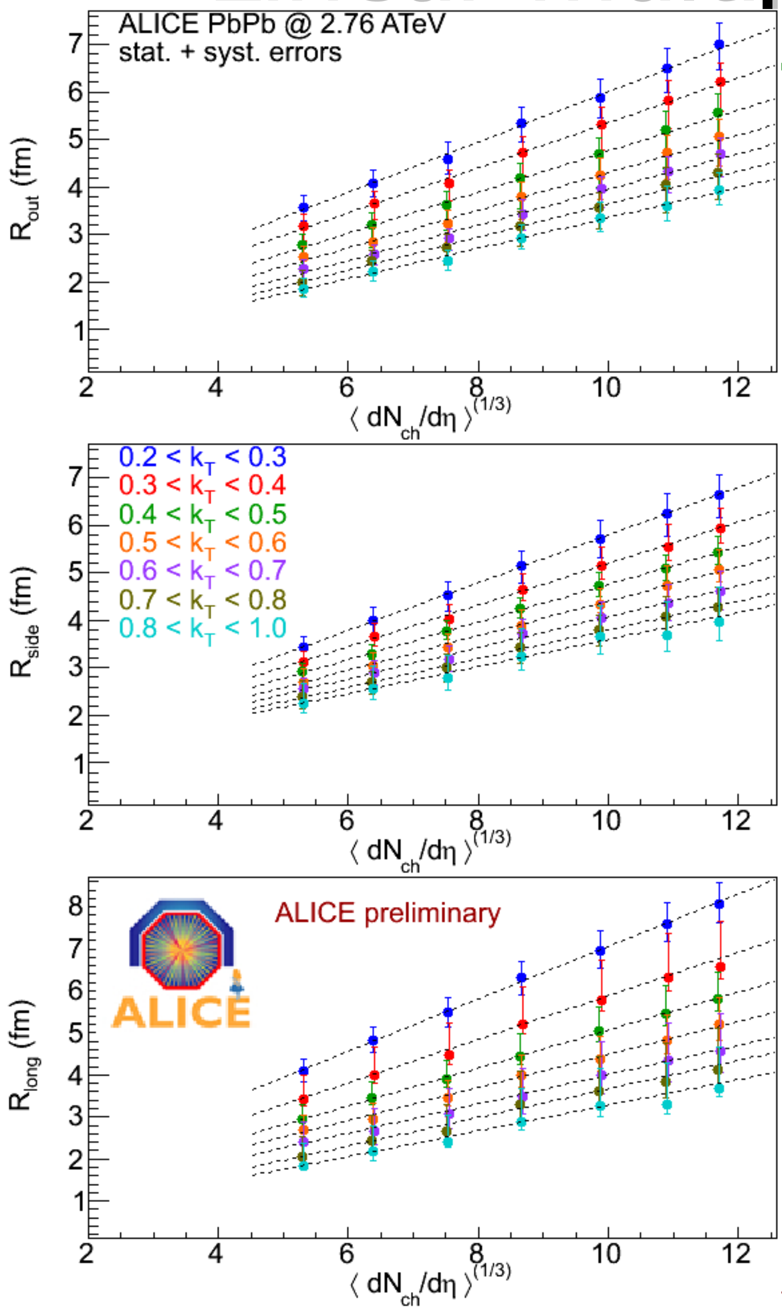
Data on radii vs. centrality and k_T



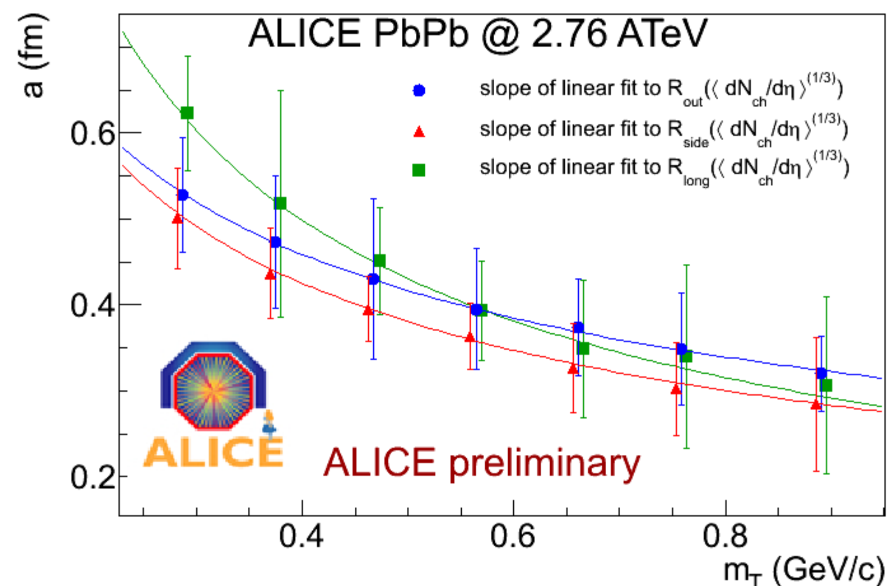
A.Kisiel, QM2011

- Femtoscopic radii vs. k_T for 7 centrality bins in central rapidity region
- Radii universally grow with event multiplicity and fall with pair momentum
- Both dependencies in agreement with calculations from collective models (hydrodynamics), both quantitatively and qualitatively
- Hydro calculations done after the release of preliminary femtoscopic data from ALICE, however reaching similar level of agreement at RHIC took 9 years!

Linear multiplicity scaling of radii

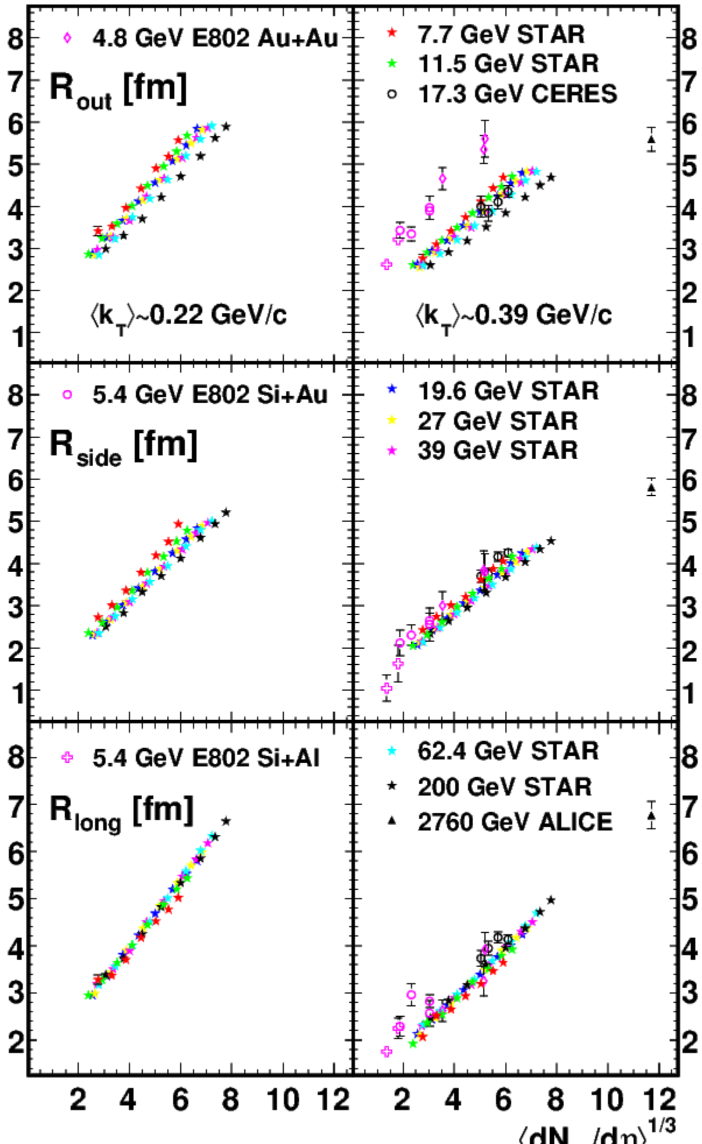


- Radii in 3 directions and all pair momentum ranges scale linearly with $dN_{ch}/d\eta$
- Slope parameters of this fit show power-law behavior, similar to hydrodynamics



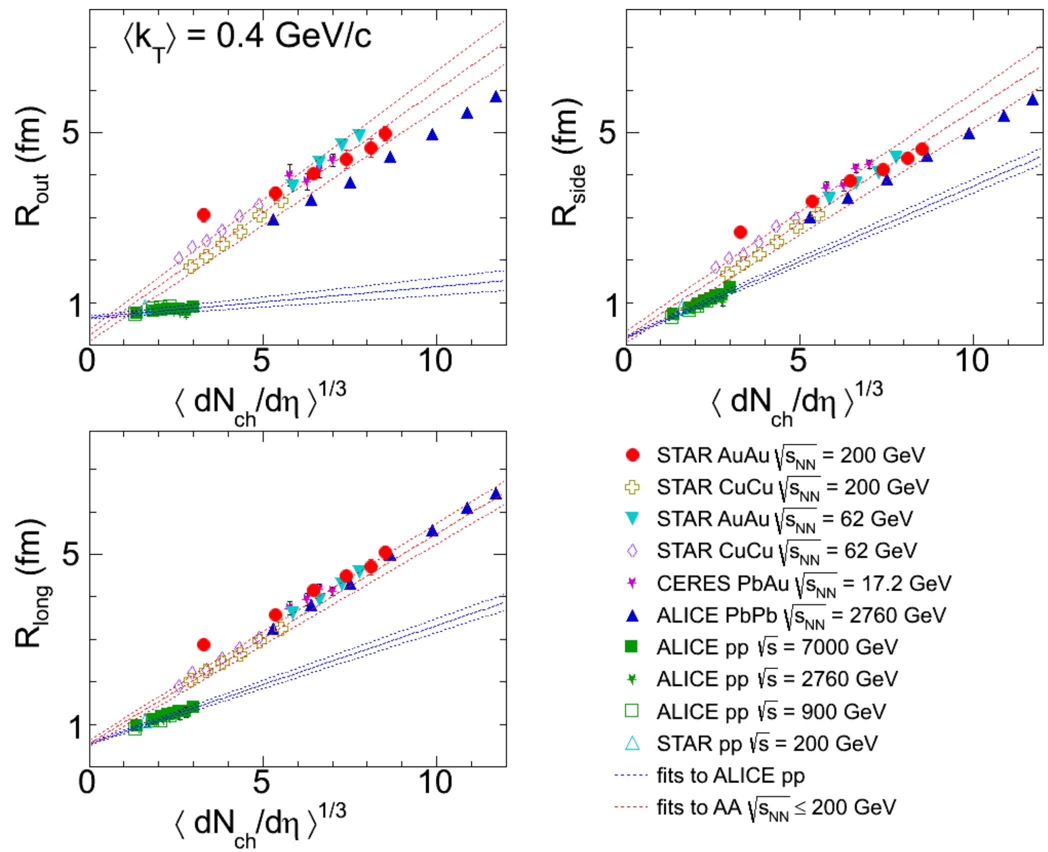
A.Kisiel, QM2011

Femtoscopy – final or initial state?



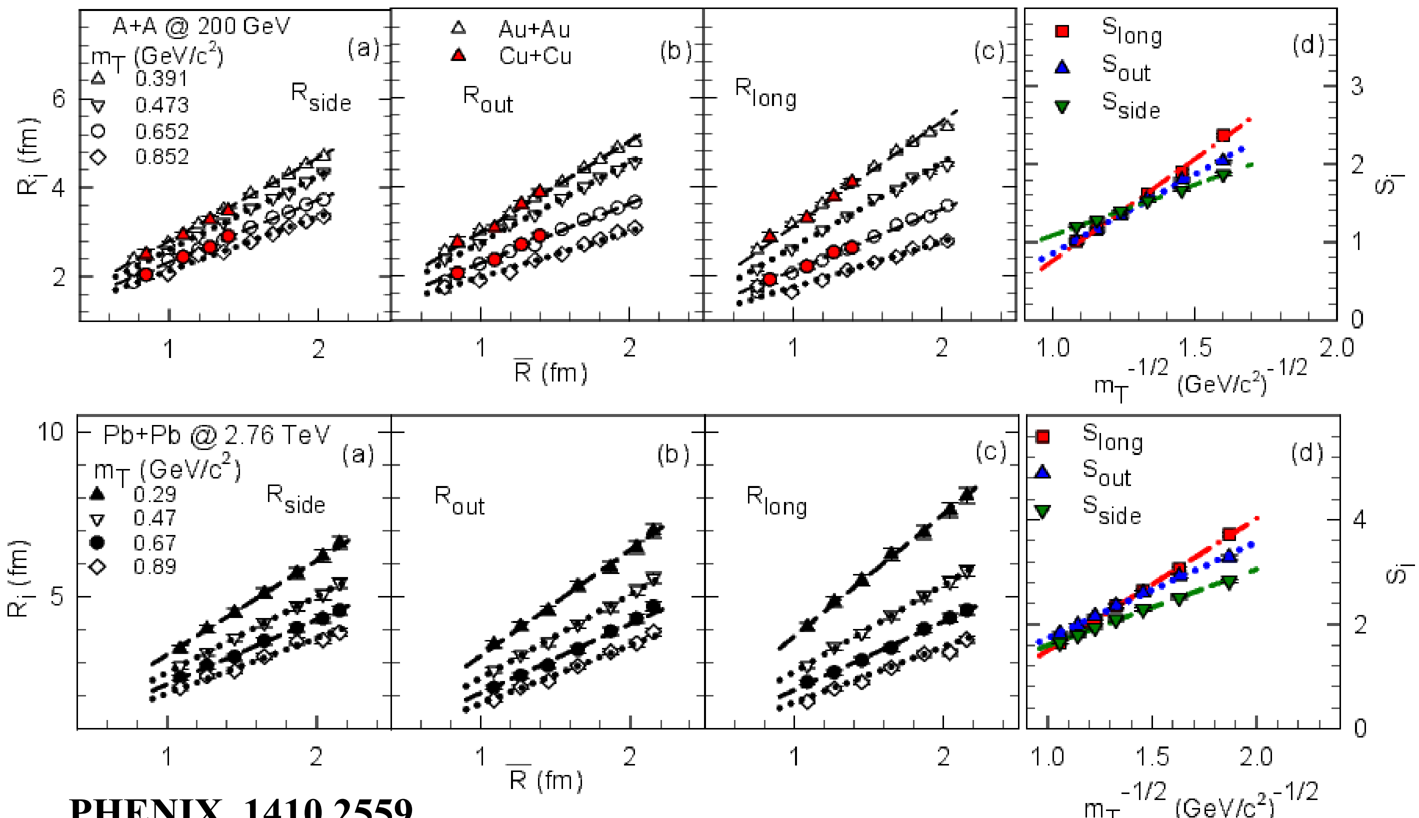
STAR, 1403.4972

- Radii scale with final-state multiplicity: R_{long} scaling very good, transverse radii more complicated
- pp scales very differently



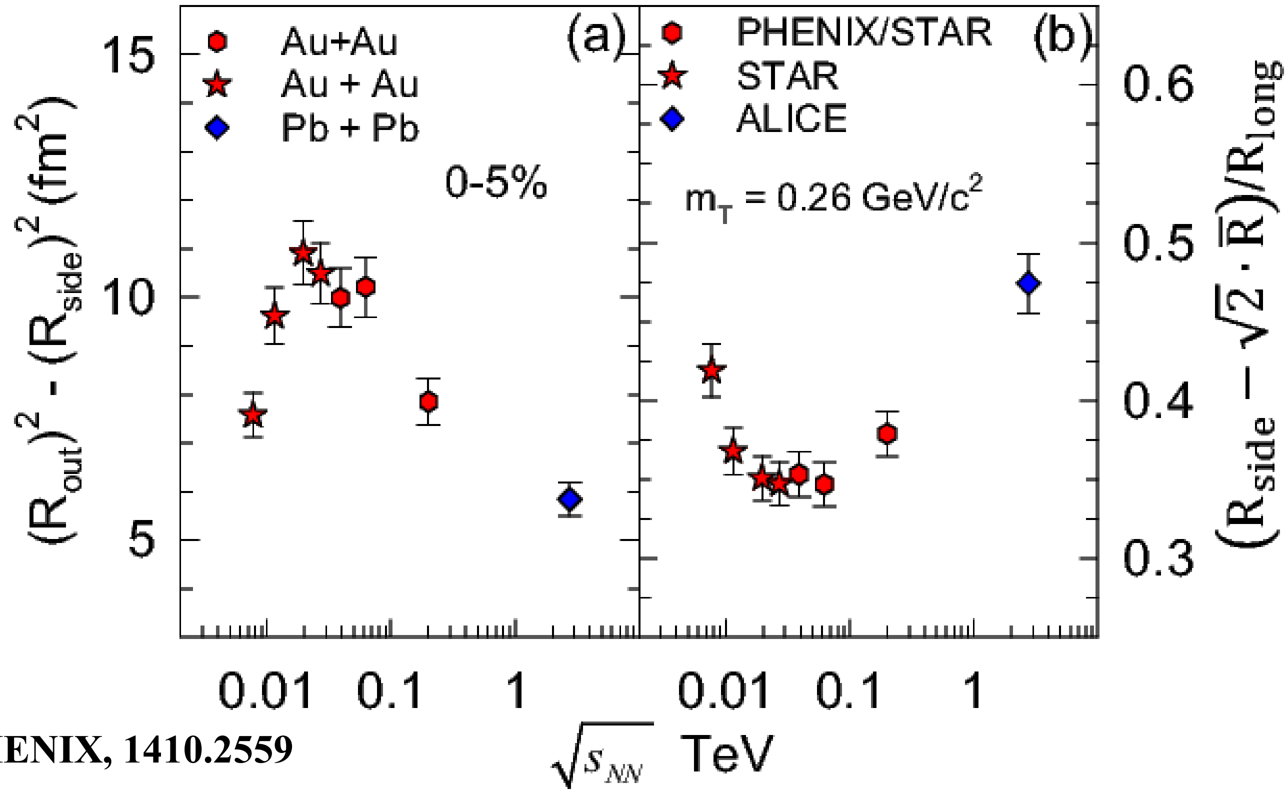
What about initial state variables?

- Initial state variables work within similar collision system and energy, but not across collision energies
- Femtoscopy clearly driven by the final-state



PHENIX, 1410.2559

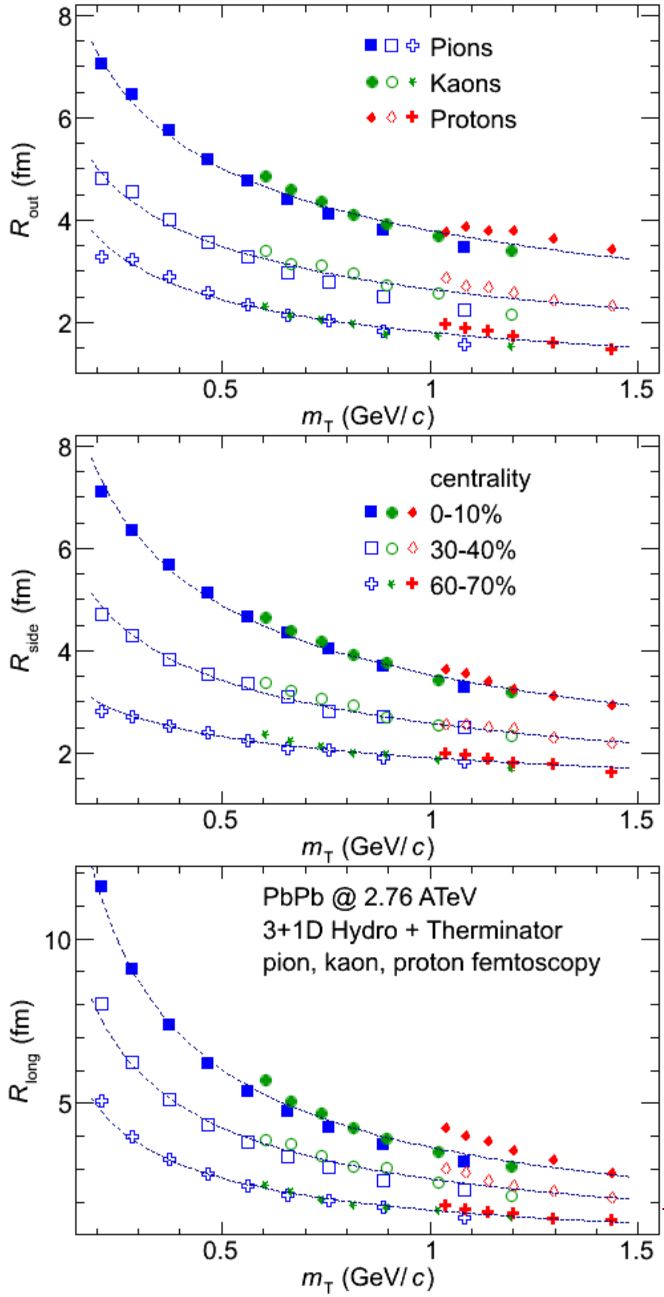
Looking for the critical point



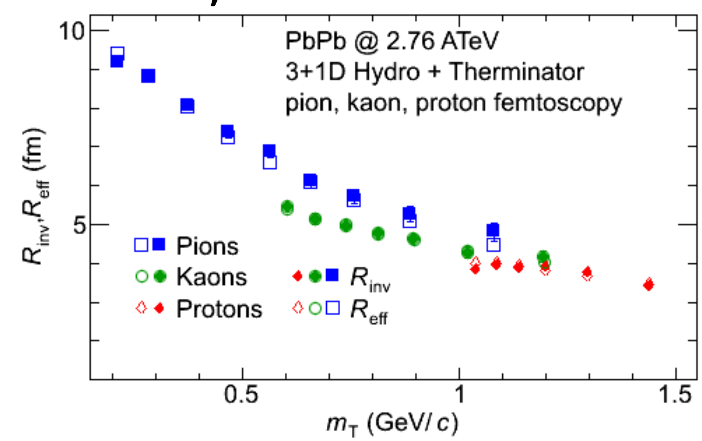
PHENIX, 1410.2559

- Looking for the non-monotonic behavior of radii in search of the critical point
- Non-monotonic behavior seen in SPS energies in "emission duration" and "expansion rate" observables

m_T scaling for heavier particles



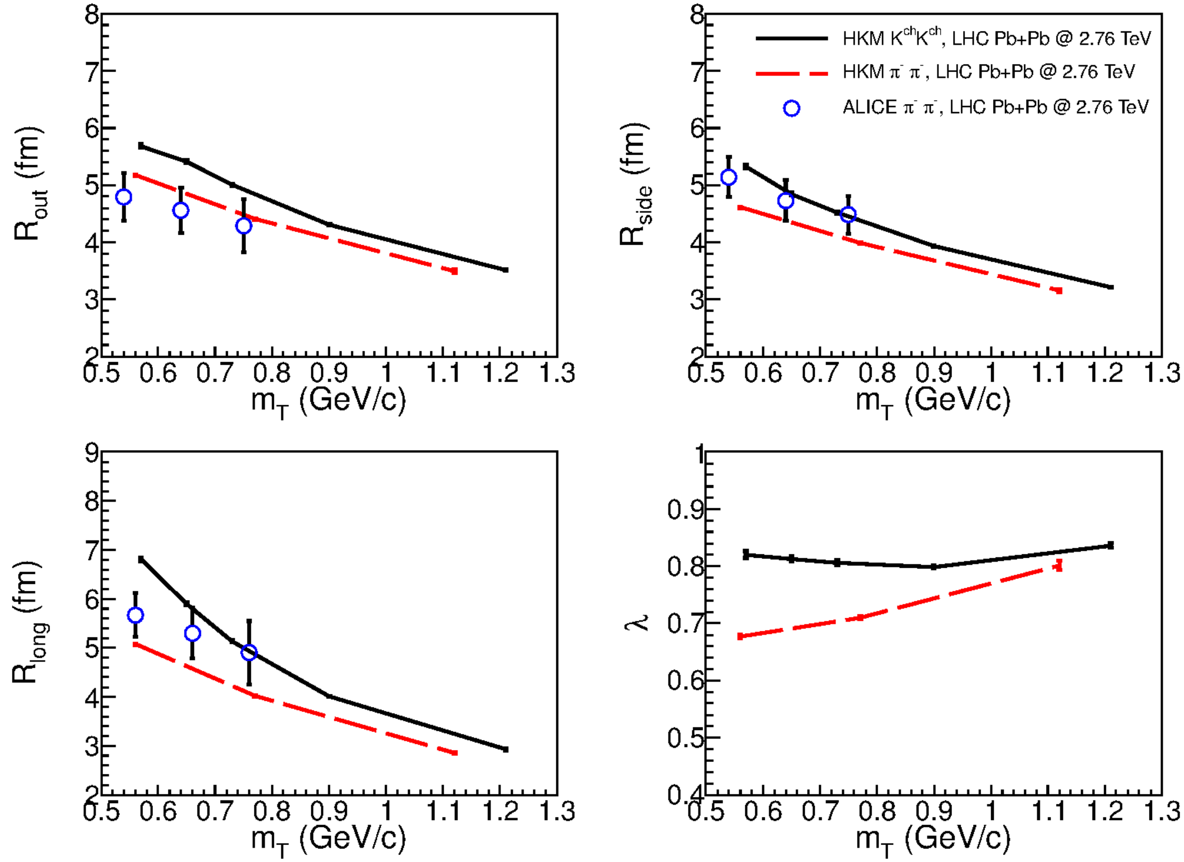
- "Collective" flow should apply to all particles
  - In ideal 1D hydro particles of all masses follow the same m_T scaling. What about "real" hydro in 3+1D and with viscosity (but no hadronic rescattering)?
  - The scaling still exists but only approximately, the deviations comparable to current experimental uncertainty
  - It only works in 3D in LCMS, not in PRF!



A.Kisiel, M.Gałażyn, P.Bożek; arXiv:1409.4571

m_T scaling with rescattering

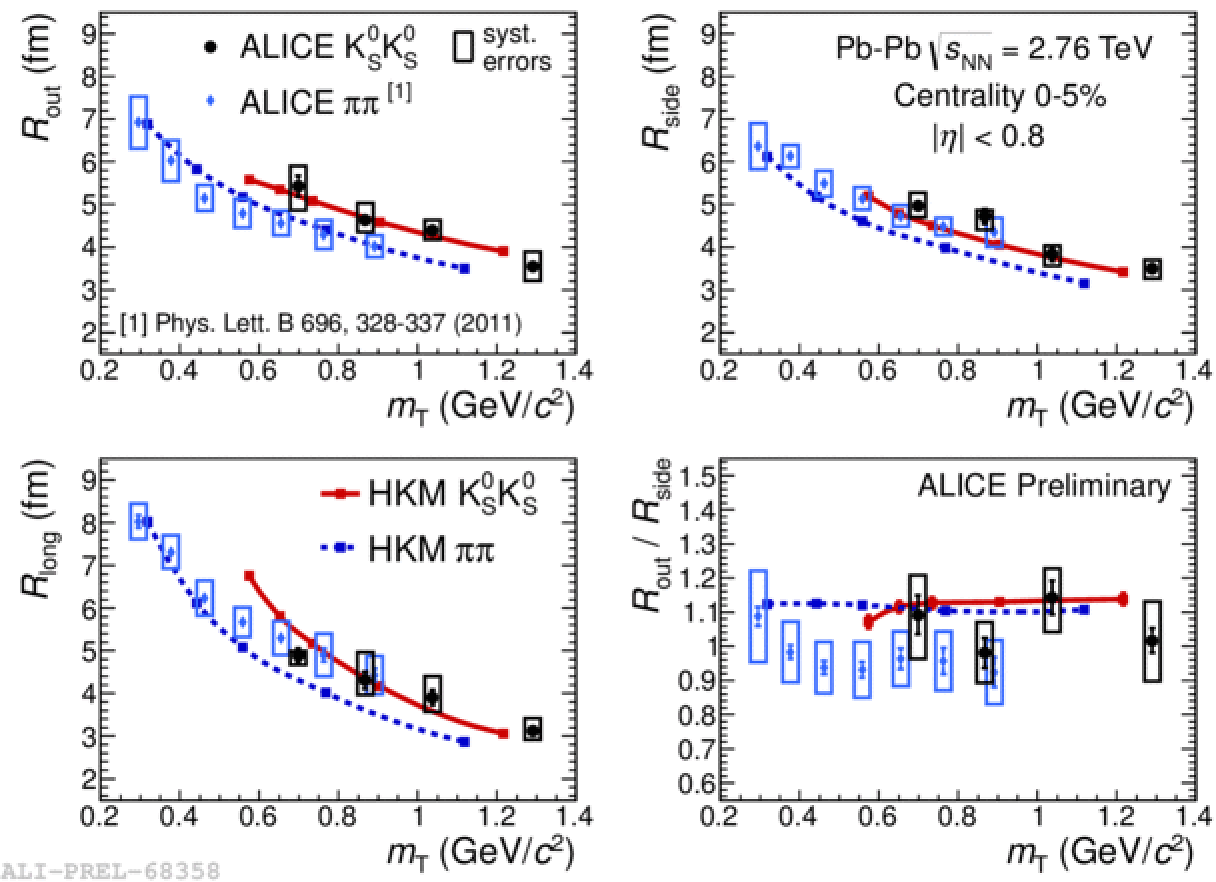
V.M.Shapoval, P.Braun-Munziger, Iu.A.Karpenko, Yu.M.Sinyukov; arXiv:1404.4501



- Hydro model + rescattering phase (UrQMD) at LHC predicts breaking of the m_T scaling for kaons – is the hydro prediction non-universal or is it the effect of the rescattering phase?

Collectivity with heavier particles

- The k_T dependence is tested with heavier mesons
- The 3D K^0_s results in central Pb-Pb consistent with collectivity (hydro) expectations
- Non-trivial data analysis (no analytic functional form for fitting QS+Strong femto signal)



M. Steinpreis, QM2014

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.

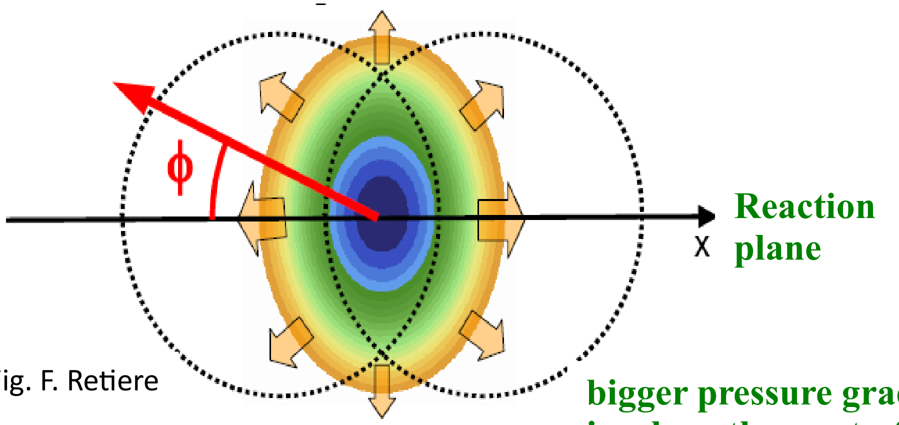
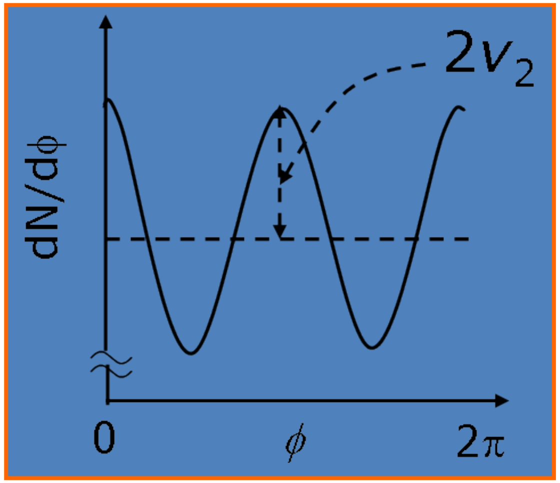
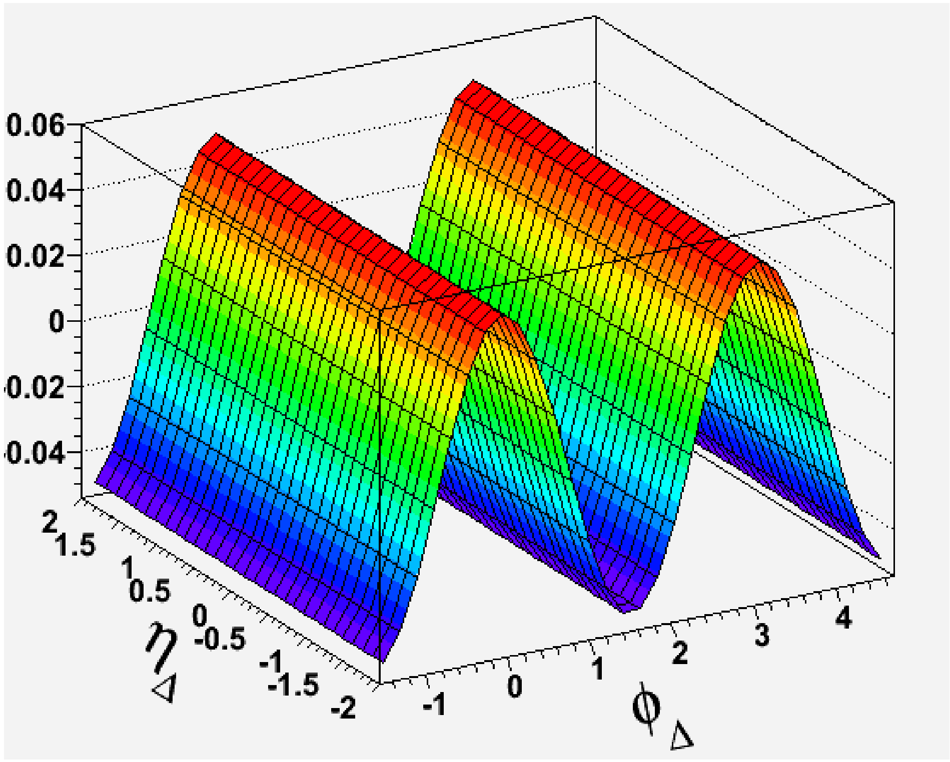


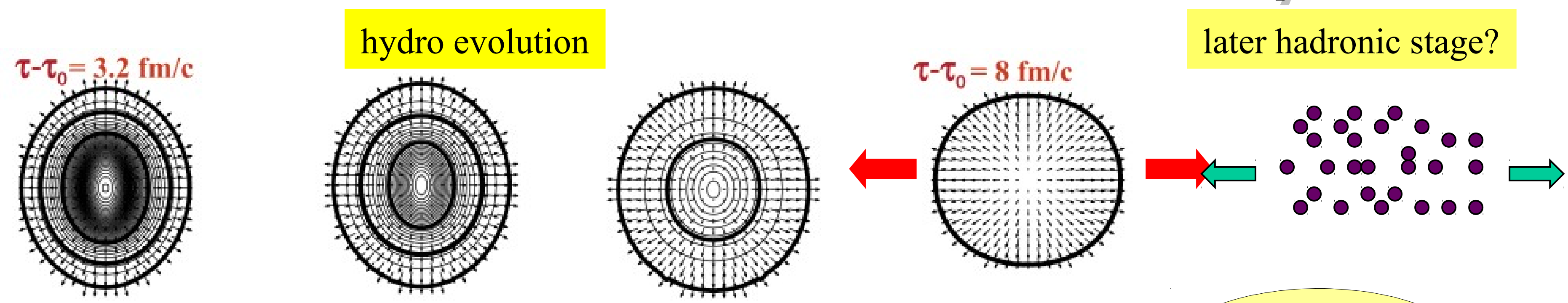
Fig. F. Retiere



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



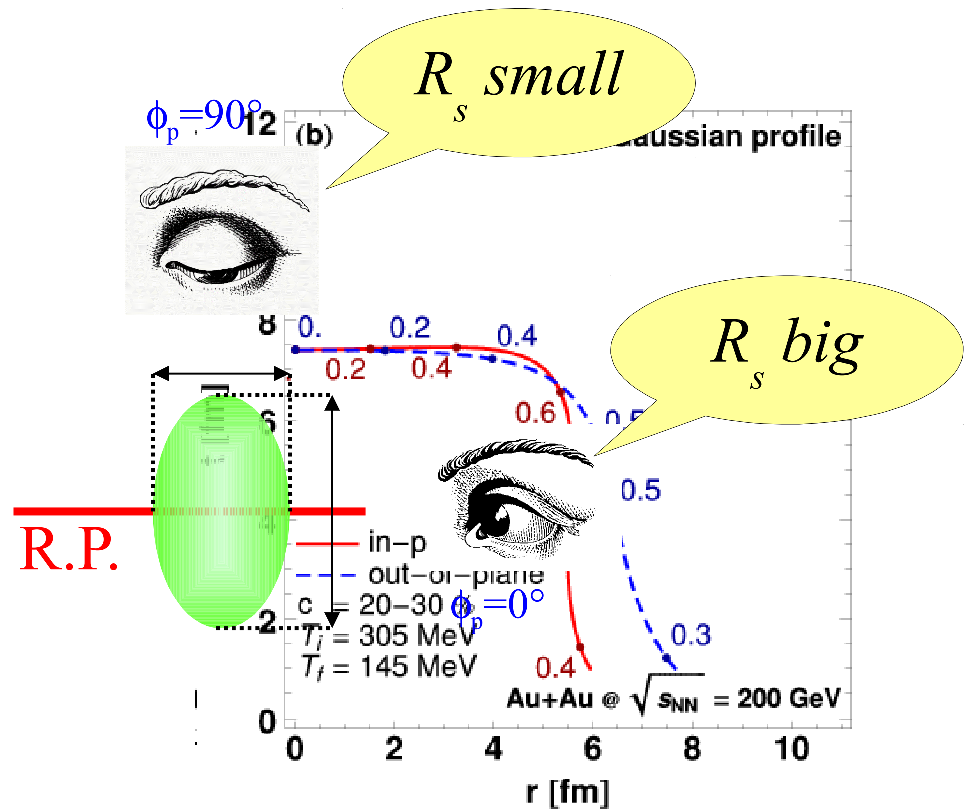
Non-central collisions: azimuthal modulation of collectivity



Kolb & Heinz

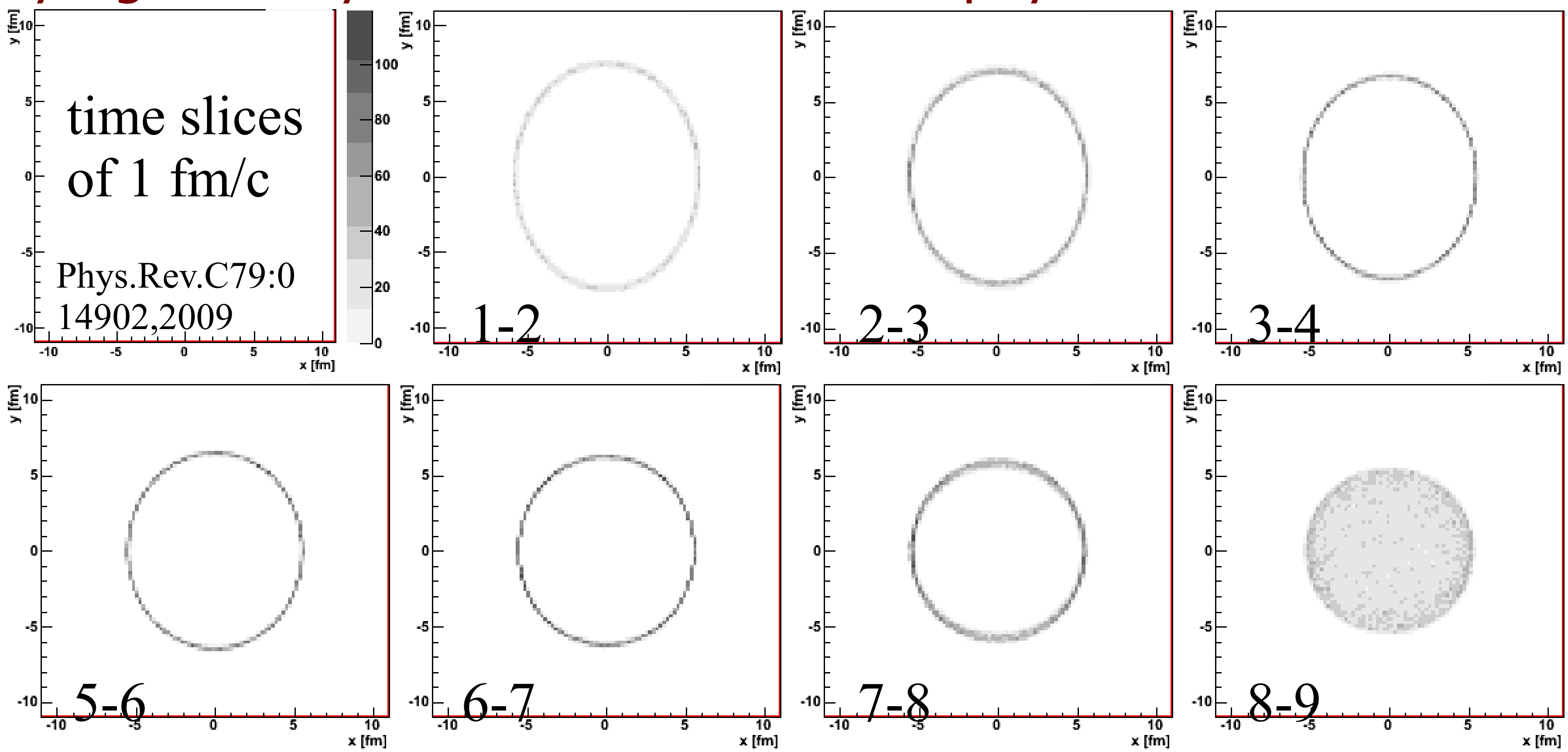
anisotropic pressure gradients

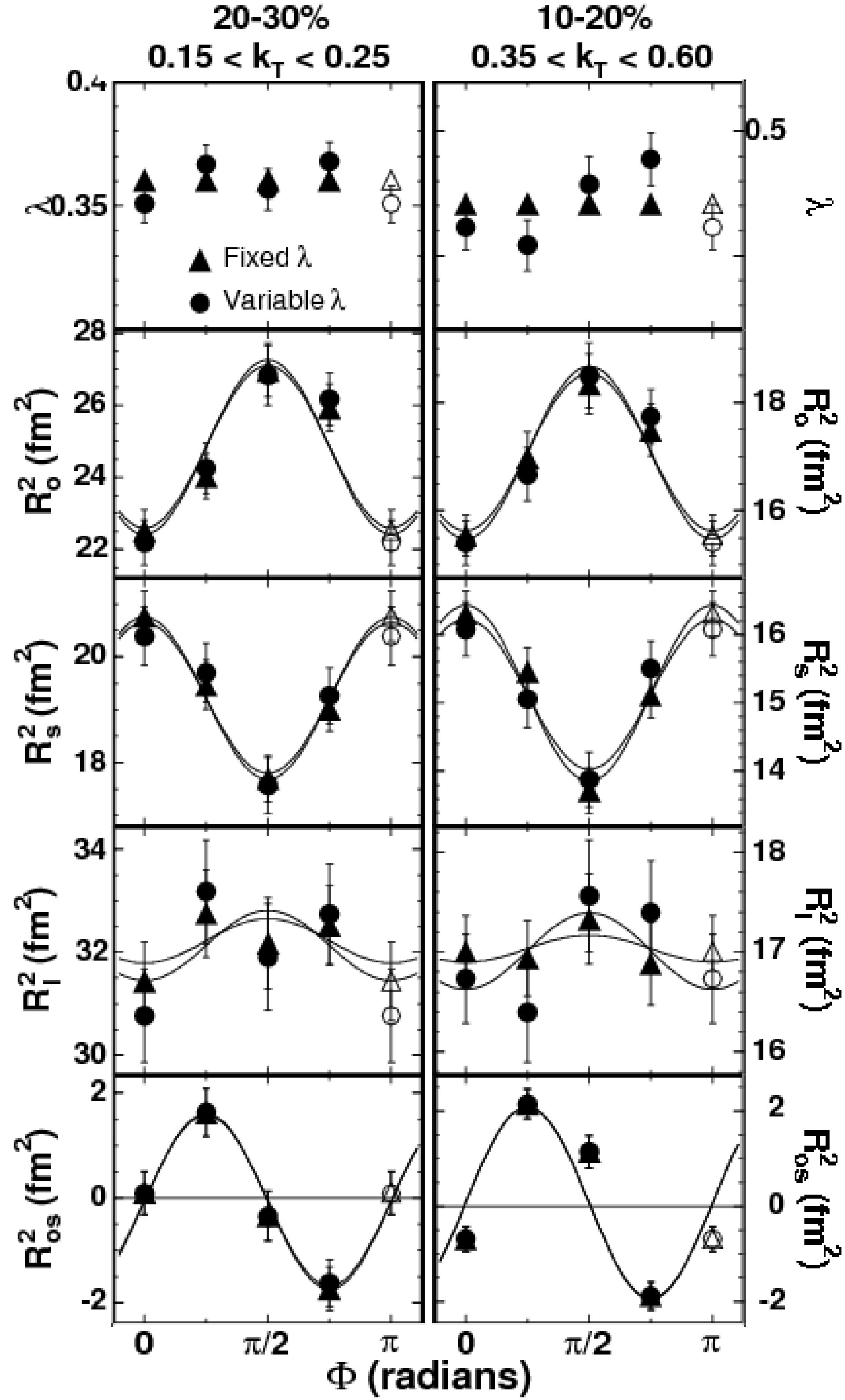
- drives the emergence of elliptic flow (v_2)
- Space-time and momentum anisotropy connected: can they be described at the same time?
- Azimuthally sensitive femtoscopy measures the space-time asymmetry by measuring radii vs. reaction plane
- Specific oscillations are expected



Emission from the source vs. time

- Azimuthal anisotropy is self-quenching – evolving towards a spherical shape
- Any change in EOS (critical point, first-order phase transition) may significantly alter azimuthal anisotrophy





Radii vs. reaction plane orientation

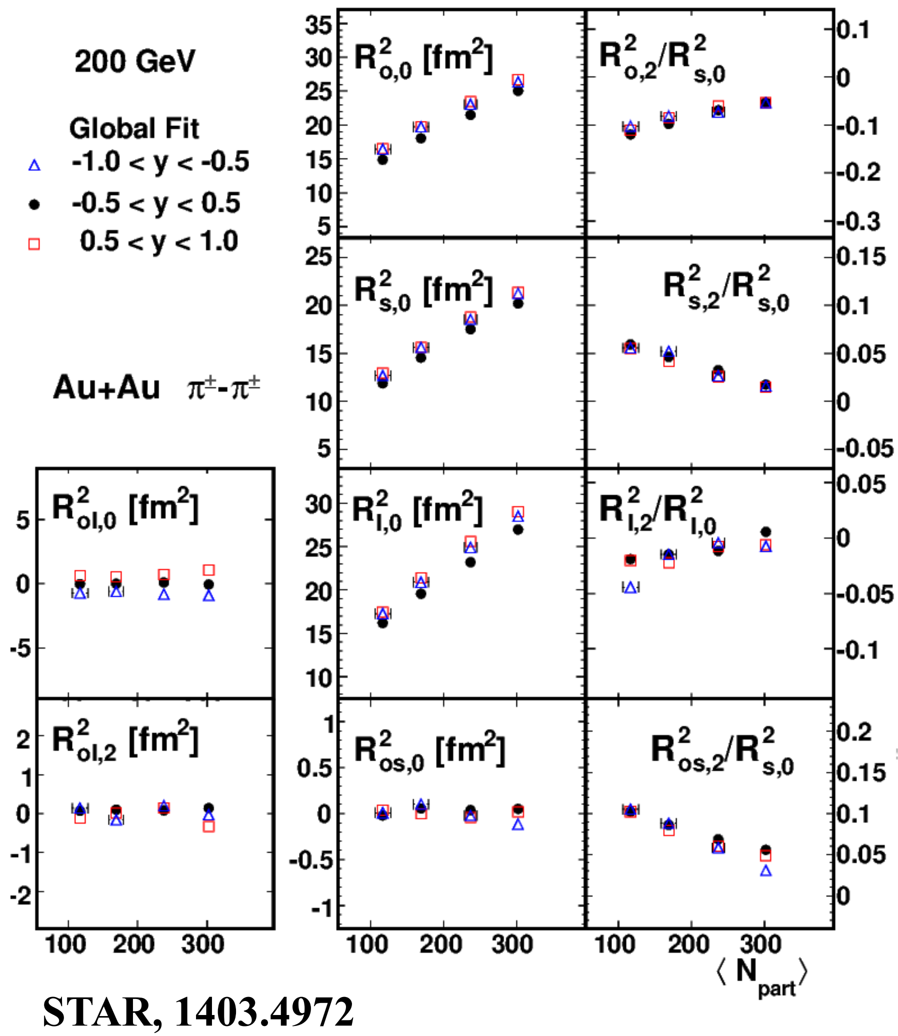
- Separate CFs are constructed for each orientations of pair k_T vs. reaction plane
- Radii are extracted vs this angle, total dependence can be characterized by 7 parameters:

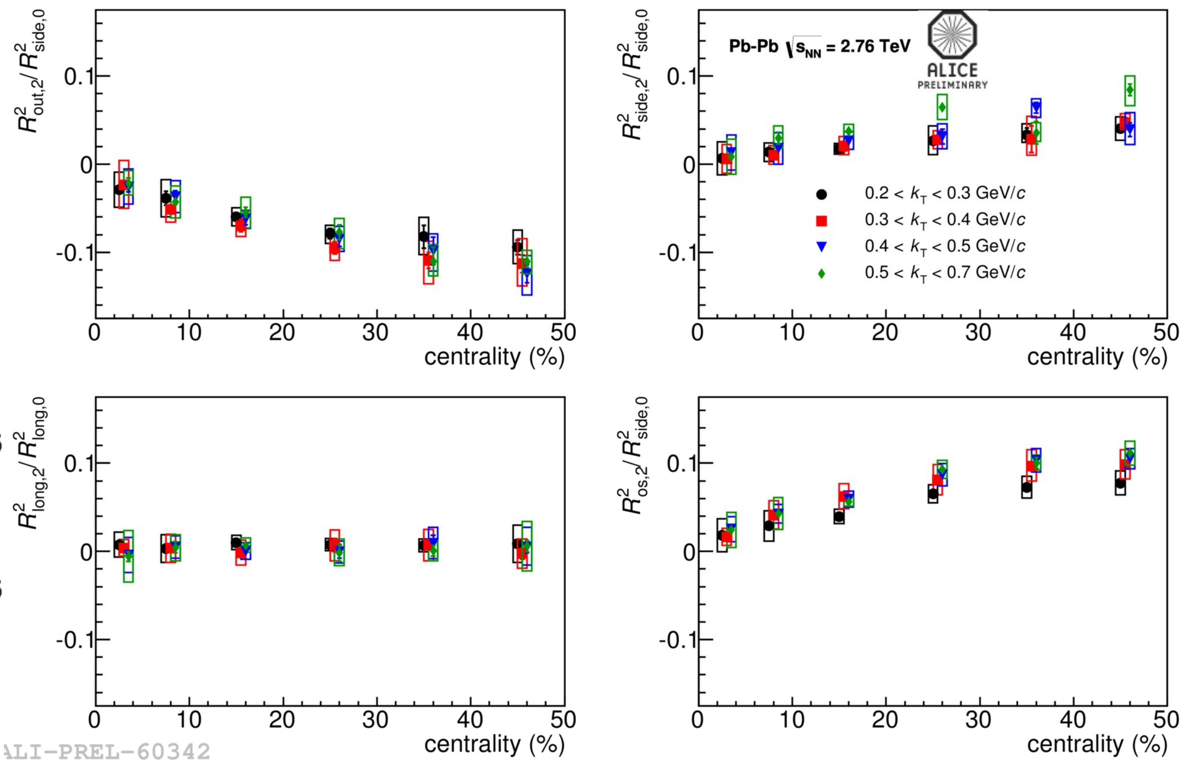
$$R^2_{out} = R^2_{out,0} + 2R^2_{out,2}\cos(2\phi_p)$$
$$R^2_{side} = R^2_{side,0} + 2R^2_{side,2}\cos(2\phi_p)$$
$$R^2_{long} = R^2_{long,0} + 2R^2_{long,2}\cos(2\phi_p)$$
$$R_{out-side} = 2R_{side-out,2}\sin(2\phi_p)$$

- Experiment clearly sees an anisotropic source shape

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

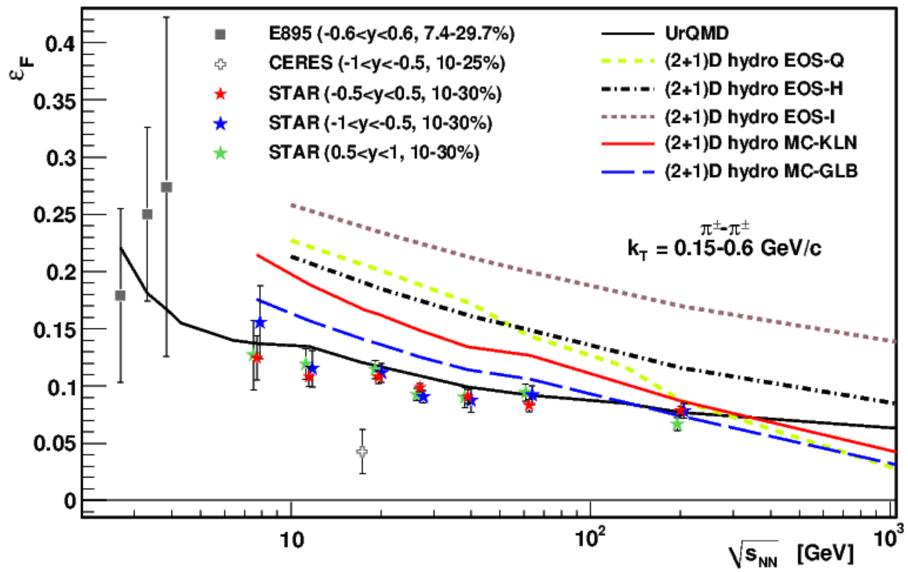
Oscillations from RHIC BES to LHC

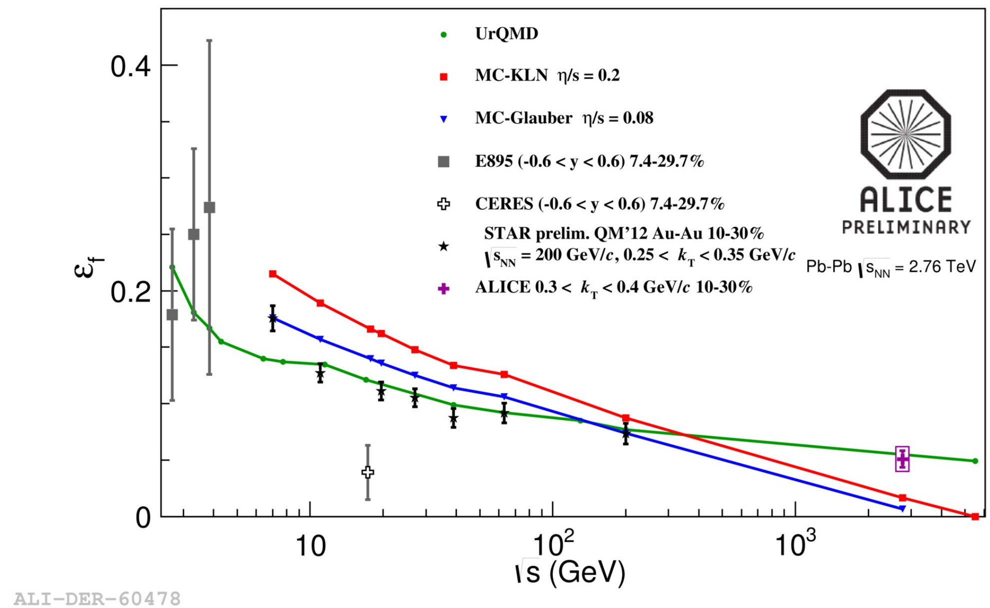




- Oscillation magnitude measured for energies spanning 3 orders of magnitude
- Relative oscillations extracted

Search for EOS change





- At BES energies STAR measures a smooth decrease of anisotrophy with energy – no signature of sharp EOS changes
- But CERES? - it appears the two measurements are not consistent
- At LHC further smooth decrease of anisotrophy, qualitatively consistent with hydro

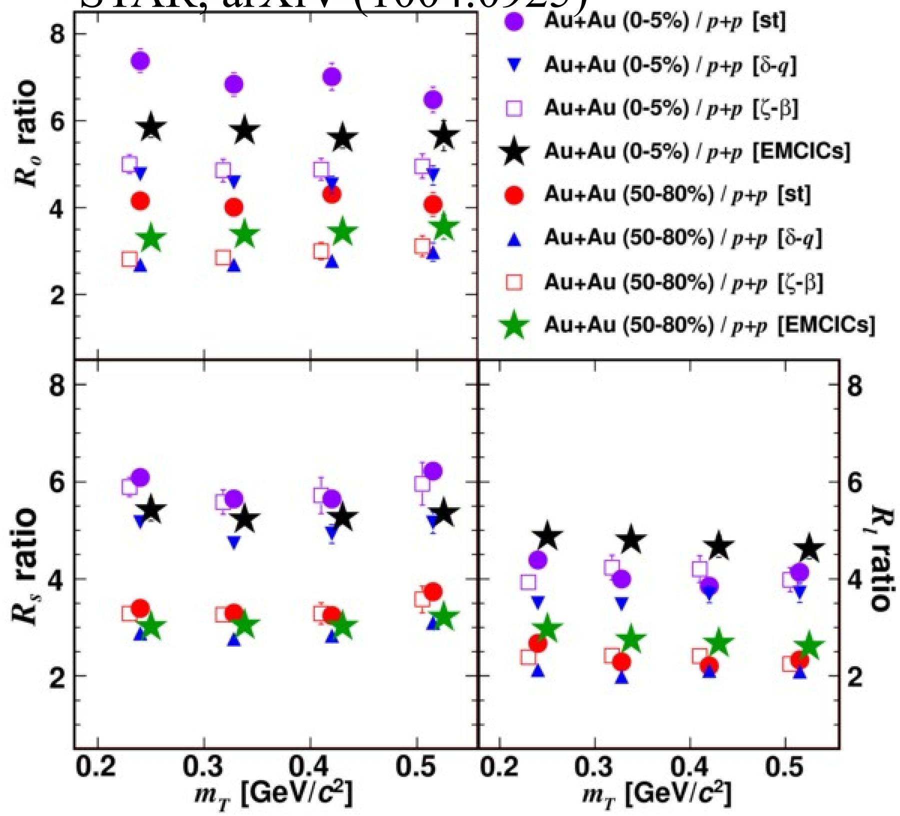
Femtoscopy in small systems

- The measurement can be done in "small" systems, such as p+p and p-Pb.
  - Need precise and differential data to address space-time characteristics of particle production in "elementary" systems
  - Significant multiplicities, comparable to peripheral heavy-ion data, now reachable in pp and p-Pb. Can directly compare pp and AA, to see if the influence of "collectivity" can be found
- But ...
  - Some basic assumptions of the femtscopic formalism are at the edge of validity (independence of emitters)
  - Conservation laws introduce large correlations for systems with small multiplicity
  - Jet phenomena a strong source of correlations as well

pp vs. AuAu: puzzling scaling ...

- STAR reports that 3D HBT radii scale in pp in a way very similar to AuAu
- m_T dependence of 3D radii in AuAu is taken as a signature of a flowing medium
- Is the scaling between pp and AuAu a signature of the universal underlying physics mechanism or a coincidence?

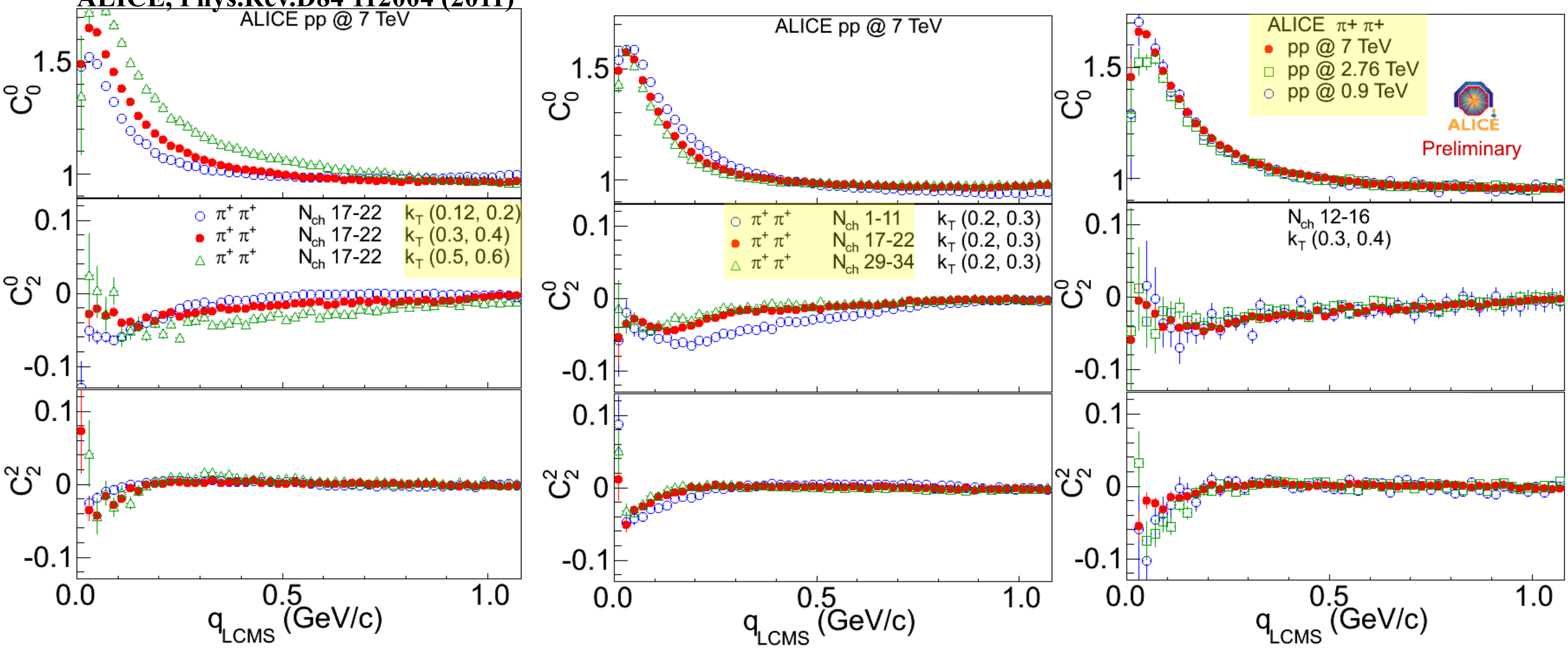
STAR, arXiV (1004.0925)

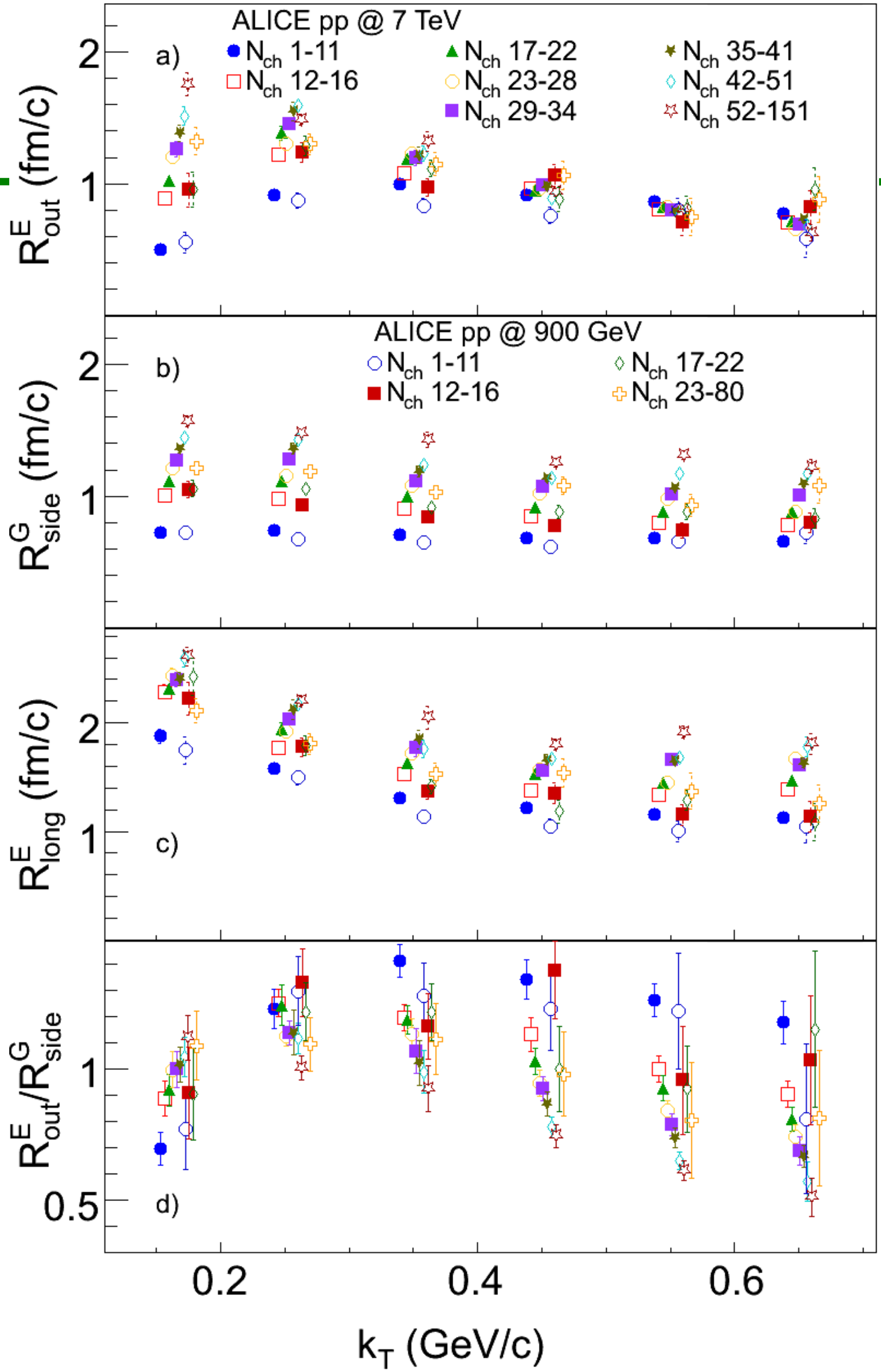


Looking for scaling variables

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

ALICE, Phys.Rev.D84 112004 (2011)



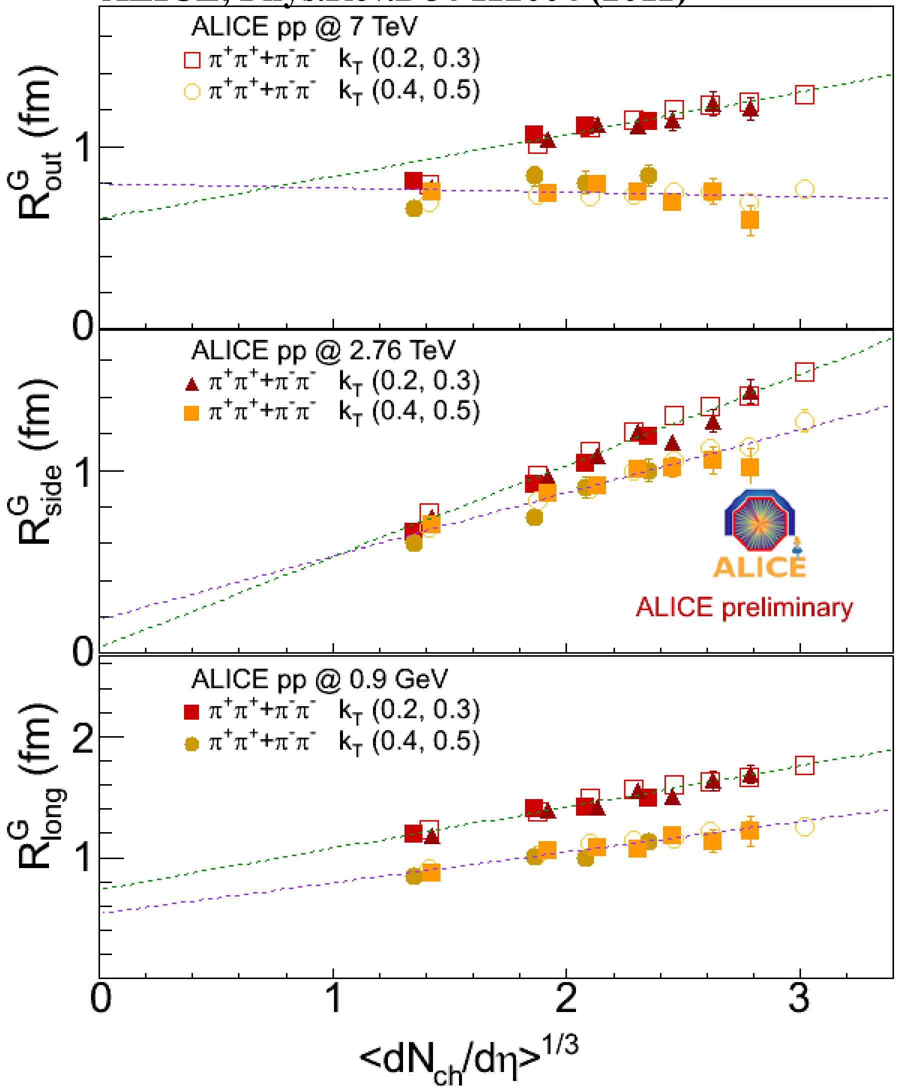


Unique measurement

- ALICE performed a unique analysis of pion femtoscopy in elementary collisions
  - Three collision energies
  - Detailed k_T dependence
  - Detailed multiplicity dependence
- Behavior in heavy-ions is not a simple scaling of pp, as suggested at RHIC
- Many aspects of the measurement not understood or predicted

Radii vs. $dN_{ch}/d\eta$

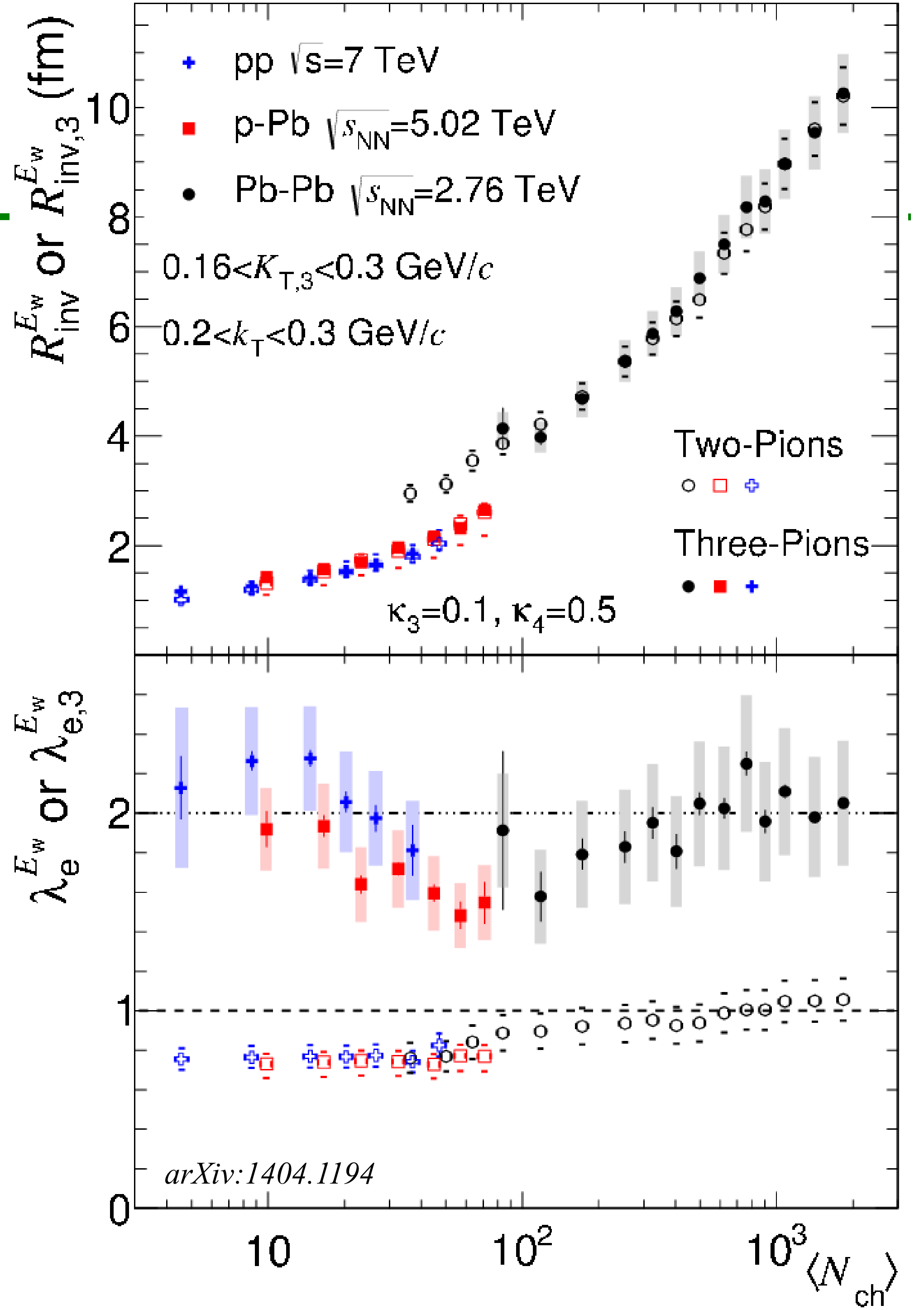
ALICE, Phys.Rev.D84 112004 (2011)



- Radii scale linearly with $dN_{ch}/d\eta$ for 3 dimensions and all pair momentum ranges
- Radii from all collision energies follow the same trend (χ^2/N_{dof}<1.0 for the fit); lowest multiplicity R_{out} points (all energies) slightly below.
- Radii grow with multiplicity for R_{side} and R_{long}
- Behavior in R_{out} is different: has flat or decreasing trend at high k_T.

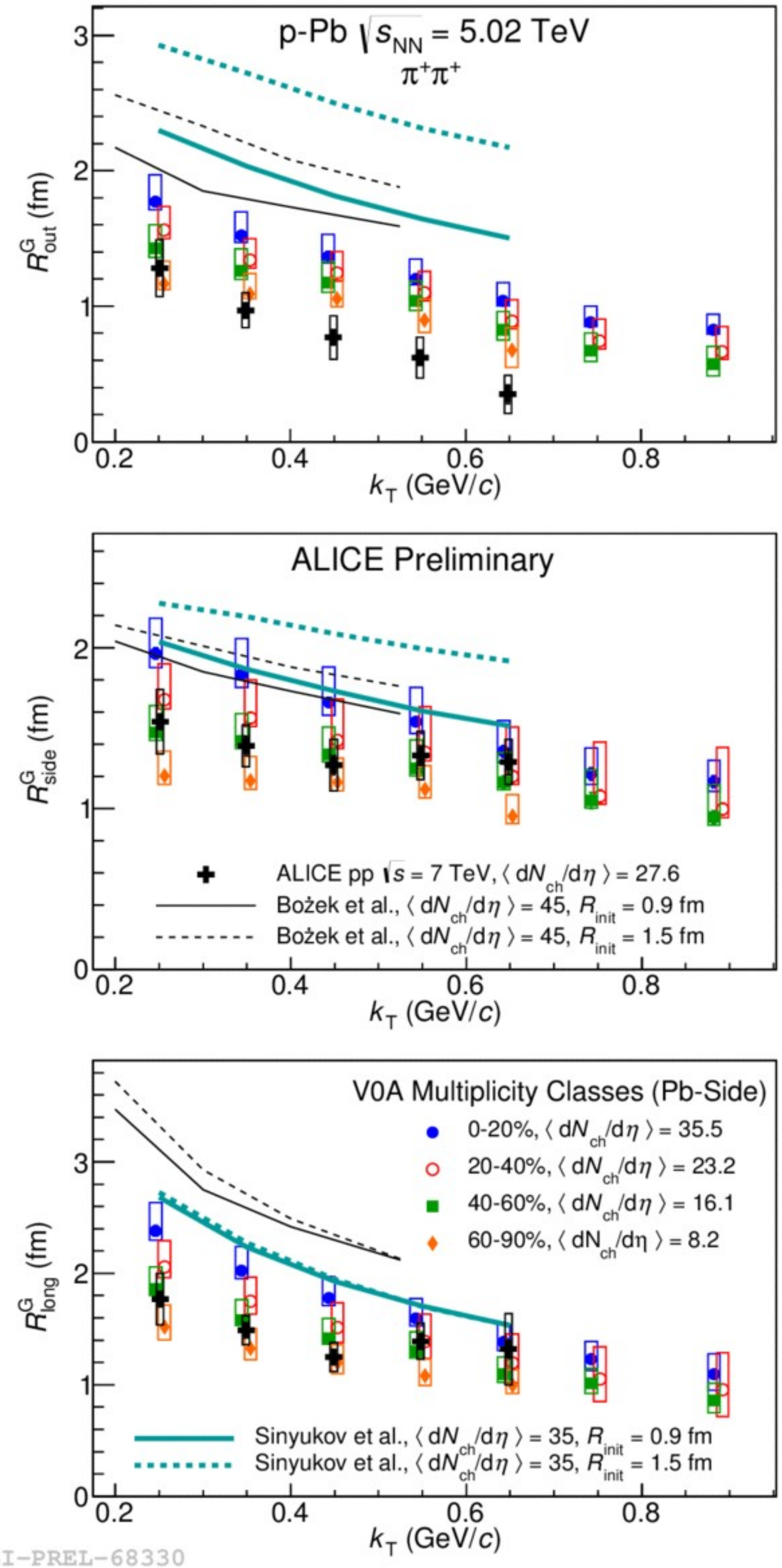
1D pPb from ALICE

- 1D analysis performed for pp, pPb and PbPb
- Uses 2-pion and 3-pion formalism, with different sensitivity to backgrounds
- pPb results 10-20% higher than pp at similar multiplicity, up to 40% smaller than PbPb
- Comparing only LHC results, pp and pPb not on the "AA line" from lower energies
- Clearly different physics (initial state?) in small systems



3D pPb in ALICE

- Analysis of pion femtoscopcy in 3D sensitive to collectivity signatures
- Hydro predictions are comparable to high-multiplicity pPb in Side and Long and overestimate Out
- k_T dependence similar in models and data
- Lower initial size brings models closer to data
- Interpretation still an open question



ALICE,1502.00559

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 SPS, RHIC and at the LHC
- Correlation for heavier particles gives independent check of collectivity, and may be sensitive to the magnitude of the rescattering phase in heavy-ion collisions
- Azimuthally sensitive femtoscopy an important cross-check of the hydrodynamic evolution of the system
- Measurements in pp show intriguing features, should they be treated as “reference”?
- pA data – an intermediate step between pp and AA?