NARODOWE CENTRUM NAUKI

Faculty of Physics Warsaw University of Technology

Recent femtoscopy results from ALICE

Adam Kisiel
(Faculty of Physics, Warsaw University of Technology)

for the **ALICE** Collaboration

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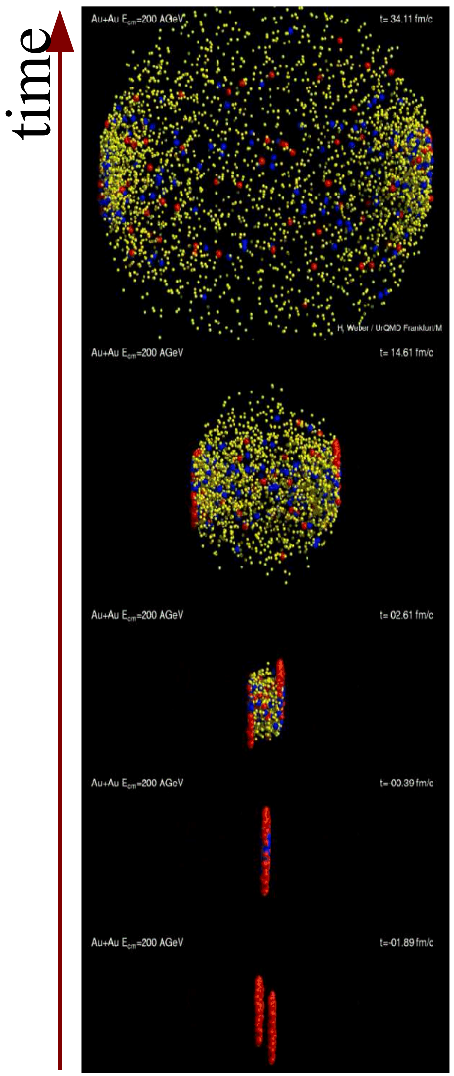
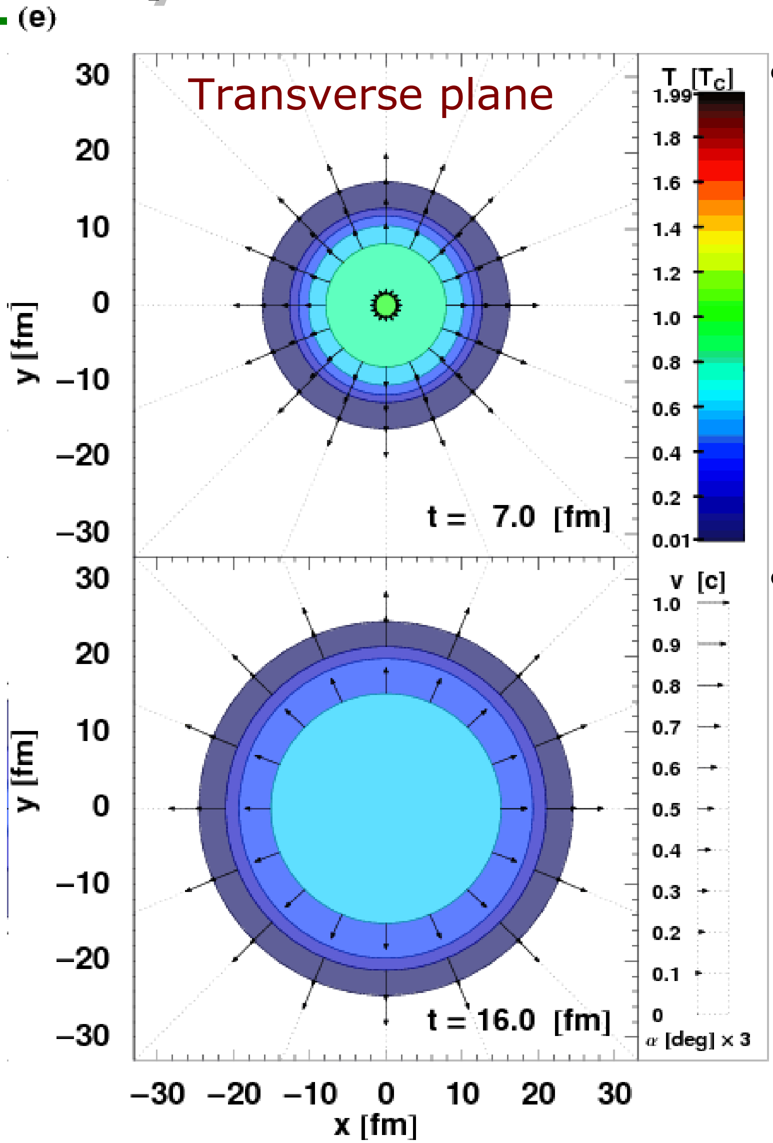
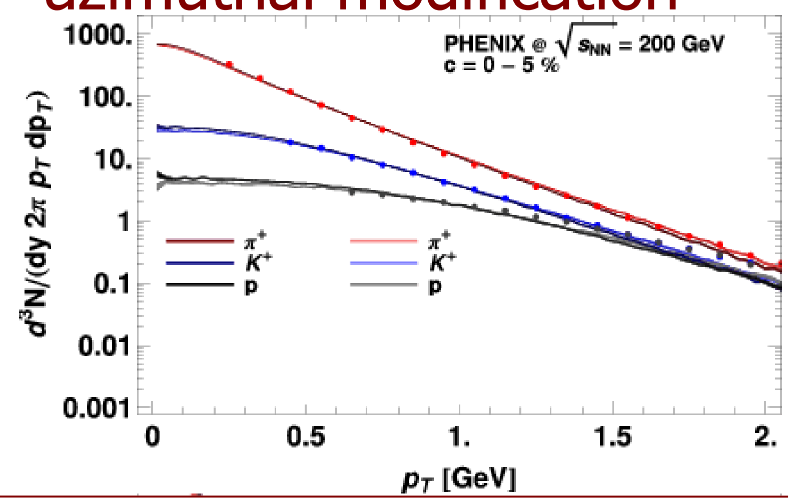
Heavy-ion collision evolution



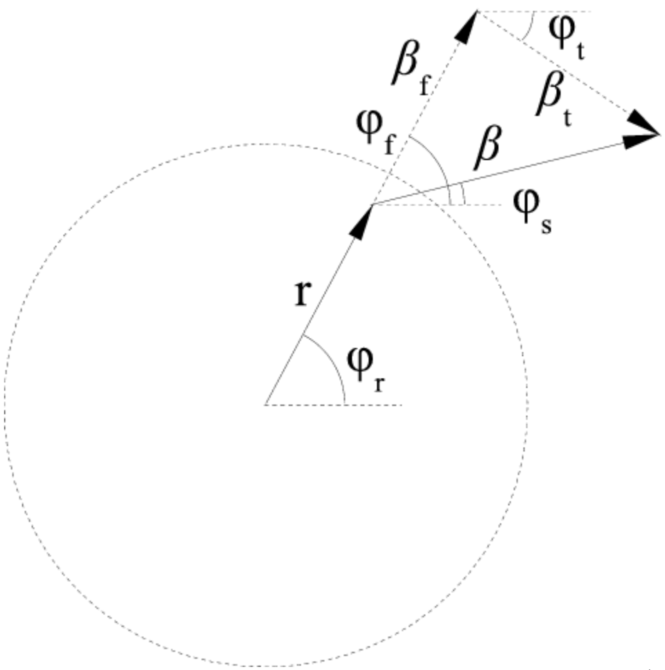


M. Chojnacki, W. Florkowski,
PRC 74 (2006) 034905

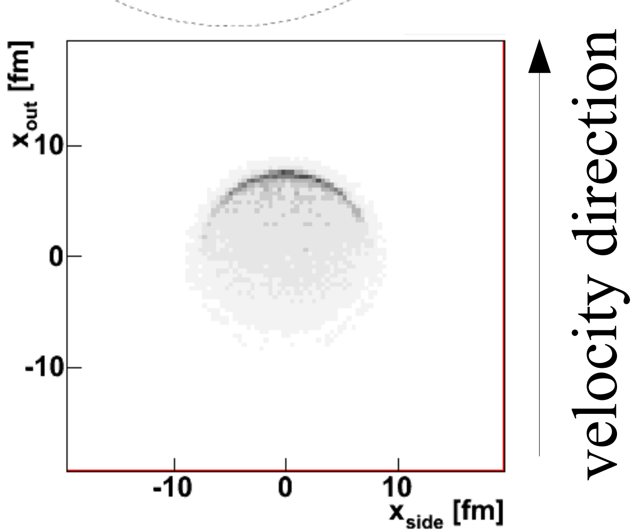
- HIC is expected to go through a QGP phase, where matter is strongly interacting – resulting in the development of collective motion
- Radial flow dominates, with elliptic flow as azimuthal modification

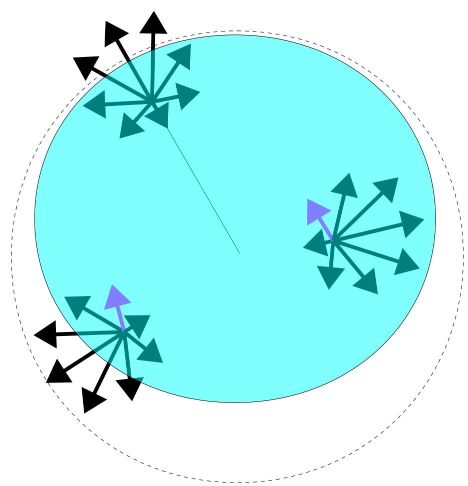


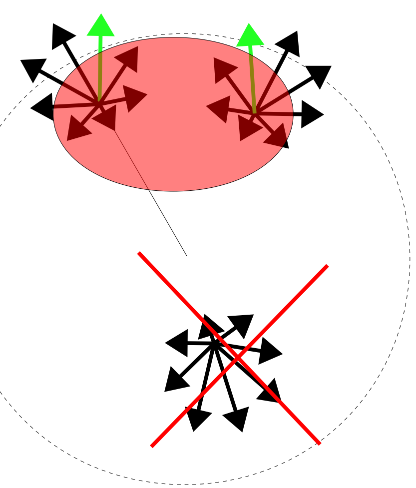
Thermal emission from collective medium



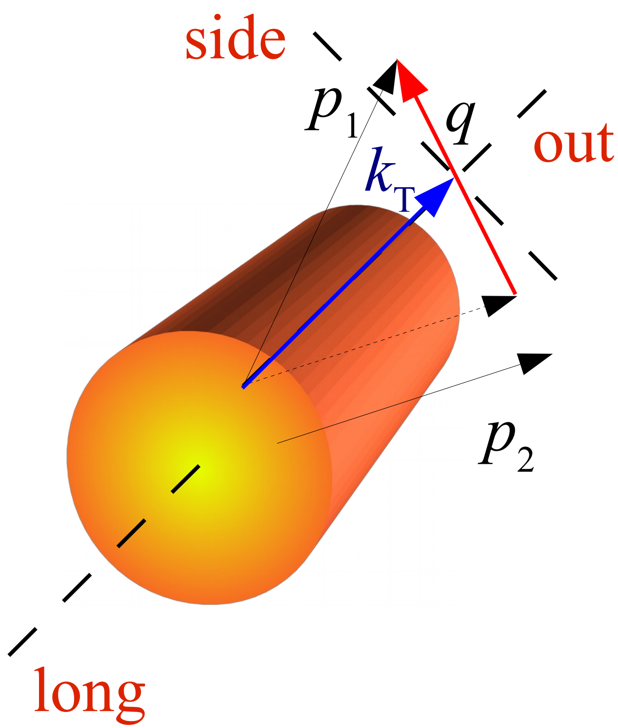
- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source







Reference frames for femtoscopy



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

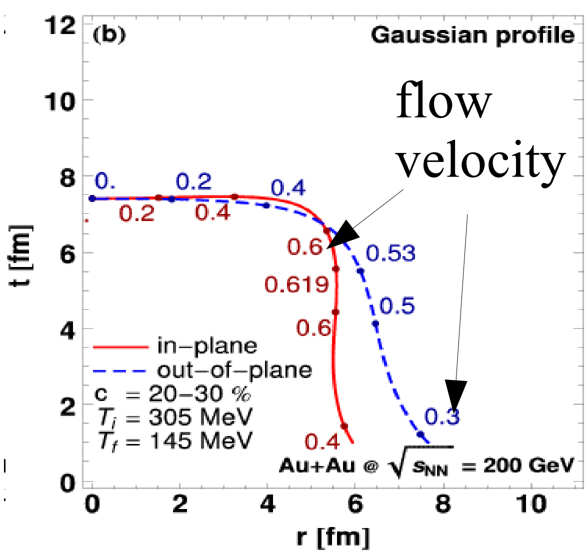
Longitudinally Co-Moving System (LCMS):
$p_{1,long} = -p_{2,long}$

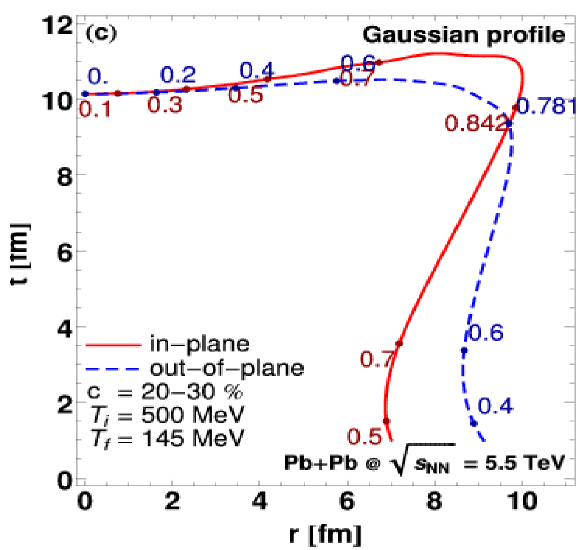
- For charged pions measurement in 3 dimensions, giving 3 independent sizes in Longitudinally Co-Moving System
- The Bertsch-Pratt decomposition of q:
  - Long along the beam: sensitive to longitudinal dynamics and evolution time
  - Out along k_T: sensitive to geometrical size, emission time and space-time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

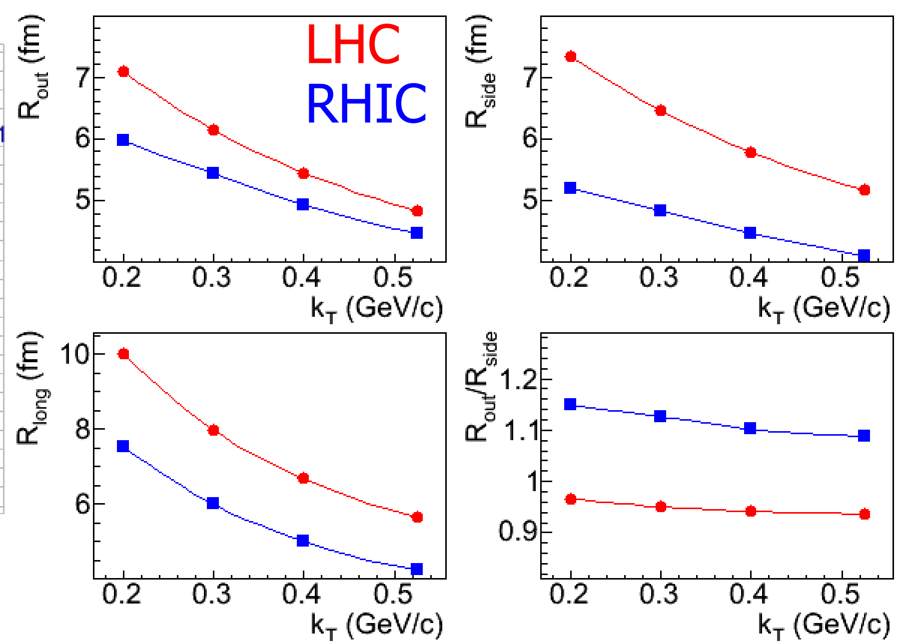
Expectations for the LHC

- 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

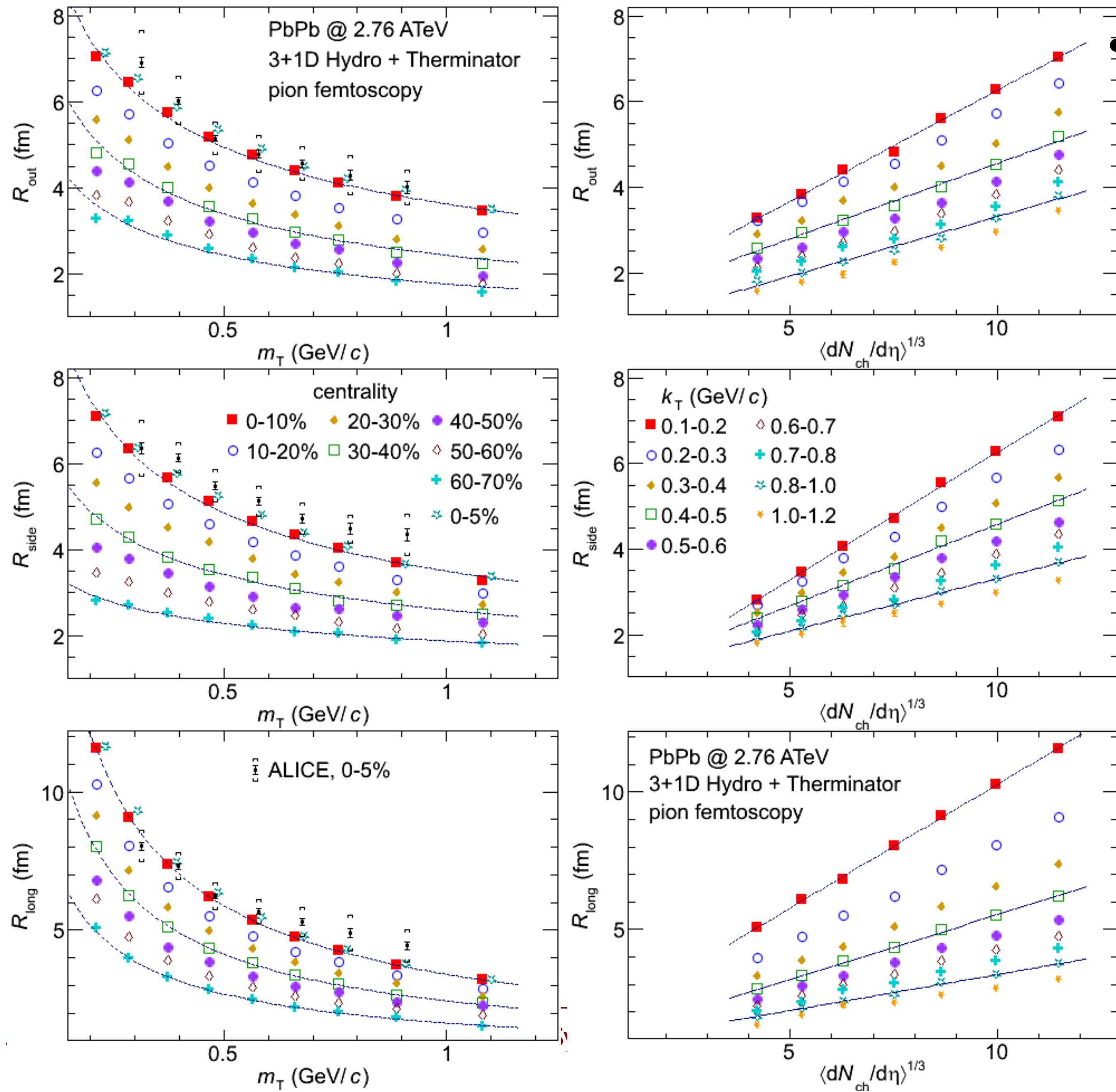






AK, W. Broniowski, W. Florkowski, et al. Phys.Rev.C79:014902,2009

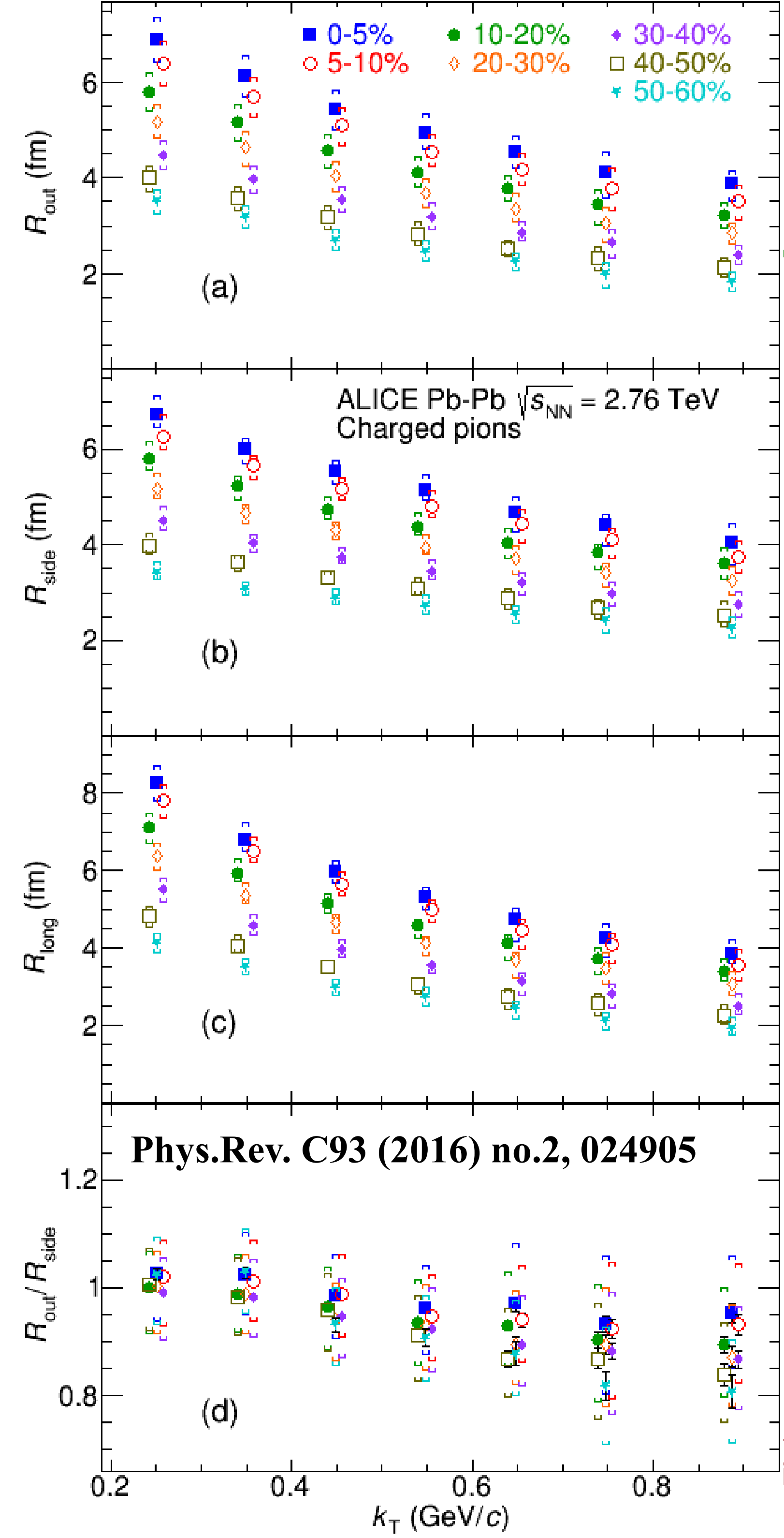
Model multiplicity and m_T dependence



- For high multiplicity AA 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 cube root of final state multiplicity

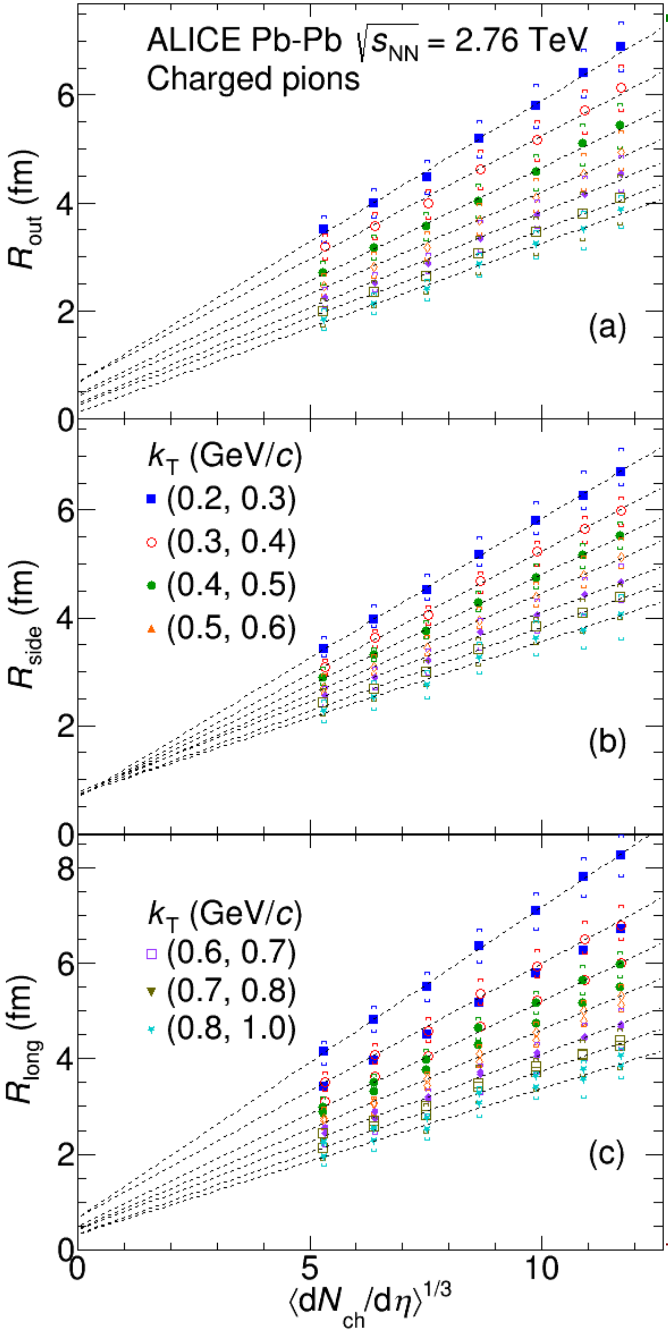
AK, M.Gałażyn, P.Bożek; Phys.Rev.C90 (2014) 6, 064914

ALICE Data on radii vs. centrality and k_T

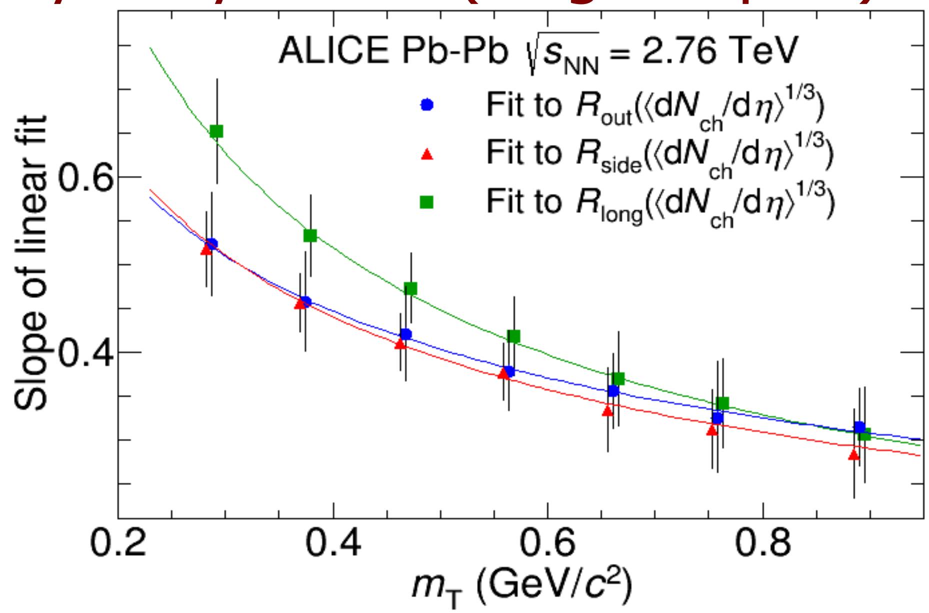


- Femtoscopic radii vs. k_T for 7 centrality classes in central rapidity region
- Radii universally grow with event multiplicity and fall with pair momentum
- Both dependencies in agreement with calculations from collective models (hydrodynamics), both quantitatively and qualitatively
- When compared to results from RHIC – all expected trends visible (larger size, steeper k_T dependence, R_{out}/R_{side}~1)

Linear multiplicity scaling of radii

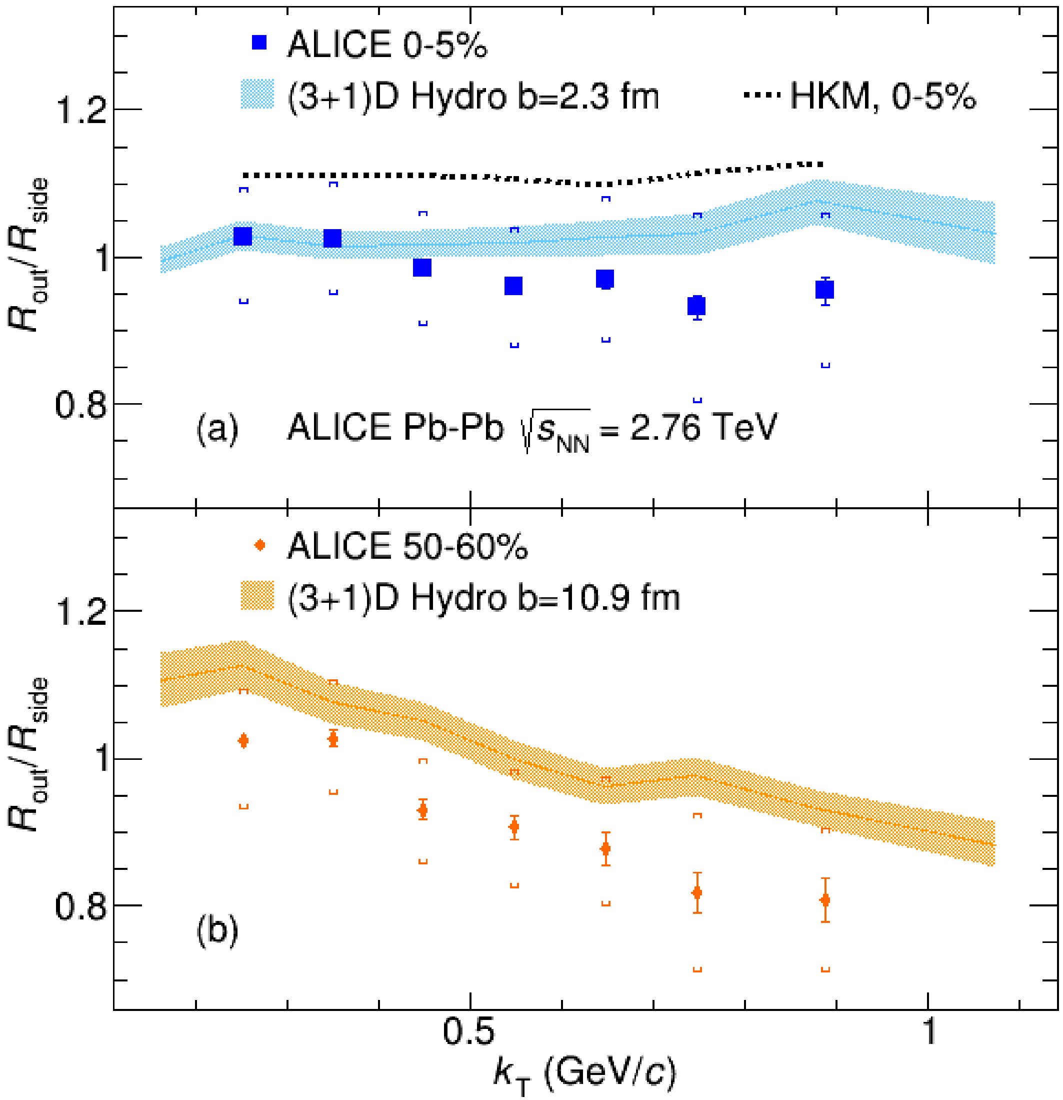


- Radii in 3 directions and all pair momentum ranges scale linearly with $dN_{ch}/d\eta^{1/3}$
- Slope parameters of this fit show power-law behavior, similar to hydrodynamics (long steepest)



Phys.Rev. C93 (2016) no.2, 024905

Freeze-out shape evolution



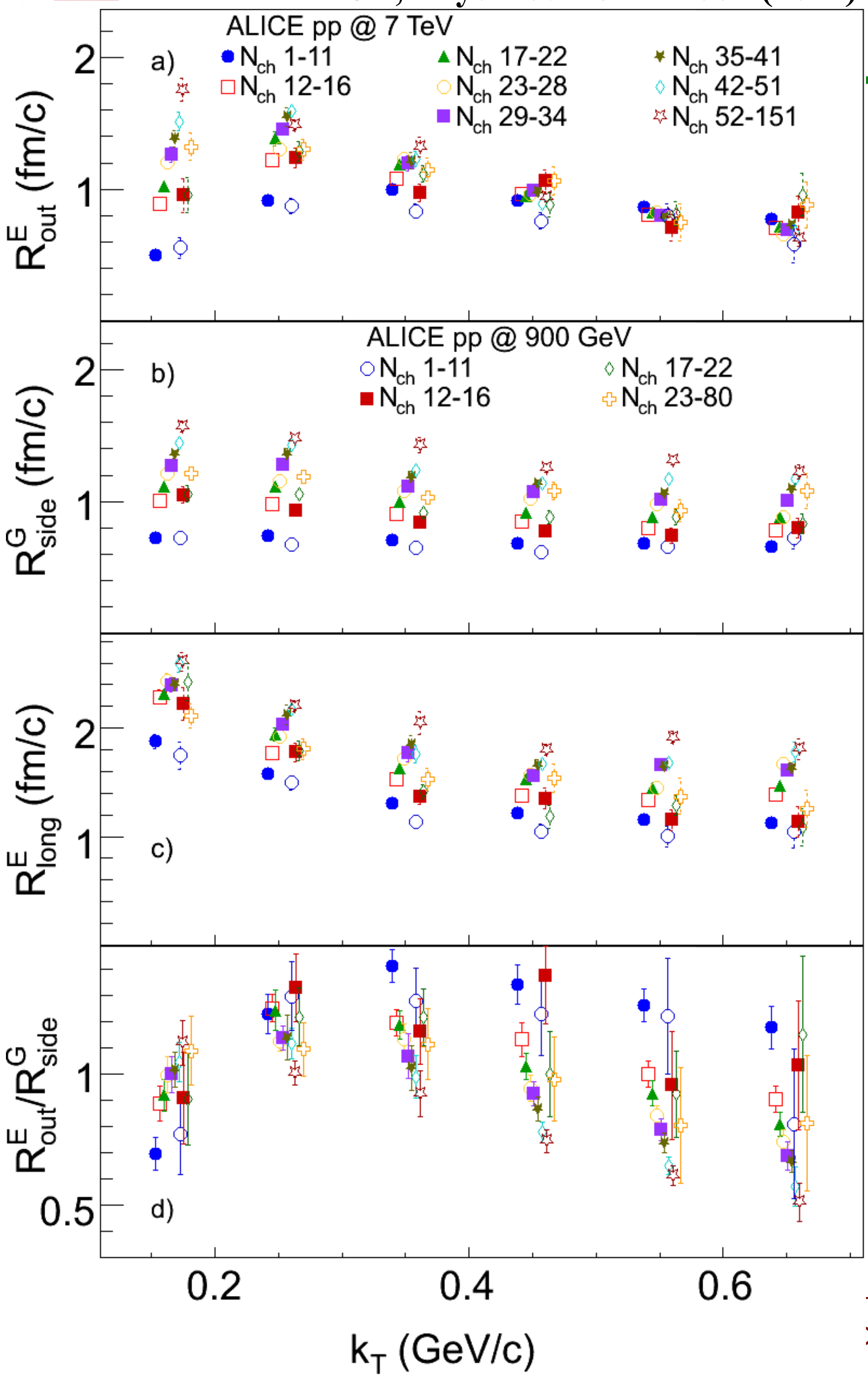
Phys.Rev. C93 (2016) no.2, 024905

- Values of R_{out}/R_{side} below unity observed, decrease with centrality
- Reproduced by hydrodynamics
- Hydro interpretation: space-time correlation at freeze-out important – freeze-out changes from outside-in or flat at RHIC to inside-out at LHC

Femtoscopy in small systems

- Measurement for "small" systems: p+p and p-Pb.
  - What's the "size" for "reference" systems?
  - Need precise and differential data on space-time characteristics of particle production in "elementary" systems
  - Significant multiplicities, comparable to peripheral heavy-ion data, now in p+p and p-Pb → Directly compare p+p and AA (onset of "collectivity" ?)
- p+p or pA really a "reference" system?
- Size difference really significant? or just reflects multiplicity?
- Questions fundamental to interpretation of AA data

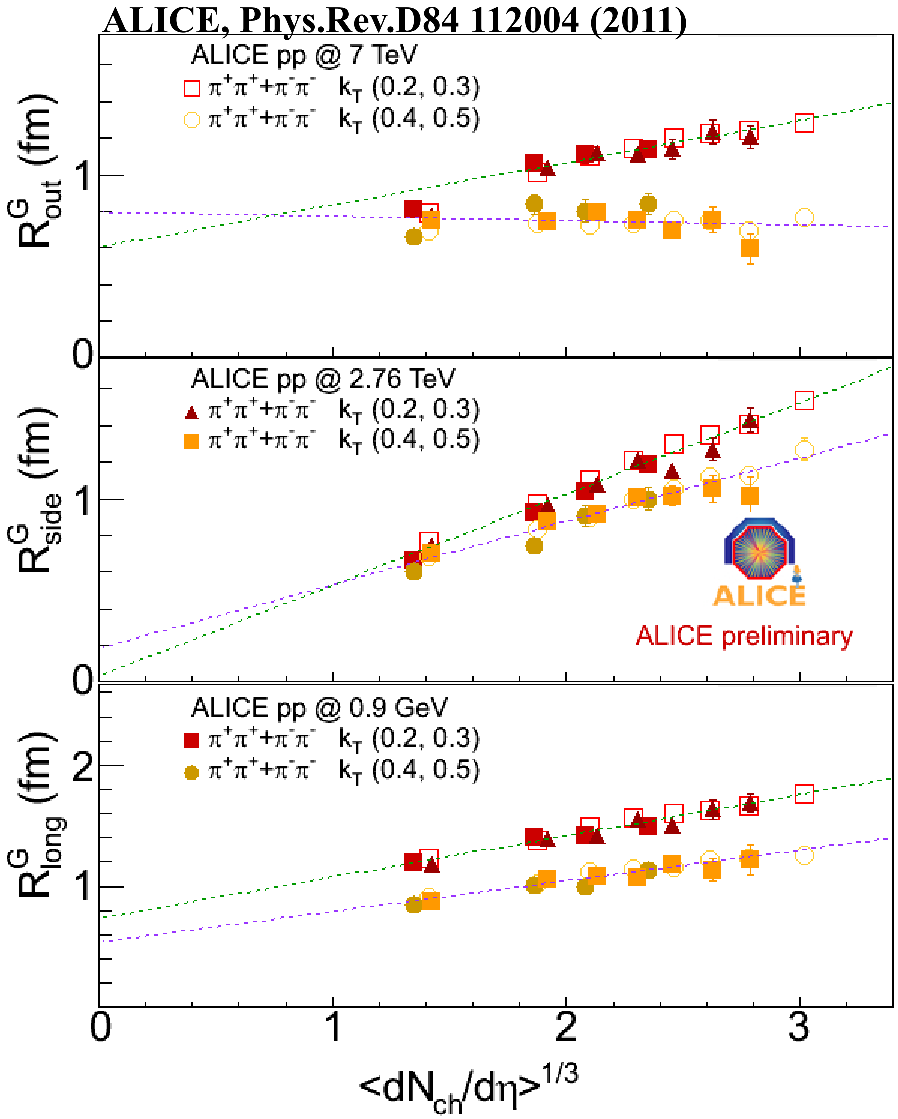
ALICE, Phys.Rev.D84 112004 (2011)



Unique measurement

- Unique analysis of pion femtoscopy in elementary collisions from ALICE
  - Three collision energies
  - Detailed k_T dependence
  - Detailed multiplicity dependence
- Behavior in heavy-ions is not a simple scaling of p+p, as suggested at RHIC
- Many aspects of the measurement not understood or predicted
- Correlation not Gaussian – comparison to AA less straightforward

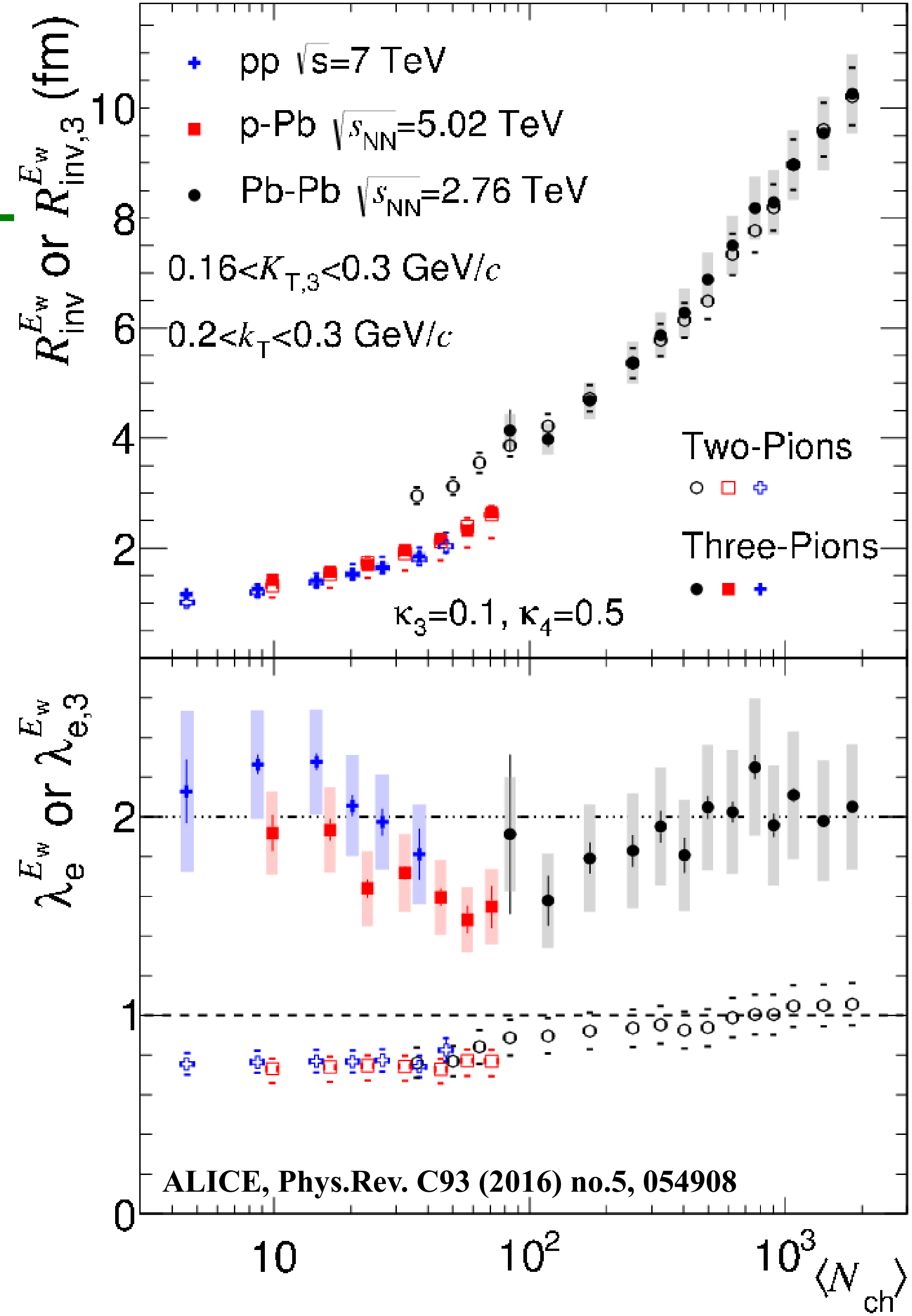
Radii vs. $dN_{ch}/d\eta$



- Radii scale linearly with $dN_{ch}/d\eta^{1/3}$ for 3 dimensions and all pair momentum ranges
- Radii from all collision energies follow the same trend ($\chi^2/N_{dof}<1.0$ 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.

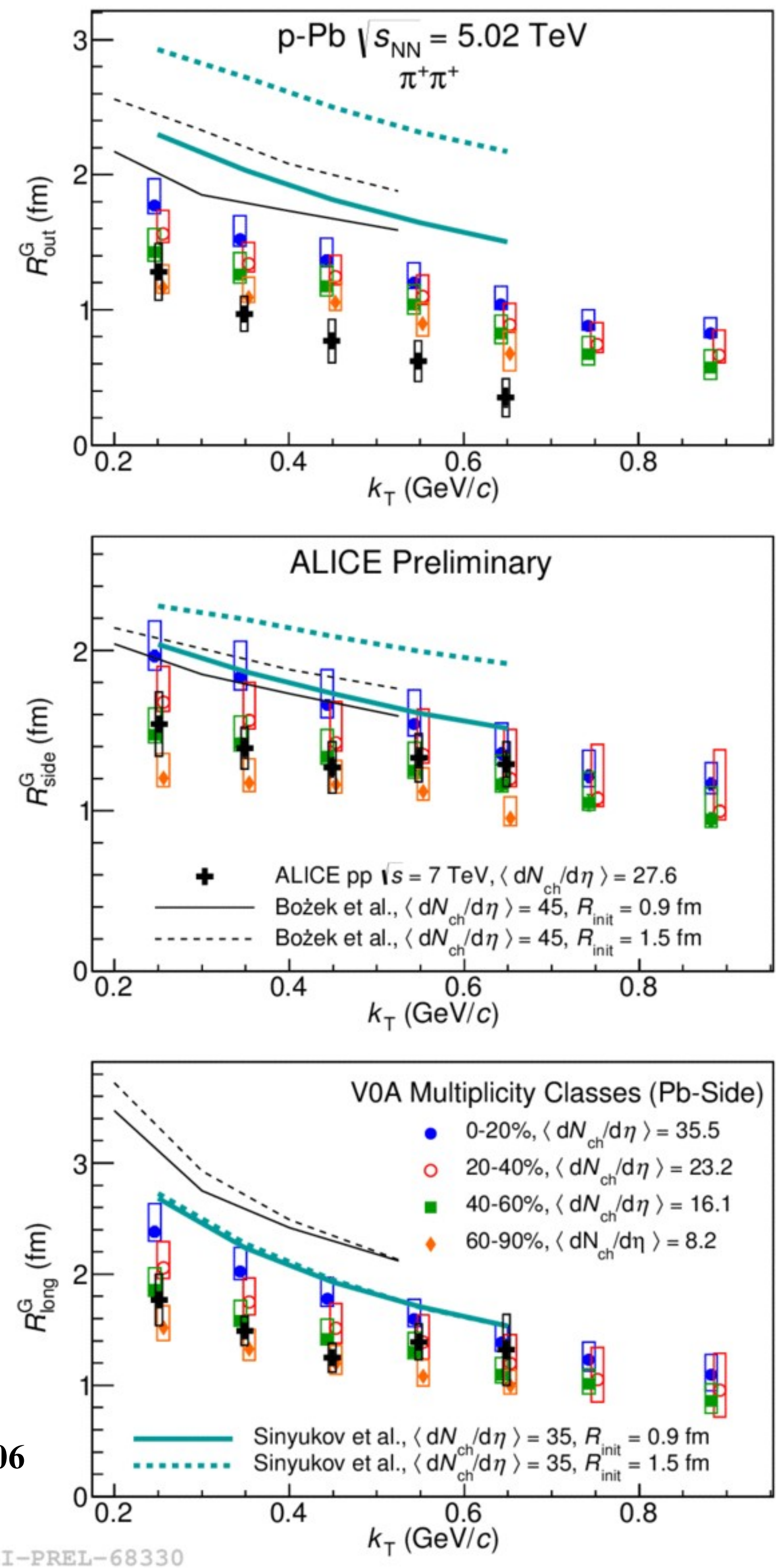
1D size in p-Pb

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



3D sizes in p-Pb

- Analysis of pion femtoscopcy in 3D sensitive to collectivity signatures
- Hydro predictions are comparable to high-multiplicity p-Pb 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

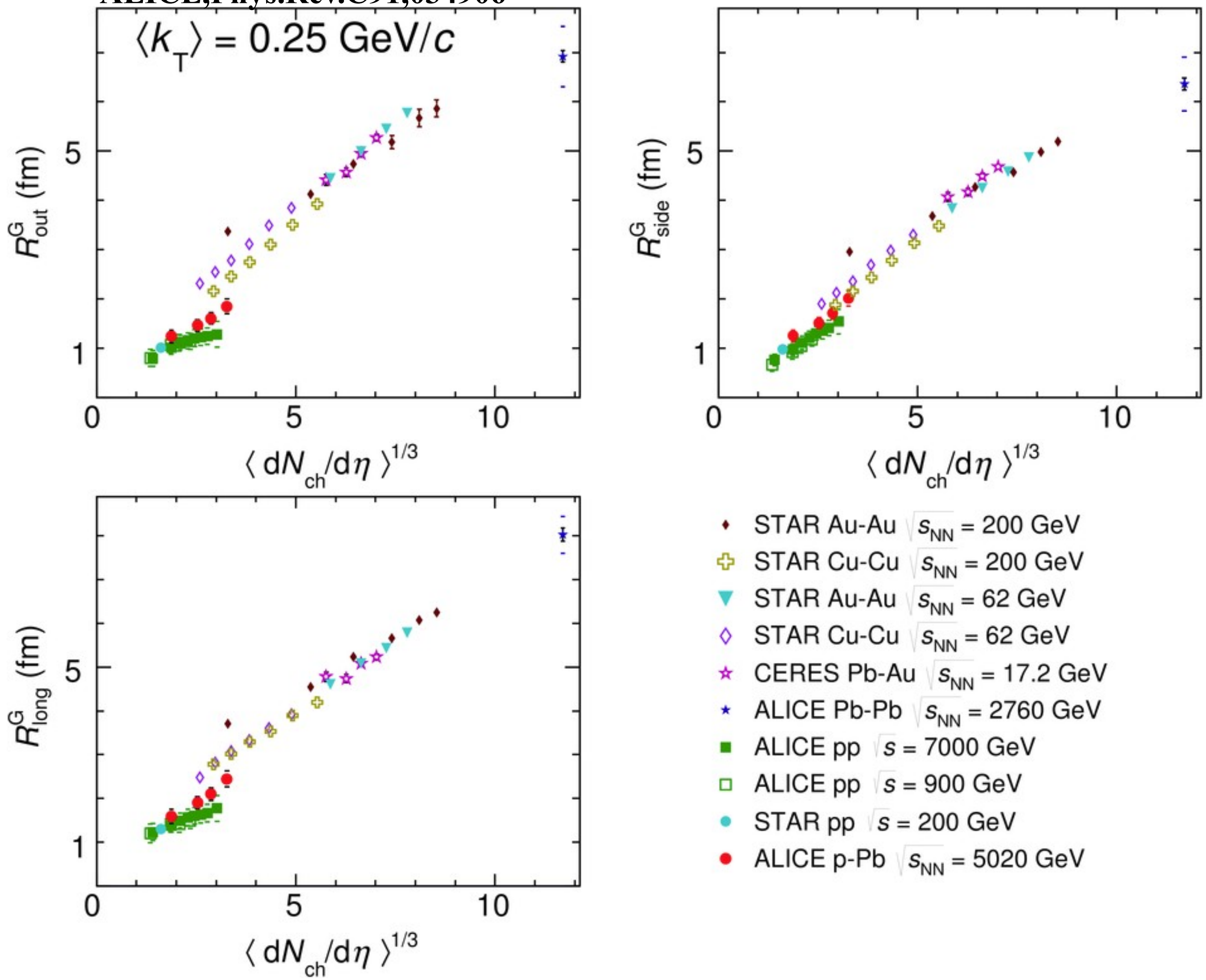


ALICE,Phys.Rev.C91,034906

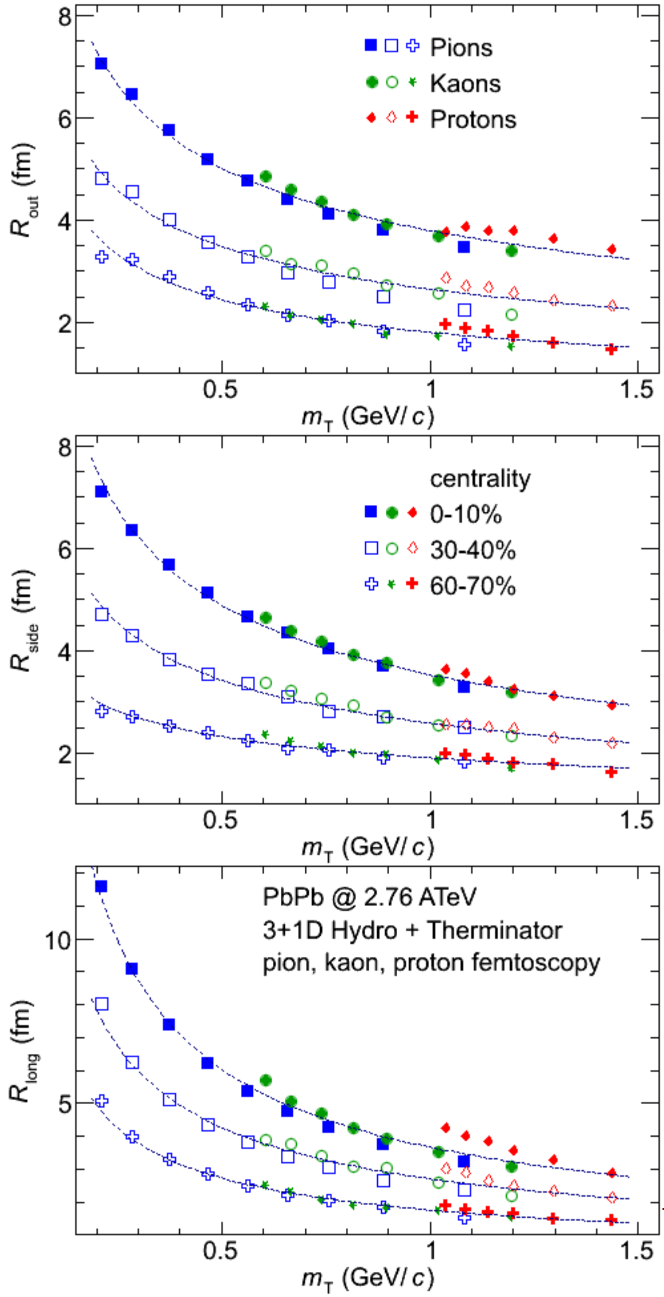
p+p and pA: Comparison with AA

- Femtoscopic radii scale approximately with cube root of multiplicity.
- Scaling for p+p is clearly different from heavy ions.
- Radii from p-Pb collisions agree with p+p for low multiplicities and start to diverge at higher multiplicities.
- Interpretation of the p-Pb data is still an open question.
- p-Pb data provide important constraints on the understanding of initial and final states in p+p, p-Pb, and Pb-Pb collisions.

ALICE,Phys.Rev.C91,034906

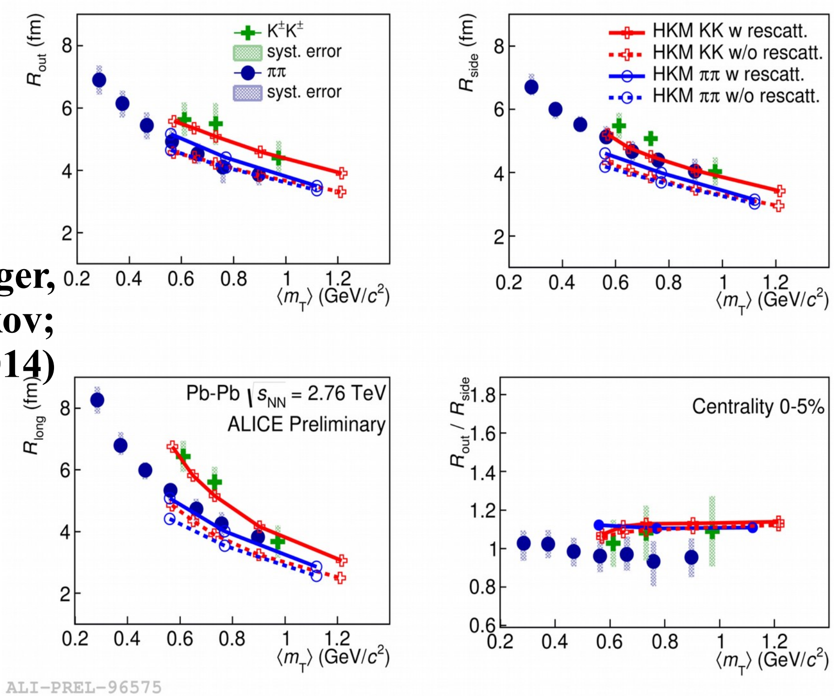


m_T scaling for heavier particles



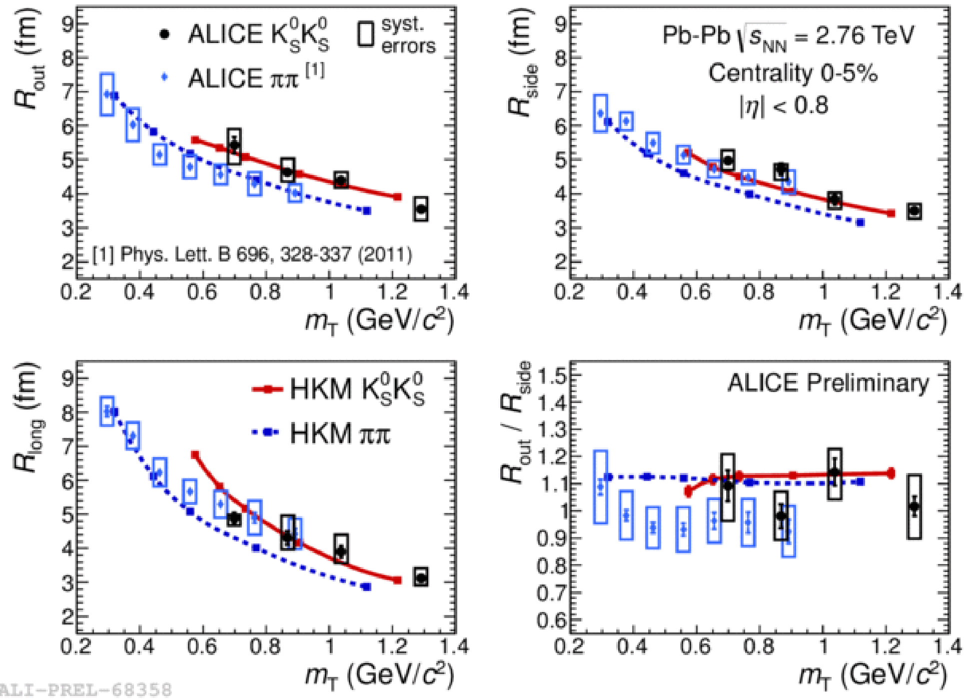
- "Collective" flow should apply to all particles
  - Ideal 1D hydro → m_T scaling for all particles
  - "Real" 3+1D hydro + viscosity (no rescattering) → approximate scaling in LCMS
  - "Hydro" + rescattering → breaking of scaling

M. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov; Nucl.Phys. A 929 (2014)

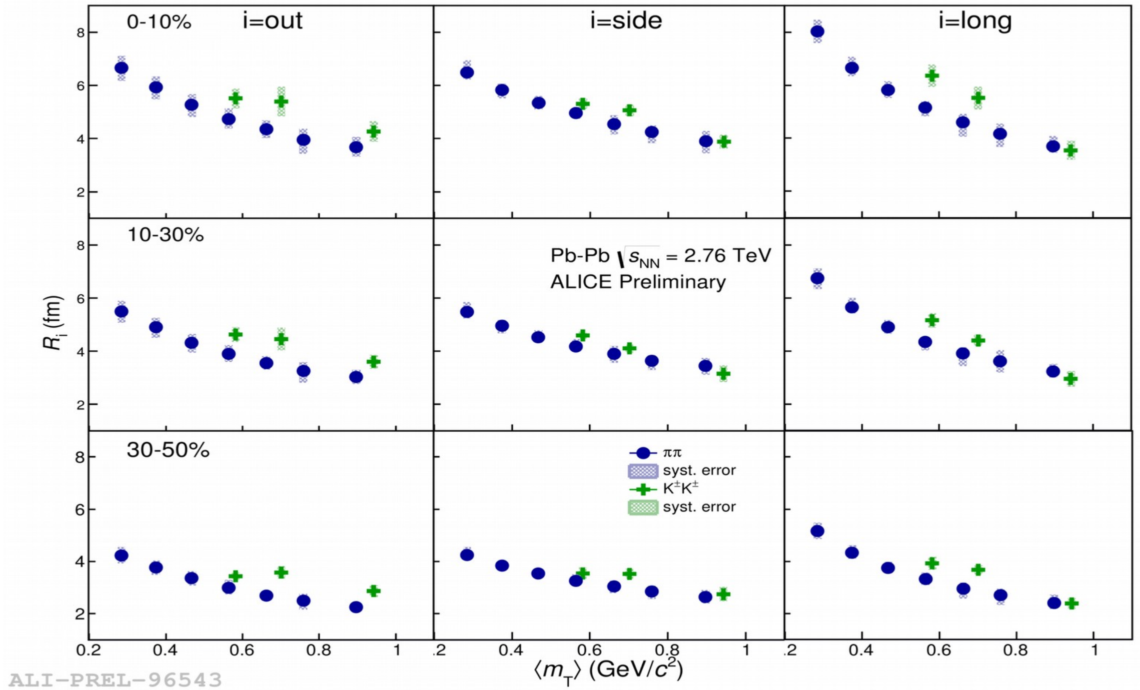


AK, M.Gałażyn, P.Bożek; Phys.Rev.C90 (2014) 6, 064914

Collectivity with heavier particles



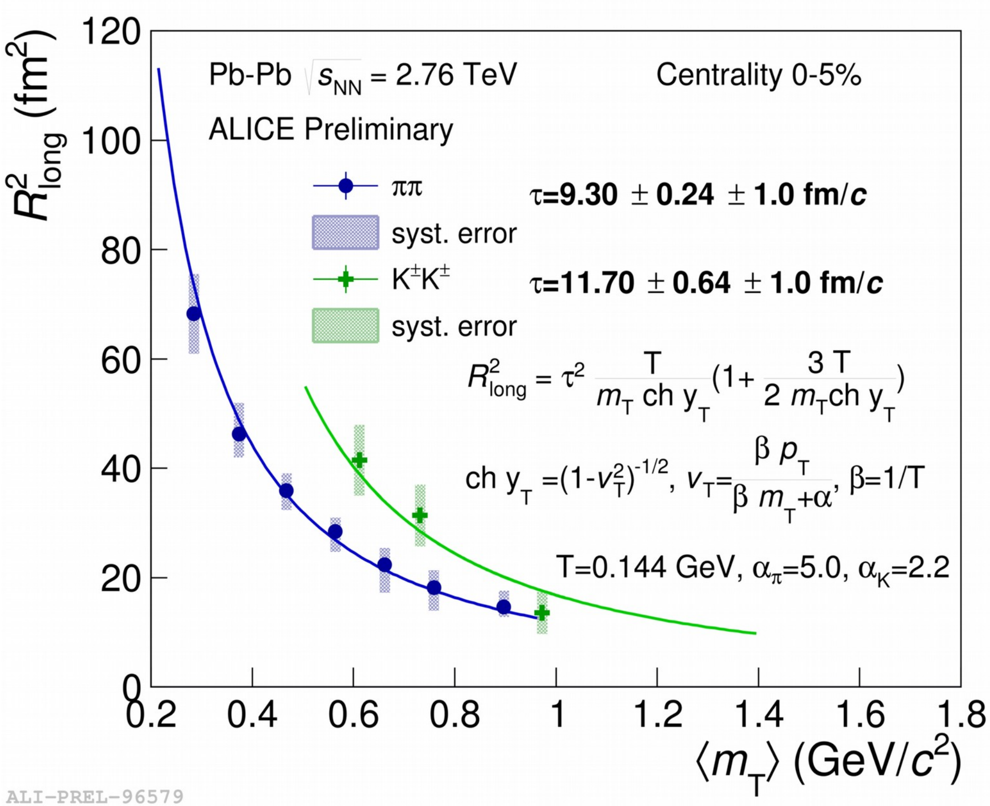
M. Steinpreis, QM2014



L. Malinina, QM2015, arXiv.org:1507.06842

- The $k_T(m_T)$ dependence is tested with heavy mesons (neutral and charged kaons)
- The 3D K^0_s and K^{ch} results show breaking of m_T scaling – effect of rescattering?
- Non-trivial data analysis for 3D K^0_s (no analytic functional form for fitting QS+Strong femto signal)

Emission time estimate



- Evolution time estimated with analytical form of $R_{long}(k_T)$
- Longer time for kaons, when compared to pions: model interpretation – influence on kaon evolution time from rescattering via K*

Femtoscopy and strong interaction

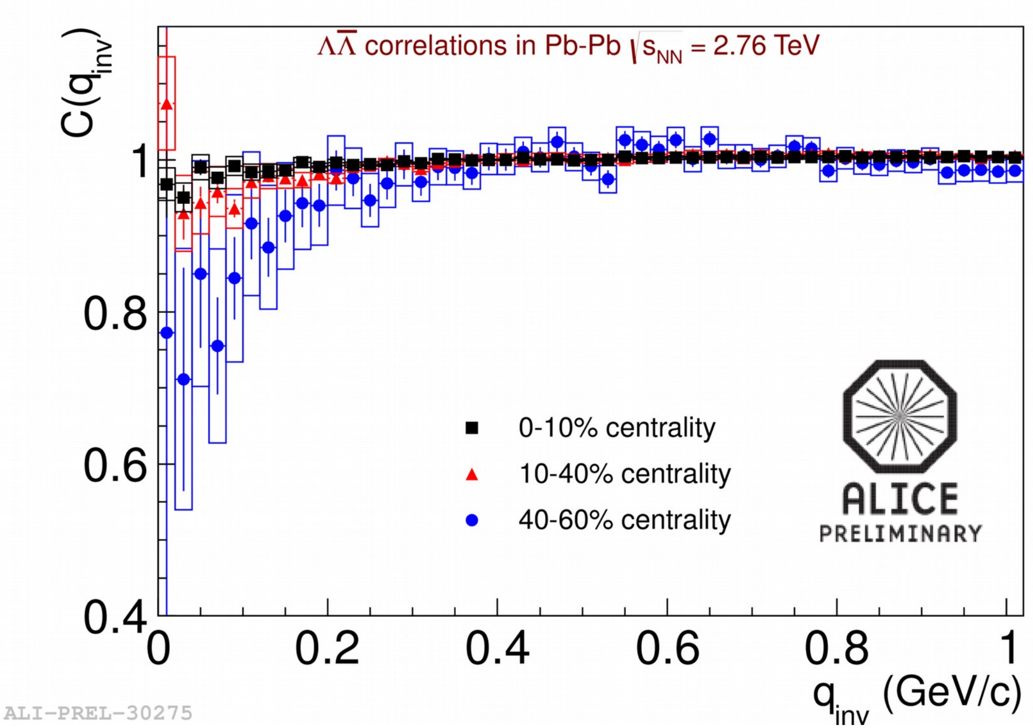
- Strong interaction for the pair gives correlation function (the Lednicky&Lyuboshits analytic formula for C):

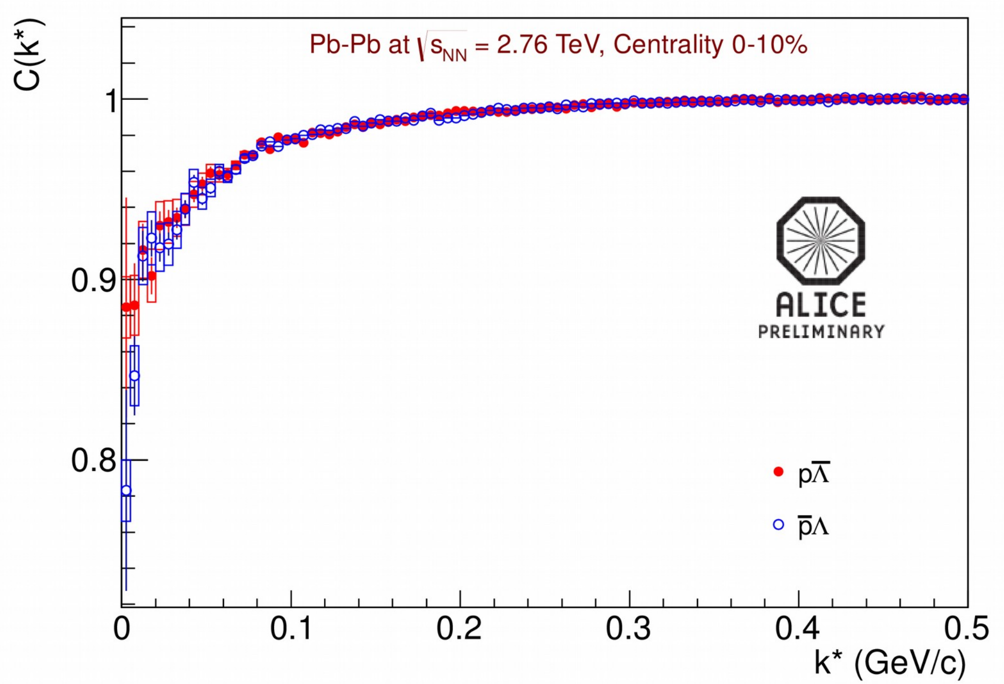
$$C(k^*) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k^*)}{r_0} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi}\, r_0} \right) + \frac{2\Re f^S(k^*)}{\sqrt{\pi}\, r_0} F_1(Qr_0) - \frac{\Im f^S(k^*)}{r_0} F_2(Qr_0) \right]$$

- Direct dependence on parameters of strong interaction
  - Complex singlet and triplet scattering length f_0, the effective radius d_0 → can be used to measure cross-sections at low k*
- Possibility to measure f_0, d_0 (and in consequence → cross-section) for all pairs produced abundantly at LHC
  - Some cross-sections were never measured (and probably never will be) in dedicated experiments
  - Crucial information for the entire nuclear physics field

R. Lednicky and V. L. Lyuboshits, Sov. J. Nucl. Phys. 35, 770 (1982).

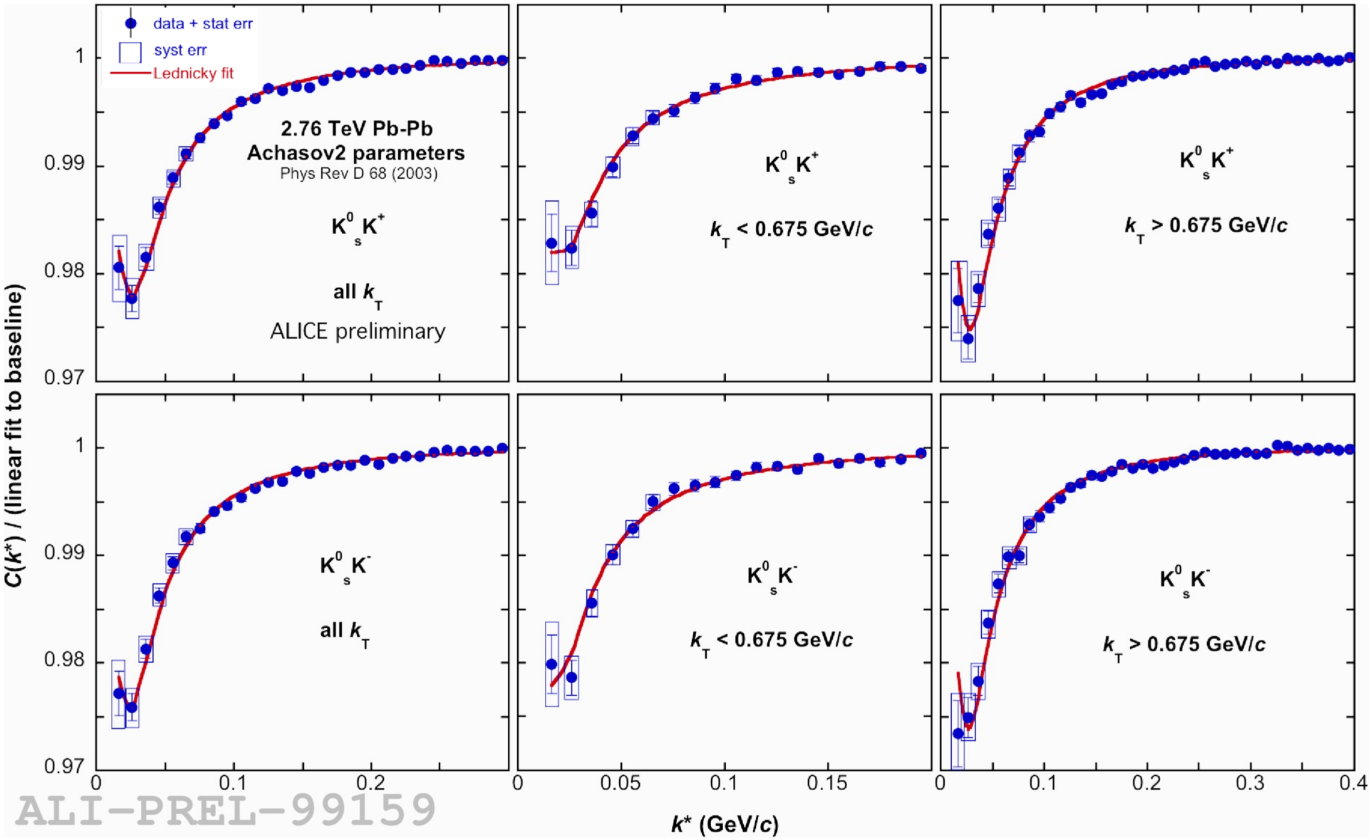
$\Lambda\bar{\Lambda}$ and $p\bar{\Lambda}$ correlation functions





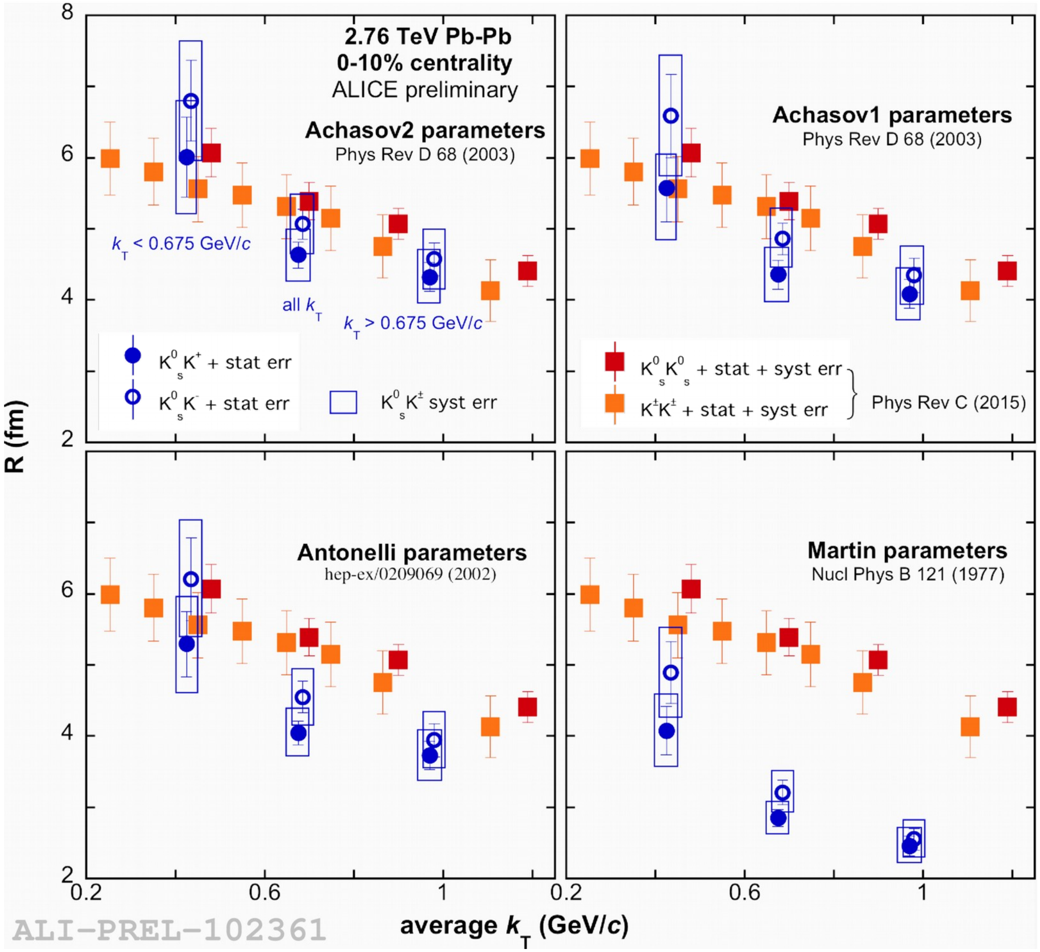
- Wide negative correlation observed, consistent with annihilation in the strong FSI
- Annihilation not limited to particle-antiparticle systems!
- Correlation strength increases with decreasing multiplicity (consistent with decrease of the system size)
- Quantitative analysis requires careful consideration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

Correlations for K^0_S-K^{ch}



- Correlation function from strong interaction well described by theoretical formula, dominated by $a_0(980)$ resonance, sensitive to the exact values of resonance parameters

Radii for K^0_S-K^{ch} correlations



- Radii for K^0_S-K^{ch} expected same as in K^0_S-K^0_S and K^{ch}-K^{ch}
- ALICE data favors Achasov a_0 resonance parameters

Summary

- Heavy-ion collisions driven by space-time considerations and system evolution → size of the system fundamental in the interpretation of the system as "Quark-Gluon Plasma"
- Femtoscopy measures the size of the system → important constraints on system dynamics and Equation of State at RHIC and at the LHC
- Measurements in p+p and pA → are they really a "reference"?
- pA data – an intermediate step between p+p and AA?
- Femtoscopy for heavier particles sensitive to rescattering
- First results from measurement of strong interaction parameters via femtoscopy give qualitatively unique information