Narodowe Centrum Nauki

Faculty of Physics Warsaw University of Technology

Femtoscopic measurements from LHC to NICA

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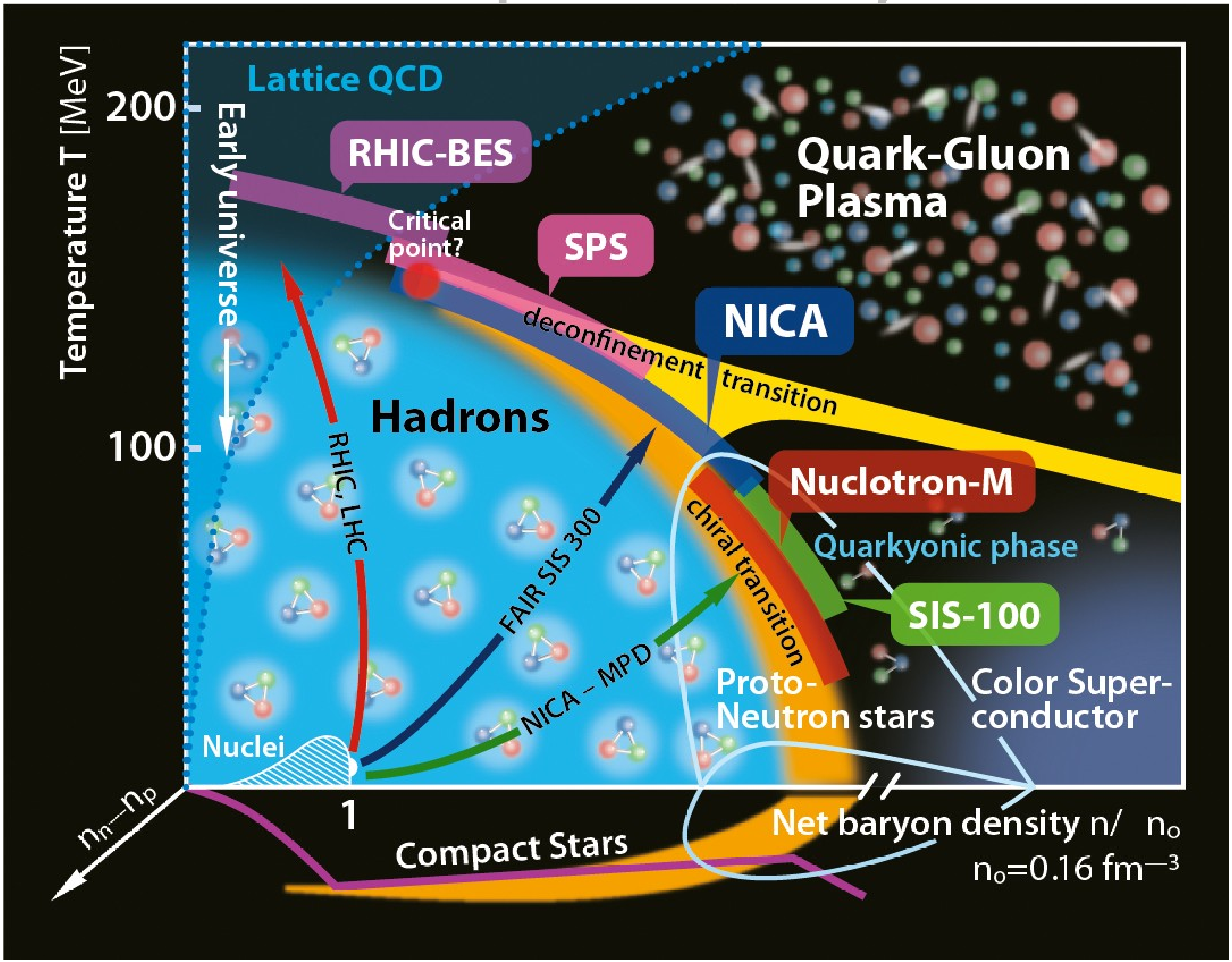
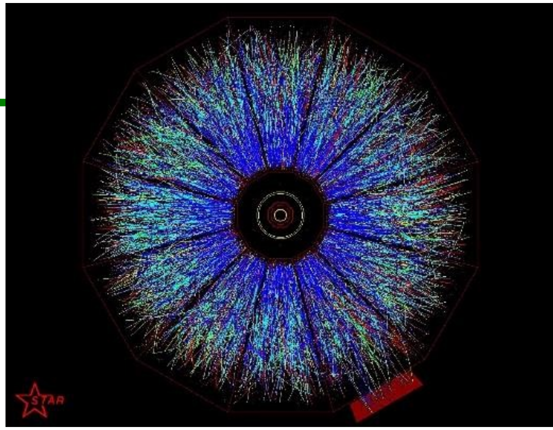
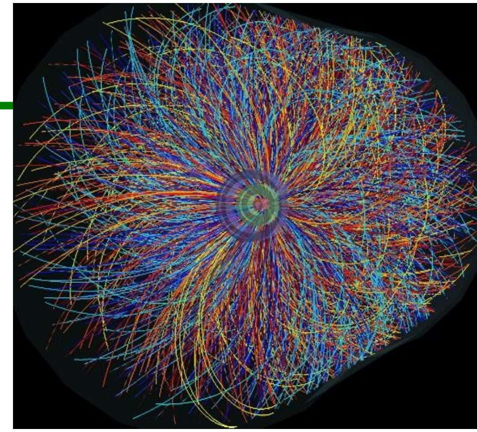
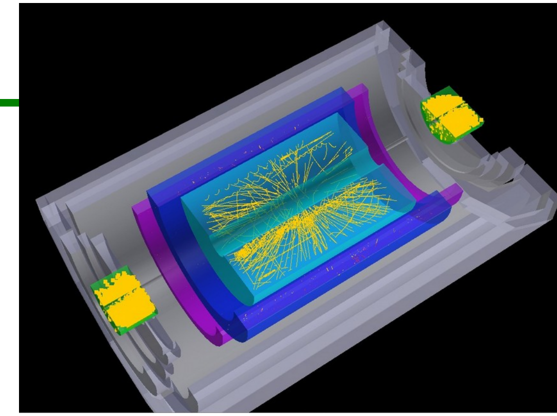
LHC, RHIC, SPS, NICA, FAIR - complementary

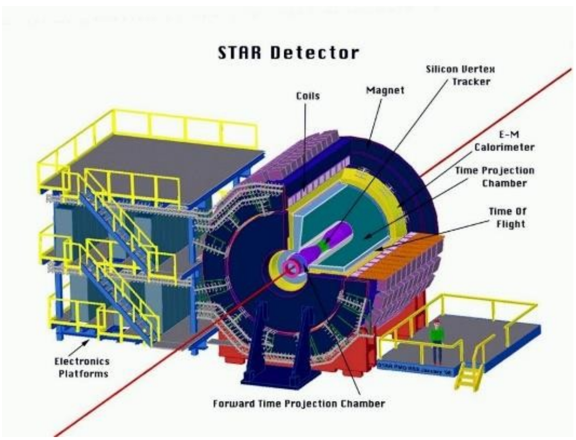


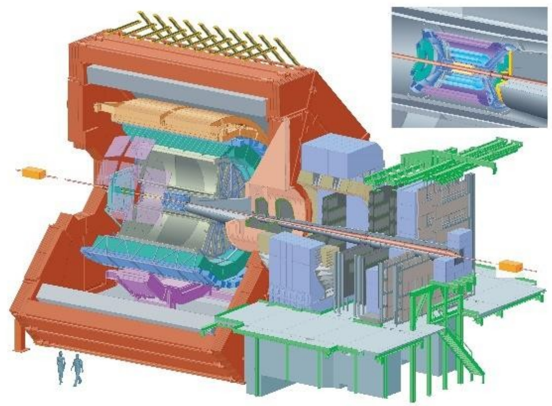
Detector evolution

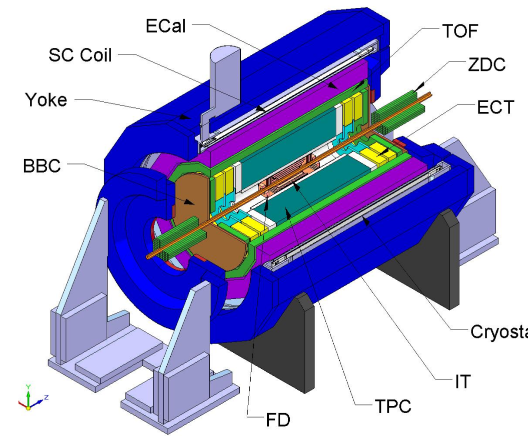










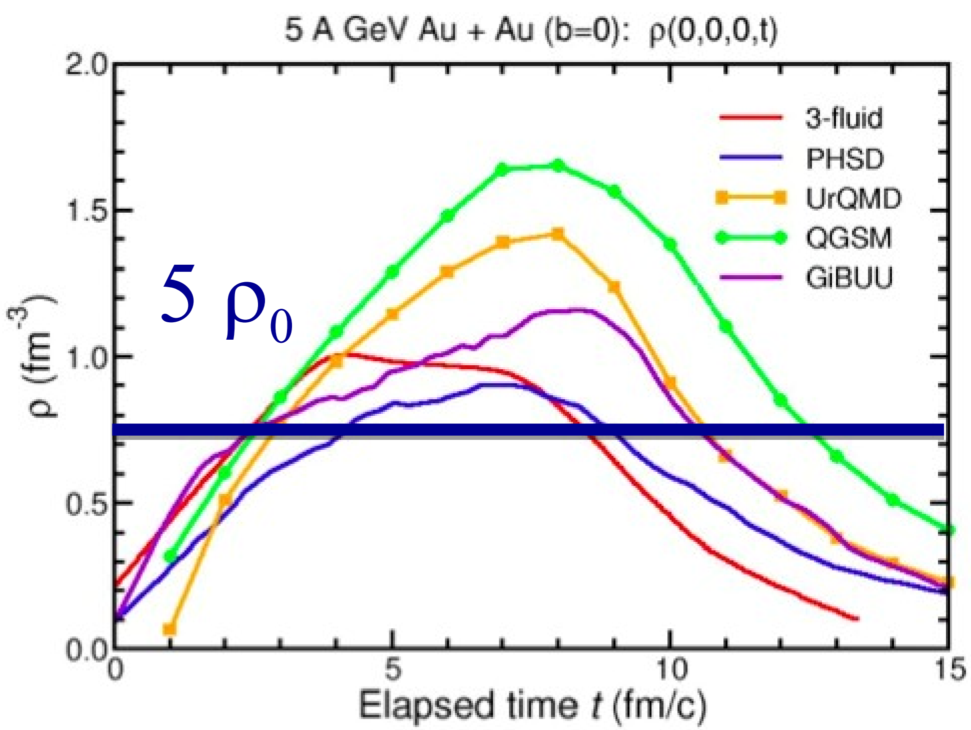


- Collider geometry
- Good tracking in high track density
- Excellent PID at low p_{T}
- Similar set of detectors at large range of collision energies

Unique system at NICA and FAIR

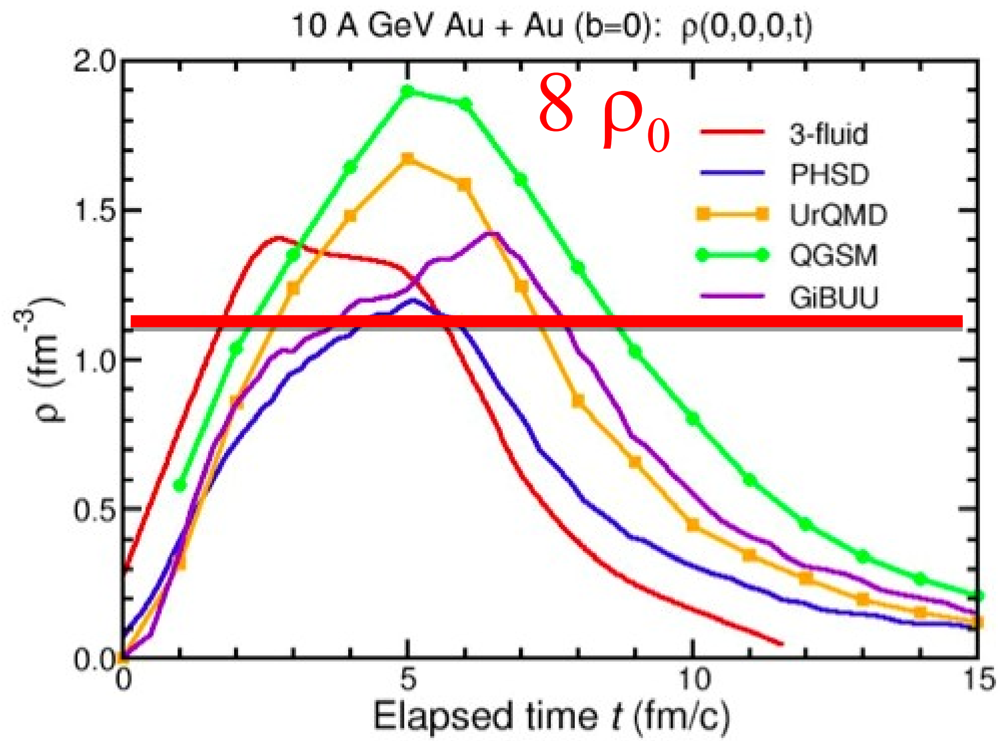
FAIR SIS-100

5 A GeV



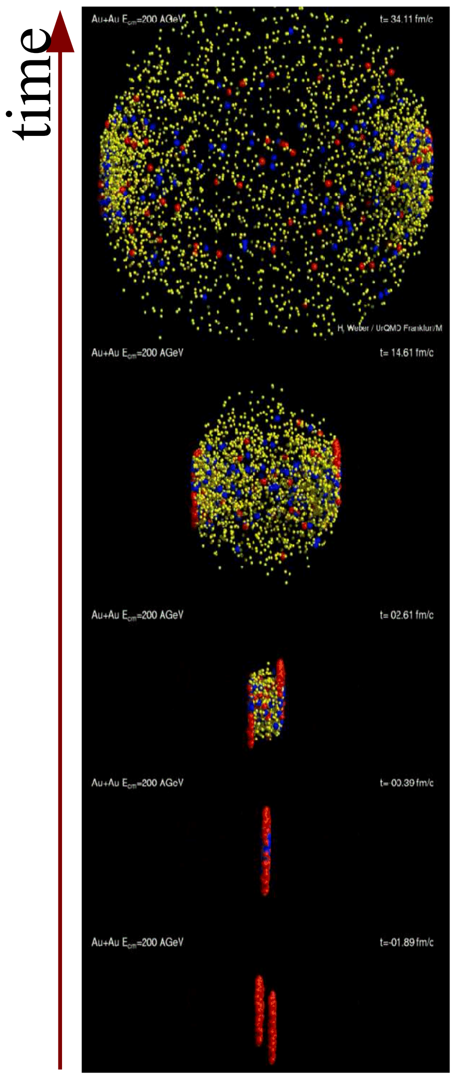
NICA

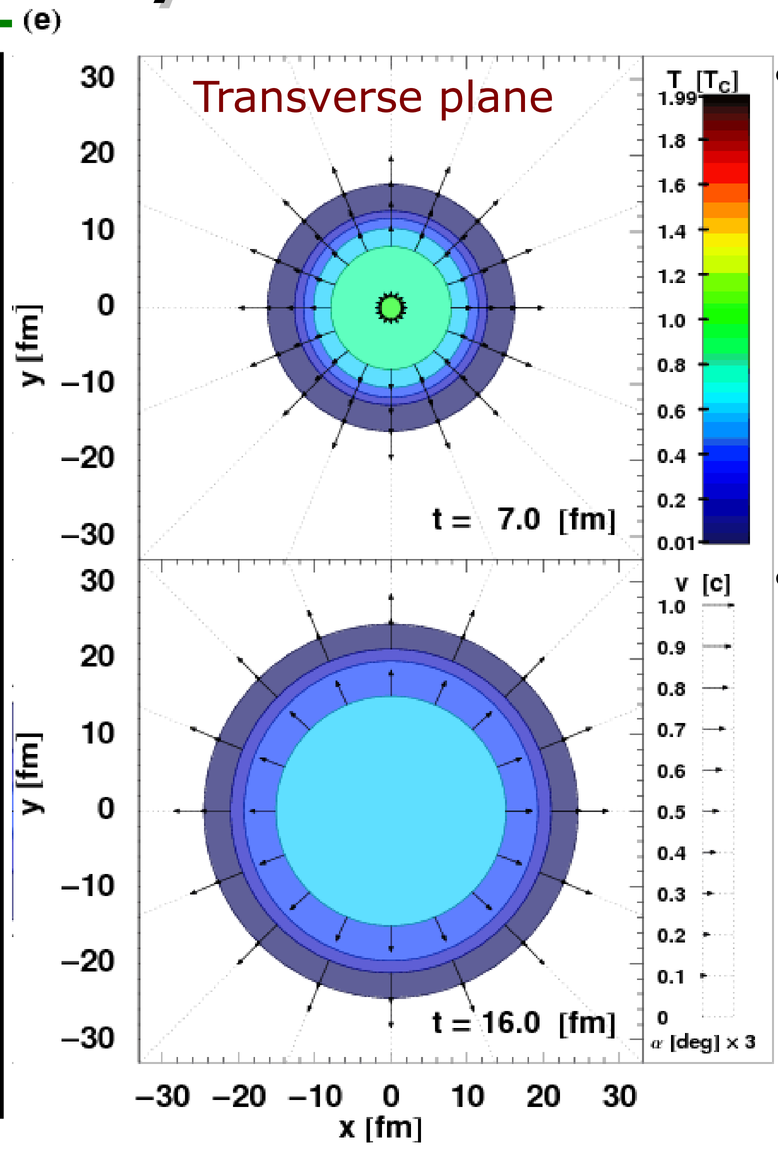
10 A GeV



I.C. Arsene at al., Phys. Rev. C75 (2007) 24902.

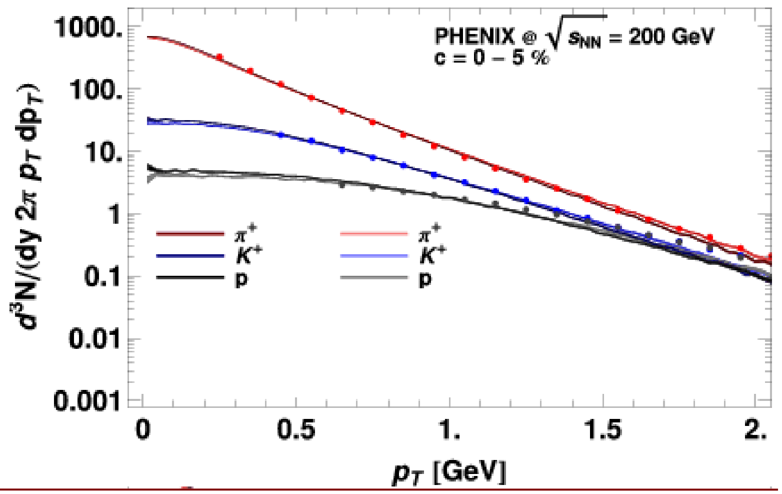
Heavy-ion collision evolution



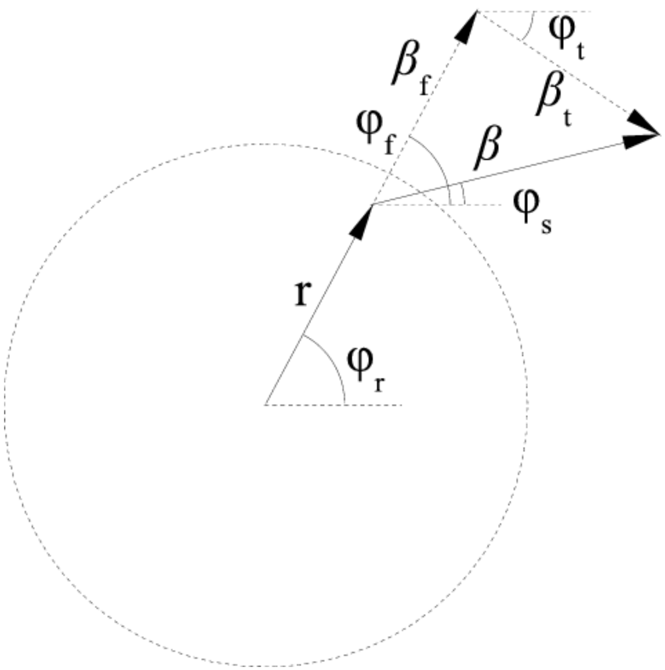


M. Chojnacki, W. Florkowski, PRC 74 (2006) 034905

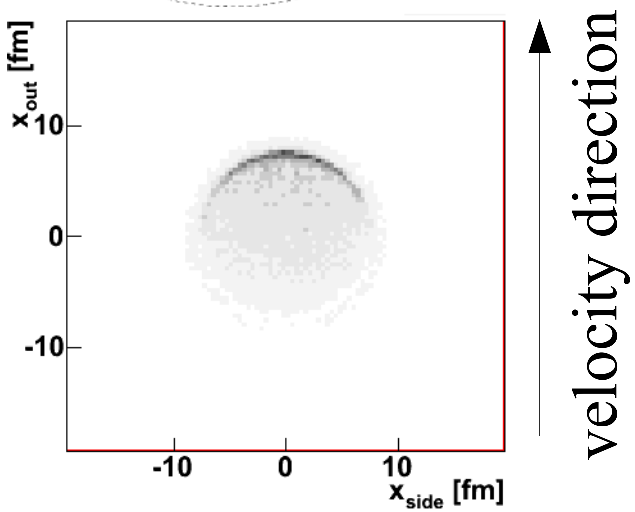
- HIC is expected to go through a QGP phase, where matter is strongly interacting – resulting in the development of collective motion
- Radial flow dominates, with elliptic flow as azimuthal modification

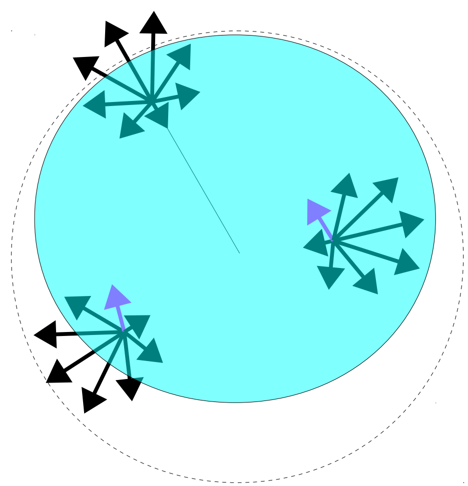


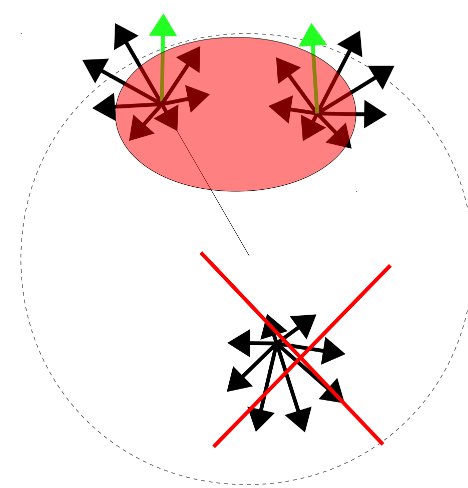
Thermal emission from collective medium



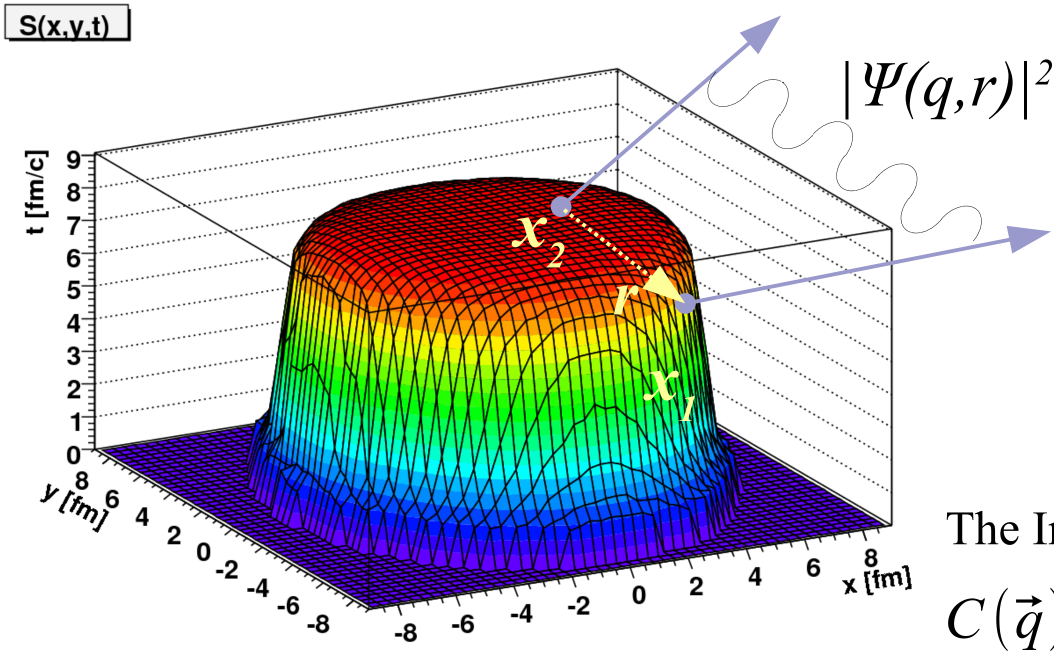
- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source

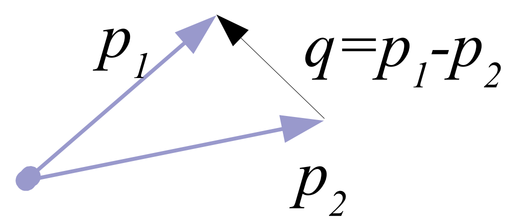






Measuring space-time extent: femtoscopy



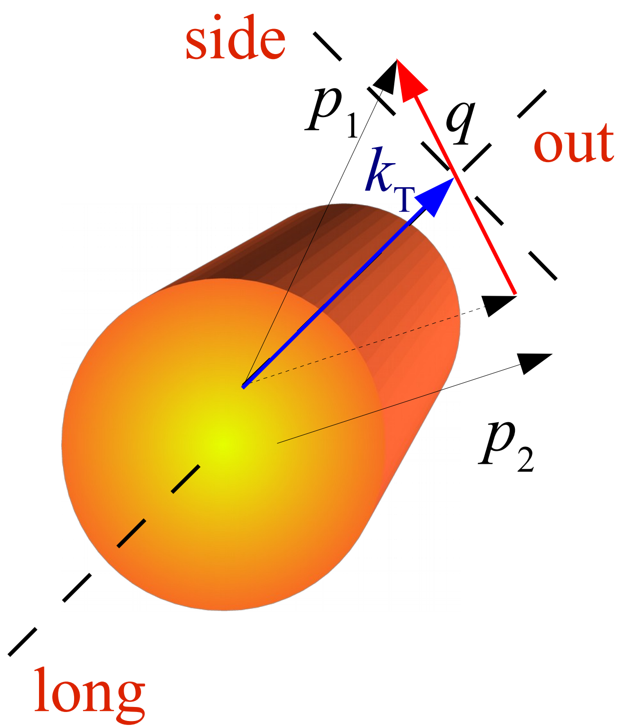


The Integral Equation for Correlation

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

- Use two-particle correlation, coming from the interaction Ψ (quantum statistics (HBT), coulomb and/or strong)
- Measure $C(q)$
- Try to invert the Koonin-Pratt eq. to gain information about S from known Ψ and measured C

Reference frames for femtoscopy



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

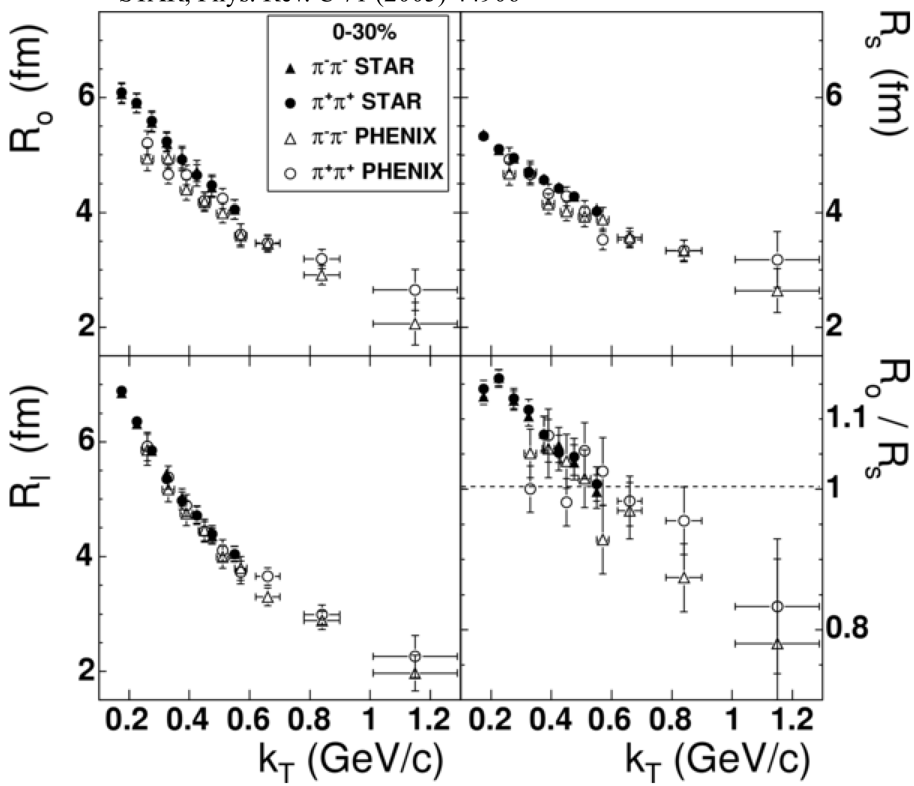
Longitudinally Co-Moving System (LCMS):
$p_{1,long} = -p_{2,long}$

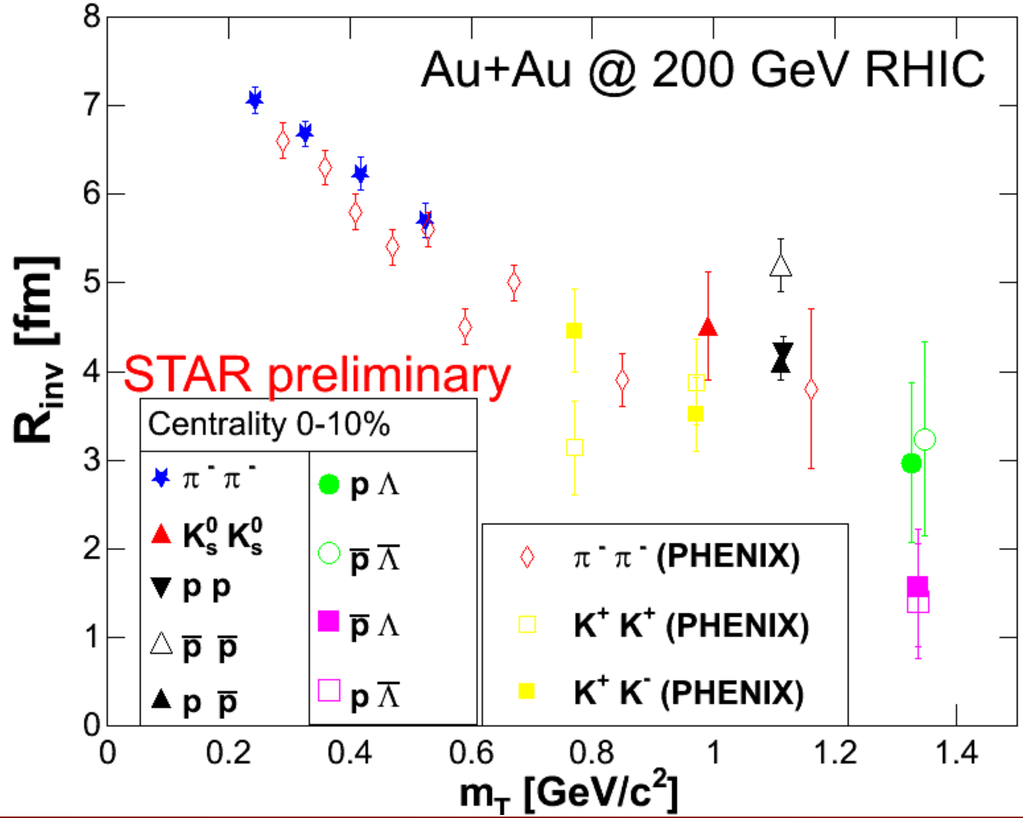
- For charged pions measurement in 3 dimensions, giving 3 independent sizes in Longitudinally Co-Moving System
- The Bertsch-Pratt decomposition of q:
  - Long along the beam: sensitive to longitudinal dynamics and evolution time
  - Out along k_T: sensitive to geometrical size, emission time and space-time 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

m_T dependence at RHIC

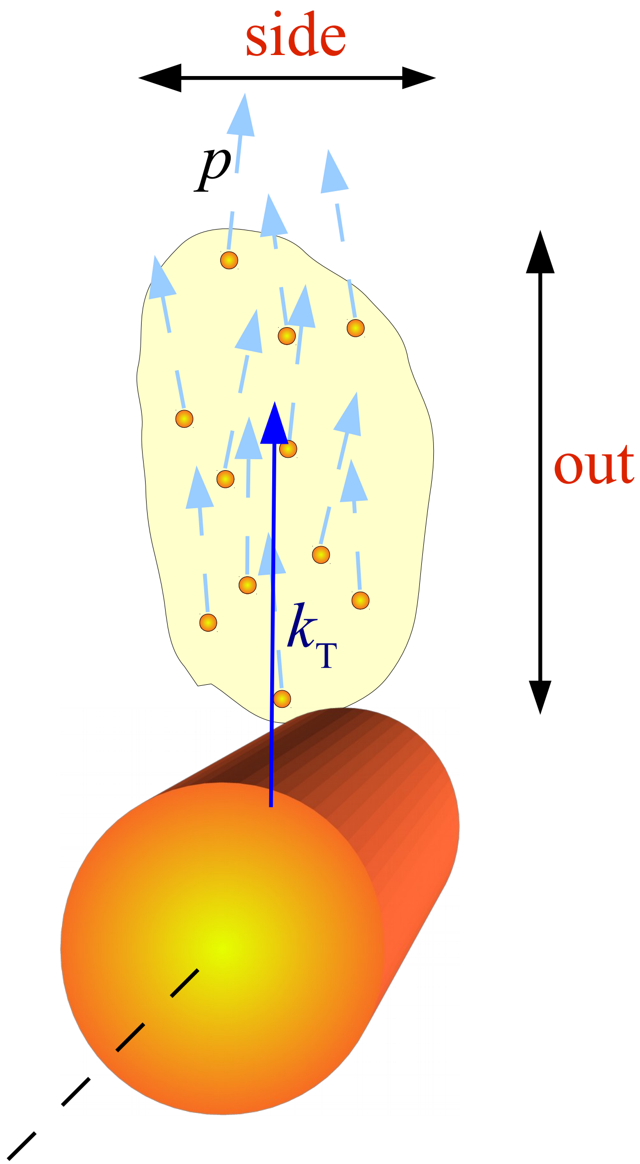
- A clear m_T dependence is observed, for all femtoscopic radii and for all particle types: but is it hydrodynamic like? And can we tell?

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





Emission duration



- Particles emitted "earlier" will travel some distance in the "out" direction (direction of velocity β)
- Radii have components from:
  - Geometrical size x (width of the space point distribution)
  - Emission duration t (width of the emission time distribution)
  - Space-time correlations

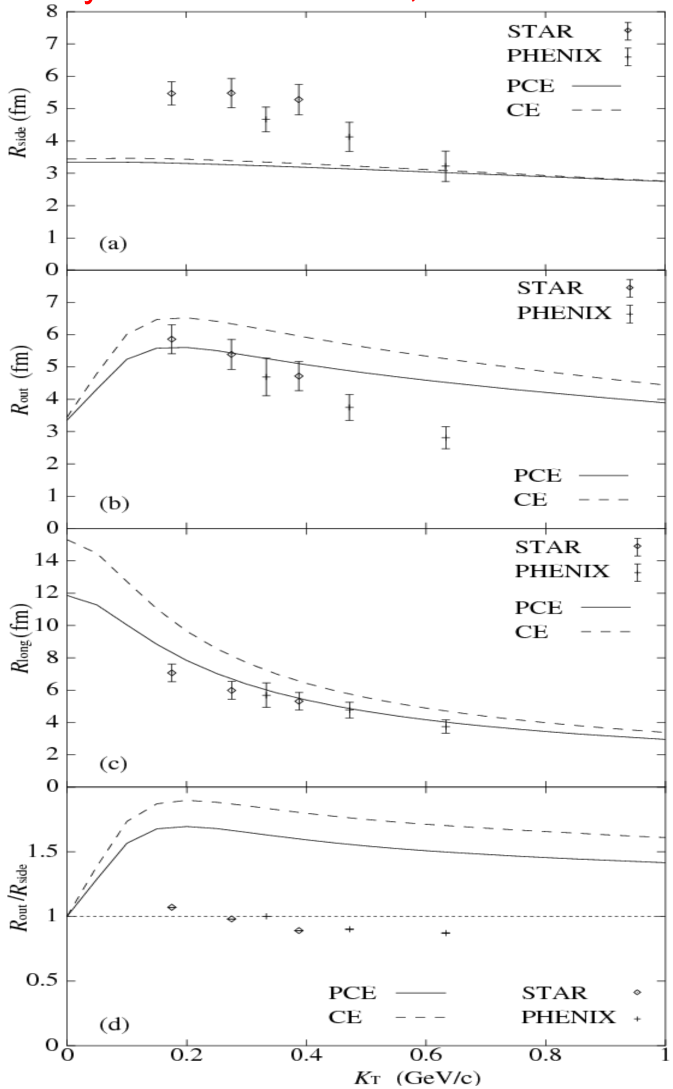
$$R_{out} = var\{x\} + \beta\, var\{t\} - \langle \beta\, t\, x \rangle$$

$$R_{side} = var\{x\}$$

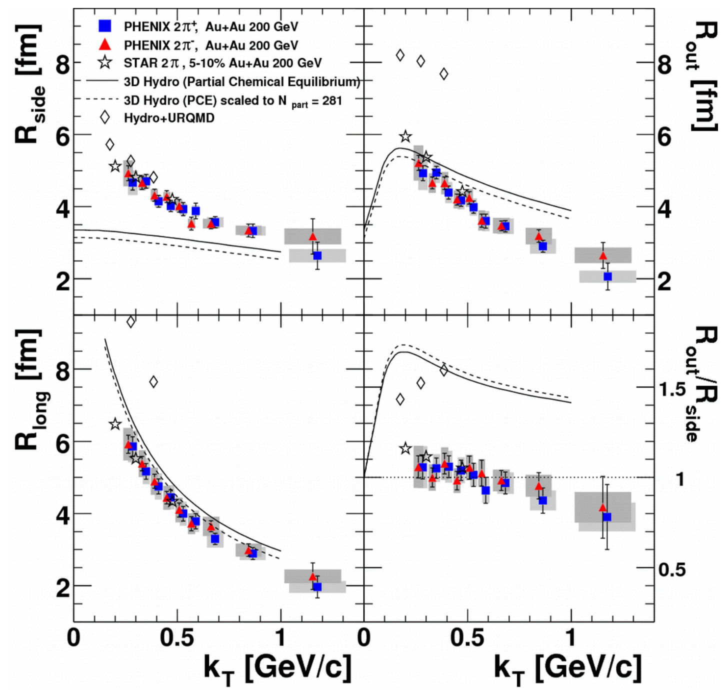
- What will R_{out}/R_{side} be?

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.

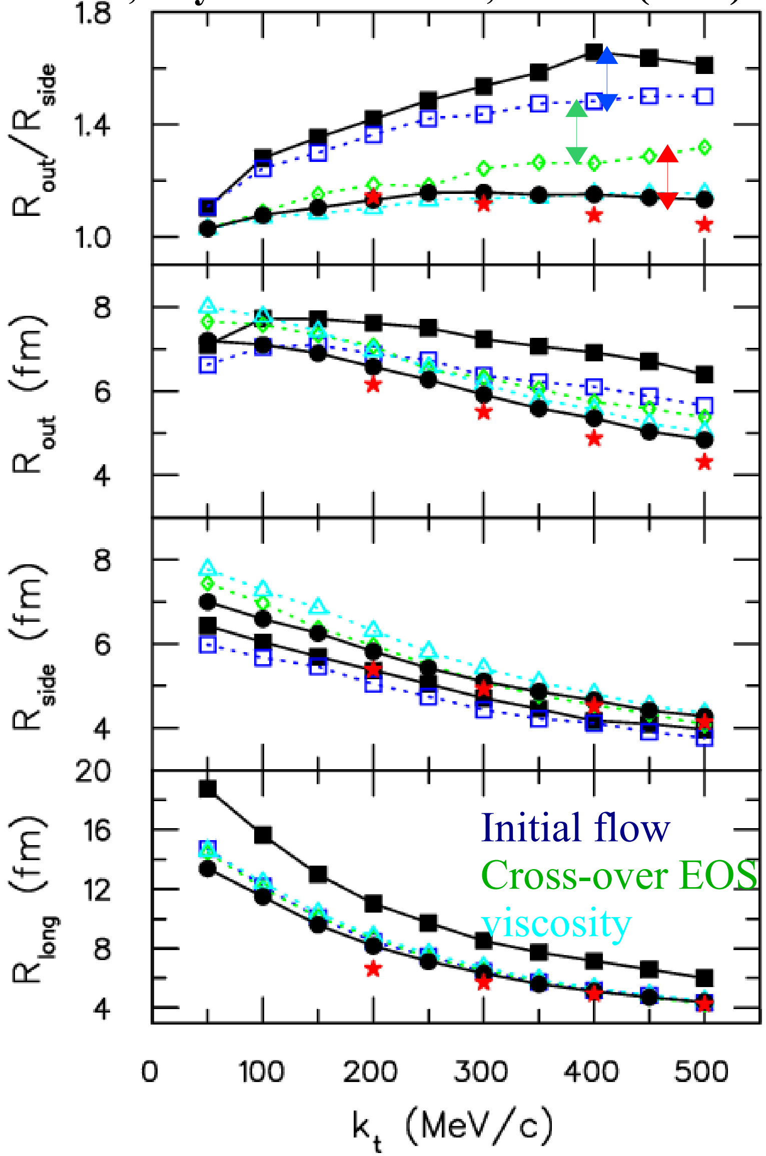


U. Heinz, P. Kolb,
hep-ph/0204061

Phys. Rev. Lett. 93, 152302 (2004) ,

Revisiting hydrodynamics assumptions

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

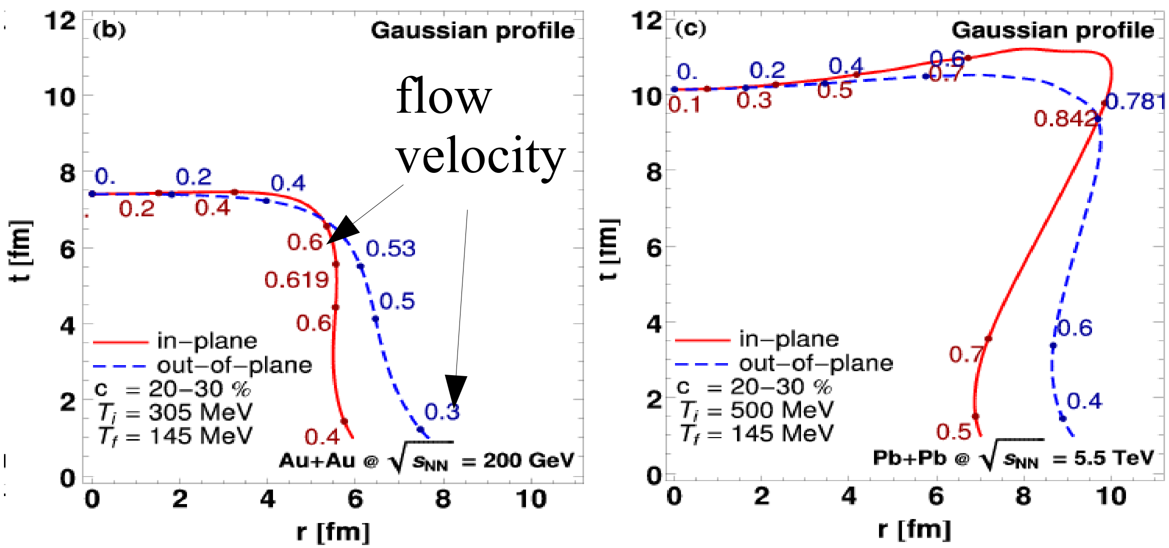


- Data in the momentum sector (p_T spectra, elliptic flow) well described by hydrodynamics, why not in space-time?
- Usually initial conditions do not have initial flow at the start of hydrodynamics (~1 fm/c) – they should.
- Femtoscopy data rules out first order phase transition at RHIC and LHC – smooth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

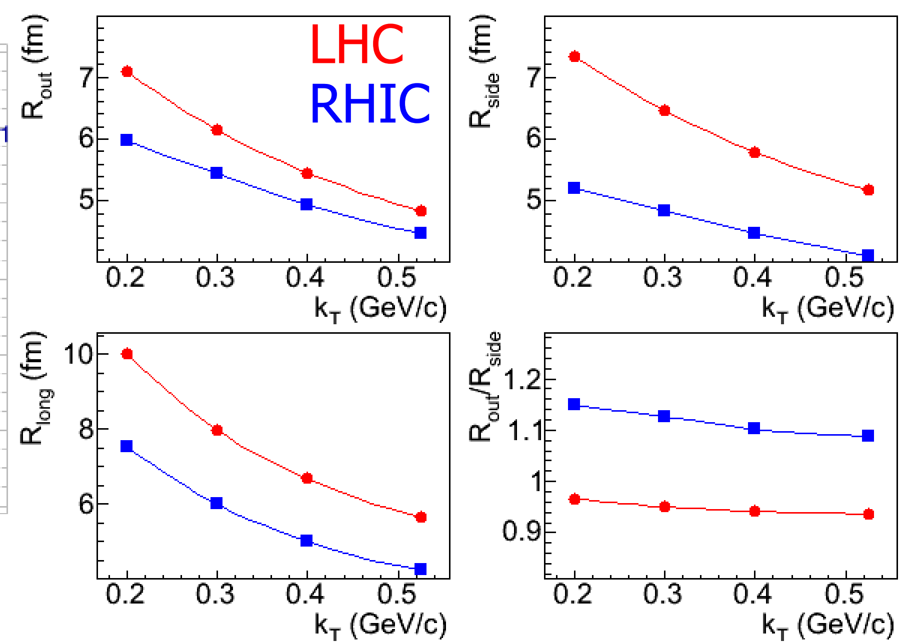
Expectations for the LHC

- 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

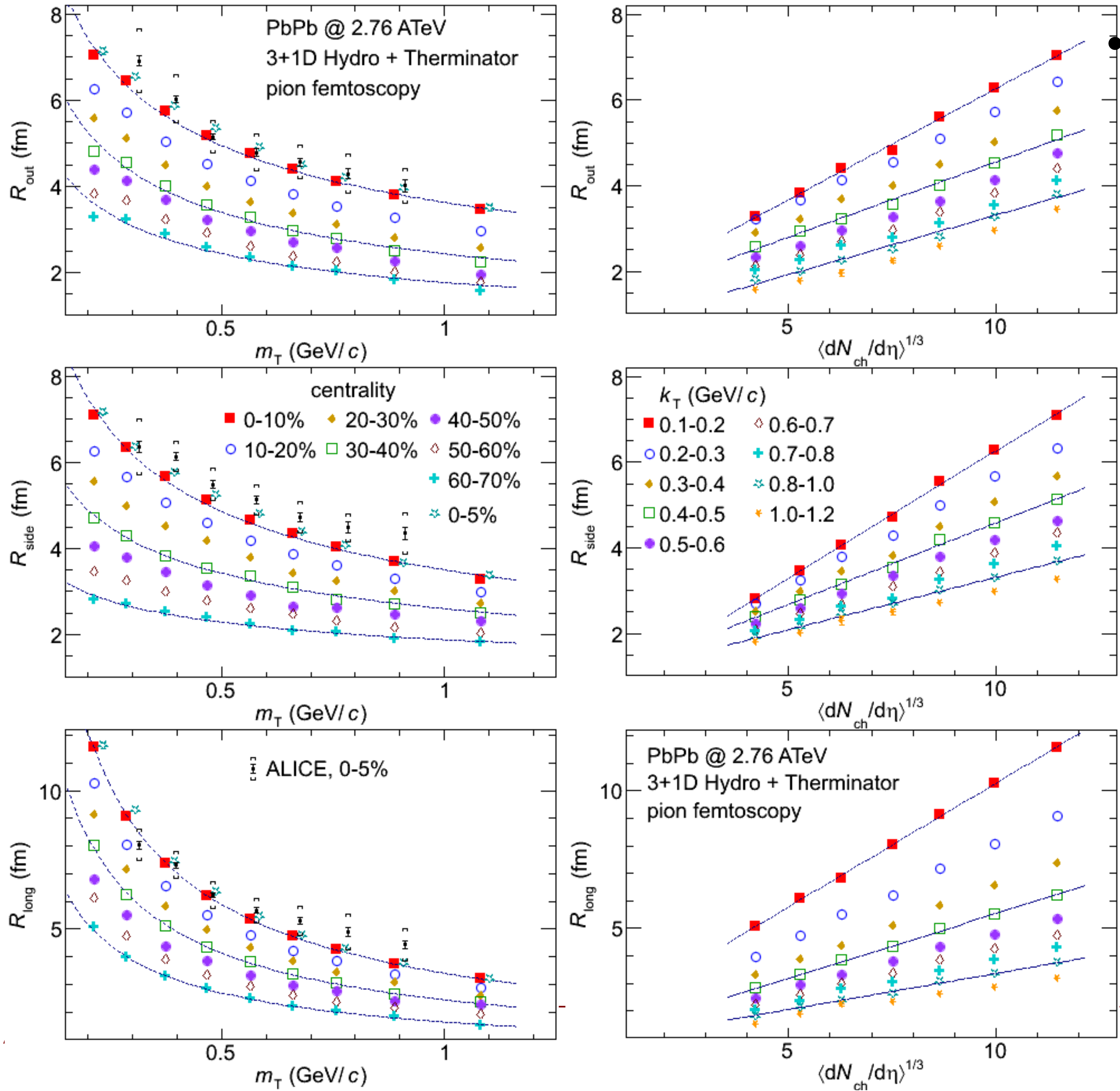
RHIC → LHC



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

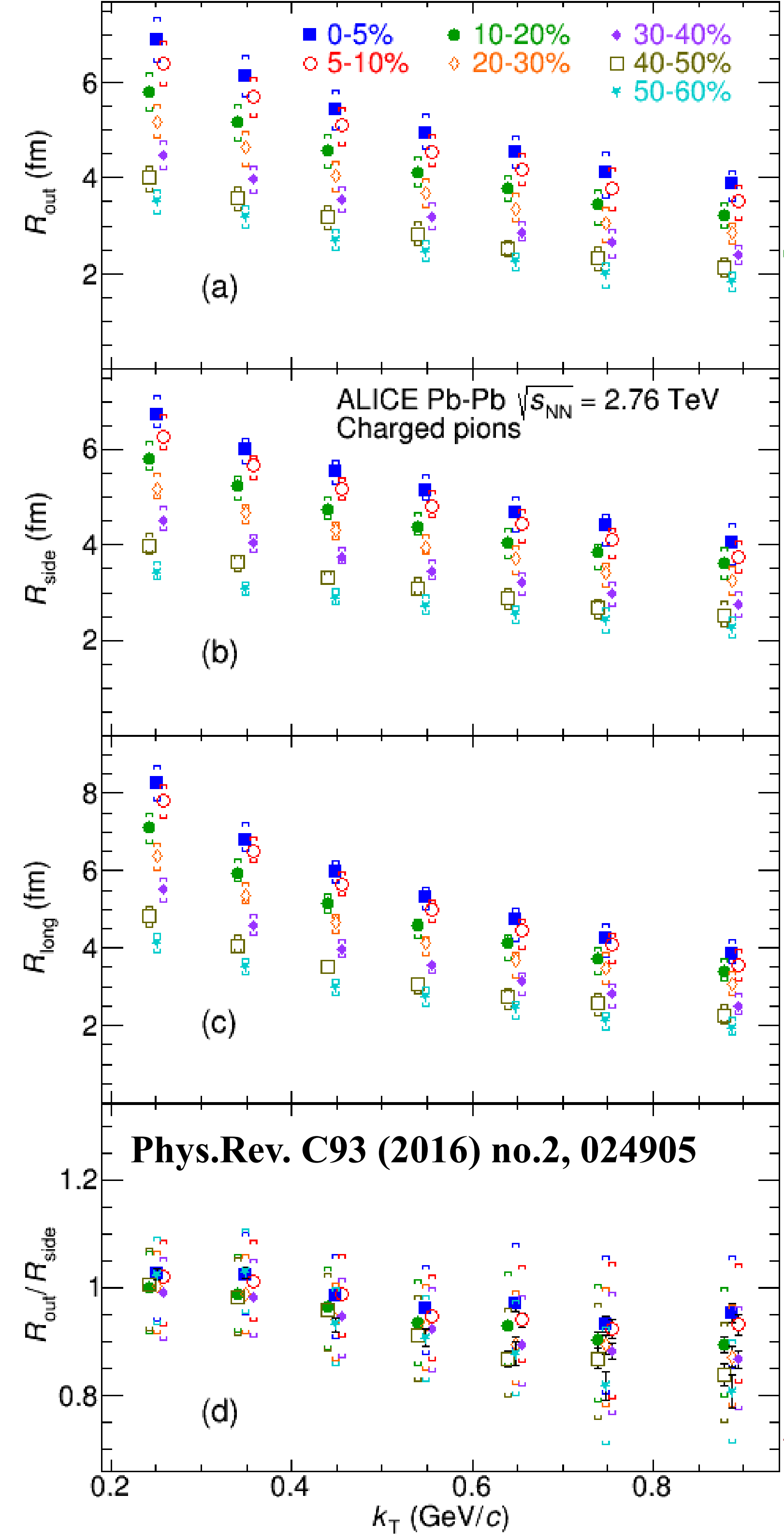


Model multiplicity and m_T dependence



- 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

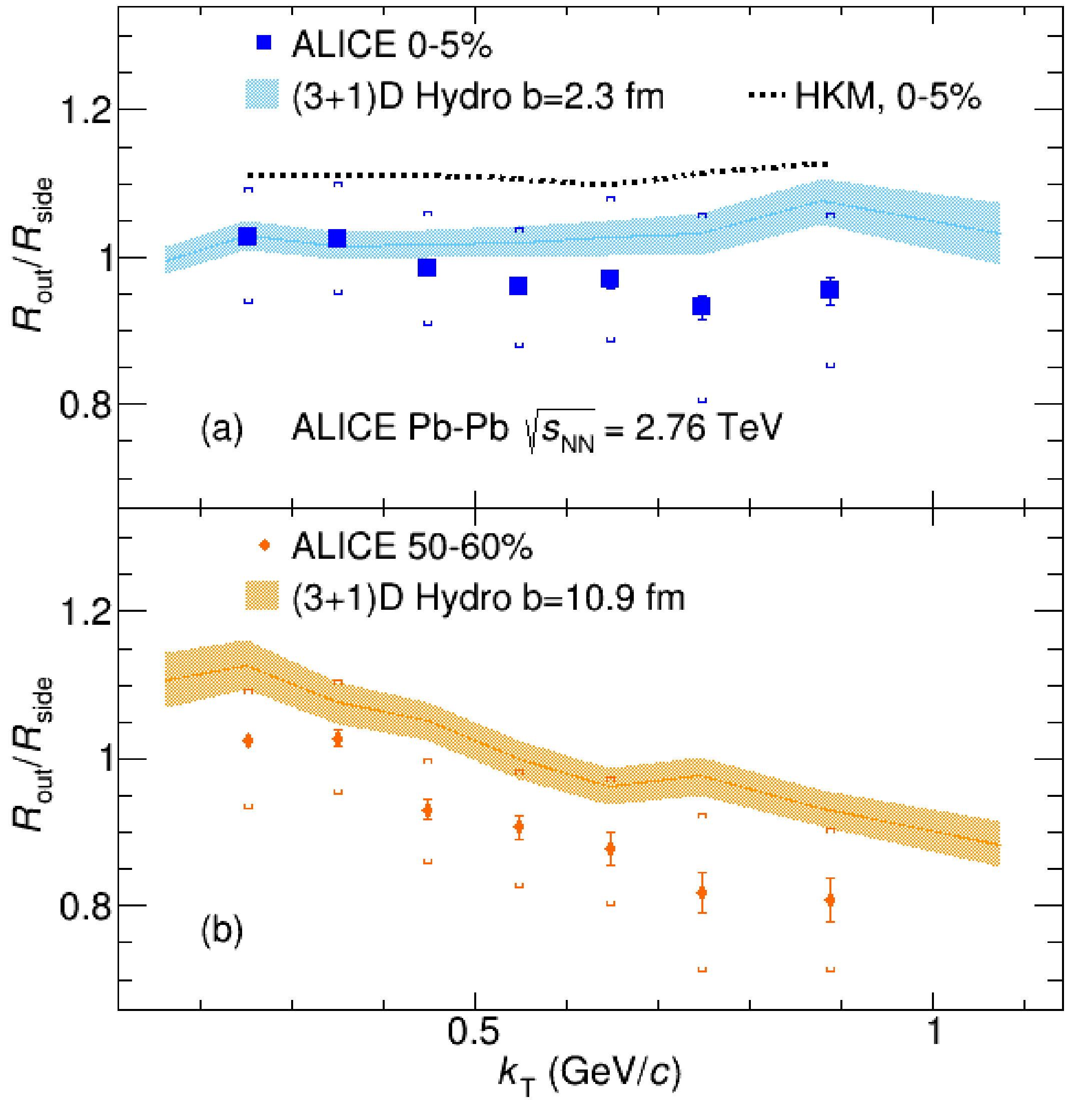
AK, M.Gałażyn, P.Bożek; Phys.Rev.C90 (2014) 6, 064914



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)

Freeze-out shape evolution



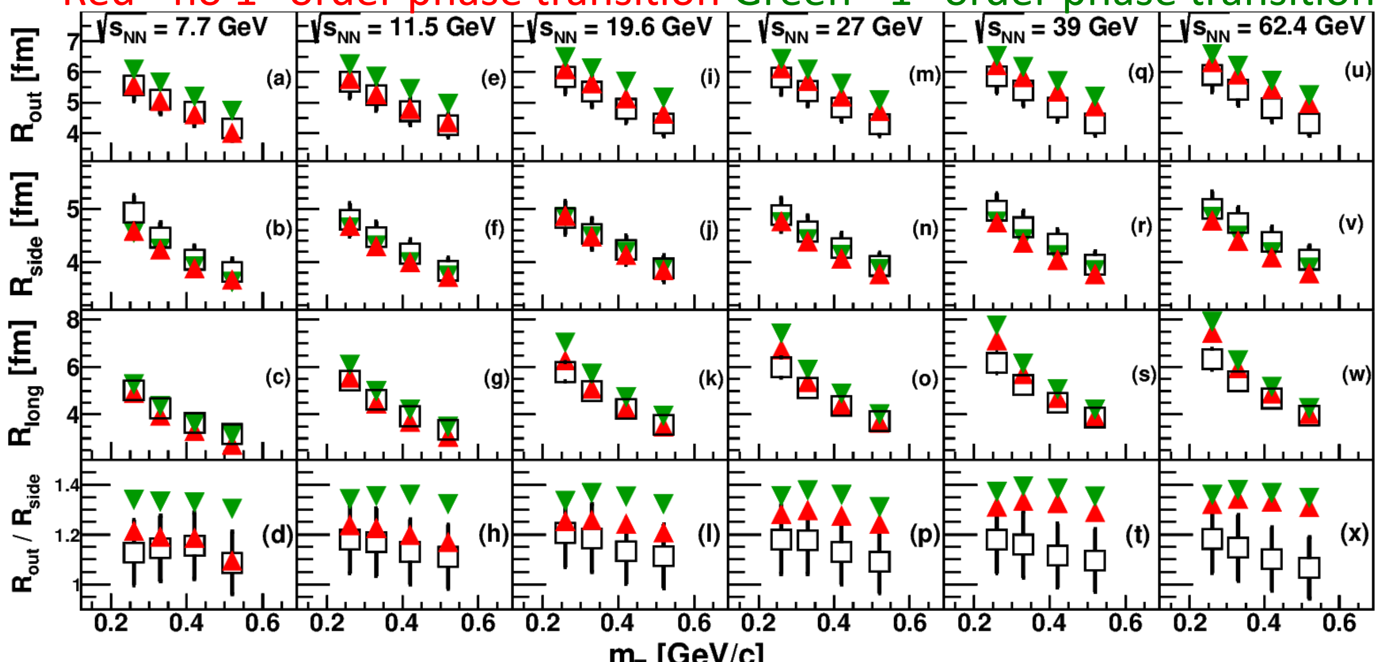
Phys.Rev. C93 (2016) no.2, 024905

- 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

Investigating phase transition

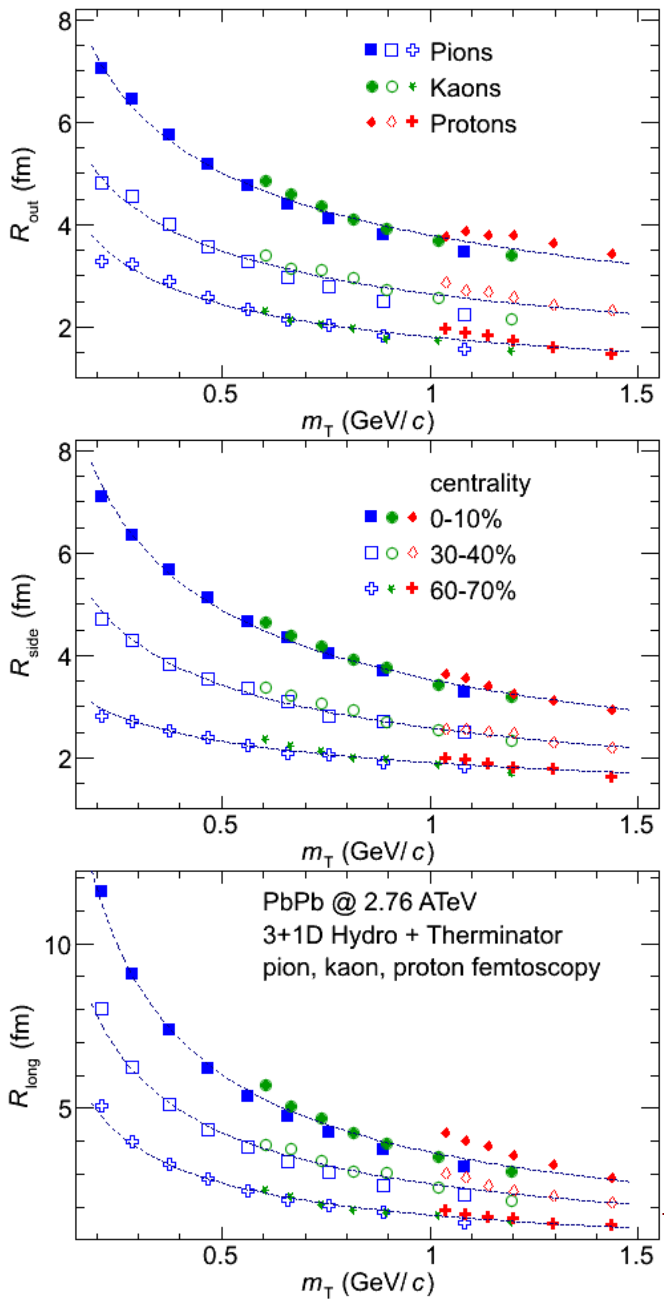
- Simulation for the energies at STAR BES
  - First order phase transition expected at NICA
  - Sensitivity to the order of transition shown for femtoscopic radii
  - Importance of energy scan

Red - no 1st order phase transition Green - 1st order phase transition

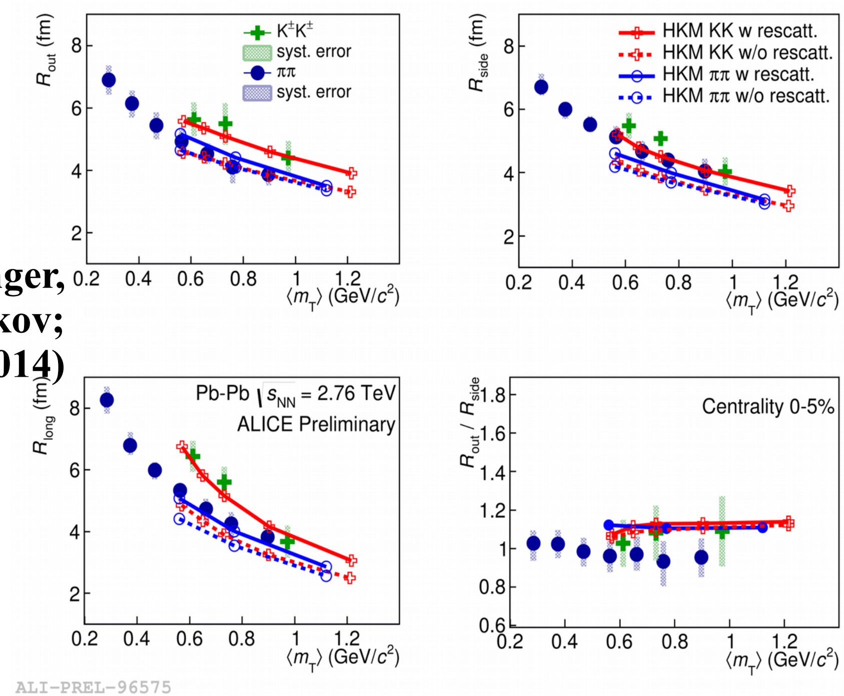


Phys.Rev. C96 (2017) no.2, 024911

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



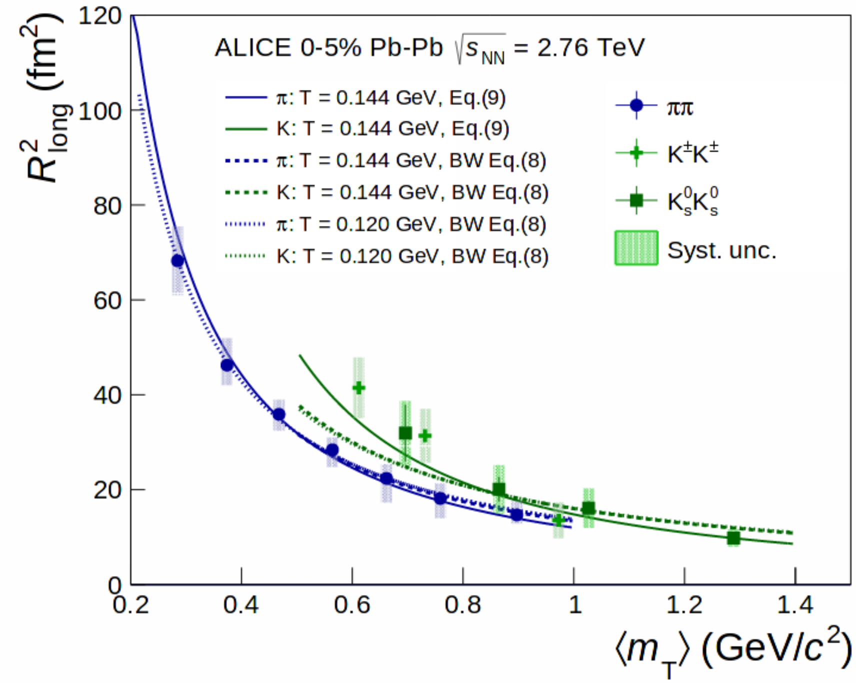
M. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov; Nucl.Phys. A 929 (2014)

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

Emission delay in data

- ALICE kaon data in hydro-based parameterization: kaons emitted on average later than pions.
- It comes from rescattering via K* resonance (**not included** in blast-wave or Therminator 2 or hydro)

ALICE, Phys.Rev. C96 (2017) no.6, 064613



method	T (GeV)	α_π	α_K	τ_π (fm/c)	τ_K (fm/c)
fit with BW Eq. (8)	0.120	-	-	9.6 ± 0.2	10.6 ± 0.1
fit with BW Eq. (8)	0.144	-	-	8.8 ± 0.2	9.5 ± 0.1
fit with Eq. (9)	0.144	5.0	2.2	9.3 ± 0.2	11.0 ± 0.1
fit with Eq. (9)	0.144	4.3 ± 2.3	1.6 ± 0.7	9.5 ± 0.2	11.6 ± 0.1

Table 4: Emission times for pions and kaons extracted using the Blast-wave formula Eq. (8) and the analytical formula Eq. (9).

V.M. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov; **Nucl.Phys. A929 (2014) 1-8**

Accessing emission delays

ELSEVIER

18 April 1996

Physics Letters B 373 (1996) 30–34

PHYSICS LETTERS B

How to measure which sort of particles was emitted earlier and which later

R. Lednický [1], V.L. Lyuboshitz [2], B. Erazmus, D. Nouais

Laboratoire SUBATECH, Université de Nantes/Ecole des Mines de Nantes/IN2P3/CNRS, 4 rue Alfred Kastler, La Chantrerie, 44070 Nantes Cedex 03, France

Received 24 November 1994; revised manuscript received 16 January 1996
Editor: R.H. Siemssen

Abstract

A method allowing to directly measure delays in the emission of particles of different types at time scales as short as 10^{-23}–10^{-22} s is suggested.

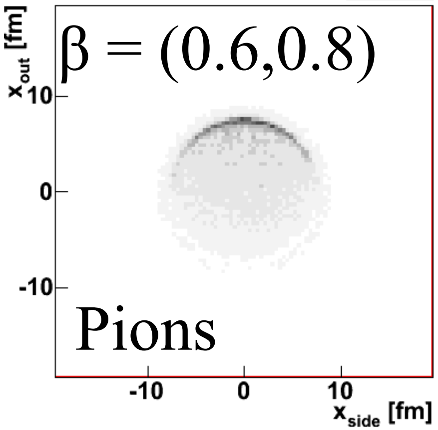
Space and time asymmetry

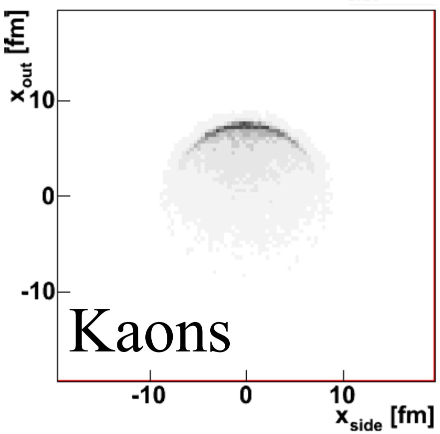
- The non-identical particle femtoscopy sensitive to the emission asymmetry between particle types, possible because they are not identical
- Measurement sensitive to the difference of the spatial and time asymmetries, not possible to distinguish between them

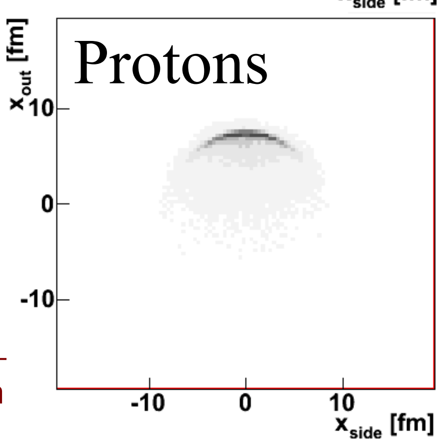
$$\mu_{out} = \langle r^*_{out} \rangle = \langle \gamma r_{out} - \beta \gamma \Delta t \rangle$$

- “Spatial” asymmetry r_{out} arises in flowing medium, difficult to produce otherwise
- “Time” asymmetry Δt may have various origins, some not connected to flow

Collectivity and emission asymmetry







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

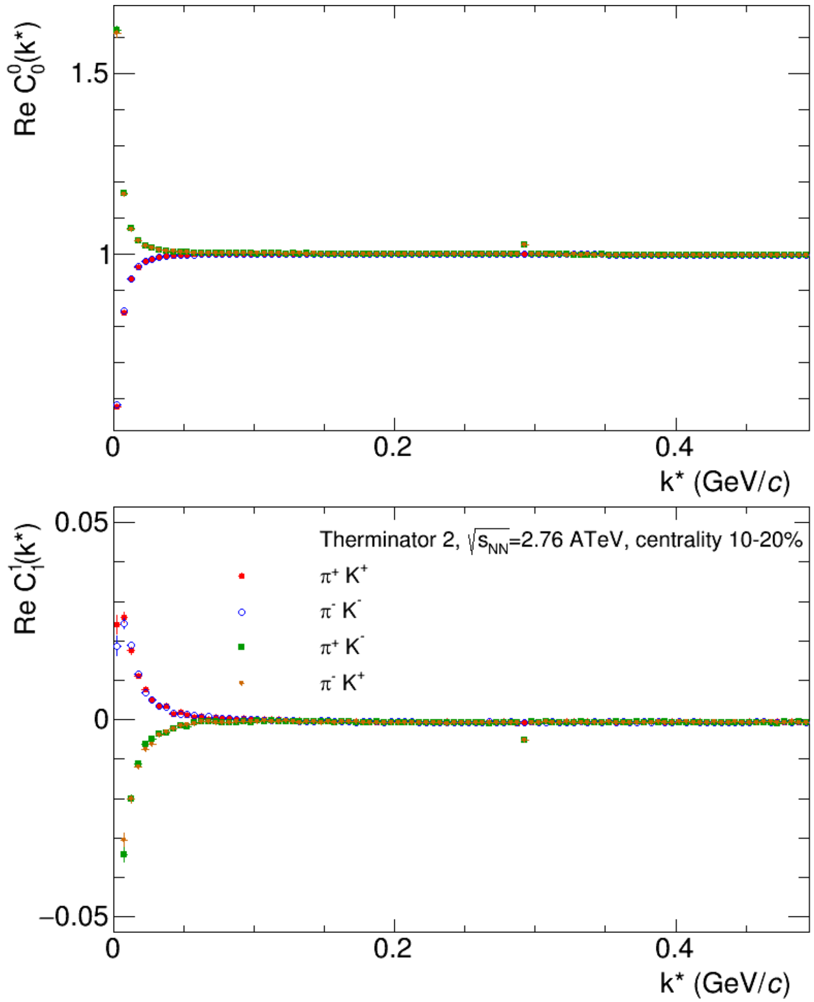
Pions $\langle x_{out}^{\pi} \rangle$	Kaons $\langle x_{out}^{K} \rangle$	Protons $\langle x_{out}^{p} \rangle$
2.83 fm	4.47 fm	5.61 fm

Asymmetry: $\langle r_{out}^{\pi K} \rangle \approx \langle x_{out}^{\pi} \rangle - \langle x_{out}^{K} \rangle$

- Heavier particles (resonances) are pushed even further out
- Significant difference between particles' average emission points at same velocity, different mass

AK, PRC 81 (2010) 064906

Pion-kaon in correlation from Coulomb

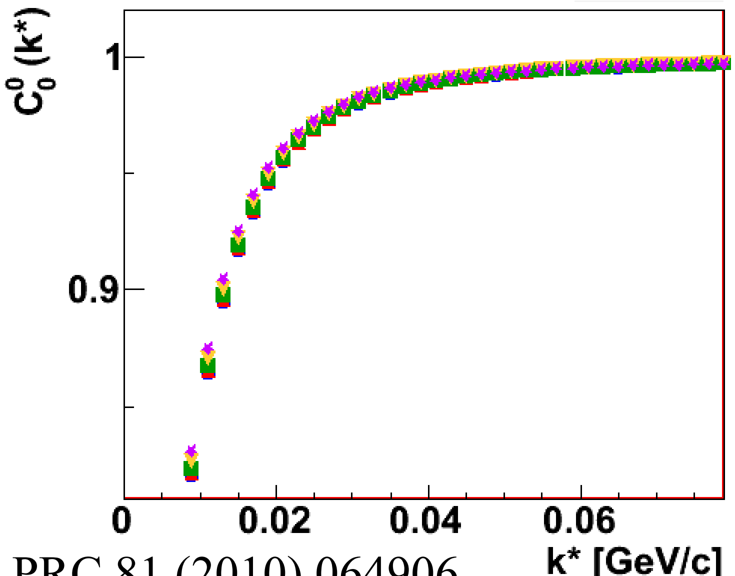


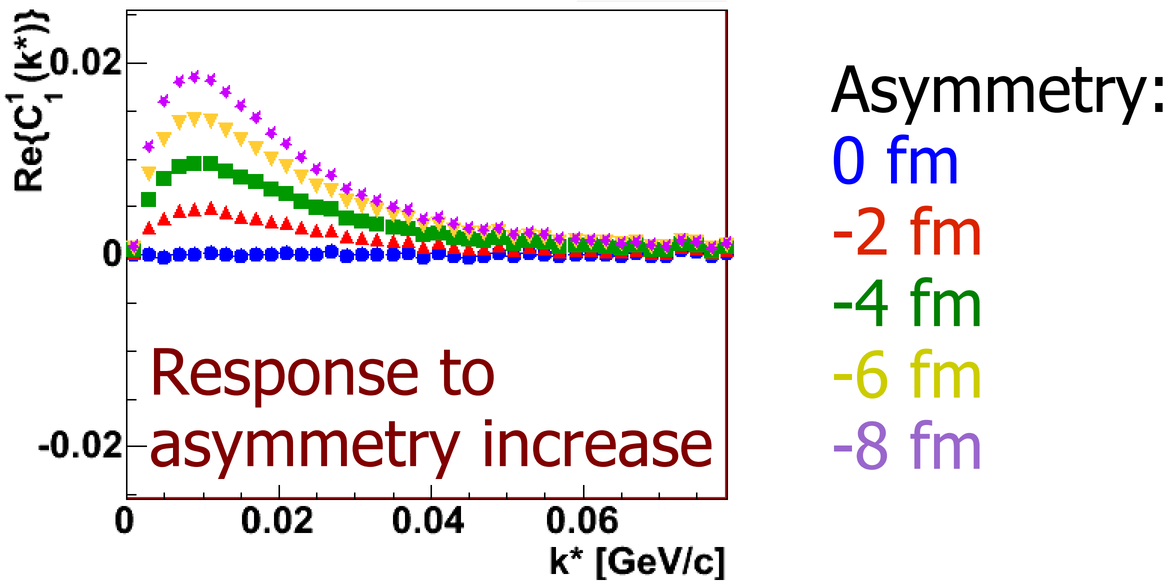
- The pion-kaon correlation dominated by Coulomb (effect is quite narrow and opposite for same-sign and opposite-sign pairs)
- Only the l=0,m=0 and l=1,m=1 real components sufficient for analysis
- l=0,m=0 component sensitive to overall system size
- l=1,m=1 component maximizes sensitivity to emission asymmetry
- Higher l – finer details of correlation – not analyze here

$$C_l^m(q) = \int C(\vec{q})\, Y_l^m(\cos(\theta), \phi)\, d\phi\, d\cos(\theta)$$

Sensitivity to emission asymmetries

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



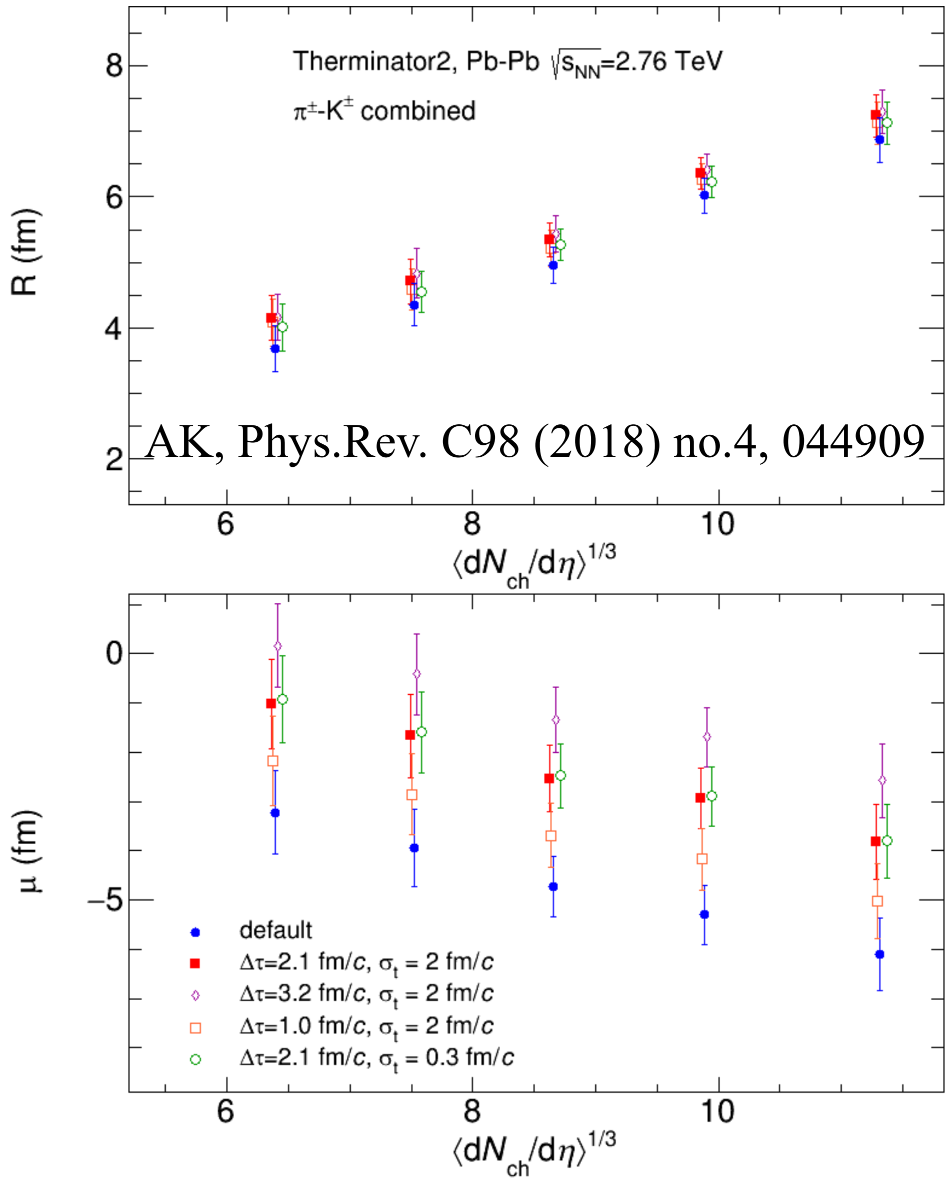


AK, PRC 81 (2010) 064906

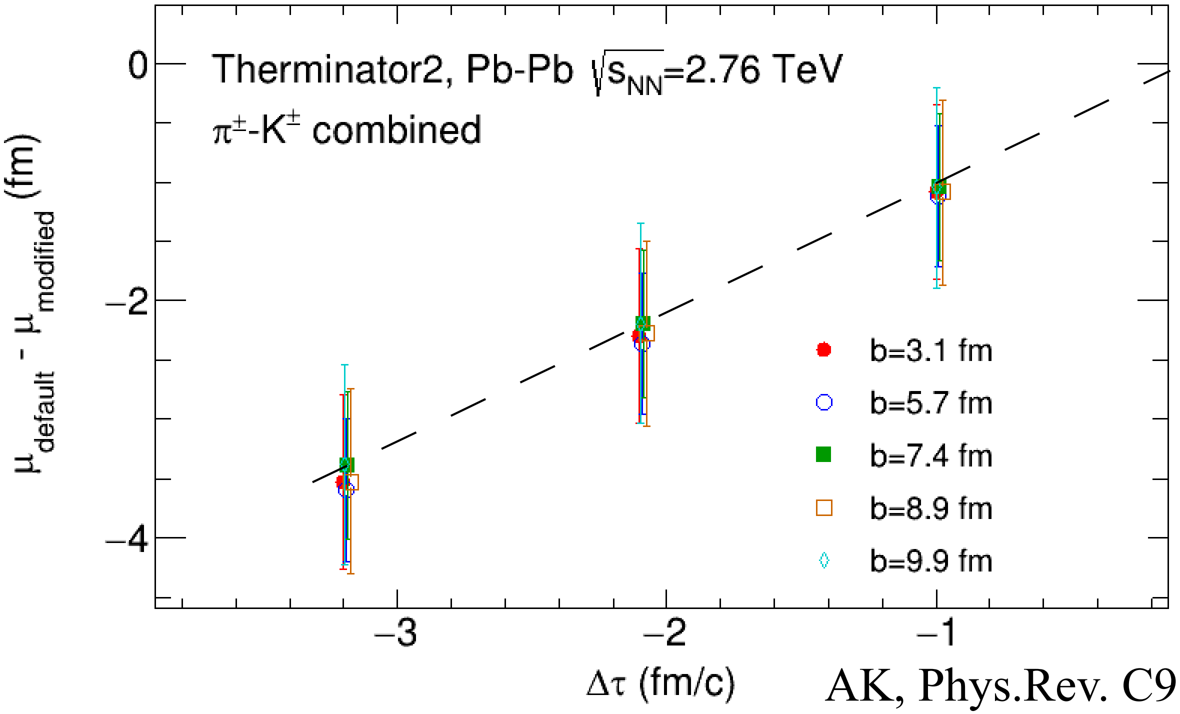
- Increasing emission asymmetry mainly affects Re$\{C_1^1\}$
- No asymmetry gives flat Re$\{C_1^1\}$
- Fitting the two components allows to extract asymmetry

Simulations in Therminator2

- Introduce “ad-hoc” time delay to mimic rescattering
- Introduction of time delay has little influence on size. Width of time delay dist. also small effect
- Emission asymmetry directly sensitive to time delay introduced in the calculation, as expected
- Direct measurement of emission time delays possible also for heavy-ion environment with flow (but model dependent)



Linearity of response

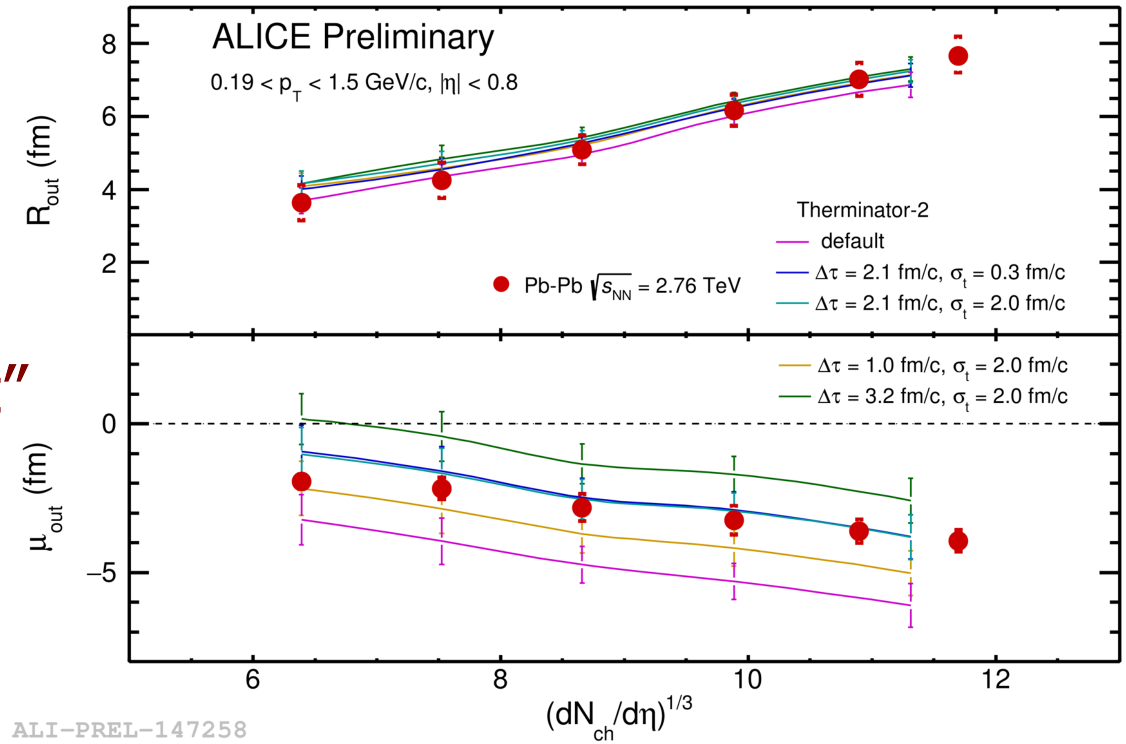


AK, Phys.Rev. C98 (2018) no.4, 044909

- Difference between “default” calculation and one with time delay plotted vs. the introduced time delay
- Clear monotonic, linear, one-to-one correspondence observed, regardless of the system size. Very robust probe.

Comparison to data

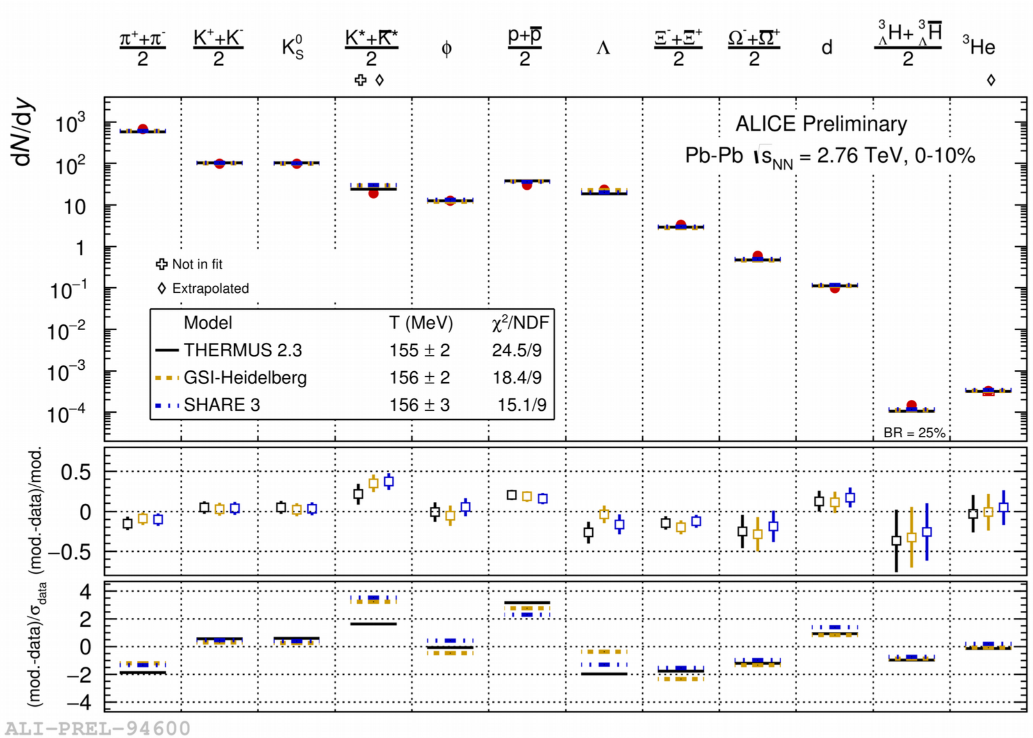
- ALICE has shown first pion-kaon results from LHC at QM2018
- System size well reproduced (similarly to identical pion and kaon femtoscopy)
- Emission asymmetry in “default” case larger than in data
- Asymmetry with 2.1 fm/c kaon delay consistent with data: internal consistency with identical kaon femtoscopy

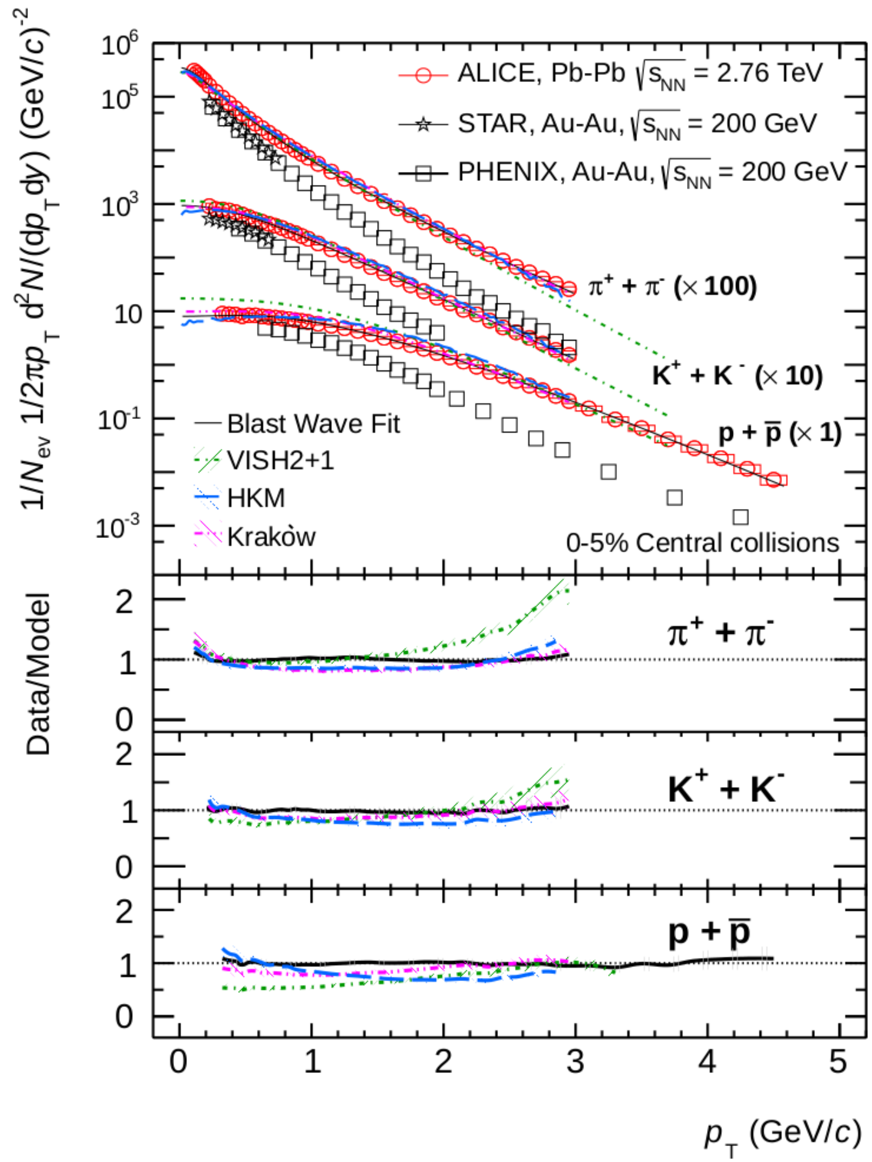


Ashutosh K. Pandey (ALICE); QM2018

(Anti-)Baryon production in HIC

- Similar no. of baryons and anti-baryons produced at RHIC and LHC, at low-p_T, PID needed (STAR, ALICE)
- HIC are matter-antimatter pair factories (p, Λ, Ξ, Ω, …)





Baryon femtoscopy

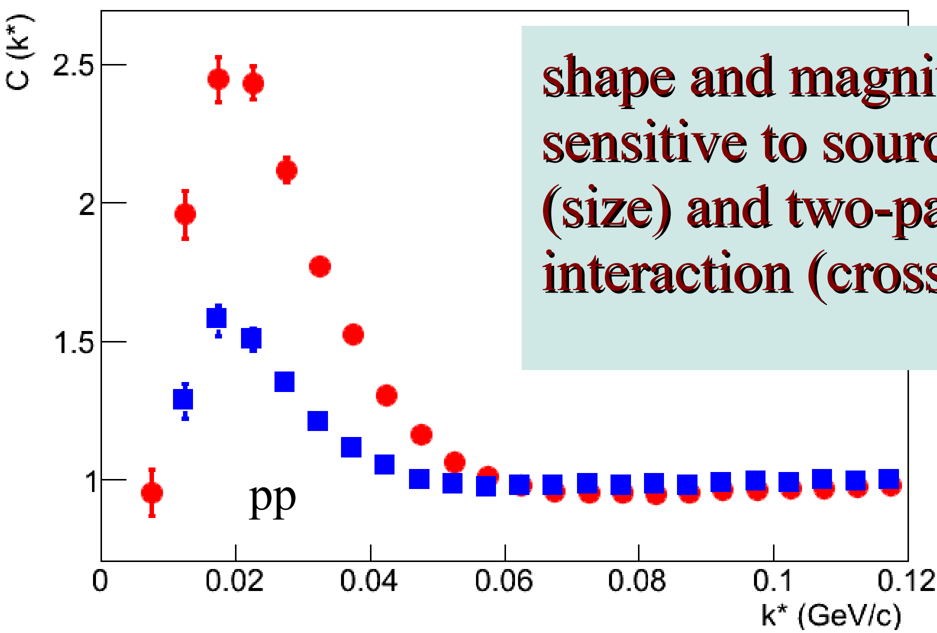
- Femtoscopy: use two-particle correlation function C and known interaction Ψ to extract information on the source emission function S

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

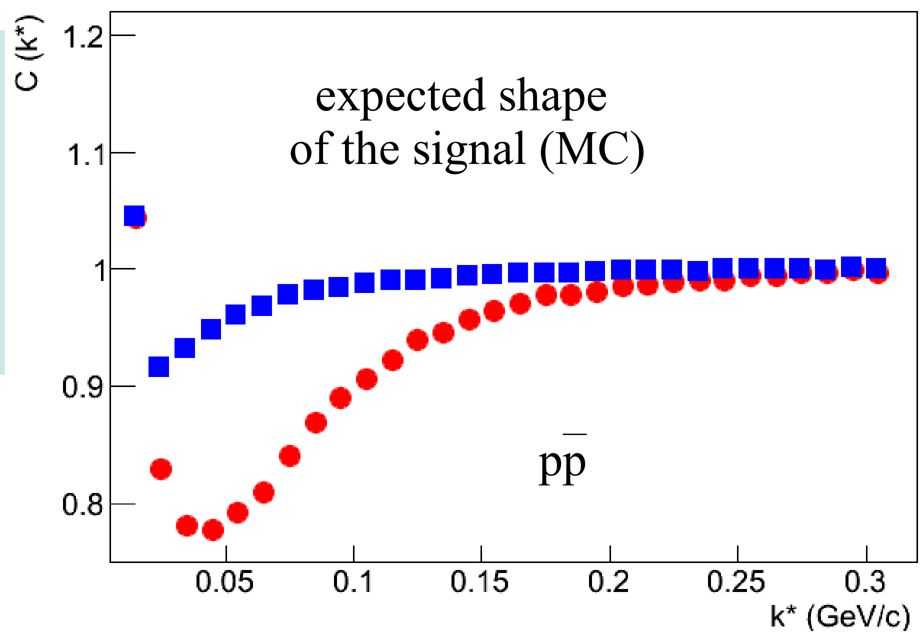
measured correlation

emission function (radius)

cross-section

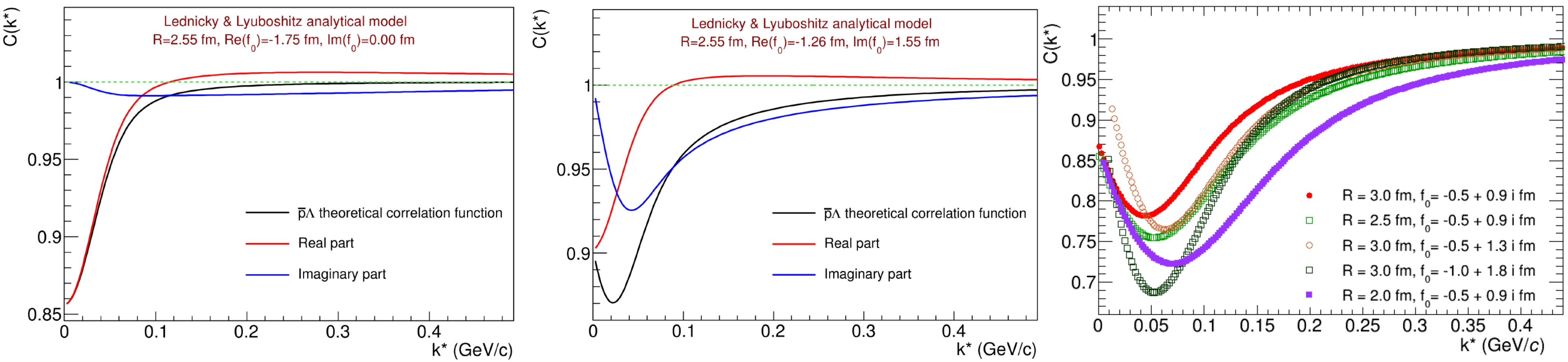


shape and magnitude sensitive to source shape (size) and two-particle interaction (cross-section)



- The procedure can be reversed: study Ψ with known S

L&L model: analytic CF for strong int.

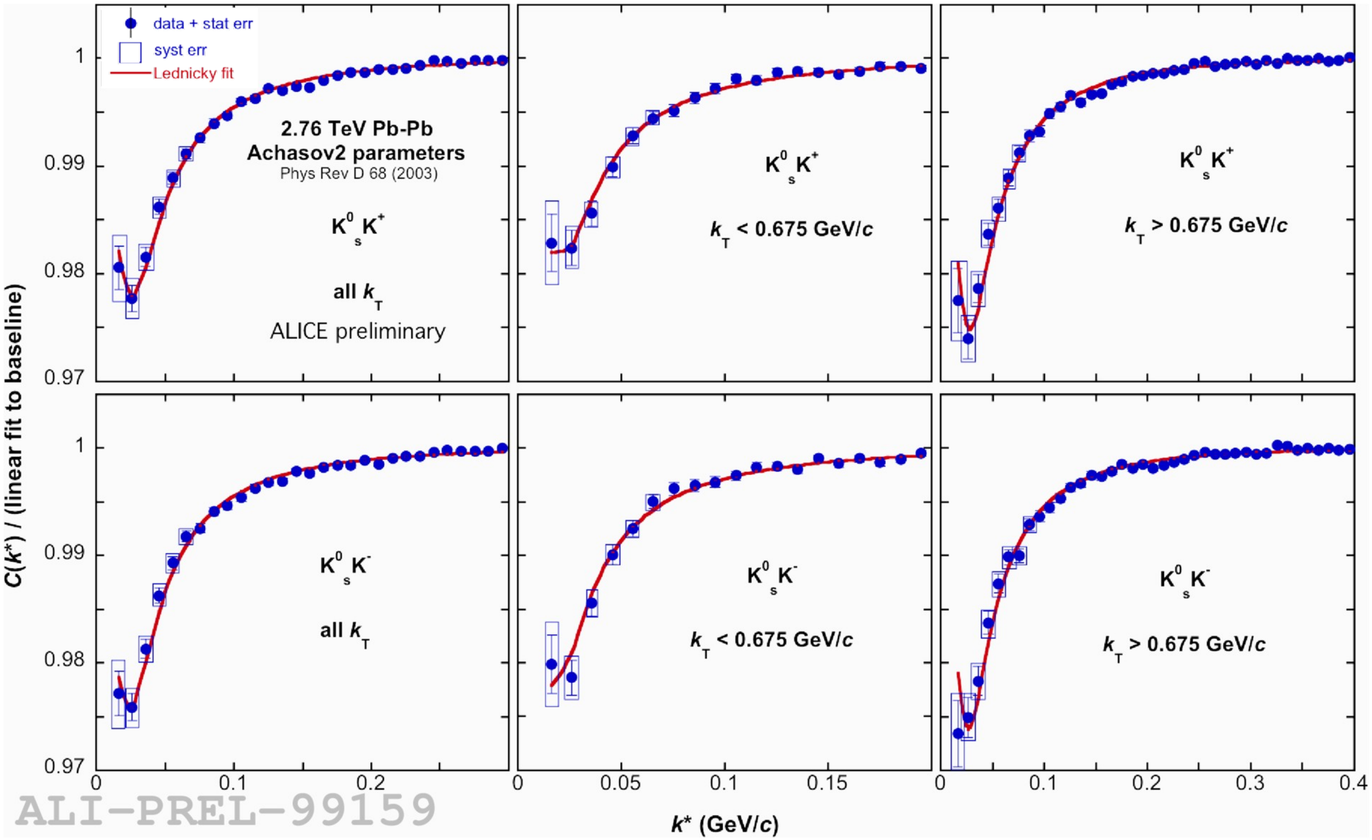


$$C(k^*) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k^*)}{r_0} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi} r_0} \right) + \frac{2 \Re f^S(k^*)}{\sqrt{\pi} r_0} F_1(Q r_0) - \frac{\Im f^S(k^*)}{r_0} F_2(Q r_0) \right]$$

- A sharp peak (depression) at low k^*, for positive (negative) value of Re(f_0) (width – up to 100 MeV/c)
- A broad depression at larger k* for non-zero values of Im(f_0) (baryon annihilation) (width – several hundred MeV/c)

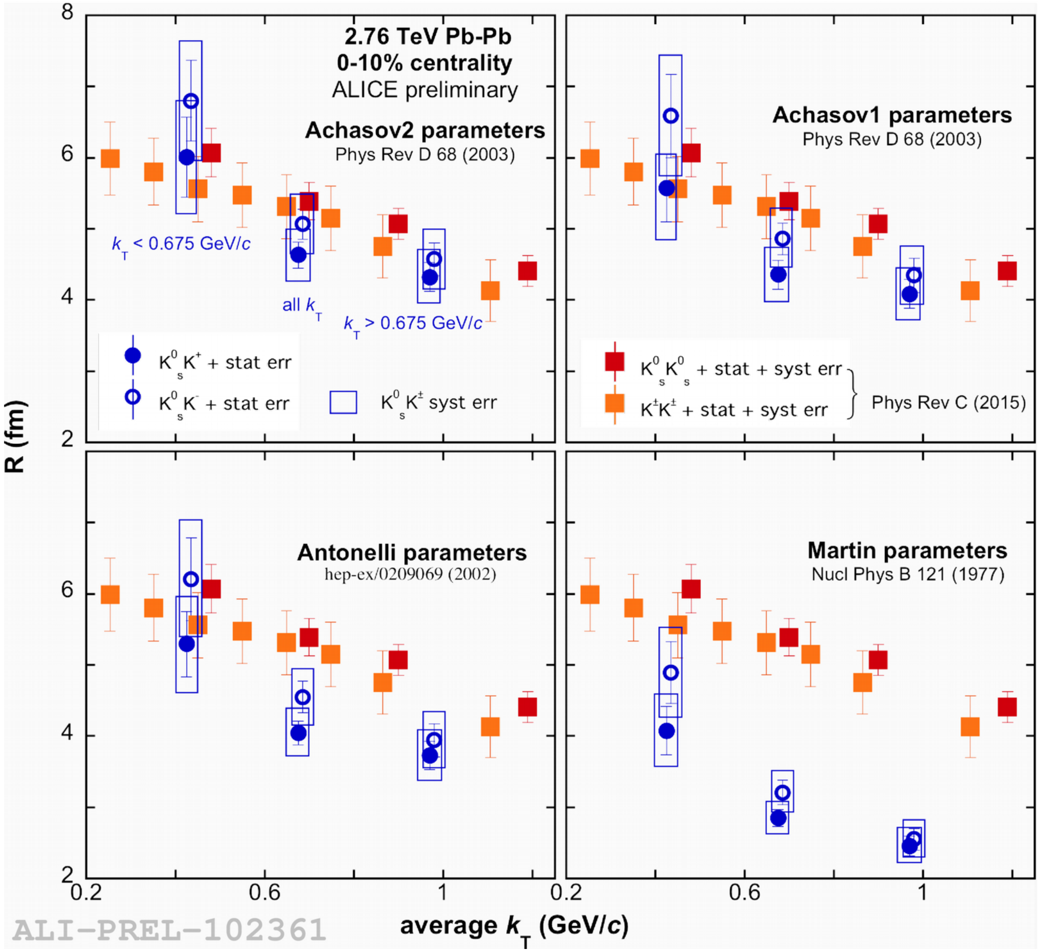
R. Lednicky and V. L. Lyuboshits, Sov. J. Nucl. Phys. 35, 770 (1982).

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

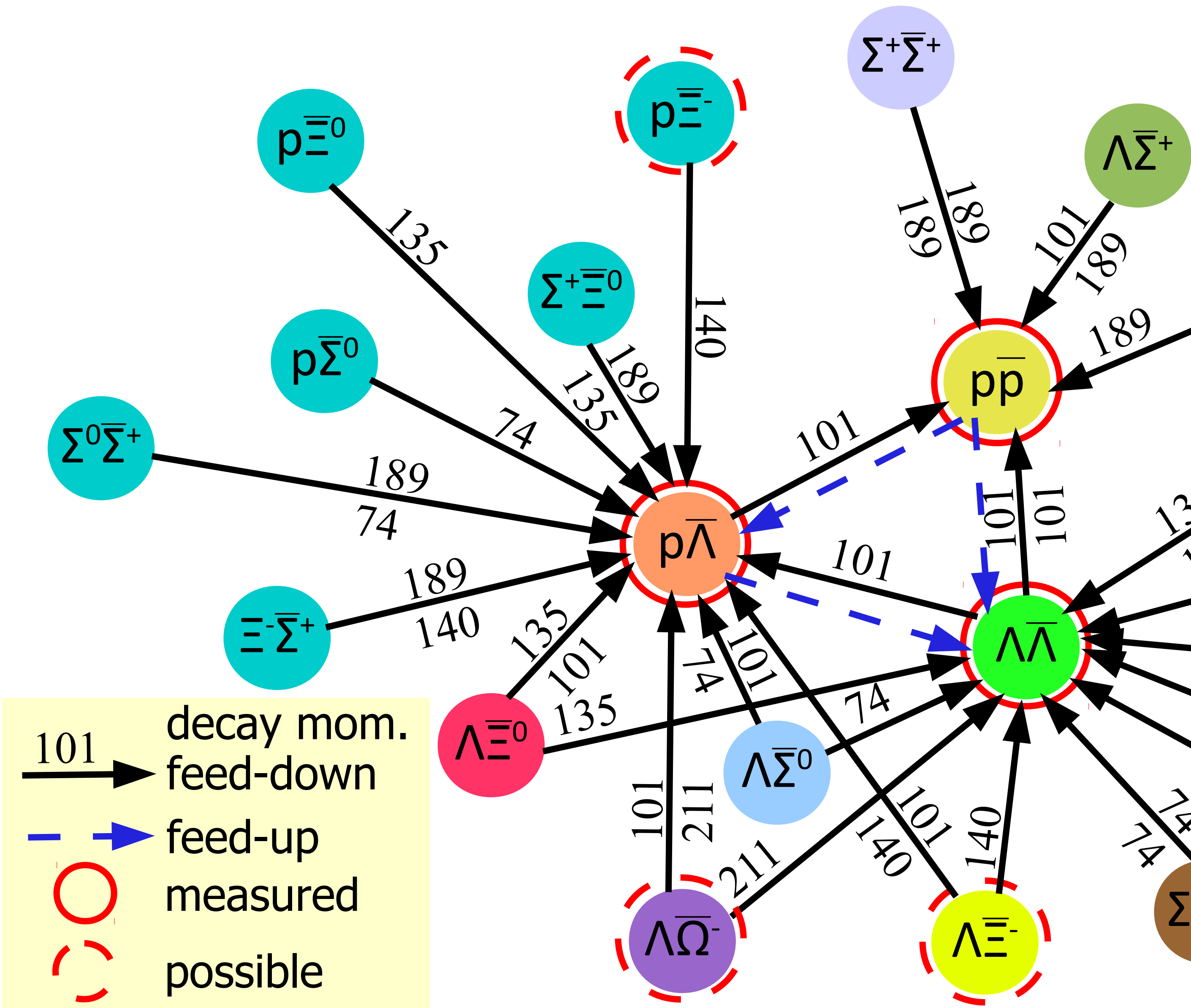


- Radii for K^0_S-K^{ch} expected same as in K^0_S-K^0_S and K^{ch}-K^{ch}
- ALICE data favors Achasov a_0 resonance parameters

Measuring $B\bar{B}$ in ALICE

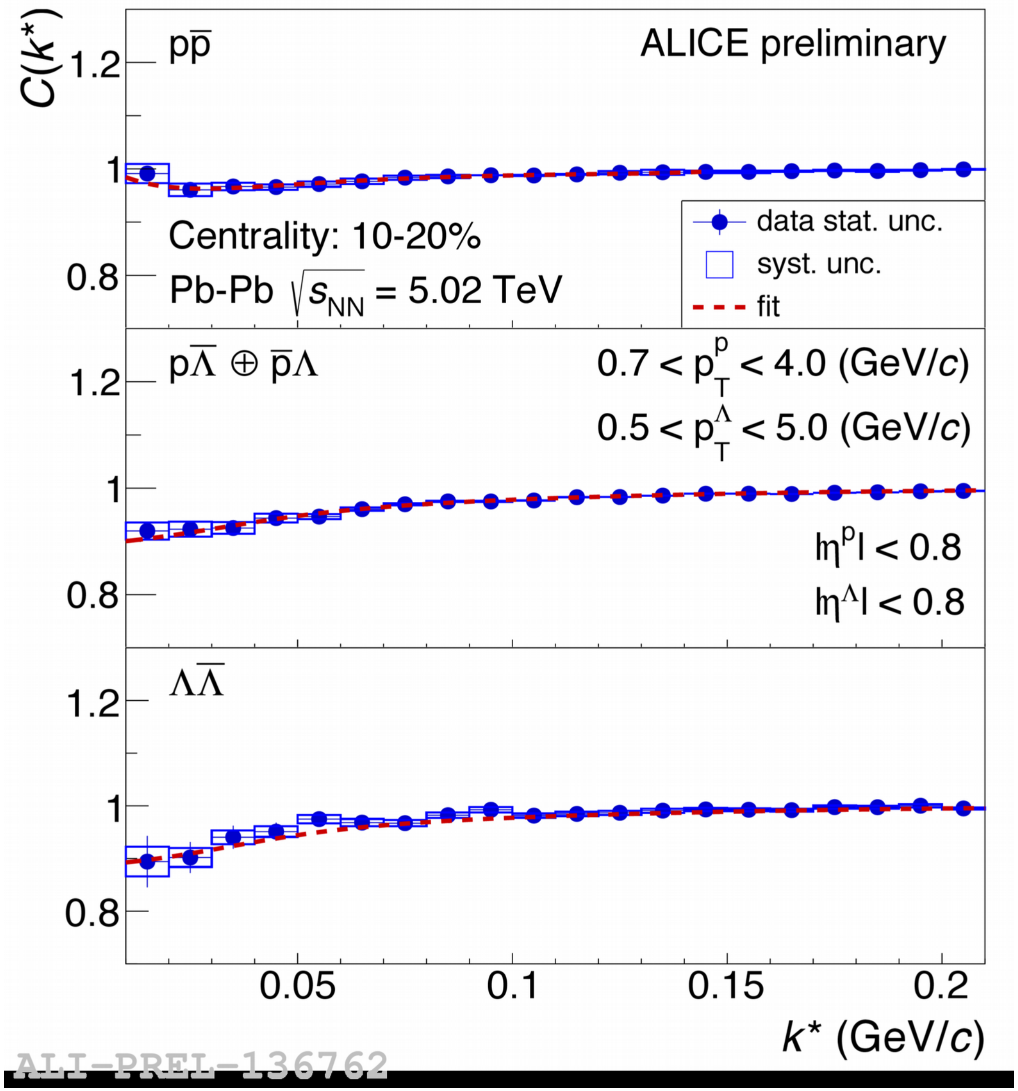
- Recent ALICE measurement of baryon-(anti-)baryon correlations
  - 6 centralities, 2 collision energies, 3 baryon-antibaryon systems (+3 baryon-baryon as well, not shown here)
- Employed dedicated PID procedures of ALICE
  - Protons measured directly in TPC, also used TOF for PID
  - Lambdas measured via V0 decay topology with TPC, PID enhanced by TOF as well
- Complete set of $p\bar{p}$, $p\bar{\Lambda}$, $\Lambda\bar{\Lambda}$ correlation functions
  - In fitting – used spin-averaged (f_0, d_0), separate sets for $p\bar{\Lambda}$, $\Lambda\bar{\Lambda}$ and a separate set for all higher-mass residual pairs

Residual correlation web



- Significant interlinks between many pair combinations

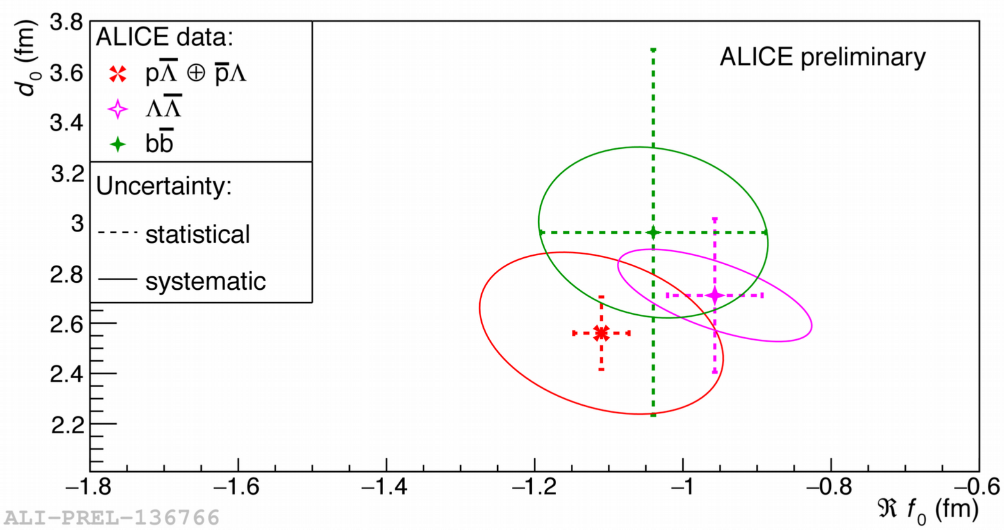
Baryon-Antibaryon in ALICE

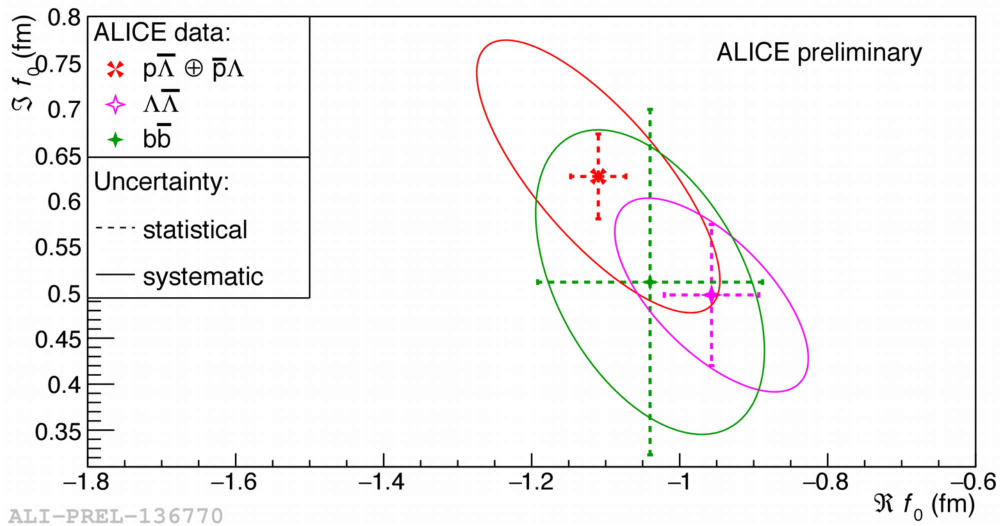


L. Barnby (ALICE), EXA 2017
Ł. Graczykowski (ALICE), ISMD 2017

- All combinations of baryon-antibaryon correlation functions with pairs containing protons and lambdas
- Fit fully including the web of residual correlations
- Combined fit to 6 centralities x 2 collision energies x 3 systems
- Interaction parameters free in the fit (3 sets)
- Sizes constrained to m_T scaling predictions

Measurement of strong $B\bar{B}$ interaction

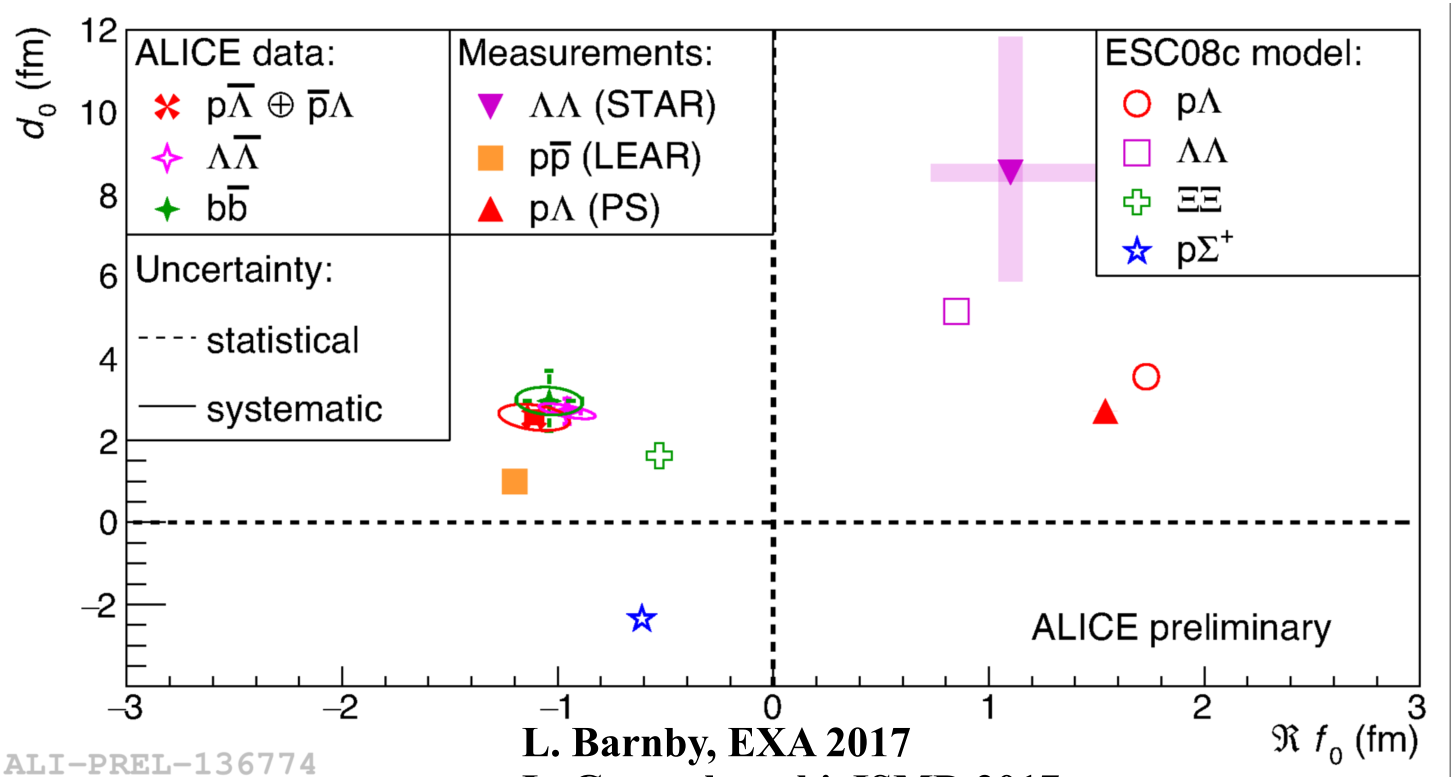




L. Barnby (ALICE), EXA 2017
Ł. Graczykowski (ALICE), ISMD 2017

- Estimation of the scattering length and effective range
- Assumption of d_0=0 not necessary
- Non-zero negative value of the real part of f_0
- Non-zero value of imaginary part of f_0 (annihilation), comparable for all pair types

Comparison to other measurements



L. Barnby, EXA 2017
Ł. Graczykowski, ISMD 2017

- ALICE measurement competitive in accuracy to world data on baryon-antibaryon interaction
- Real part of f_0 for baryon-antibaryon – comparable value but opposite sign to baryon-baryon

Summary

- Femtoscopy a significant part of the physics message from STAR and ALICE – similar possibilities for MPD
- Sensitivity to first order phase transition of identical pion femtoscopy – used in STAR and ALICE, can be cross-checked in MPD
- Non-identical particle correlations sensitive to emission time ordering and the existence and duration of hadronic rescattering phase
- Unique possibility to study baryon and antibaryon interaction – especially interesting in the maximum baryonic potential environment at MPD