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

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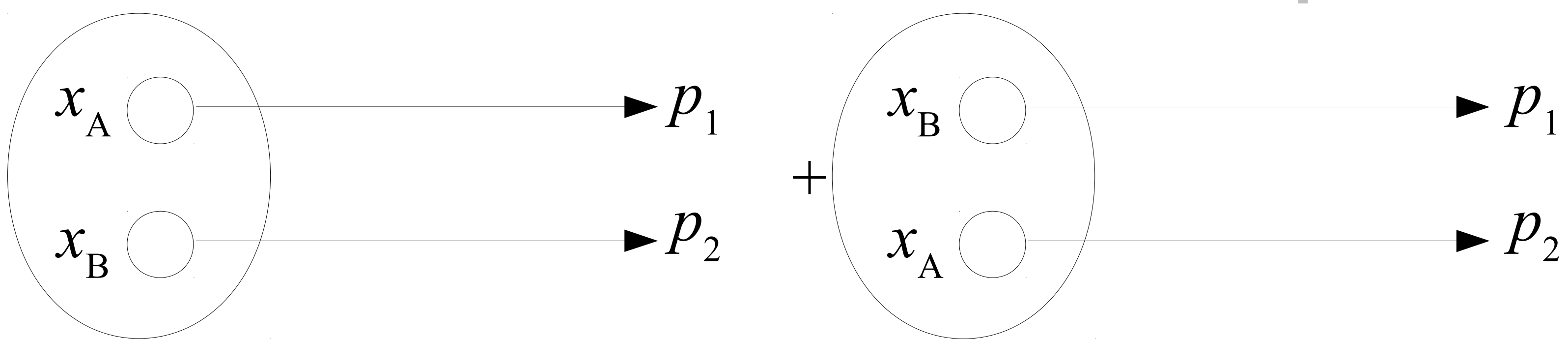
Overview

- 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
  - Hydro predictions for the LHC
  - Azimuthally sensitive femtoscopy
  - Femtoscopy in small systems
- Femtoscopy of heavier particles
  - What more can we learn from baryon correlations
  - Importance of residual correlations

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)

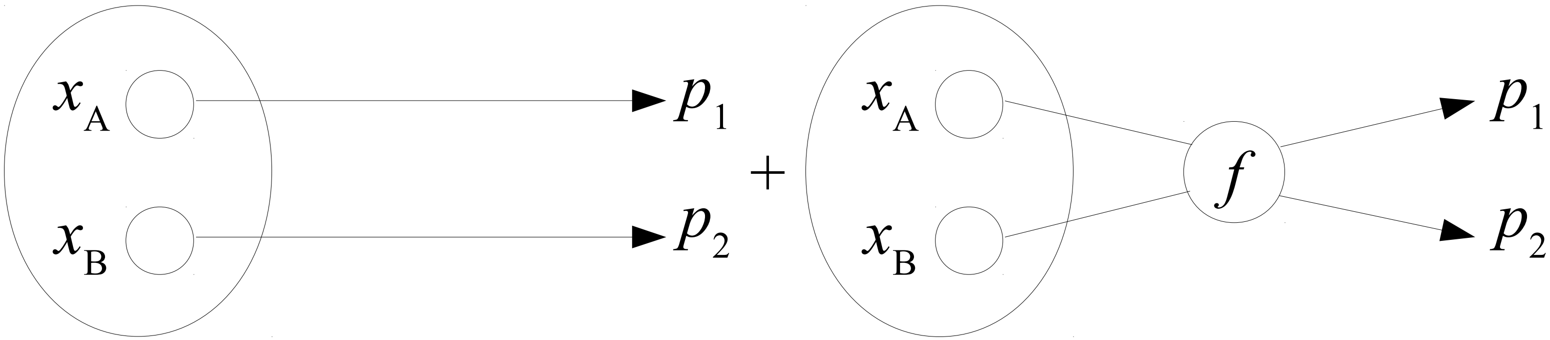
$$\Psi = \frac{1}{\sqrt{2}}\left[\exp(-i\,p_1 x_A - i\,p_2 x_B) + \exp(-i\,p_1 x_B - i\,p_2 x_A)\right]$$

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

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

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

Correlation – hadrons



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

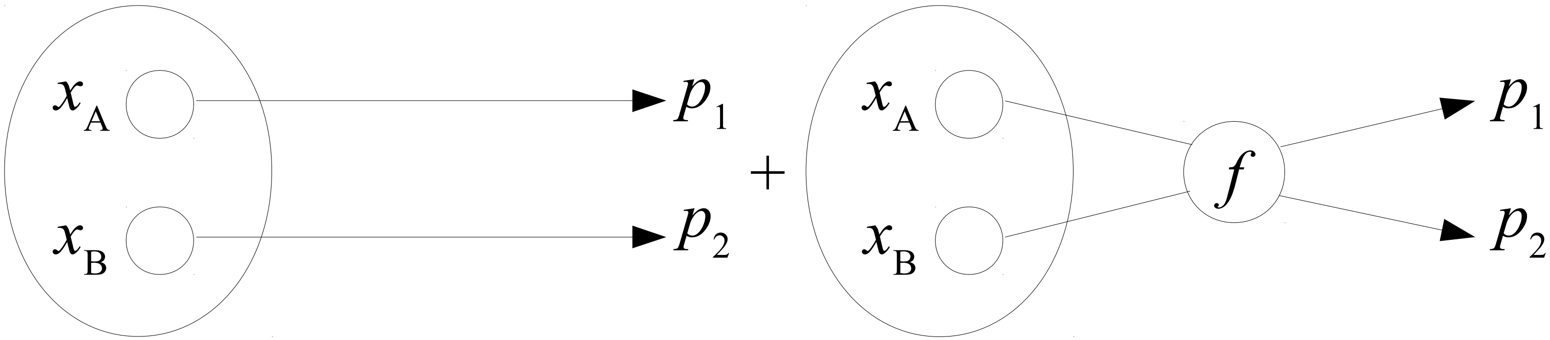
$r = x_A - x_B$

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

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

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

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

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

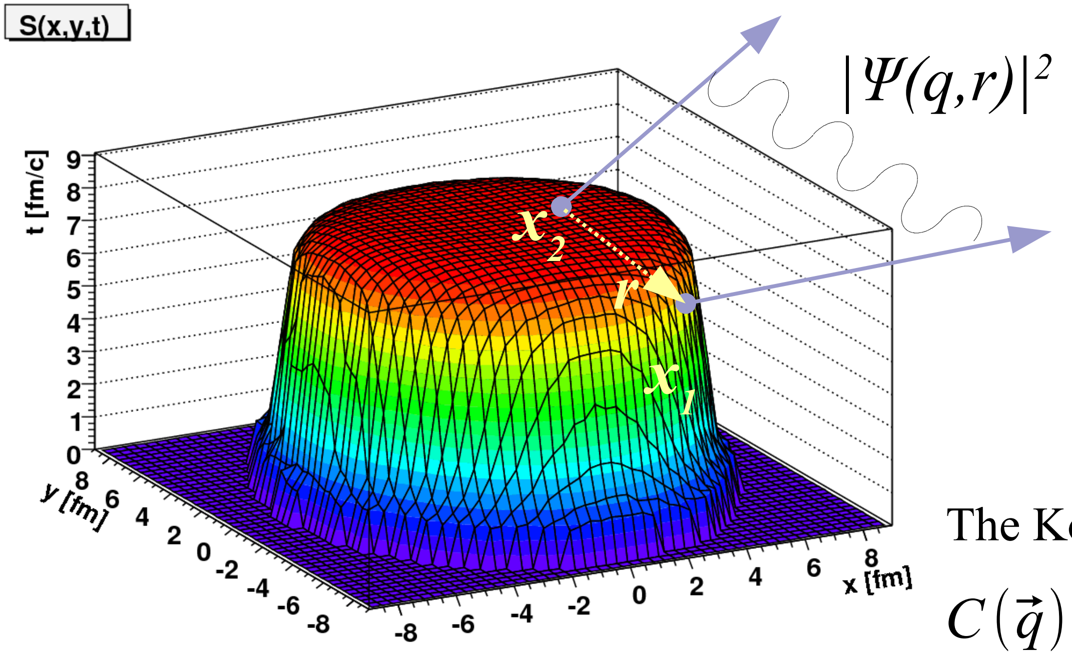
Gamow factor — Coulomb part — Strong+Coulomb part

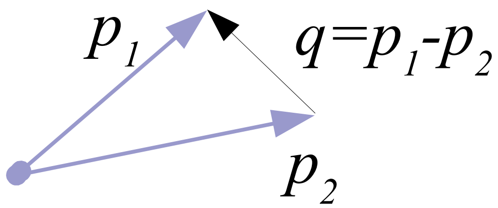
$$\xi = \boldsymbol{k}^*\boldsymbol{r}^* + k^*r^* \equiv \rho(1+\cos(\theta^*)),\quad \rho = k^*r^*,\quad \eta = (k^*a)^{-1},\quad a = (\mu z_1 z_2 e^2)^{-1}$$

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

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

Measuring space-time extent: femtoscopy





The Koonin-Pratt (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:

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

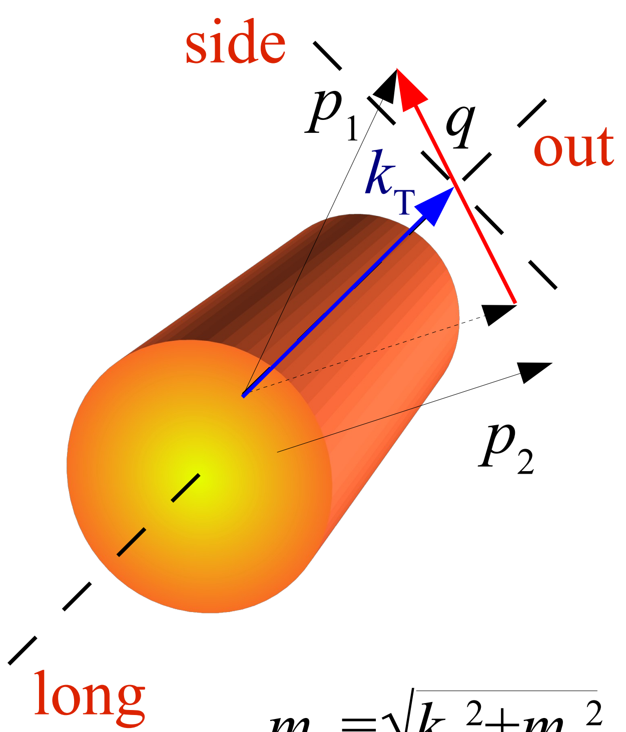
- For identical pions coulomb factor K is factorized out, Ψ is then $1+\cos(qr)$. Then KP gives the femtoscopic part of CF:

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

  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):

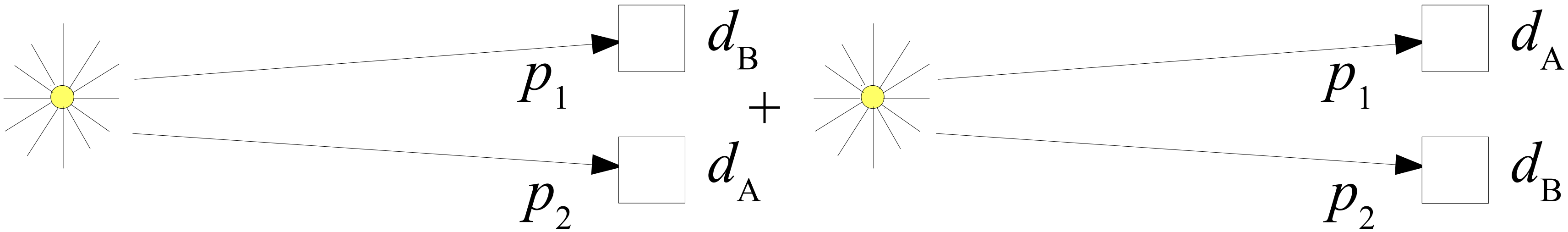
$$p_{1,long} = -p_{2,long}$$

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

Why is it called "HBT" ?



$q = p_1 - p_2$

$d = d_A - d_B$

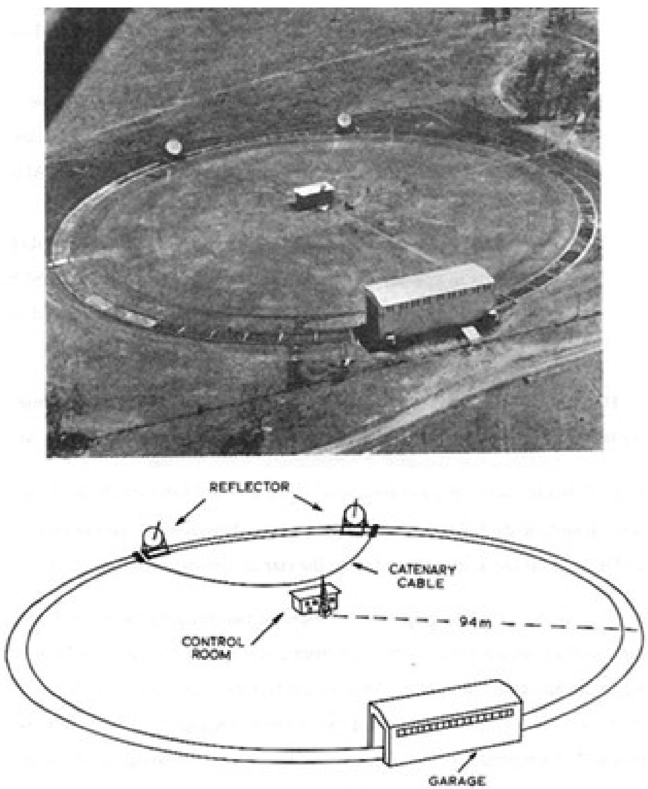


Figure 1. Aerial photo and illustration of the original HBT apparatus. They have been extracted from Ref.[1].

- 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**:

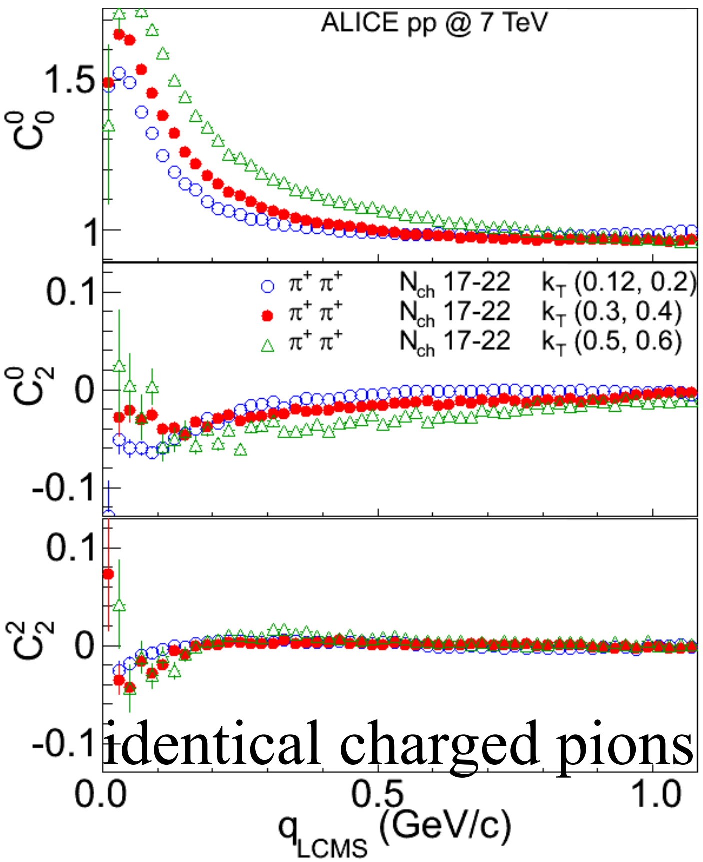
$$C_e(\vec{q}) = S(\vec{q}) / B(\vec{q})$$

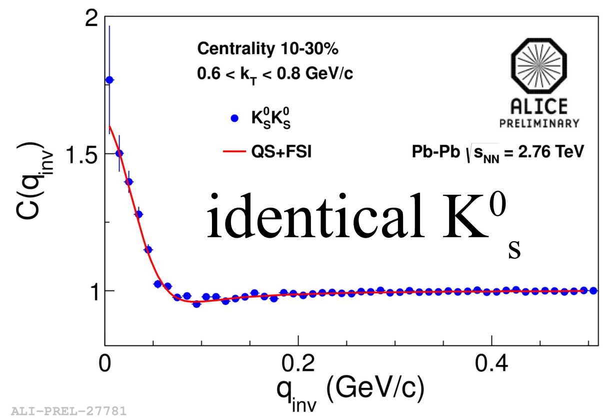
- The "Signal" **S** is a distribution of pairs where both particles come from **the same event**, "background" **B** can be constructed in many ways. Most common is "event mixing" where the two particles come from **two different events**, similar in terms of single-particle acceptance.
- However a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

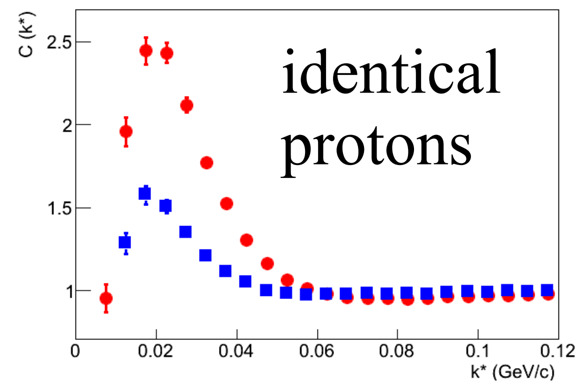
How does it look like?

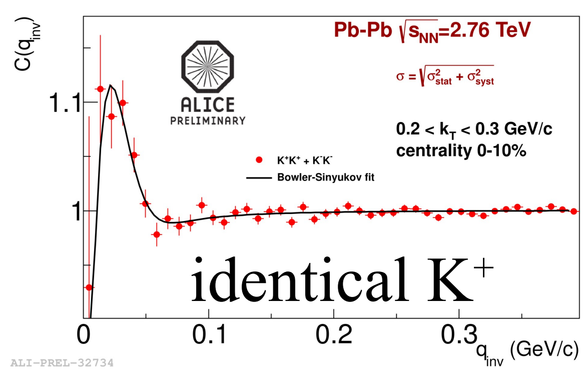
- Various shapes and momentum scales, depending on the pair type (interactions involved), collision system and energy, pair transverse momentum, etc.

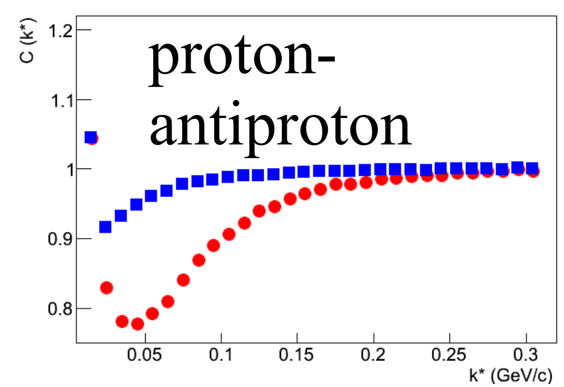
$$e.g: \quad C_e(\vec{q}) = (1-\lambda) + \lambda K(q)[1+\exp(-R^2 q^2)]$$



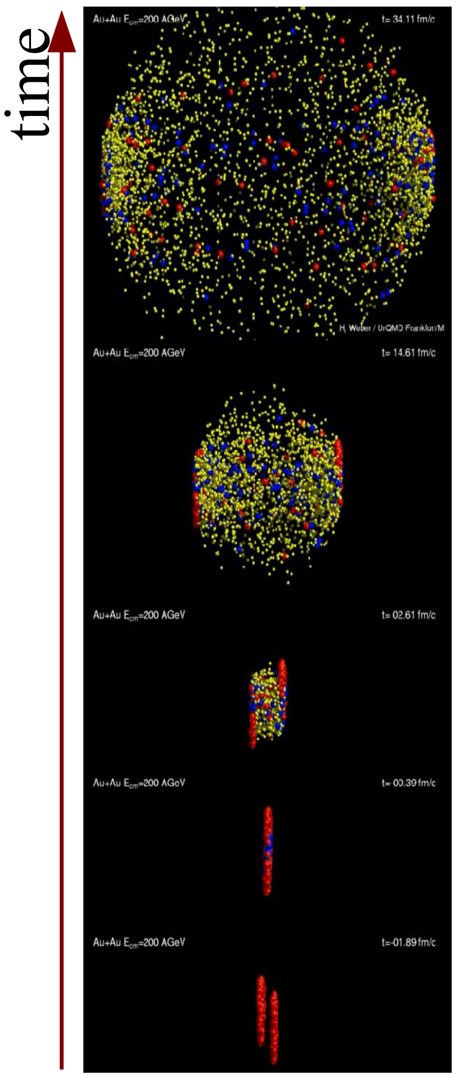


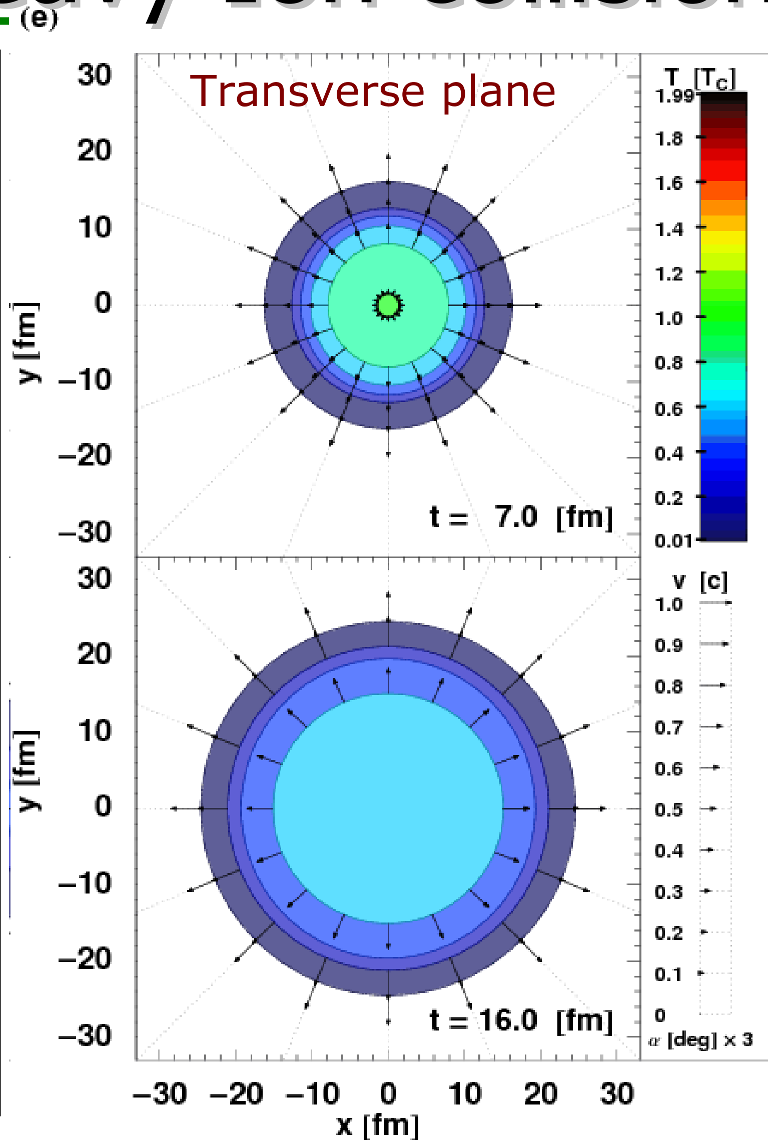






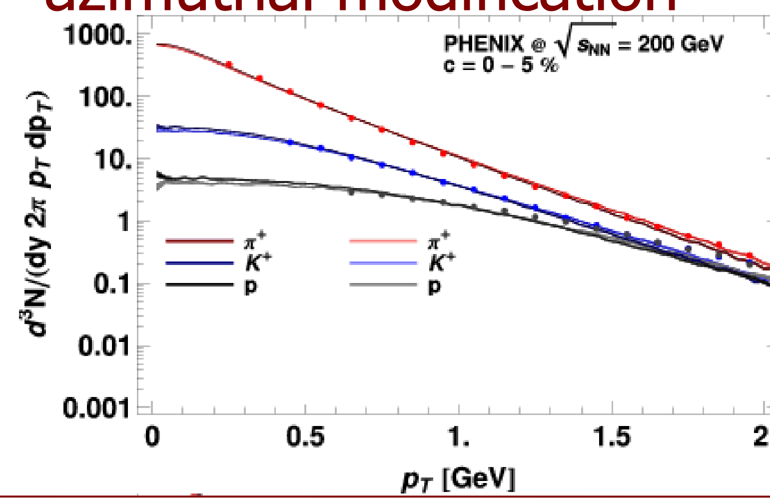
Heavy Ion collision evolution



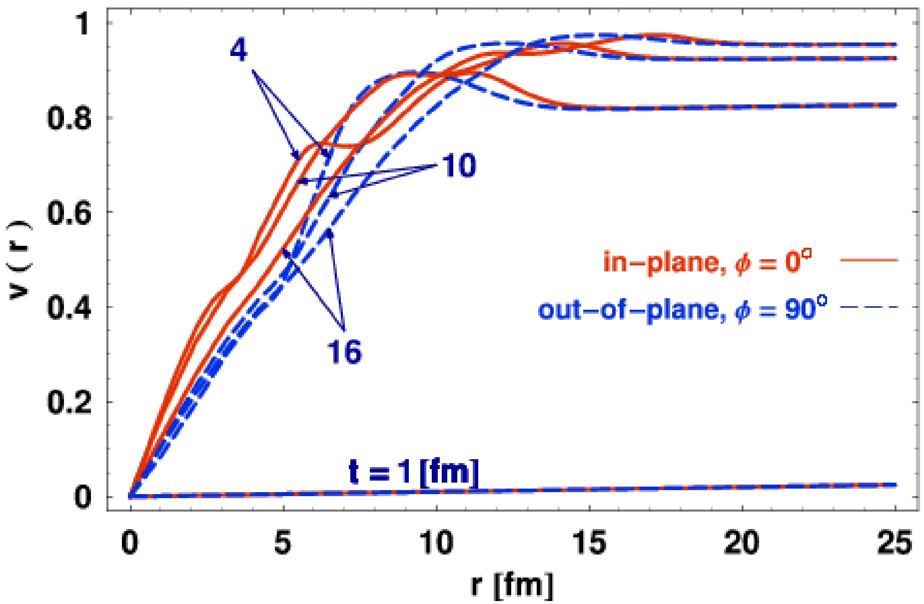


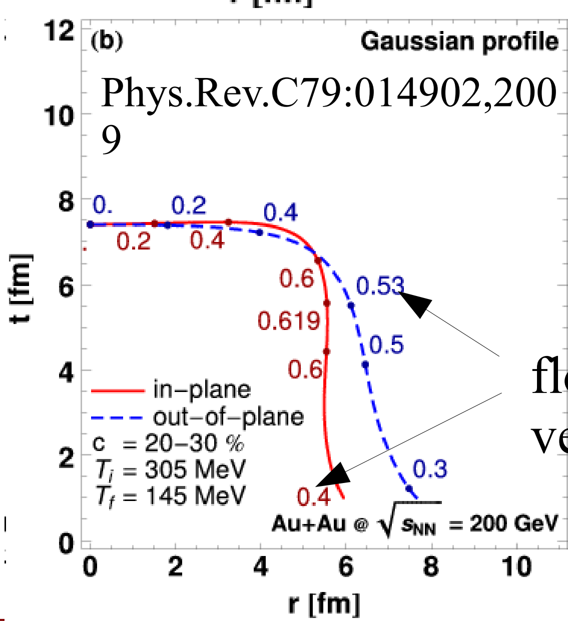
M. Chojnacki, W. Florkowski,
PRC 74 (2006) 034905

- 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



Quantifying collectivity





Phys.Rev.C79:014902,2009

flow velocity

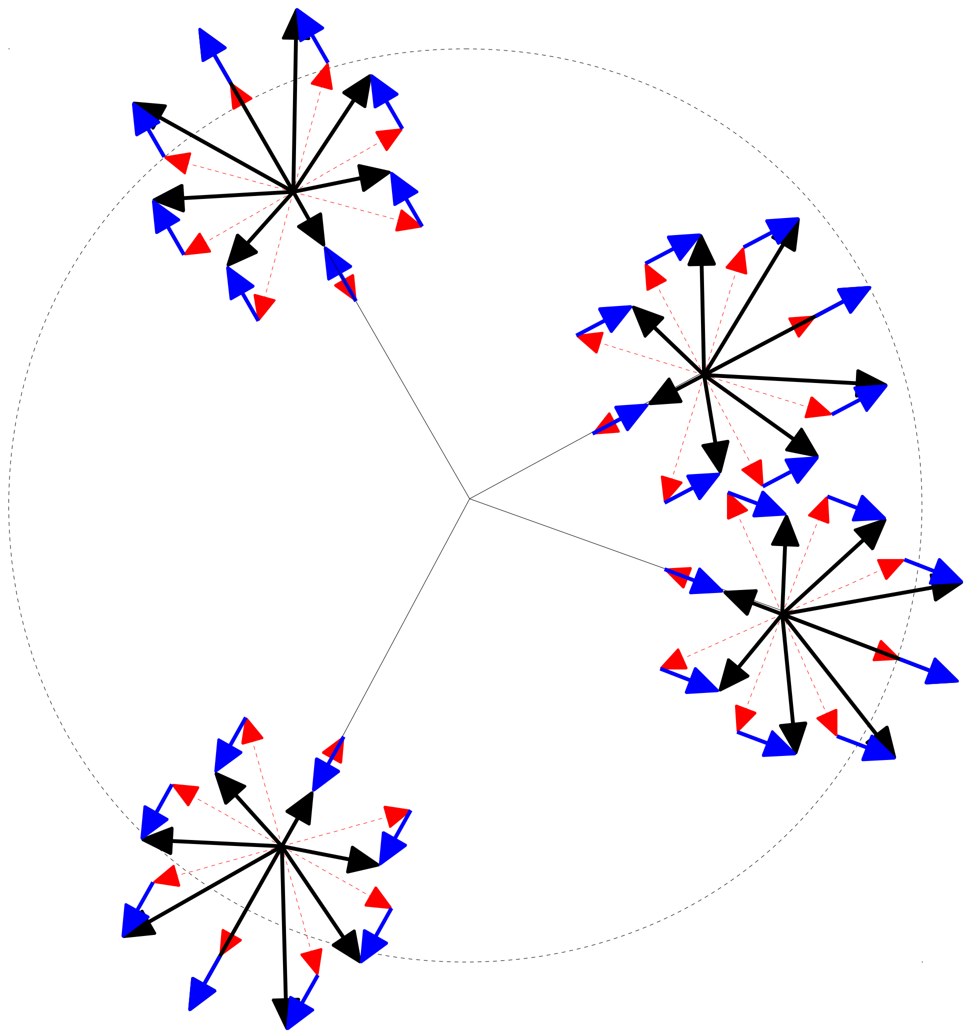
Chojnacki M., Florkowski W.
nucl-th/0603065, Phys. Rev. C74: 034905 (2006)

- Hydrodynamics produces collective flow: common velocity of all particles

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

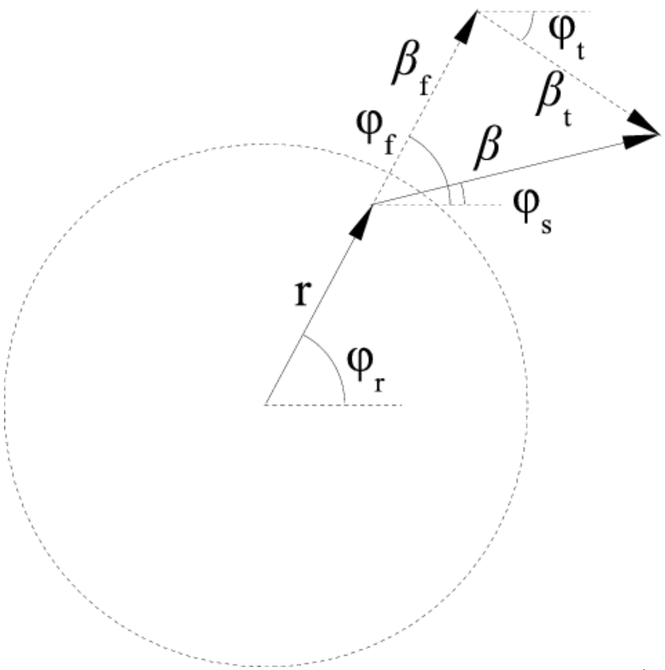
- The process drives the space-time evolution of the system
- For non-central collisions differences between in-plane and out-of plane velocities arise
- Space and time azimuthal evolution closely connected.

Which collectivity do we seek?

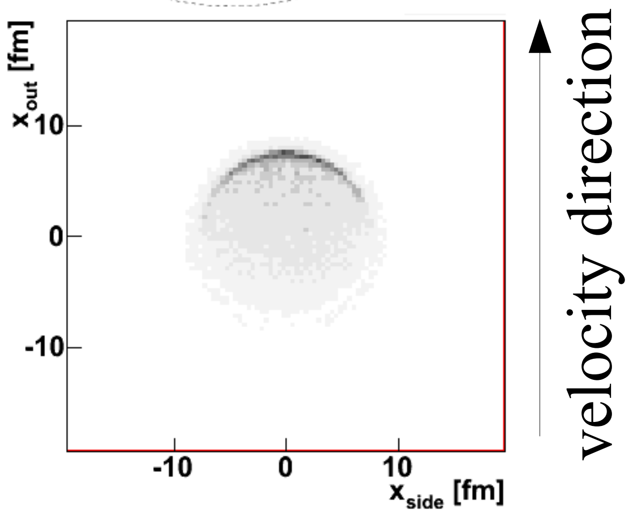


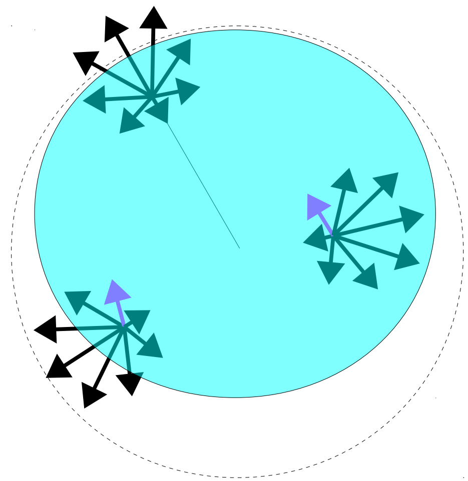
- A collective component is a "common" velocity for all particles emitted close to each other
- To that one adds "thermal" (random) velocity
- We expect specific "common" velocity – radial direction, pointing outwards from the center

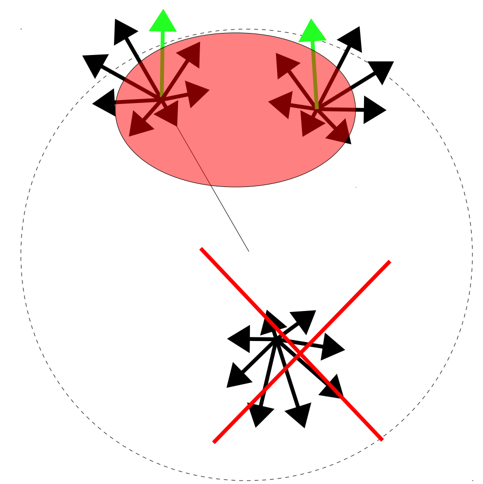
Thermal emission from collective medium



- 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 pairs can be emitted gets smaller and shifted to the outside of the source

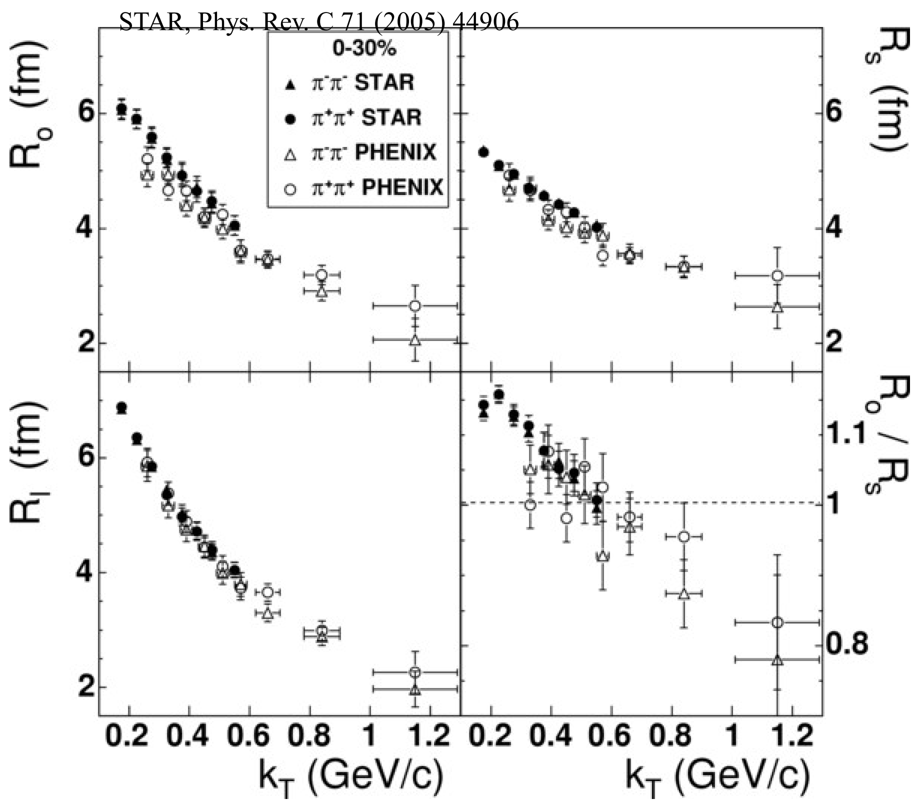


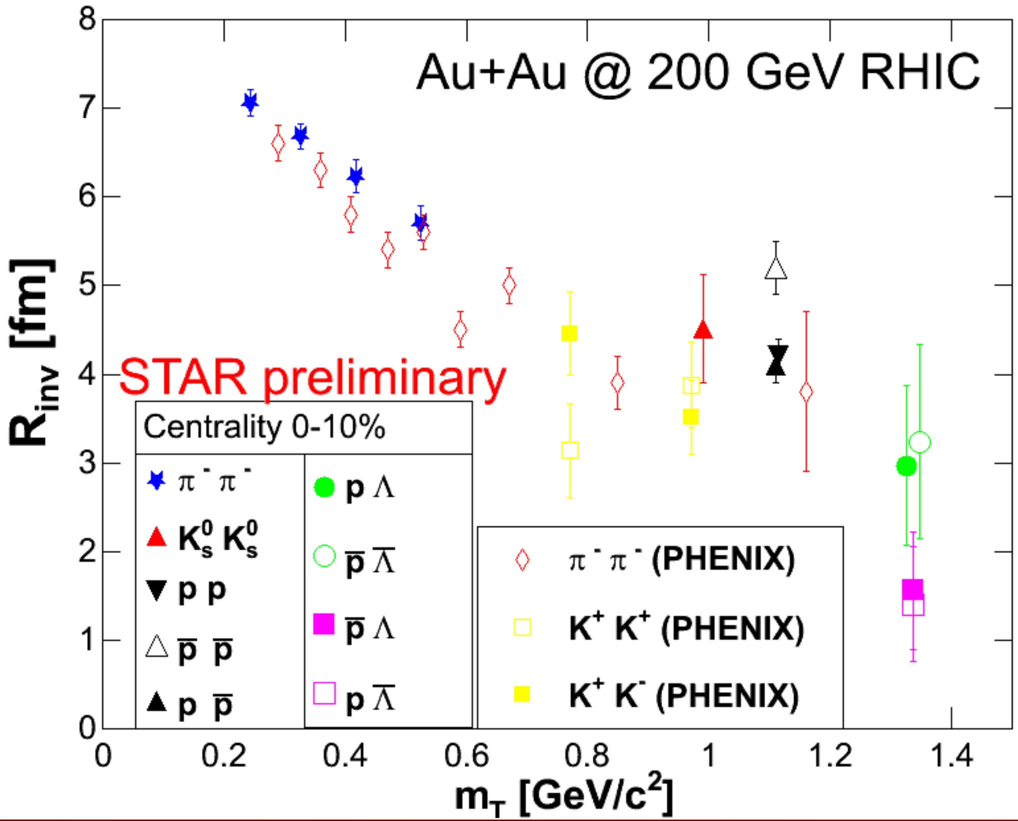




m_T dependence at RHIC

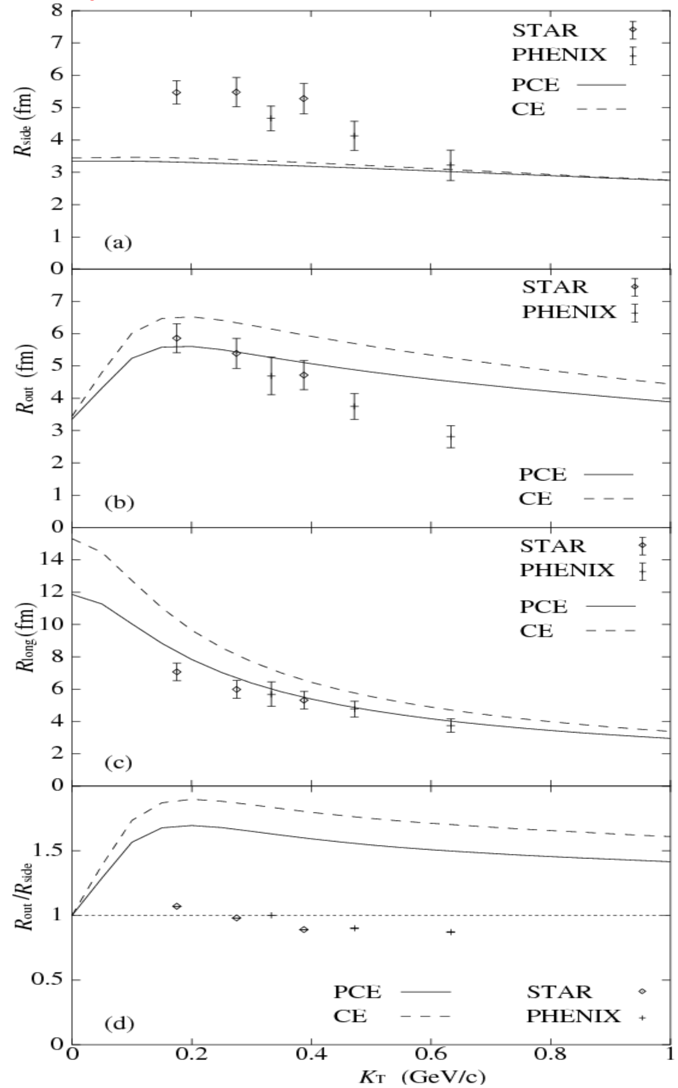
- A clear m_T dependence is observed, for all femtoscopic radii and for all particle types: but is it hydrodynamic like? And can we tell?



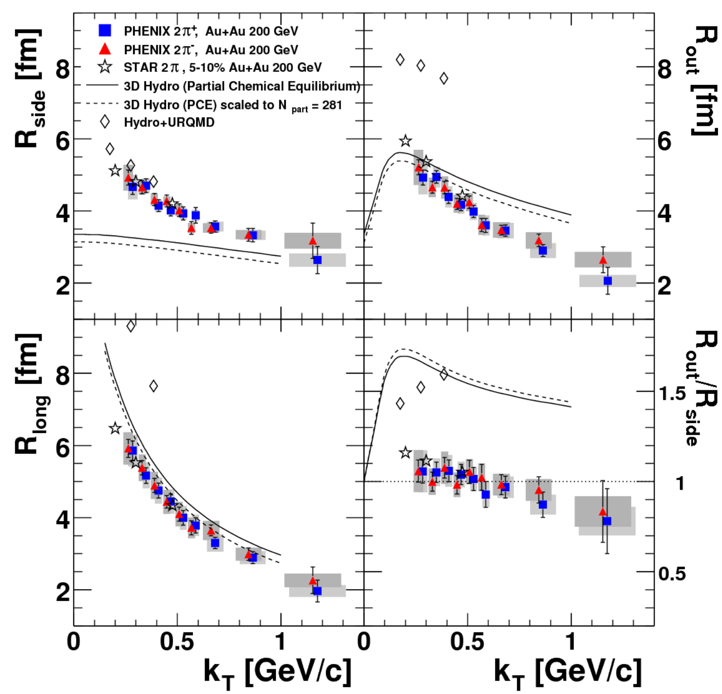


RHIC Hydro-HBT puzzle

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



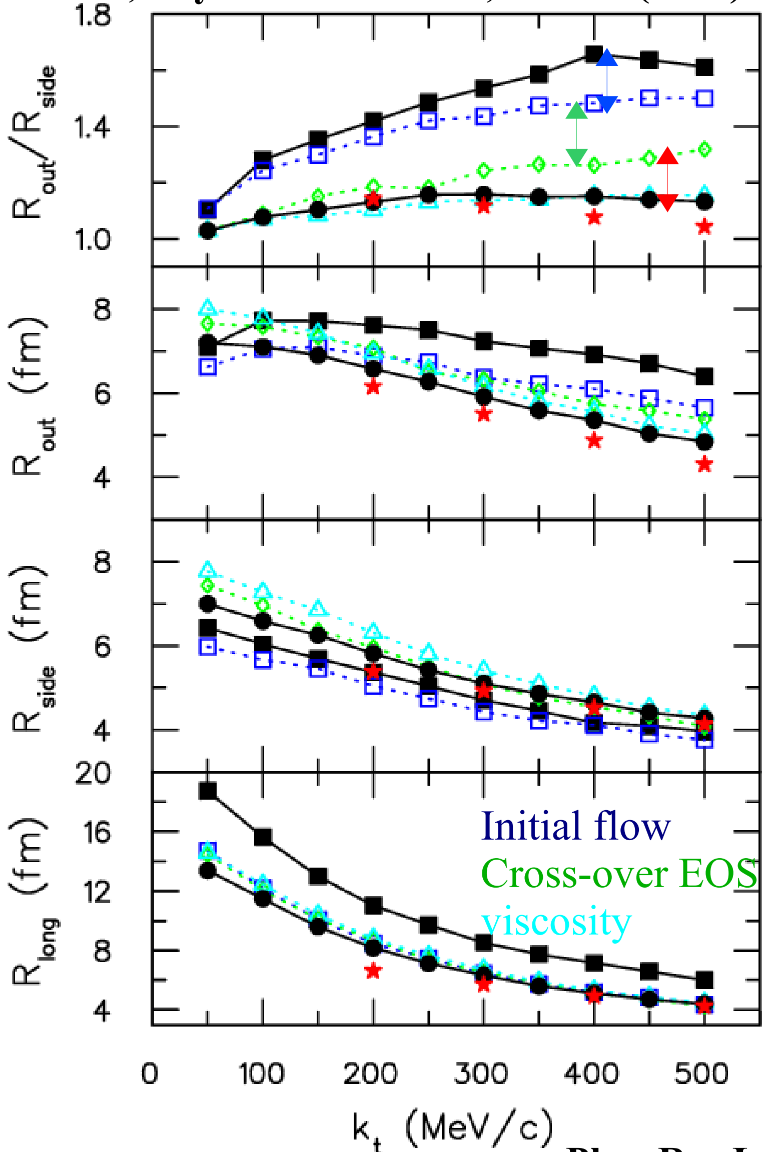
- First hydro calculations struggled to describe femtoscopic data: predicted too small R_{side}, too large R_{out} – too long emission duration
- No evidence of first order phase tr.



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

Revisiting hydrodynamics assumptions

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



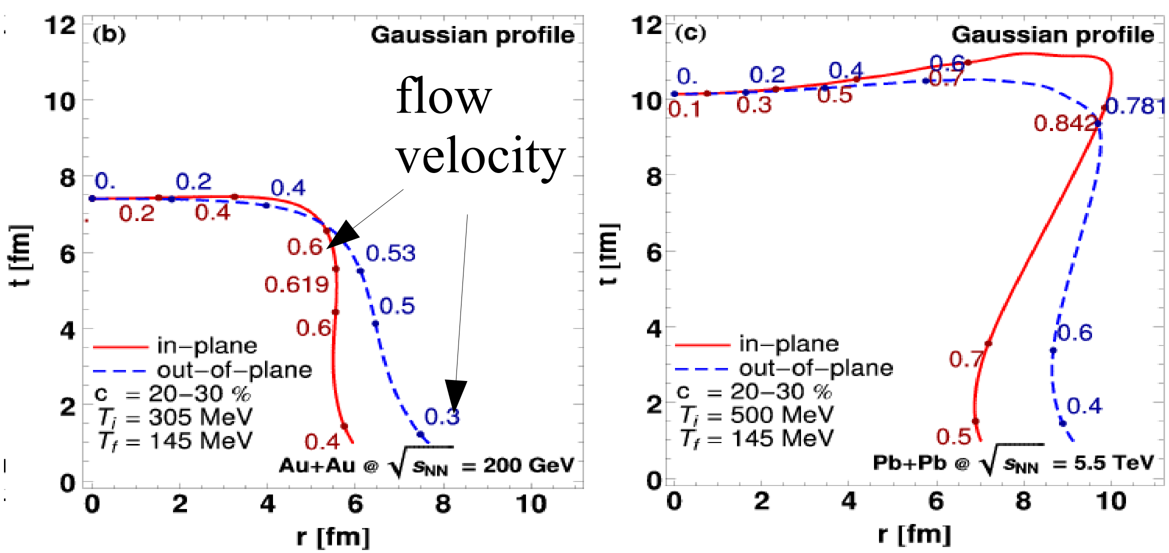
Phys.Rev.Lett. 101 (2008) 022301

- 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

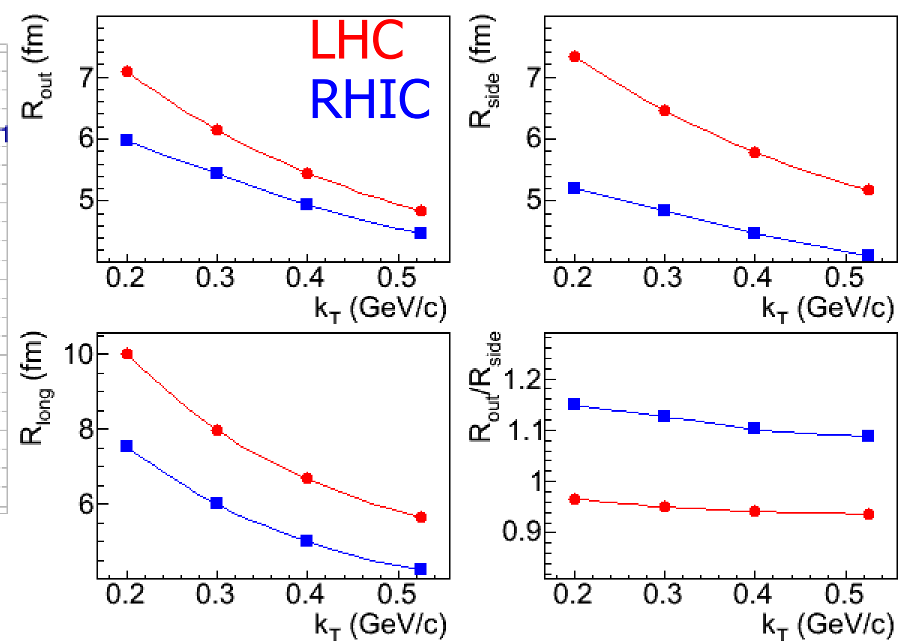
Expectations for the LHC

- 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



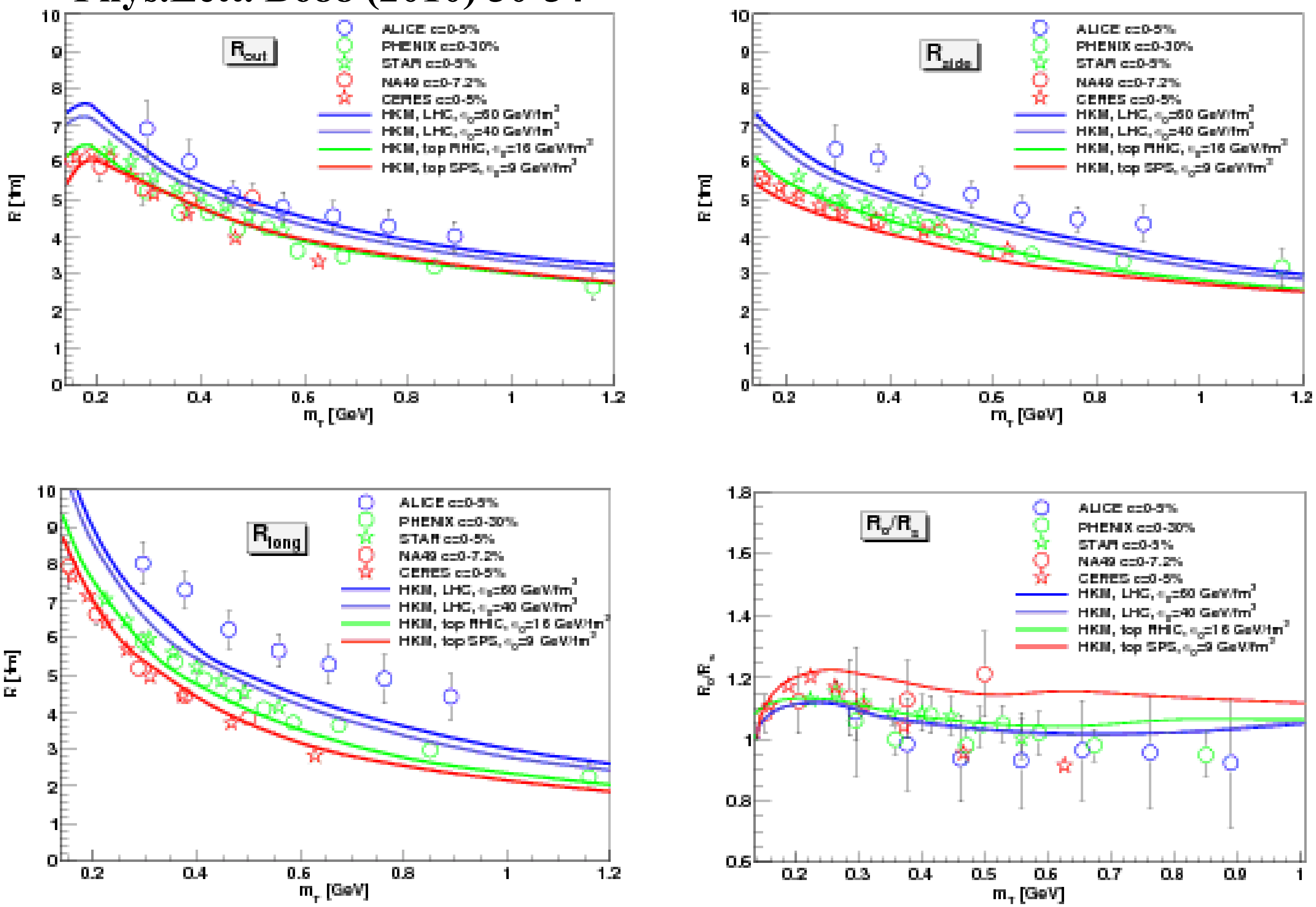
Phys.Rev.C79:014902,2009

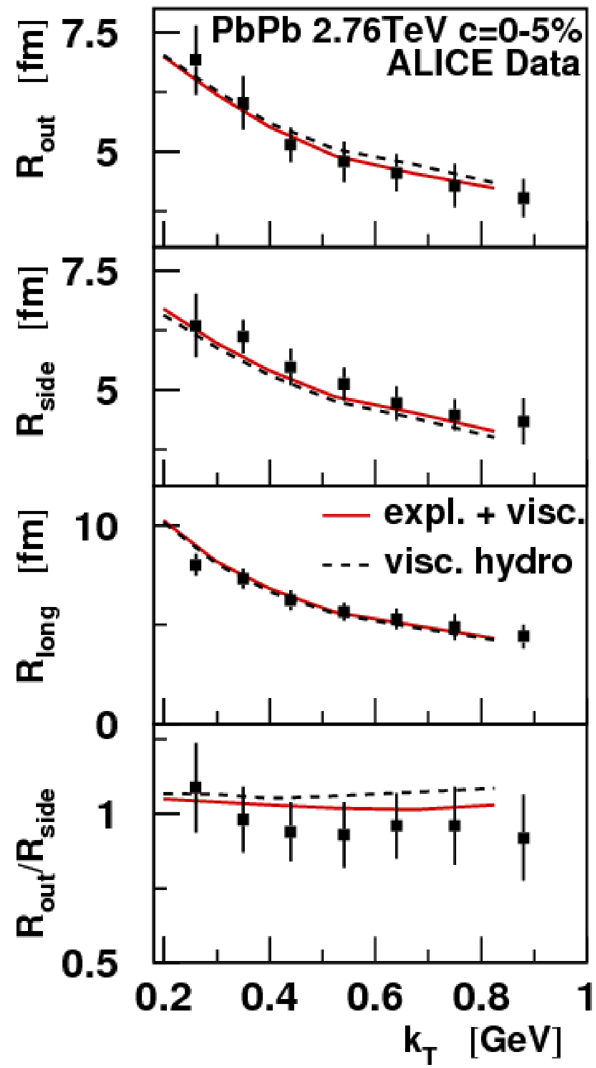


Hydrodynamic calculations

- Hydro-Kinetic Model and 3D Hydro+Therminator calculations for pion HBT radii at the LHC

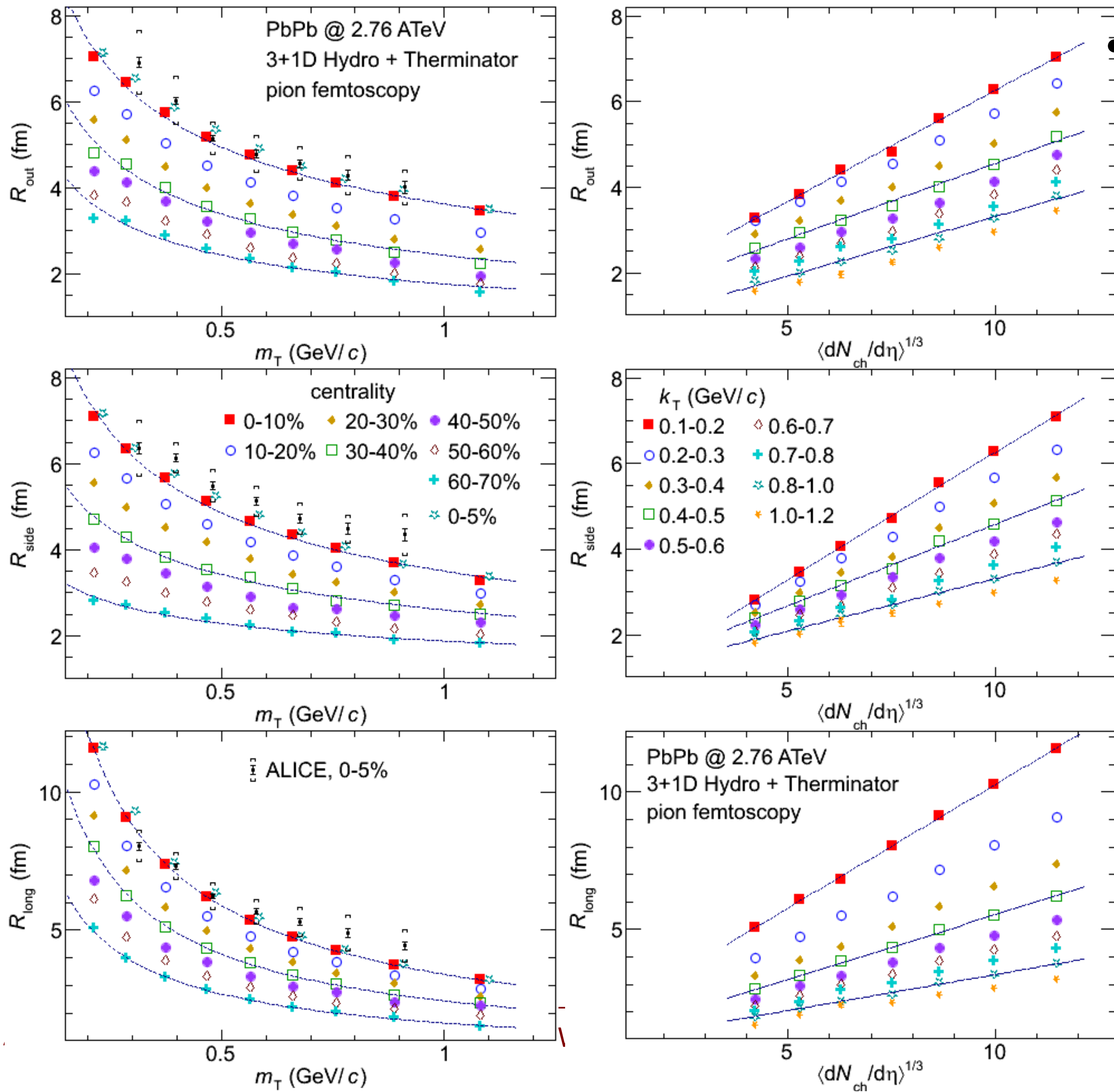
Yu. Karpenko, Yu. Sinyukov, Phys.Lett. B688 (2010) 50-54





P. Bożek, Phys.Rev. C83 (2011) 044910

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

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.

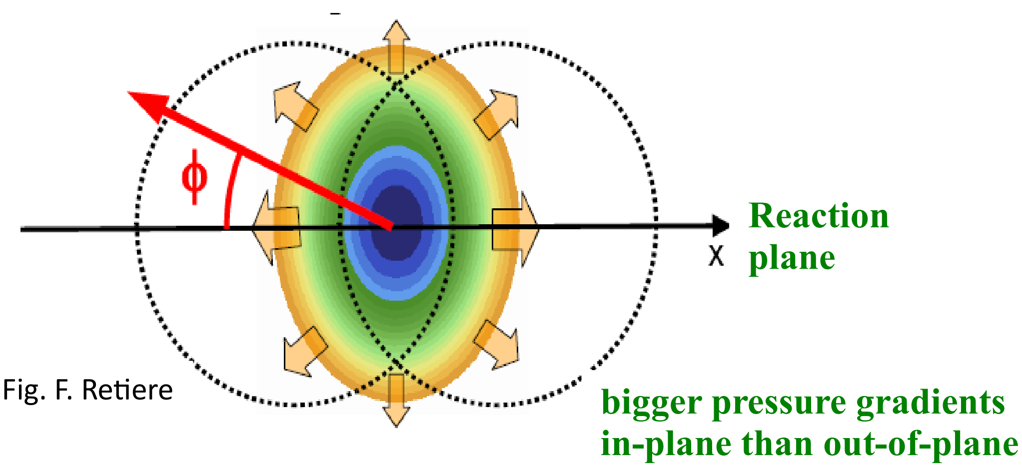
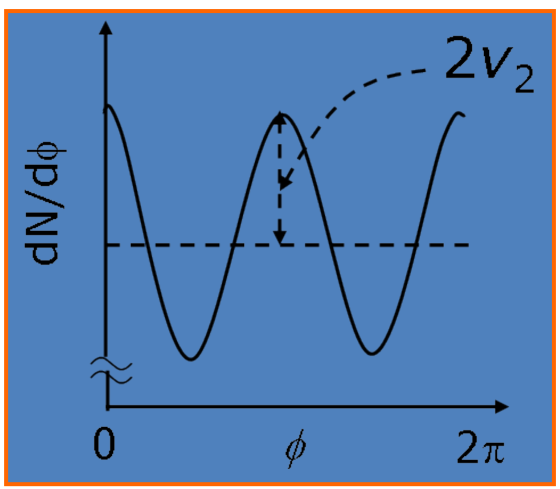
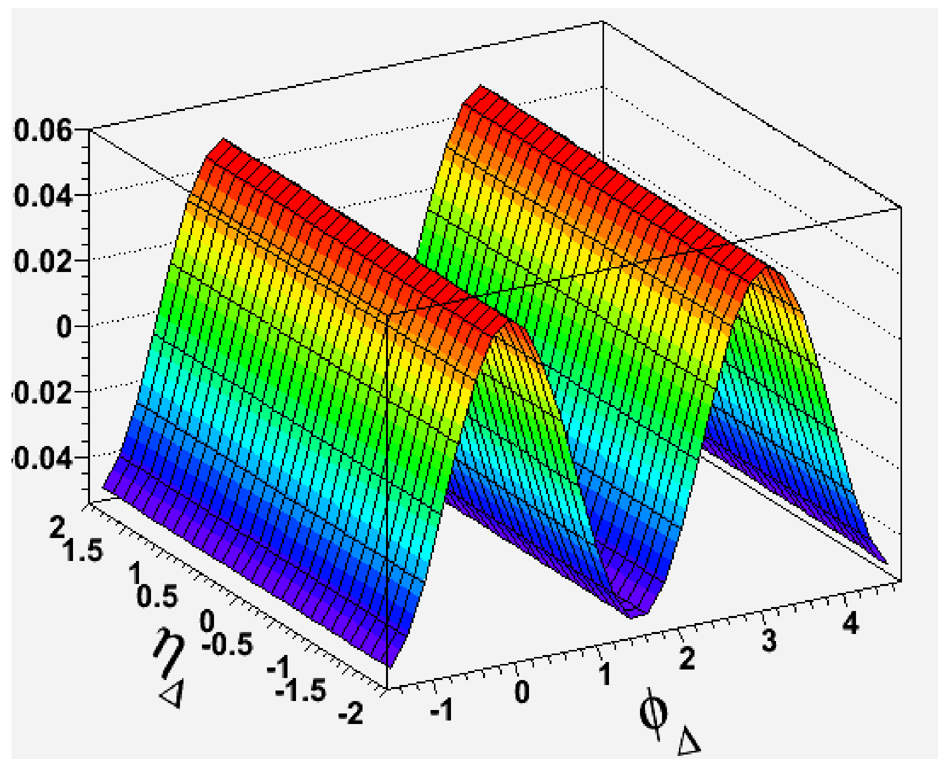


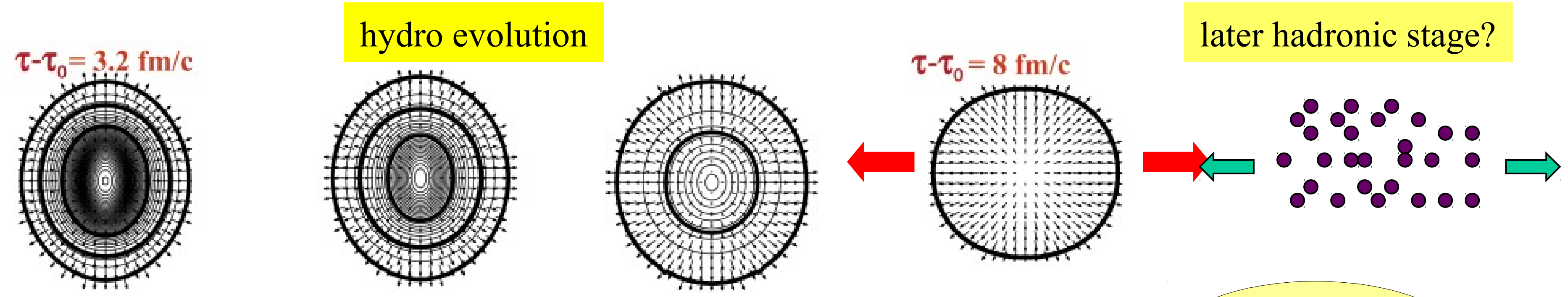
Fig. F. Retiere

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





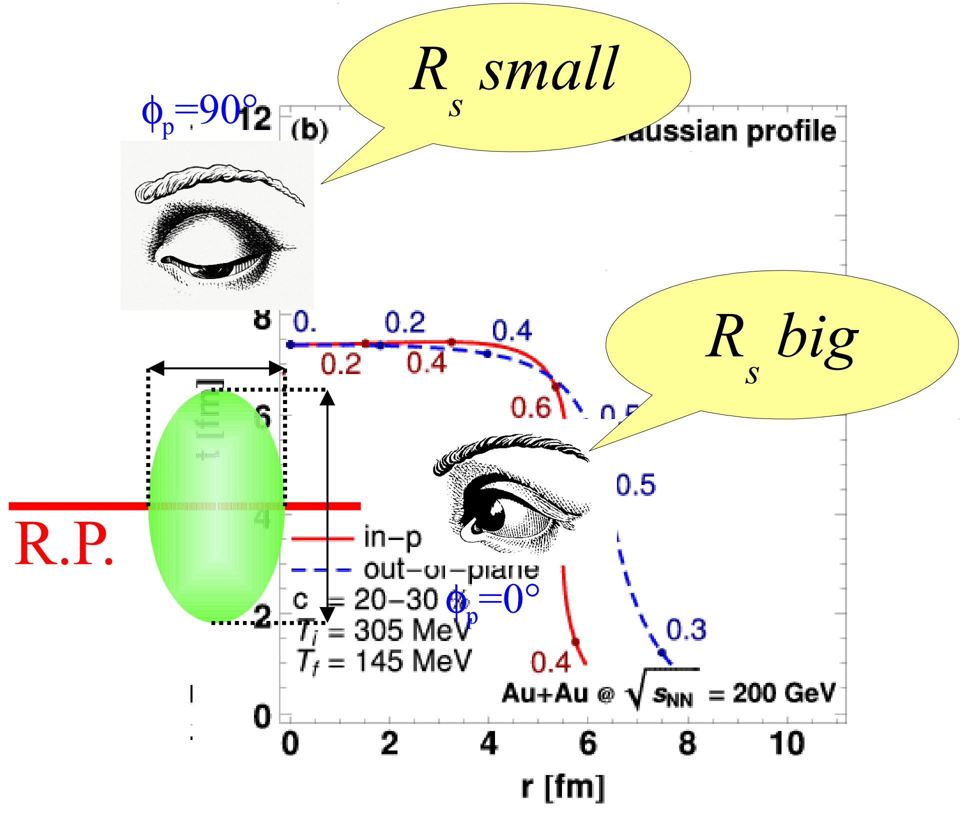
Non-central collisions: azimuthal modulation of collectivity



Kolb & Heinz

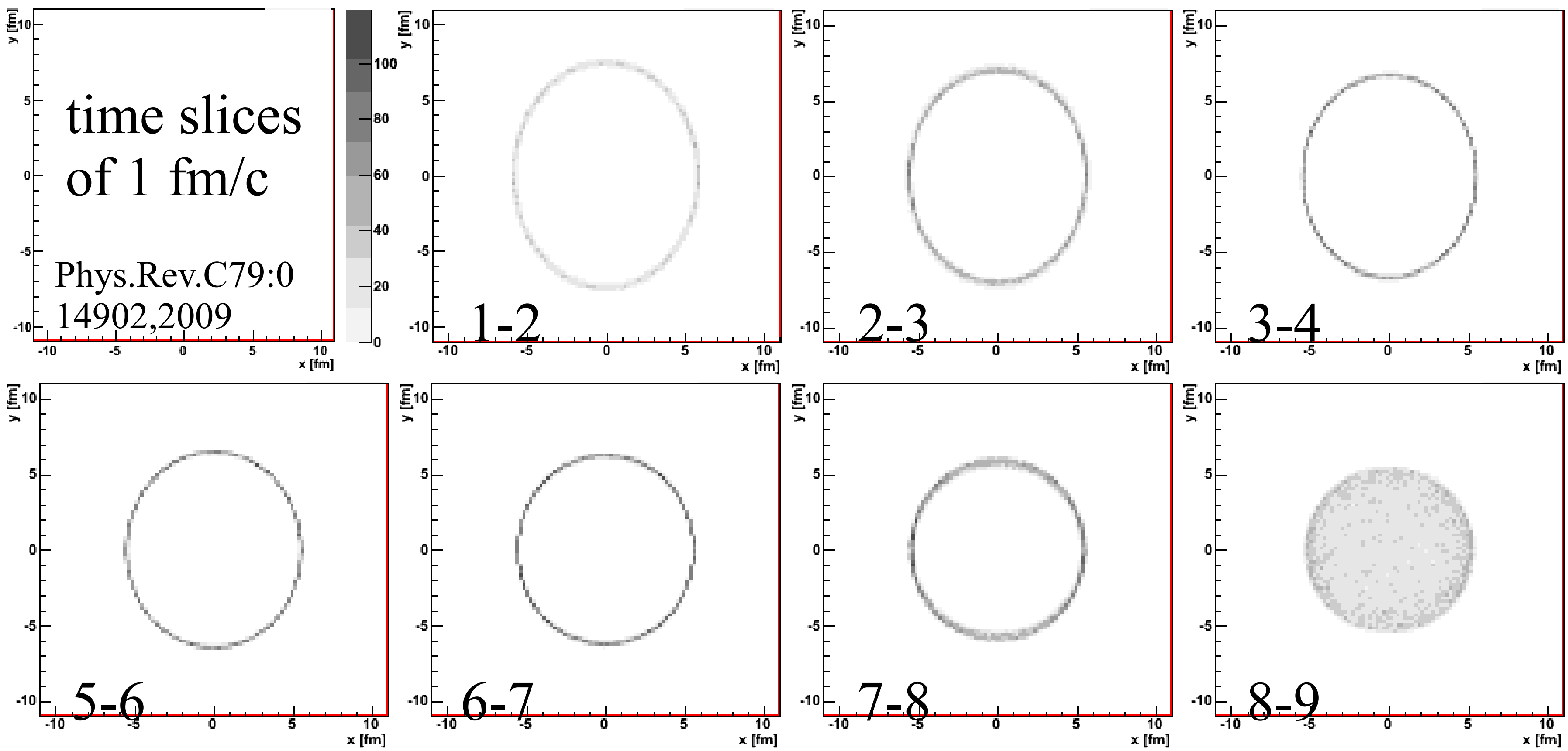
anisotropic pressure gradients

- 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

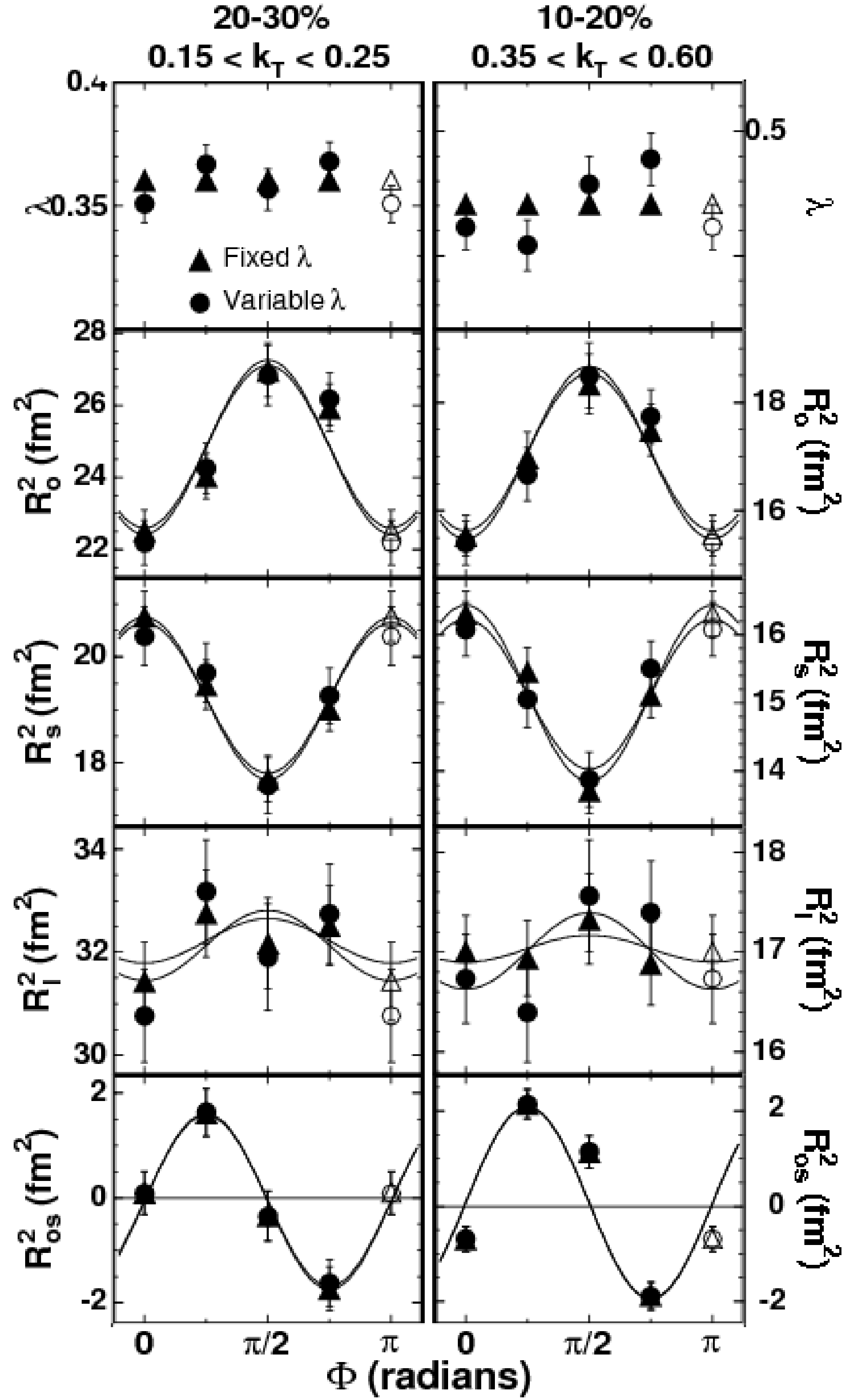


Emission from the source vs. time

- Azimuthal anisotropy is self-quenching – evolving towards a spherical shape
- 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)

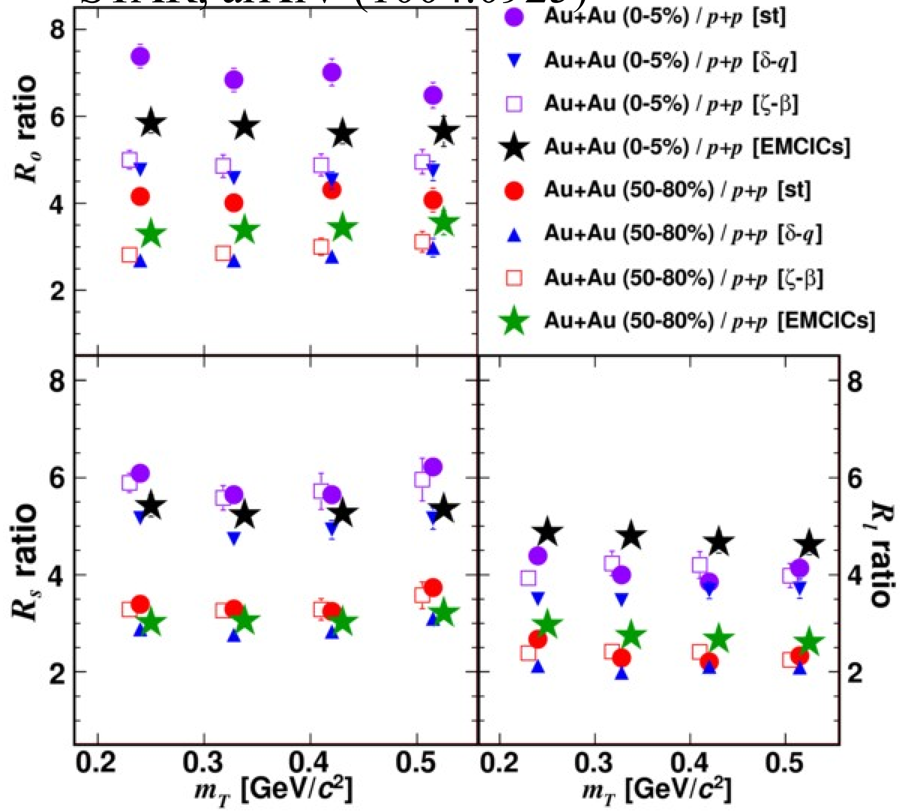
Femtoscopy in small systems

- 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)



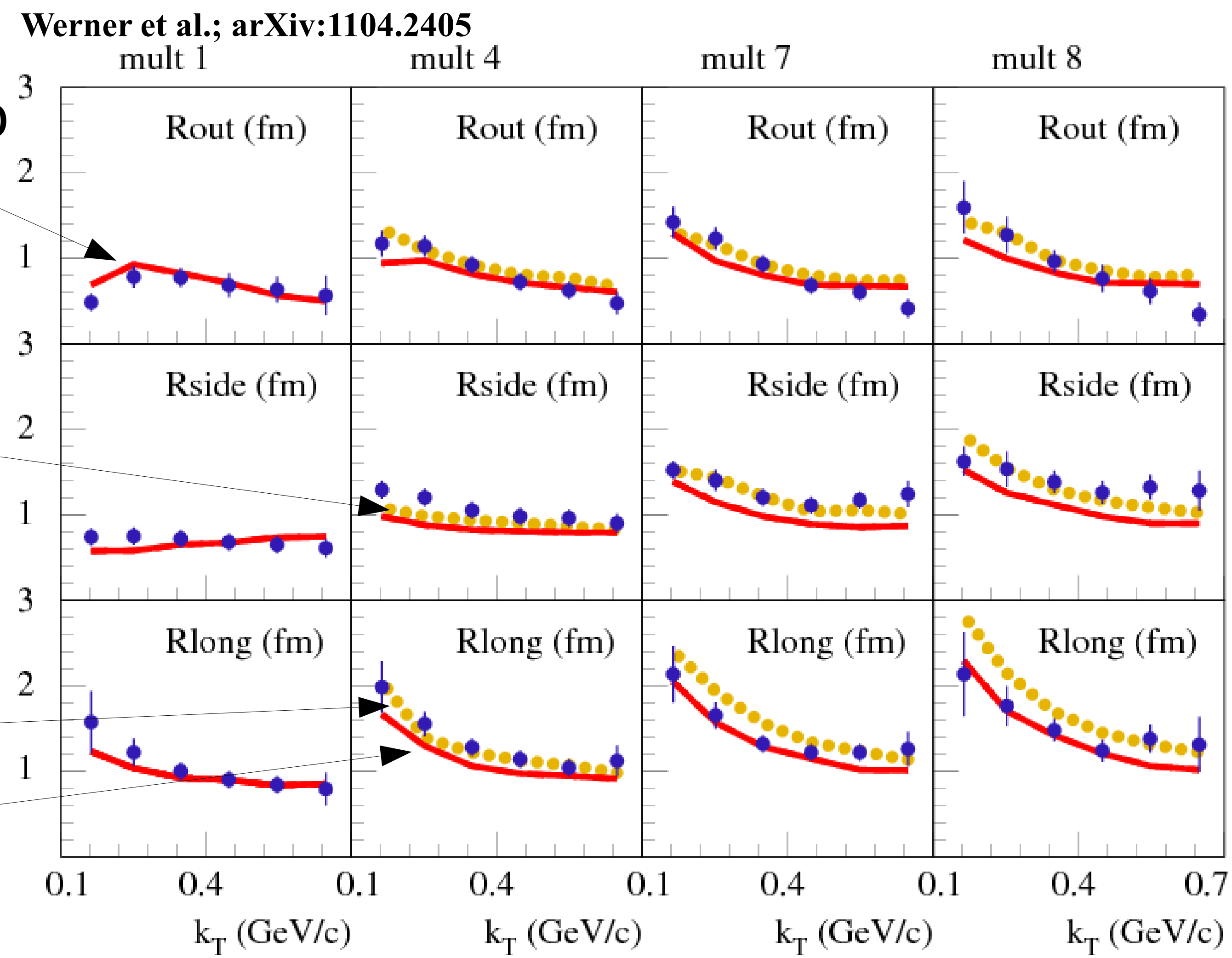
Interpreting k_T dependence

- EPOS model LHC post-dictions, pp collisions with hydro phase

No hydro phase at low mult

Hydro phase at high mult

Options for EOS

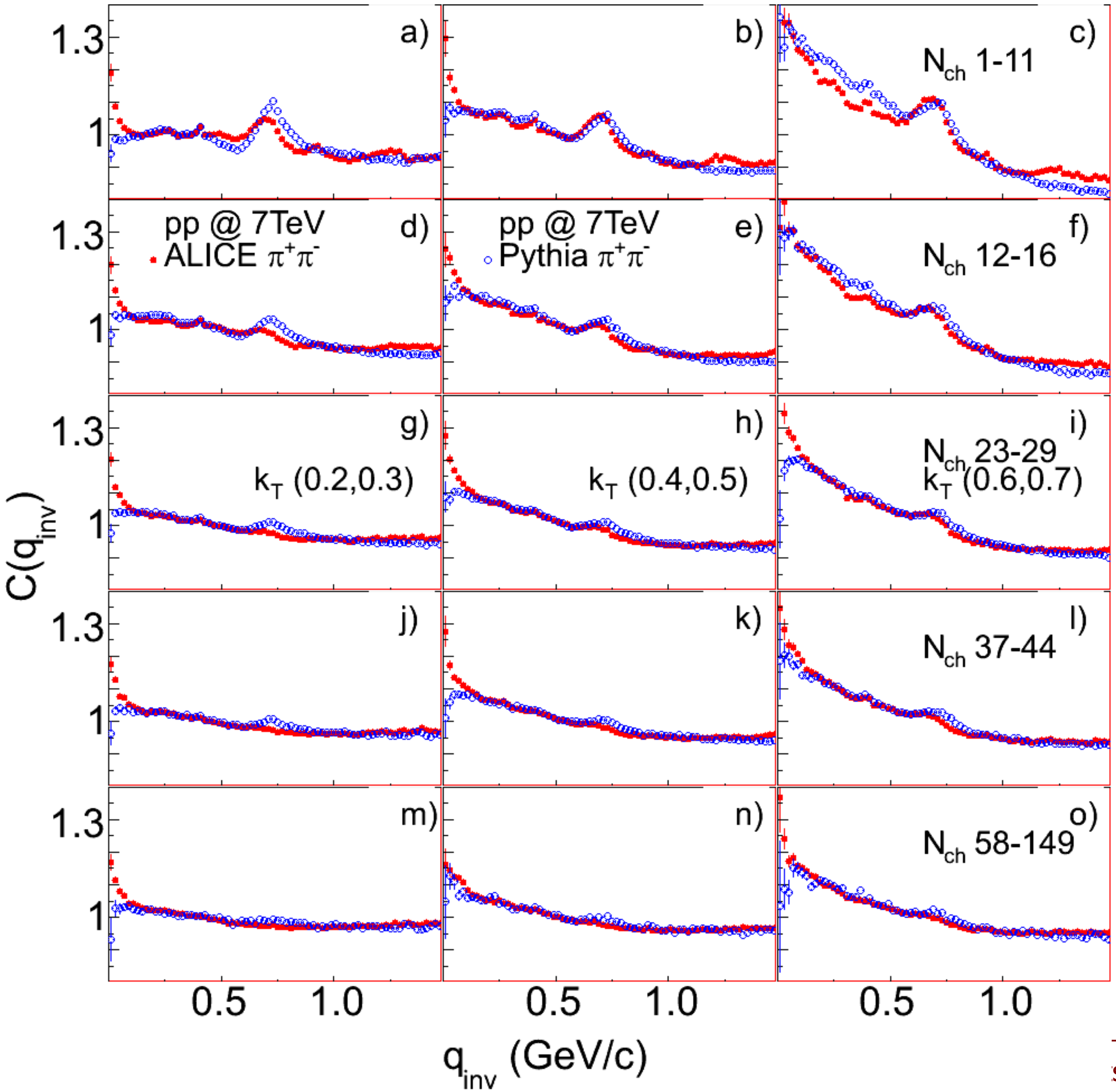


Hydro phase is consistent with HBT data, but is it the only explanation?

How big is the role of resonances?

What drives the radii behavior?

Mini-jets in $\pi^+\pi^-$ correlations

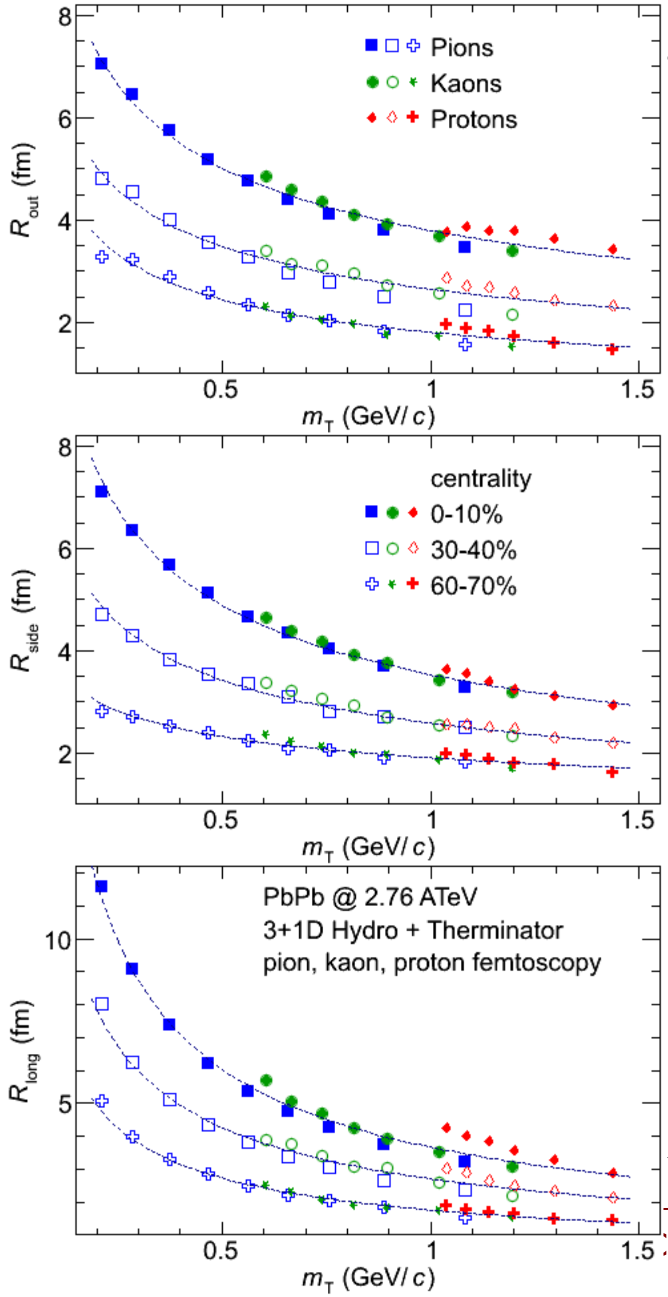


- Non-femtoscopic correlations present for opposite-charge pairs, a clear manifestation of the “mini-jet” pheonmena
- Pythia describes the correlation to within 10%
- Additional correlated yield due to resonances visible, Pythia's not able to describe it properly

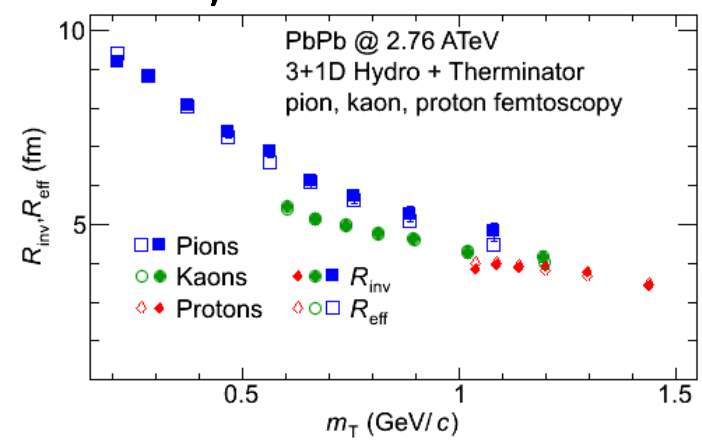
Heavier particles: physics motivation

- Full set of pion, kaon and proton femtoscopic results
  - wide range of transverse mass: test of hydrodynamic collectivity prediction (if truly general, it should include heavier mesons and baryons)
  - non-trivial consistency checks – different sources of femtoscopic correlations (QS, Coulomb FSI, Strong FSI), different detection procedures and systematics (primary, V0, PID techniques)
- Deviation of proton yields from chemical models expectations
  - Proton (and Lambda) yield in Pb-Pb at LHC below thermal model expectations (extrapolated from RHIC)
  - models claim that annihilation in "rescattering" phase should be taken into account while determining yields
  - Annihilation **is** the source of the femtoscopic correlation observed for many $B\bar{B}$ pairs – must be observed if this explanation is correct.

m_T scaling for heavier particles



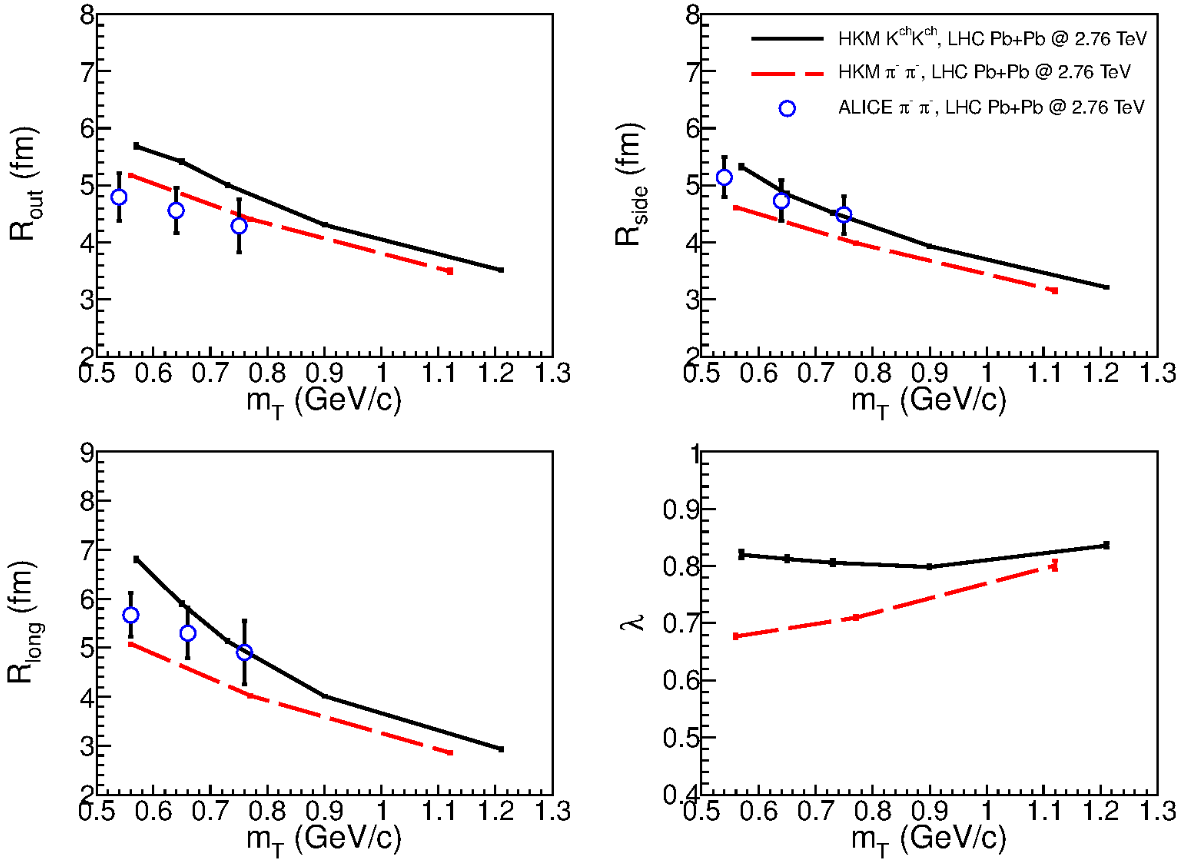
- "Collective" flow should apply to all particles
  - In ideal 1D hydro particles of all masses follow the same m_T scaling. What about "real" hydro in 3+1D and with viscosity (but no hadronic rescattering)?
  - The scaling still exists but only approximately, the deviations comparable to current experimental 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



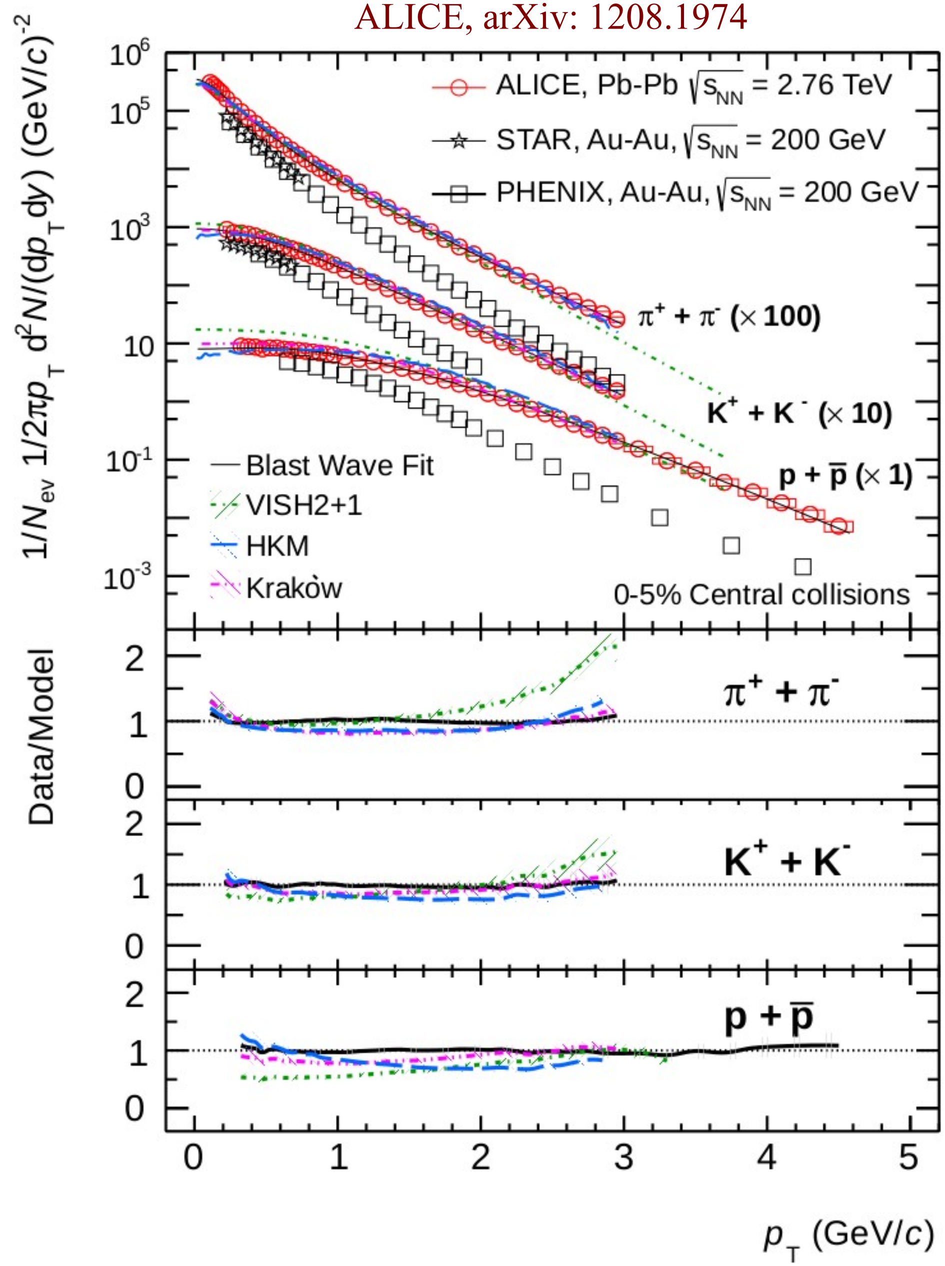
- Hydro model + rescattering phase (UrQMD) at LHC predicts breaking of the m_T scaling for kaons – is the hydro prediction non-universal or is it the effect of the rescattering phase?

Annihilation in baryon-antibaryon correlations

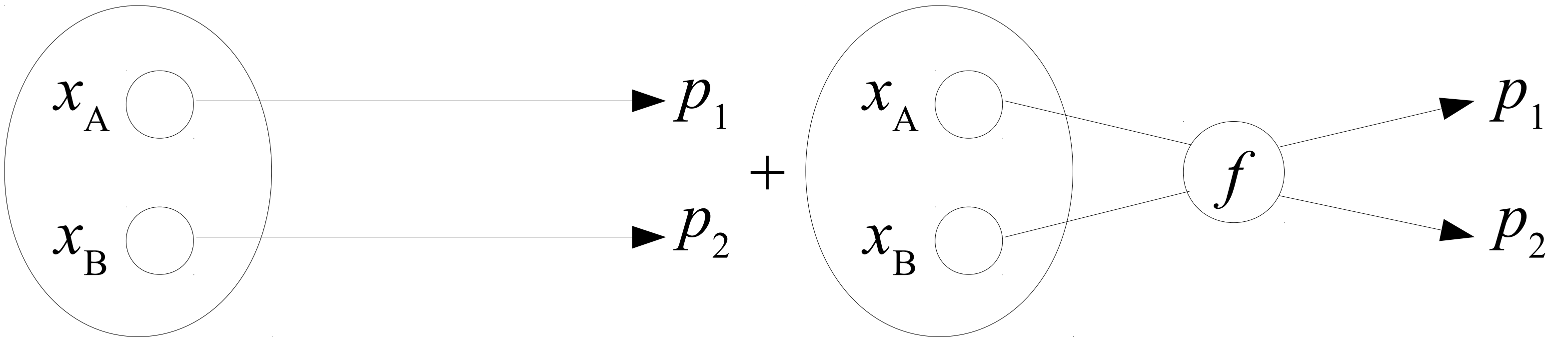
- Deviation of proton yields from chemical model expectations
  - "rescattering" phase should be taken into account while determining yields
    - Steinheimer, Aichelin, Bleicher; arXiv:1203.5302
    - Werner et al.; Phys.Rev. C85 (2012) 064907
    - Karpenko, Sinyukov, Werner; arXiv:1204.5351
  - If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



Strong interaction contribution



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

- Two hadrons interact via the strong interaction after their last scattering (emission)
  - Ψ is the Bethe-Salpeter amplitude, corresponding to the standard quantum scattering problem, taken with inverse time direction

$$\Psi = \exp(-i\vec{k}^*\vec{r}) + f\frac{\exp(ik^*r)}{r} \qquad f^{-1} = \frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - ik^*$$

  - For identical hadrons: also properly (anti-)symmetrized
- f is directly related to the cross-section (at low q)

$$\sigma = 4\pi|f|^2$$

Lednicky&Lyuboshits analytical form

- Analytic formula for the correlation function needs:
  - The $|\Psi|^2$ – here for the strong interaction only
  - The shape of the source – here Gaussian with radius r_0
  - The Koonin-Pratt equation to combine the two
- The result: the Lednicky&Lyuboshits analytic formula for C:

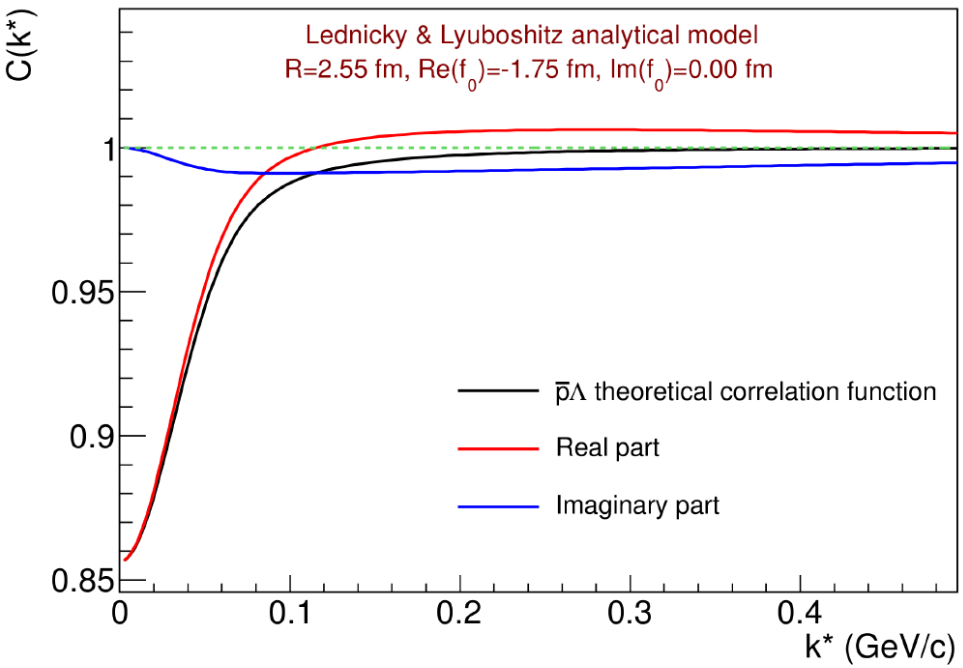
$$C(k^*) = 1 + \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f^S(k^*)}{r_0} \right|^2 \left(1 - \frac{d_0^S}{2\sqrt{\pi}\, r_0} \right) + \frac{2\Re f^S(k^*)}{\sqrt{\pi}\, r_0} F_1(Qr_0) - \frac{\Im f^S(k^*)}{r_0} F_2(Qr_0) \right]$$

- Direct dependence on parameters of strong interaction:
  - Real and imaginary part of singlet, triplet scattering length f_0
  - The effective radius d_0
  - Can be used to measure cross-sections at low k*!

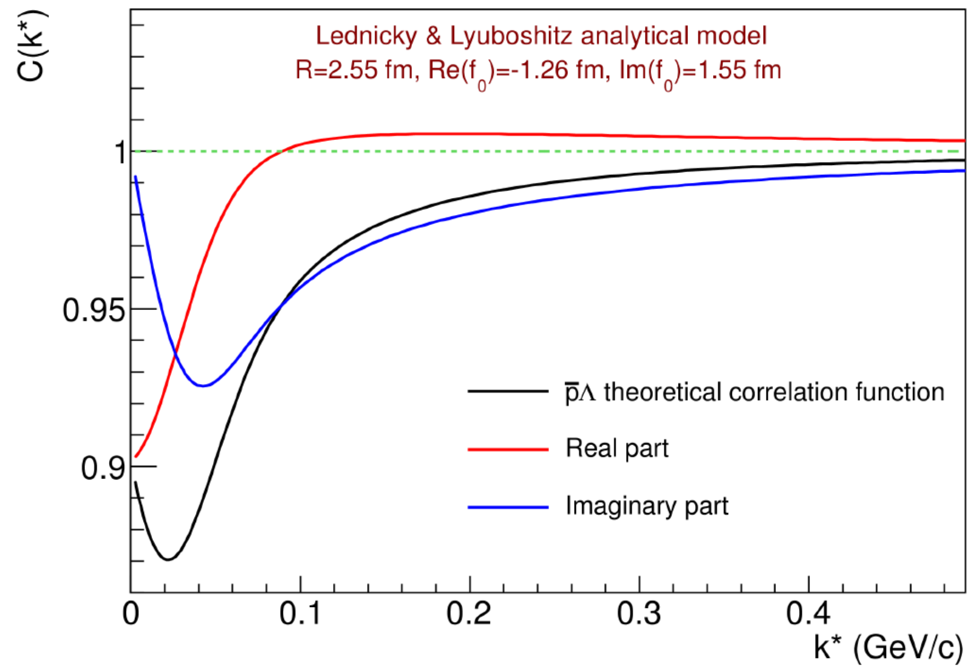
R. Lednicky and V. L. Lyuboshits, Sov. J. Nucl. Phys. 35, 770 (1982).

Shape of the correlation from strong

no annihilation

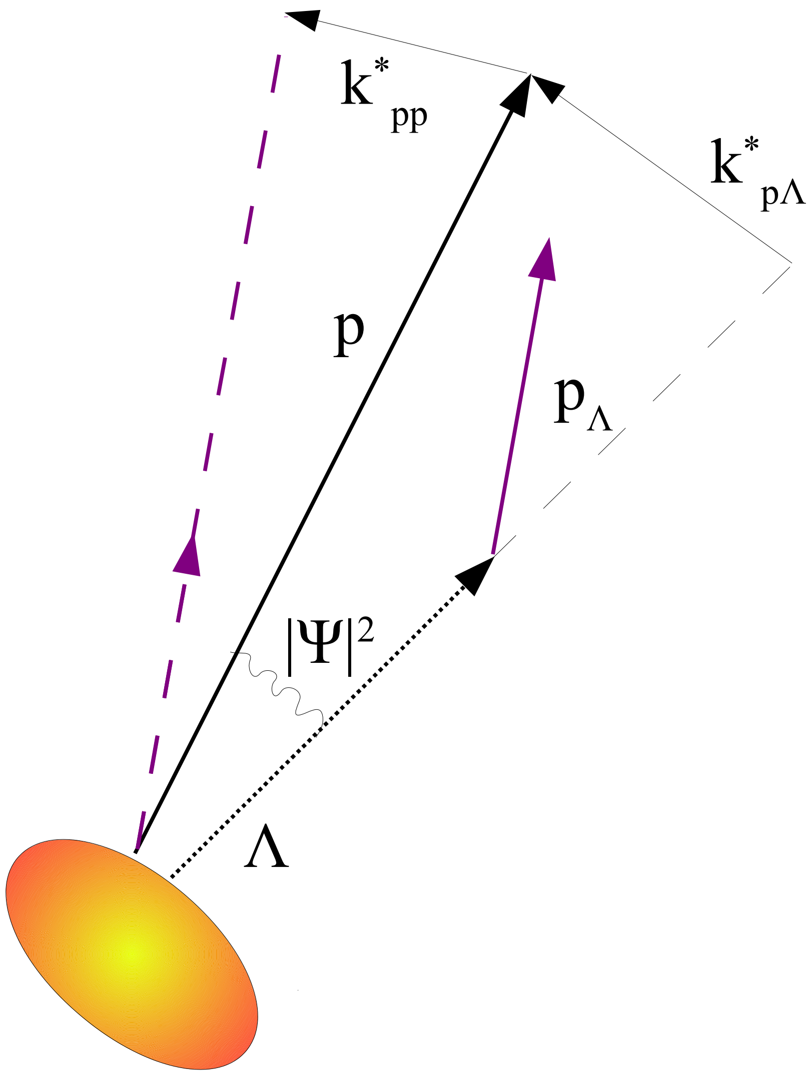


with annihilation



- Strong interaction with zero imaginary part of f_0 (no annihilation): limited width – up to 100 MeV/c in q
- Finite imaginary part of f_0: significant negative contribution to the correlation extending even up to 400 MeV/c

Residual correlations



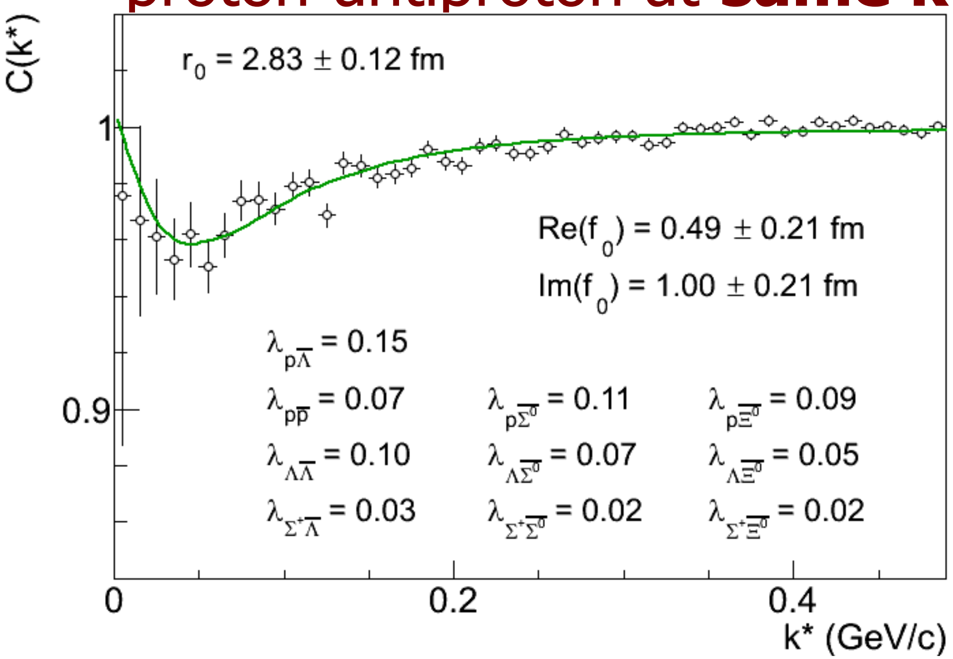
- In a collider setup baryons from weak decays often travel in a similar direction as the parent – decay momentum is small with respect to the baryon momentum (e.g. Λ -> p decay: 101 MeV/c)
- The femtoscopic correlation exists for the parent pair
- It is smeared by the decay momentum, but can still be significant – if the correlation width is comparable to decay momentum

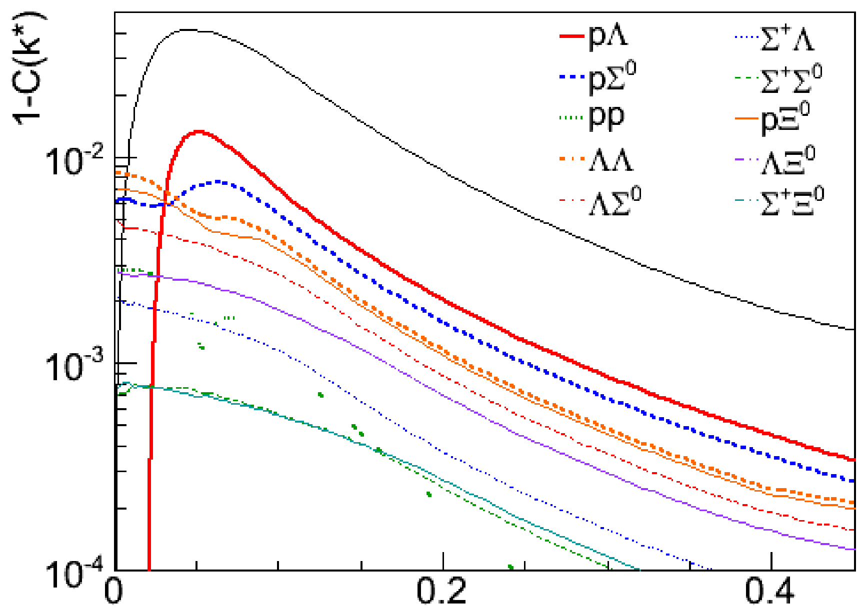
STAR data on p$\bar{\Lambda}$ correlations

- The correlation is fitted with:

$$C^{\bar{X}Y\rightarrow\bar{p}\Lambda}(k^*_{\bar{p}\Lambda})=1+\lambda_{p\Lambda}\left(C^{\bar{p}\Lambda}(k^*_{\bar{p}\Lambda})-1\right)+\sum_{\bar{X}Y}\lambda_{\bar{X}Y}\left(C^{\bar{X}Y}(k^*_{\bar{p}\Lambda})-1\right)$$

- Radius comparable to the expectations is obtained
- All pairs provide a significant contribution to the correlation
- Im f_0 (for all baryon-antibaryon pairs!) is consistent with proton-antiproton at **same k***





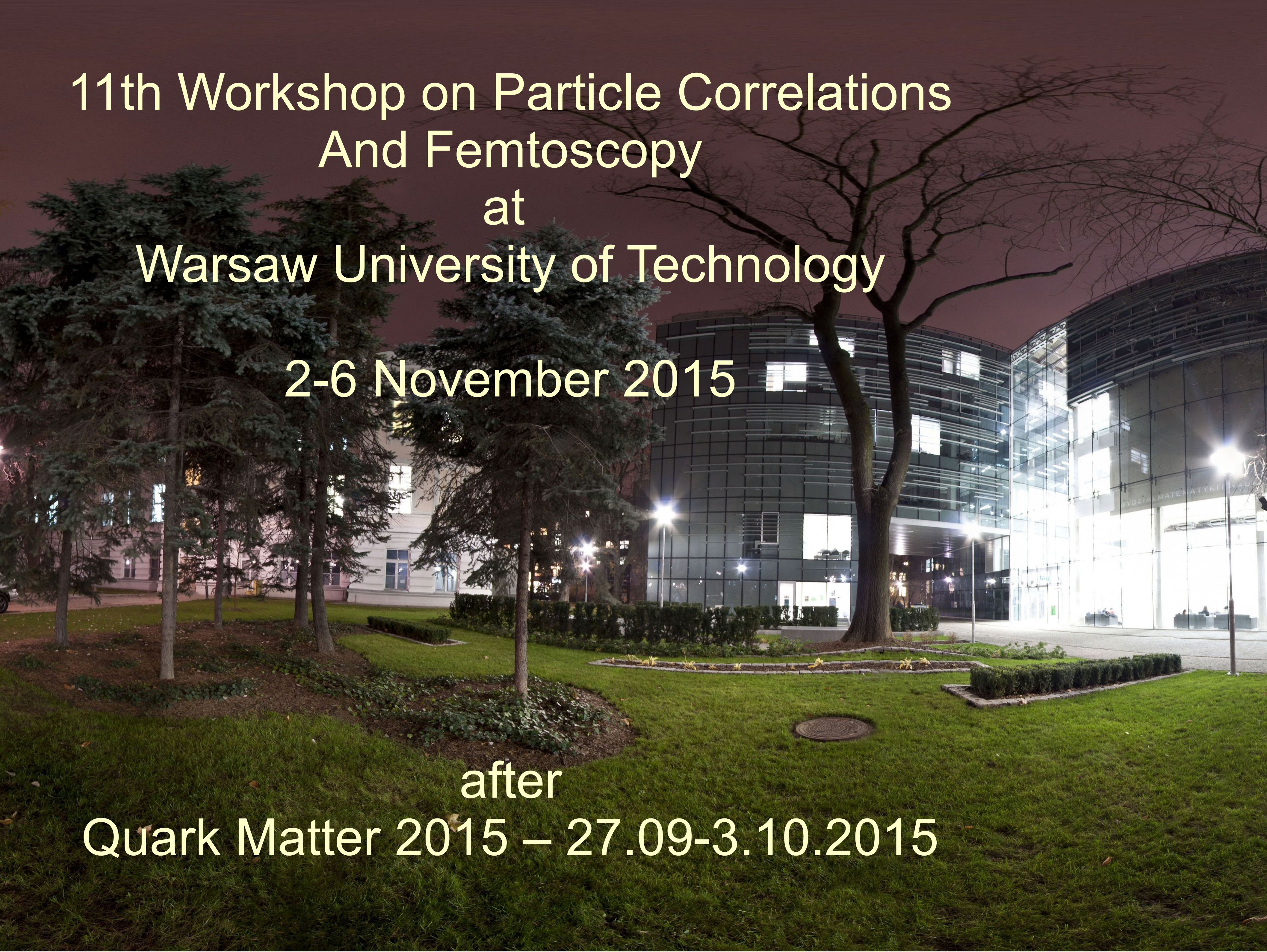
Phys.Rev. C89 (2014) 054916

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
- 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"? What about p-Pb?
- Correlation for heavier particles gives independent check of collectivity
- Significant annihilation for $B\bar{B}$ systems observed, could provide better data on cross-sections

11th Workshop on Particle Correlations And Femtoscopy at Warsaw University of Technology

2-6 November 2015



after

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