Femtoscopy of heavy ion and pp collisions at high energies

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for the ALICE collaboration

Outline

- **Introduction**
- **Physics motivation**

Heavy ion collisions

- **Femtoscopy of identical particles: QS correlations.**

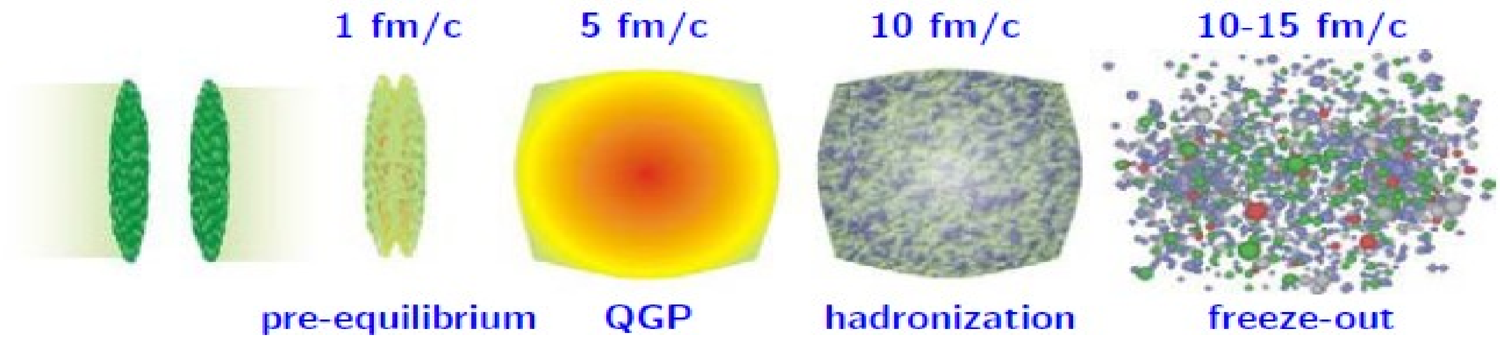
- RHIC puzzles & revising hydro models
- pion femtoscopy & ALICE data
- Theoretical interpretations
- heavy particles femtoscopy

- **Azimuthally sensitive femtoscopy**

PP & P-Pb collisions

- **Summary**

Femtoscopy



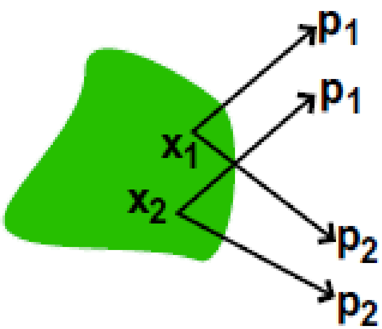
Correlation femtoscopy : measurement of space-time characteristics R, $c\tau$ ~fm of particle production using particle correlations due to the effects of QS and FSI

G. Goldhaber, S. Goldhaber, W-Y Lee, A. Pais (Phys.Rev. 120 (1960) 300):
first showed the BE correlation of identical pions in $p\bar{p}$ collisions

G.I. Kopylov and M.I. Podgoretsky (1971-1975) (review: Phys.Part.Nucl. 20, iss. 3 (1989) 629, in Russian): elaborated basics of correlation femtoscopy

V.G. Grishin, G.I. Kopylov, and M.I. Podgoretsky showed analogy (Sov.J.Nucl.Phys. 13 (1971) 638) and difference (G.I. Kopylov and M.I. Podgoretsky, Sov.J.Nucl.Phys. 15 (1972) 219) between femtoscopy in particle physics and HBT effect in astronomy (R. Hanbury-Brown and R.Q. Twiss, Phil.Mag. 45 (1954) 633):
HBT effect is the change of intensity of the signal received from the particle emission source

Femtoscopy: Momentum Correlations due to QS

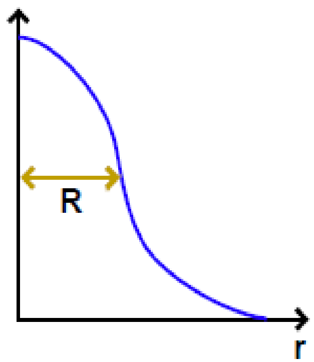


$$U_{x1p1} = U(x_1, p_1),\ V_{x2p2} = V(x_2, p_2)$$

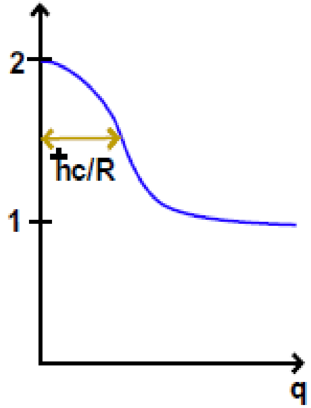
$$A(x_1, x_2; p_1, p_2) \sim U_{x1p1}V_{x2p2} + U_{x1p2}V_{x2p1} \ \rightarrow\ <|A|^2>_{x_1x_2}$$

$$W(p_1, p_2) \sim <|U_{x1p1}|^2><|V_{x2p2}|^2> + <|U_{x1p2}|^2><|V_{x2p1}|^2>$$
$$+ <U_{x1p1}U^*_{x1p2}><V_{x2p2}V^*_{x2p1}> + <U^*_{x1p1}U_{x1p2}><V^*_{x2p2}V_{x2p1}>$$

$$|p_1 - p_2| \gg 0 \ \longrightarrow\ W \sim 2|U|^2|V|^2$$
$$|p_1 - p_2| \sim 0 \ \longrightarrow\ W \sim 4|U|^2|V|^2$$



$\Rightarrow$



two-particle correlation function:

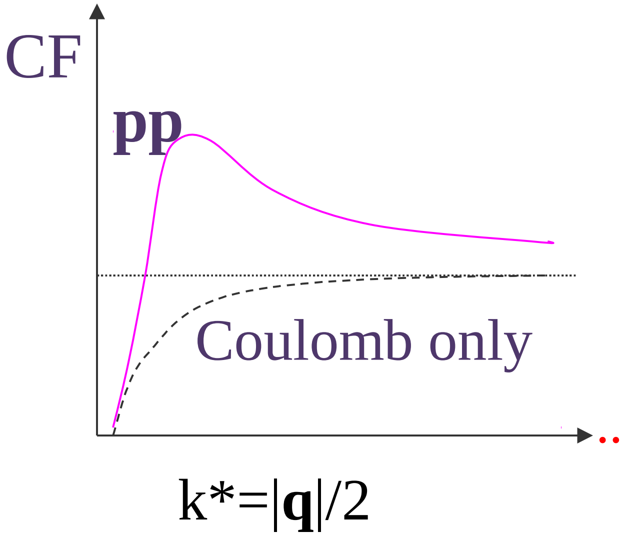
theory : $C(q) = \dfrac{N_2(p_1, p_2)}{N_1(p_1)N_2(p_2)}, \quad C(\infty) = 1$

experiment : $C(q) = \dfrac{S(q)}{B(q)}, \quad q = p_1 - p_2$

S - distribution of pair momentum difference of particles from the same events

B - reference distribution, built by mixing particles from different events

Introduction: Final State Interaction



FSI is sensitive to source size and scattering amplitude. It complicates CF analysis but makes possible:

Femtoscopy with nonidentical particles:
πK, πp, πΞ ...

Study of the "exotic" scatterings: ππ, πK, KK, πΛ

Study of the relative space-time asymmetries of particles emission πK, pK, πΞ **..**

Lednicky, Lyuboshitz et al. PLB 373 (1996) 30

Femtoscopy: frequently used parametrizations

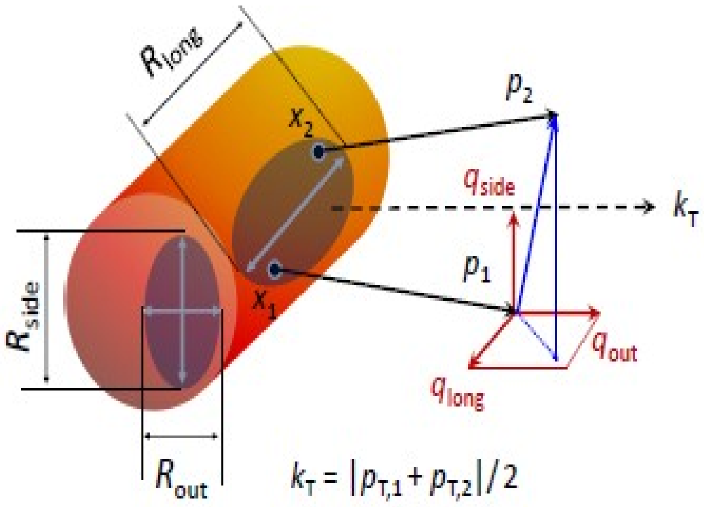
$C(q) = 1 + \lambda \exp(-R_{inv}^2 q_{inv}^2)$, λ– correlation strength,

R_{inv}, -- assumes Gaussian radius in Pair Rest Frame (**PRF**)

1d- analysis is only sensitive to the system size averaged over all directions ;

$$C(q) = 1 + \lambda \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2),$$

where both *R* and *q* are in Longitudinally Co-Moving Frame. In LCMS the pair momentum in long vanishes. Gives access to three system sizes in these directions separately.



long || beam;

out || transverse pair velocity $\mathbf{v}_T$

side normal to out,long

3D- analysis

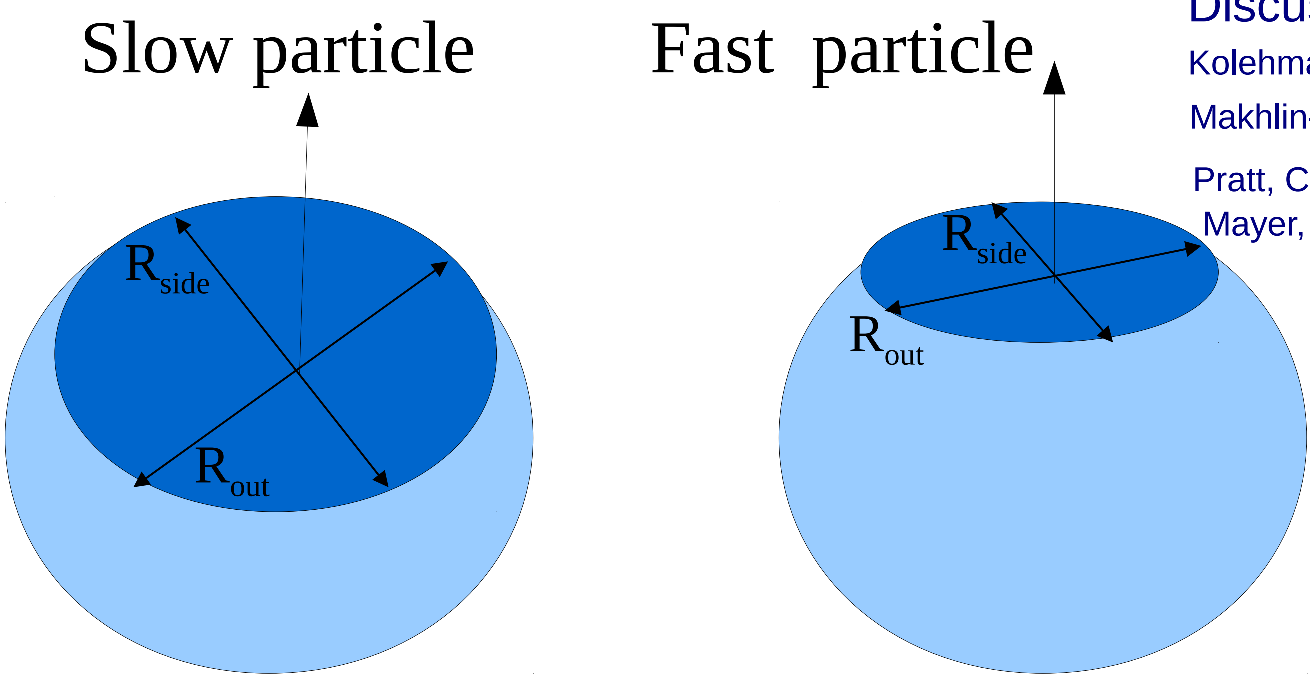
R_{side} sensitive to geometrical transverse size.

R_{long} sensitive to time of freeze-out.

R_{out} is sensitive to the geometrical size+emission duration

Femtoscopy: expanding source

- **x-p** correlations -> interference dominated by particles from nearby emitters.
- interference probes only parts of the source at close momenta – **homogeneity regions.**
- longitudinal and transverse expansion of the source -> significant reduction of the radii with increasing pair velocity, consequently with k_T (or $m_T=(m^2+k_T^{\,2})^{1/2}$)



Discussed in e.g.:

Kolehmainen, Gyulassy'86

Makhlin-Sinyukov'87

Pratt, Csörgö, Zimanyi'90

Mayer, Schnedermann,Heinz'92

$R_{side} \sim R/(1+m_T\beta_T^{\,2}/T)^{½}$

β_T collective transverse flow

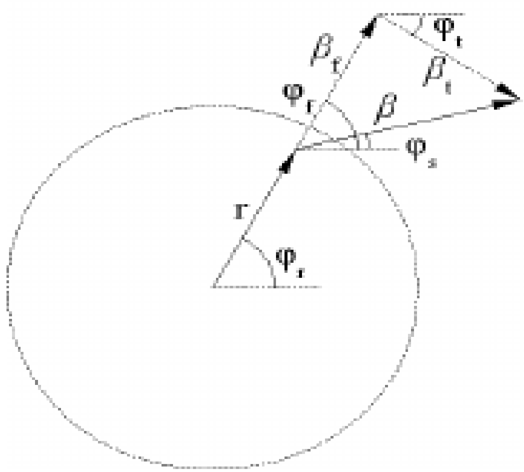
$R_{long} = \tau\ (T/m_T)^{1/2}$, assuming a longitudinal boost invariant expansion

Expanding source

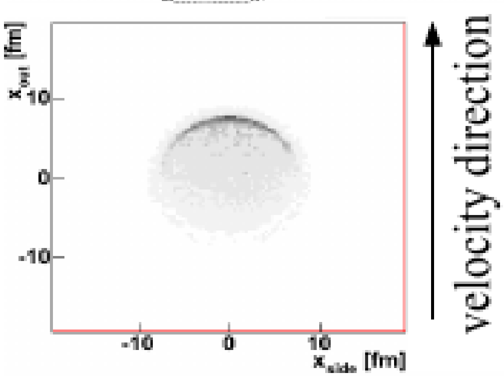
interference probes only parts of the source at close momenta – **homogeneity regions.**

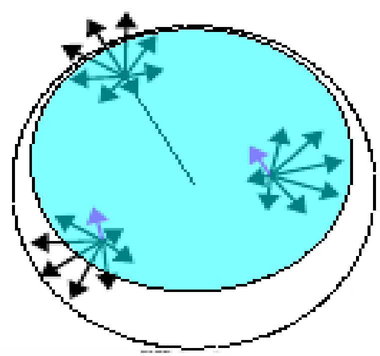
(Yu.M. Sinyukov, Nucl. Phys. A 566, 589 (1994);)

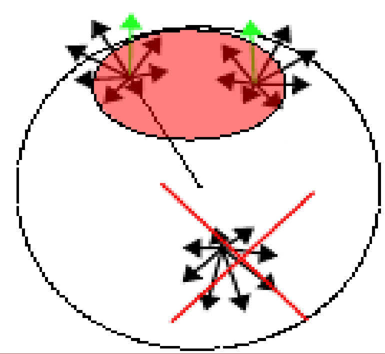
Dynamics via momentum dependence



- 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, region emitting such particles gets smaller and shifted to the outside: "lengths of homogeneity". Femtoscopy always measures only the "homogeneity size".







Femtoscopy: physics motivation

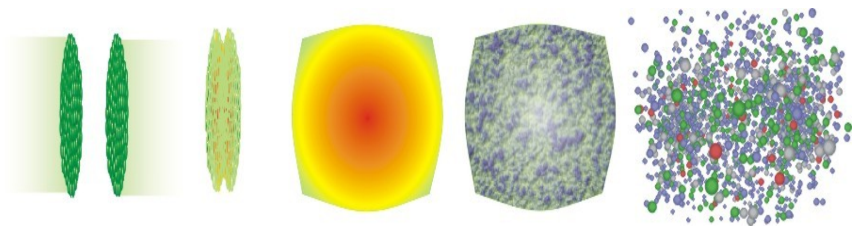
HI collisions

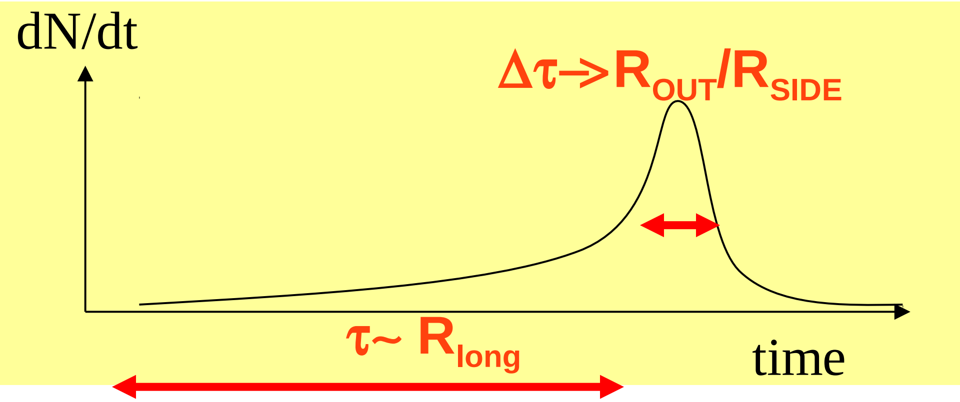
• Measure the size of the homogeneity region from which the volume of the QGP can be inferred

• Study of radii dependence on transverse momentum -> manifestation of collective motion of matter

• Study of transverse mass dependence for different particle types (π, K, p, ...)- additional confirmation of the hydrodynamic type of expansion: m_T scaling & asymmetries

• Study of source shape at freeze-out: az-femtoscopy





pp collisions

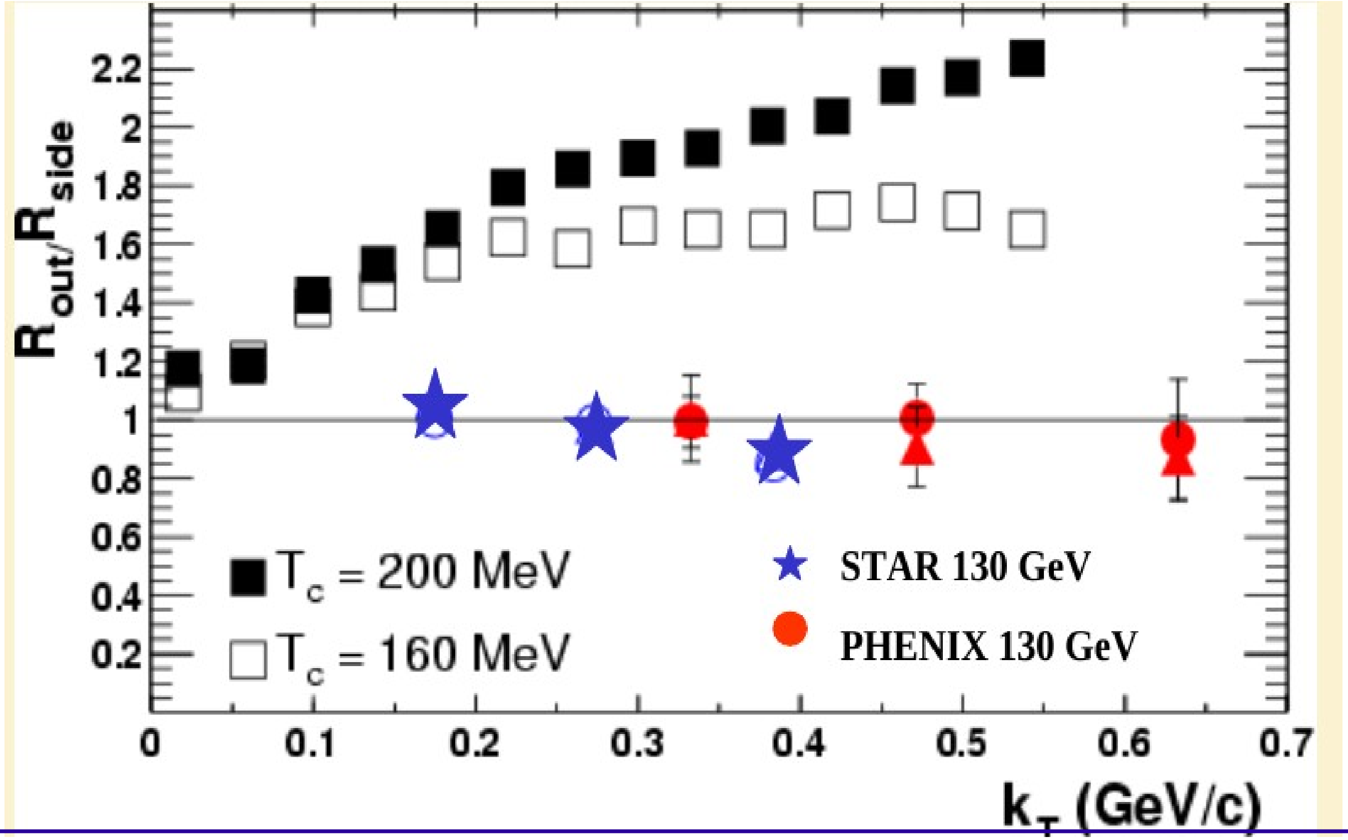
• Study space-time characteristics of particle production in "elementary process"

• Multiplicities, comparable to peripheral AA collisions**:** collectivity in pp as in AA ?

Constraints on model parameters.

"RHIC-HBT puzzles"

- **Unexpected small sizes AGS-SPS-RHIC**
- **R_{out}/R_{side} ~1**
- **Hydro models well describe momentum observables fail to describe coordinate ones**



It was predicted that for a 1st order phase transition R_{out}/R_{side} >>1 due to a stalling in the emission during the phase transition

(G. J. Wang, R. Bellwied, C. Pruneau, and G. Welke (1998) nucl-th/9806006.
D. H. Rischke and M. Gyulassy, Nucl. Phys. A608, 479 (1996) , nucl-th/9606039.)

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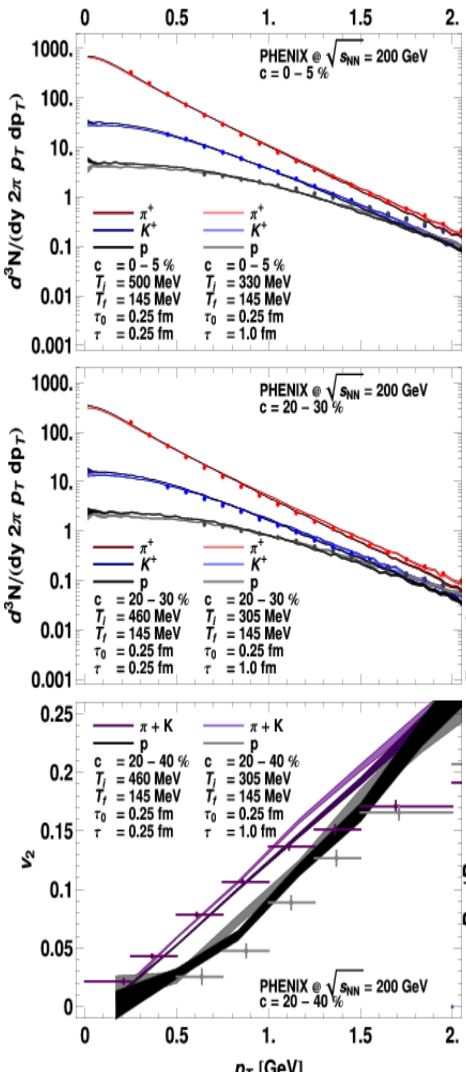
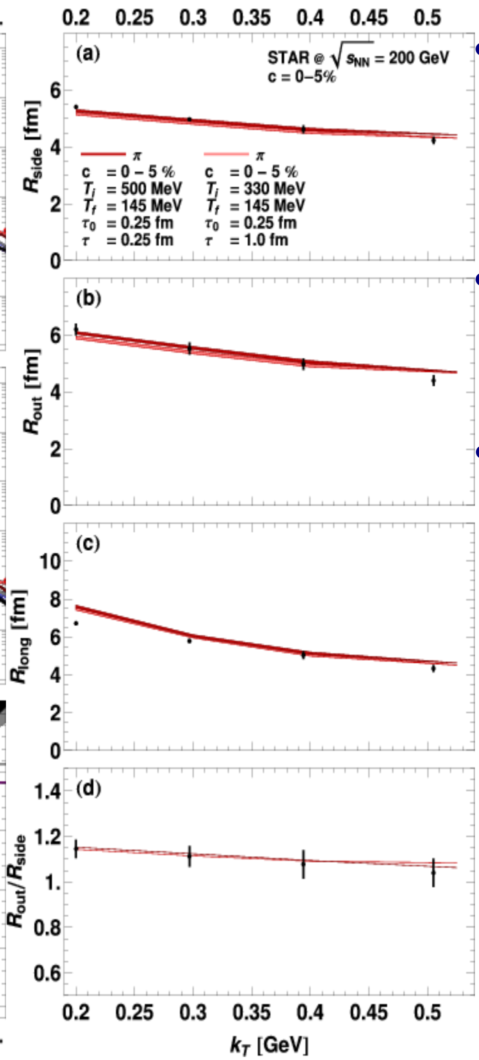
Revising hydrodynamics





W.Broniowski, W.Florkowski, M.Chojnacki, AK
nucl-th/0801.4361; nucl-th/0710.5731

- The attempts to describe the correlation radii together with momentum observables (v2 , pT) stimulated the development hydrodynamic models.
- Usually initial conditions did not have initial flow at the start of hydrodynamics (~1 fm/c) – now they have it.
- Femtoscopy data excluded 1-st order phase transition – smooth cross-over is needed
- Resonance propagation & decays & particle rescattering after freeze-out have to be taken into account: similar in effects to viscosity

Some hydro models successfully describing RHIC spectra, flow & femtoscopy radii

-- W. Florkowski, W. Broniowski, M. Chojnacki and A. Kisiel, arXiv:0811.3761 [nucl-th].
--S. Pratt, arXiv:0811.3363 [nucl-th]; Phys. Rev. Lett. 102, 232301 (2009);
--Yu. M. Sinyukov, S. V. Akkelin, I. A. Karpenko and Y. Hama, Acta Phys. Polon. B 40, 1025 (2009) [arXiv:0901.1576 [nucl-th]];

AGS-SPS-RHIC-LHC radii versus sqrt(s_{NN})

STAR 1403.4972 (hep-exp)

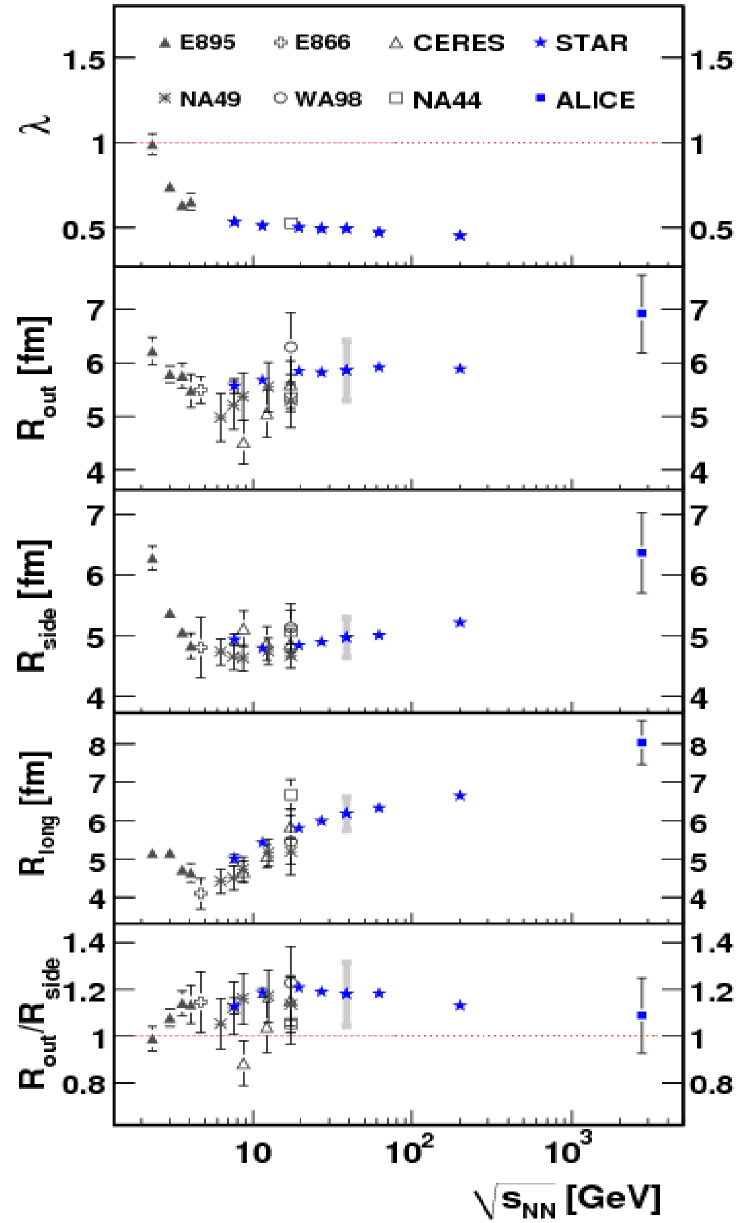
- **LHC** Pb-Pb : **sqrt(s_{NN}) ~ 2.76 TeV**
- **RHIC sqrt(s_{NN}) ~ 62 to 200 GeV**

large T & small μ_B

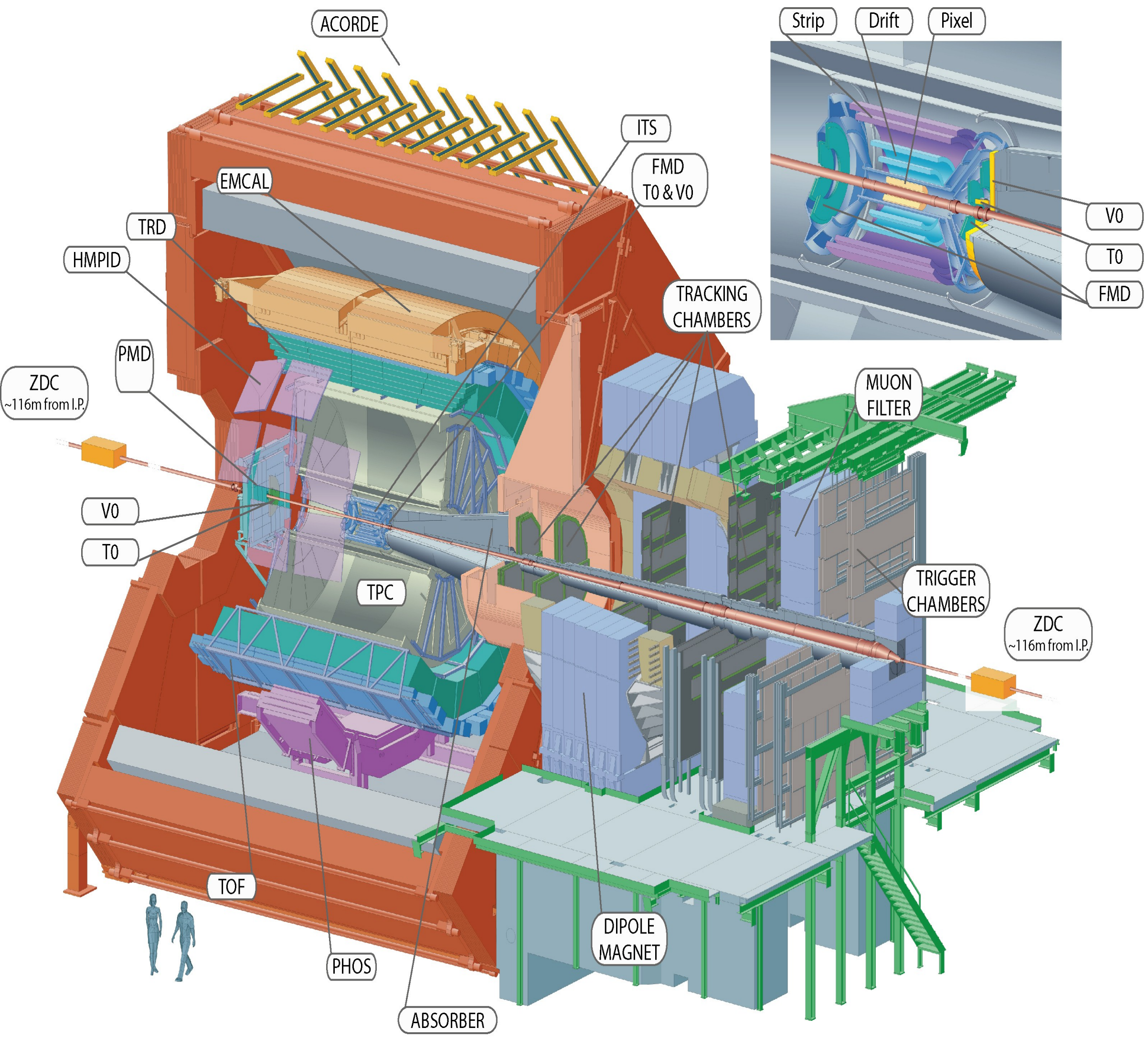
- **RHIC Beam Energy Scan program (BES)**

sqrt(s_{NN}) = 7.7, 11.5, 19.6, 27, 39 GeV

small T & large μ_B – 1st order phase transition; **search for "critical point"**

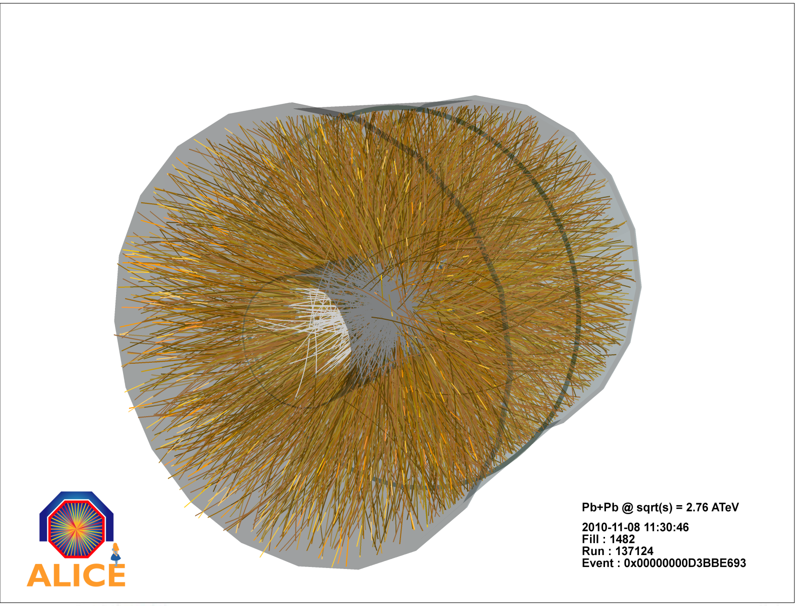


ALICE at LHC

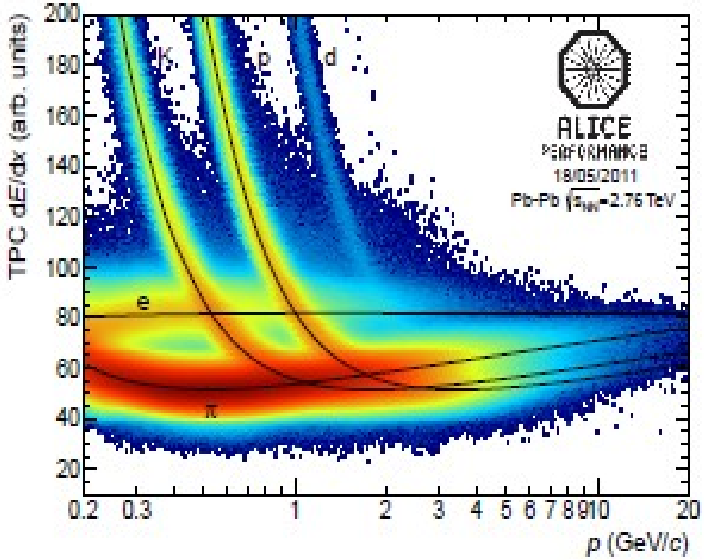


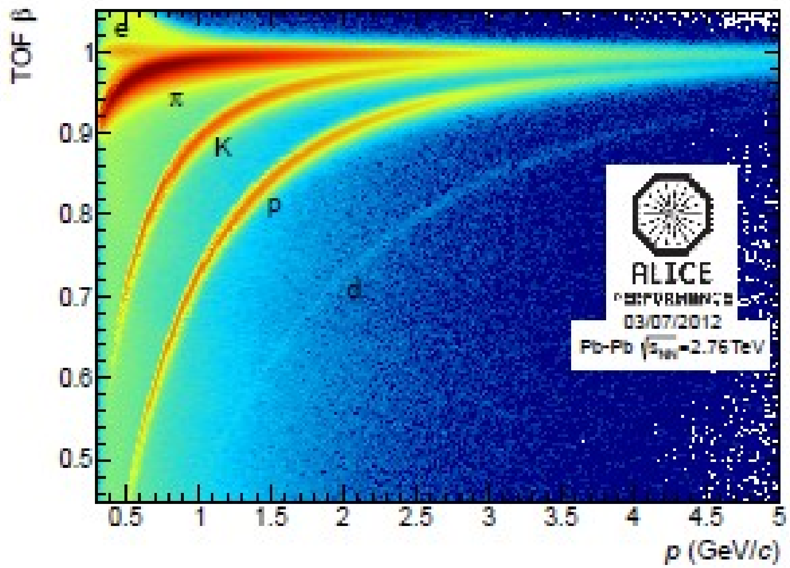
- Main tracking detector:
  Time Projection Chamber(TPC)
- Vertexing and tracking:
  Inner Tracking System (ITS)
- Trigger and centrality:
  VZERO, ZDC, ITS
- Particle identification (PID):
  TPC & ITS (energy loss)
  Time-of-Flight (TOF)

ALICE experiment at LHC



- Low momenum cut-off (p_T>100 MeV/c)
- Small material budget
- Excellent particle identification (PID) by specific energy loss (dE/dx) & time of flight & transition radiation & Cherenkov radiation
- Good primary and secondary vertex resolution allows for measurements of strangeness and heavy flavor with low background





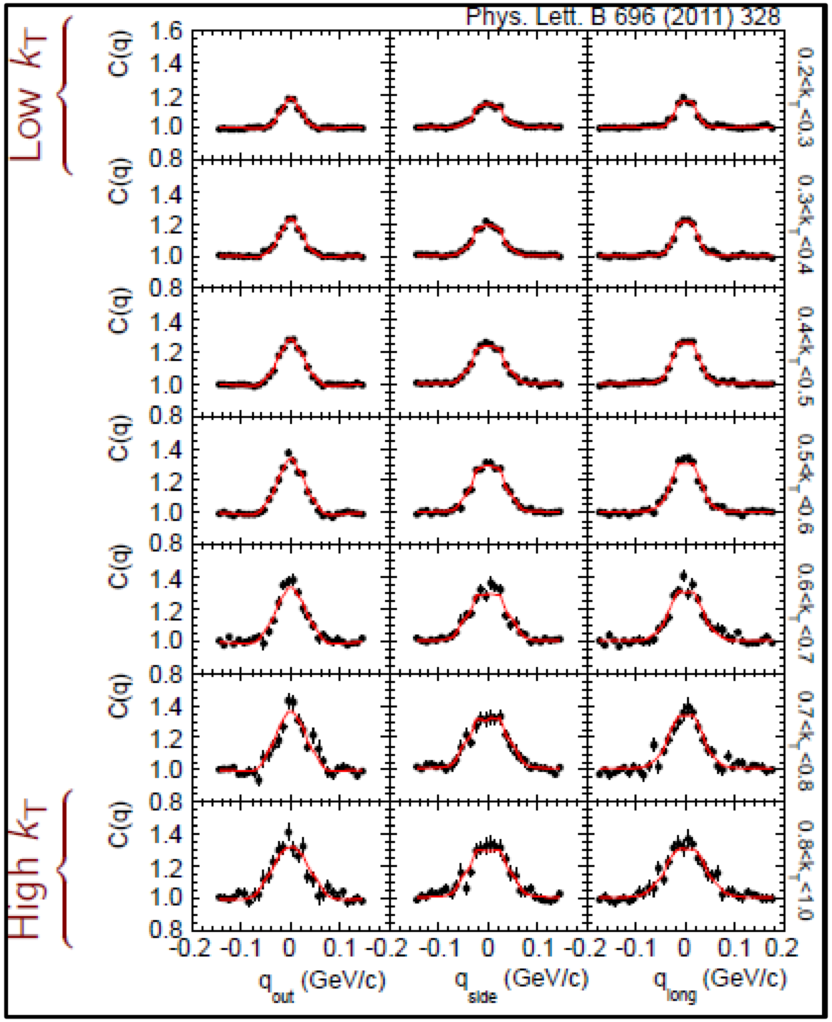
3D Correlation functions: pion CFs measured by ALICE in Pb-Pb at 2.76 TeV

- Correlation functions measured in three dimensions (out, side, long)
- Seven average transverse pair momenta, kT (0.2 - 1.0) GeV/c
- Fitted using the Bowler-Sinyukov formula:

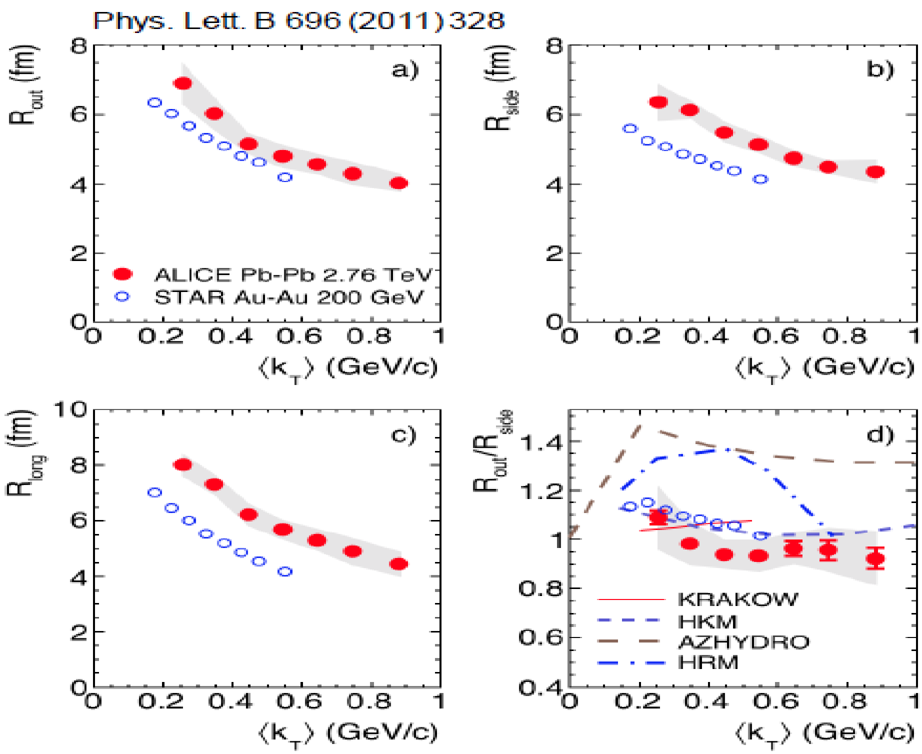
$$C(q) = \mathcal{N}\{(1-\lambda) + \lambda K(q_{\rm inv})[1+G(q)]\},$$
$$G(q) = \exp\left[-(R_{\rm out}^2 q_{\rm out}^2 + R_{\rm side}^2 q_{\rm side}^2) + R_{\rm long}^2 q_{\rm long}^2)\right],$$

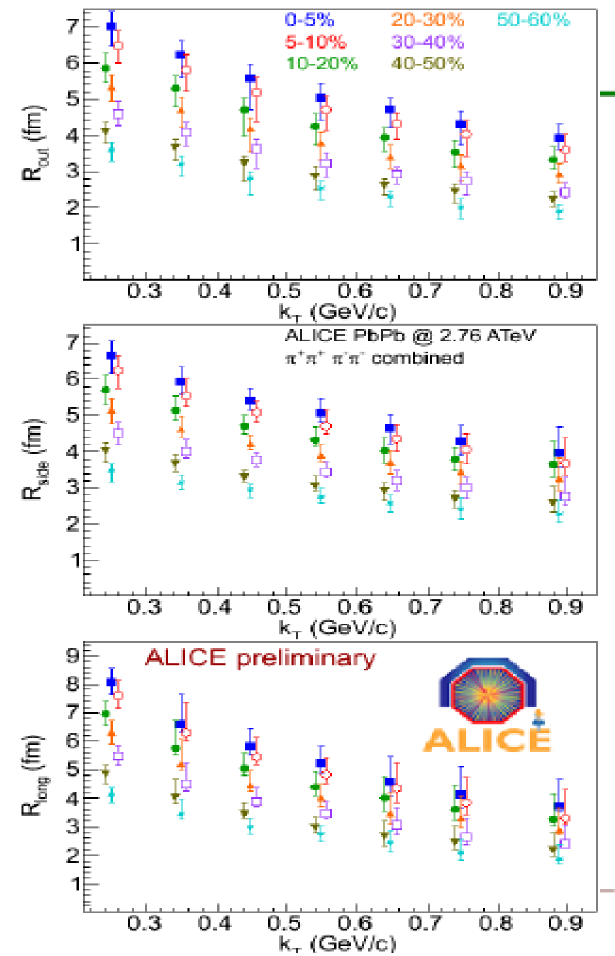
with λ the correlation strength and K(qinv) the Coulomb factor.

- BE peak width increases with kT, so radii decrease with kT.



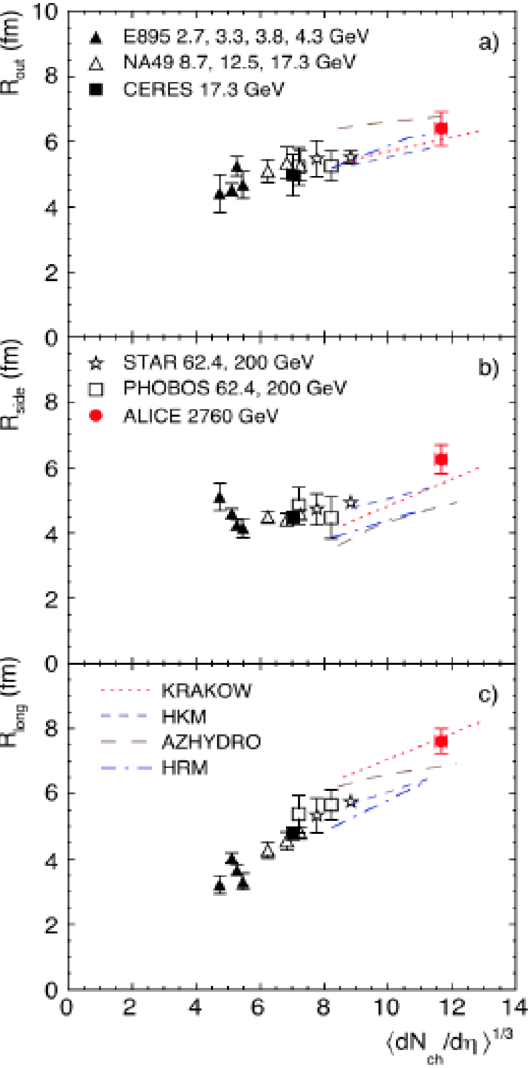
Main ALICE results of the pion femtoscopy analysis in Pb-Pb: radii versus k_T

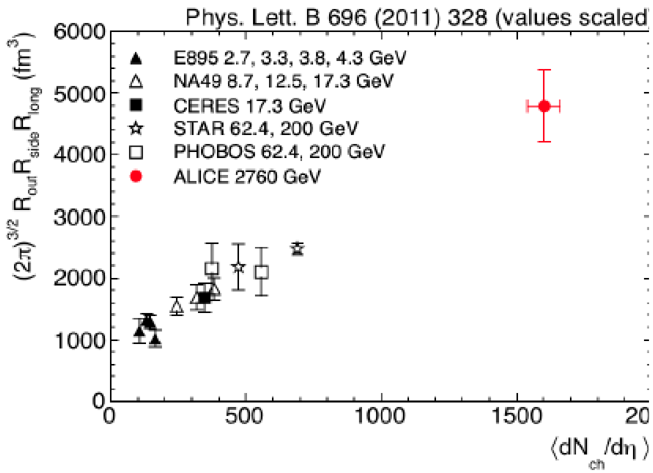


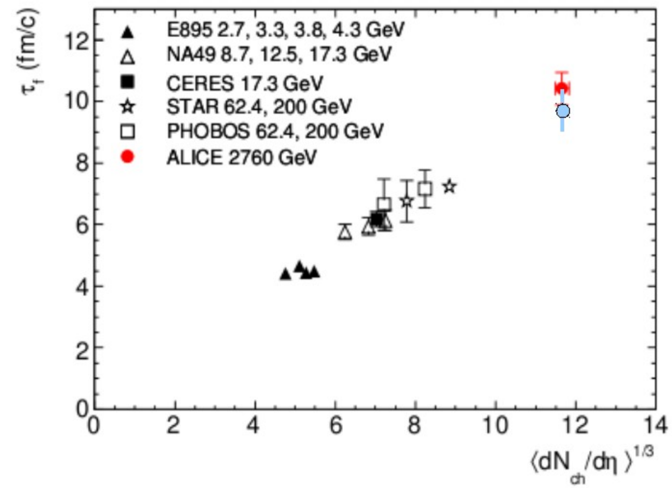


- Strong k_T dependence of radii - sign of transverse flow
- Decrease of size with decreasing multiplicity
- Linear scaling of radii with $dN_{ch}/d\eta$ – similar to hydrodynamic
- Rout/Rside smaller then at RHIC

Main ALICE results of the pion femtoscopy analysis in Pb-Pb: radii versus $dN_{ch}/d\eta$

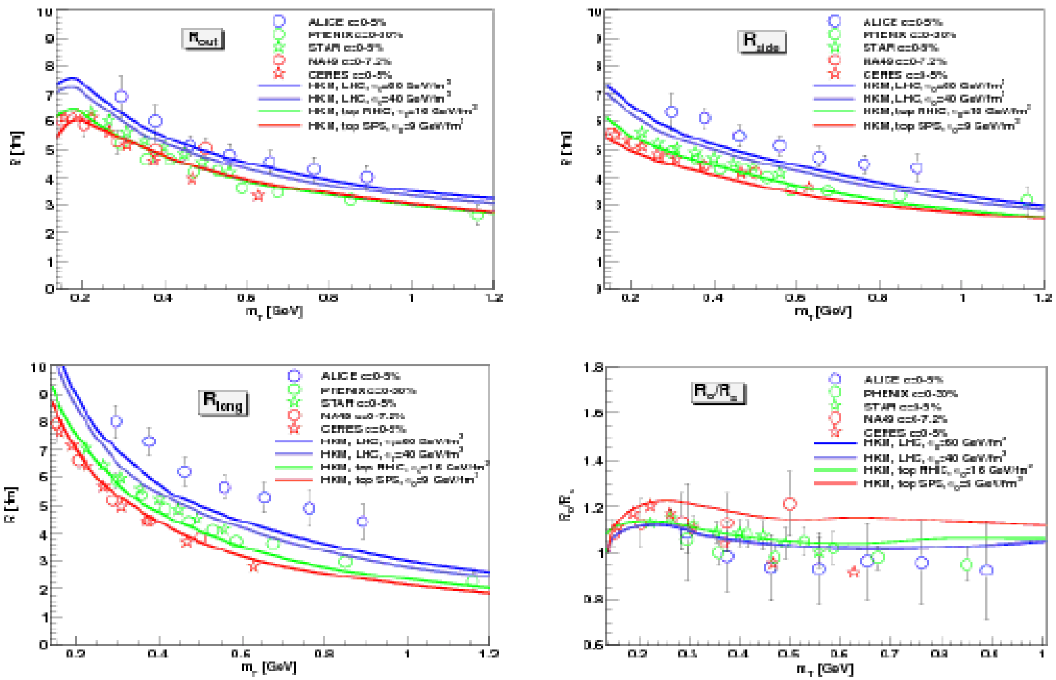


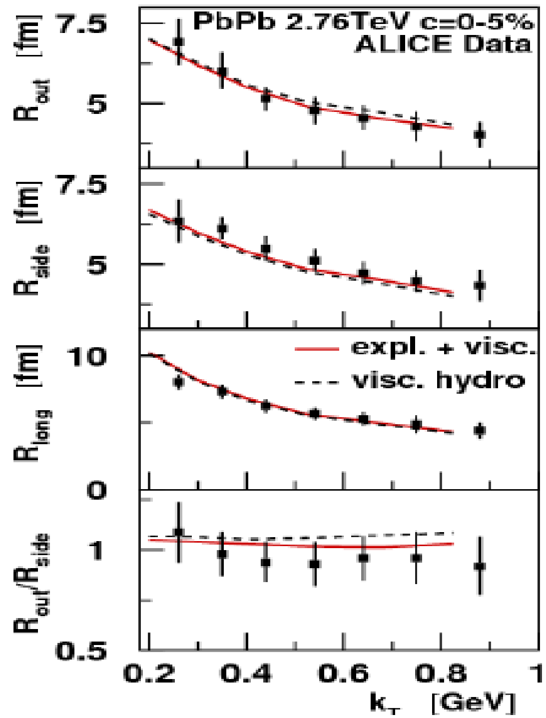




- Homogeneity volume 2 times larger than at RHIC
- Scaling of the radii with($dN_{ch}/d\eta)^{1/3}$
- ALICE significantly extends the range of the radii world systematics.
- R_{long} is proportional to the total duration of the longitudinal expansion.
- Decoupling time τ ~ 40% larger than at RHIC.

Theoretical interpretations LHC





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

Hydro-Kinetic Model: **the same hydrokinetic basis as was used for RHIC** supplemented by hadronic cascade model at the latest stage of the evolution:.**The following factors are important**: a presence of prethermal transverse flow, a crossover transition between quark-gluon and hadron matters, non-hydrodynamic behavior of the hadron gas at the latest stage, and correct matching between hydrodynamic and non-hydrodynamic stages.

P. Bożek,Phys.Rev. C83 (2011) 044910

3D relativistic viscous hydrodynamics

Glauber model initial conditions

EoS based on lattice results and hadron-gas model- crossover.

The viscosities and the EoS are the same as used for RHIC energies.

Physical motivation for femtoscopy with heavier particles (kaons, protons...)

● **Wide range of pair transverse mass (m_T): strong constrains for hydrodynamic model predictions (its should work for heavier mesons and baryons)**

● **Consistency checks:**

- Different sources of correlations: Quantum Statistics (QS), Coulomb and Strong Final State Interactions (FSI)

- Complementary systems (e.g. charged and neutral kaons)

- Overlapping m_T ranges
- Different systematics

$K^{\pm}K^{\pm}$, $K^0_sK^0_s$, pp in Pb–Pb at 2.76 TeV

Neutral kaons:

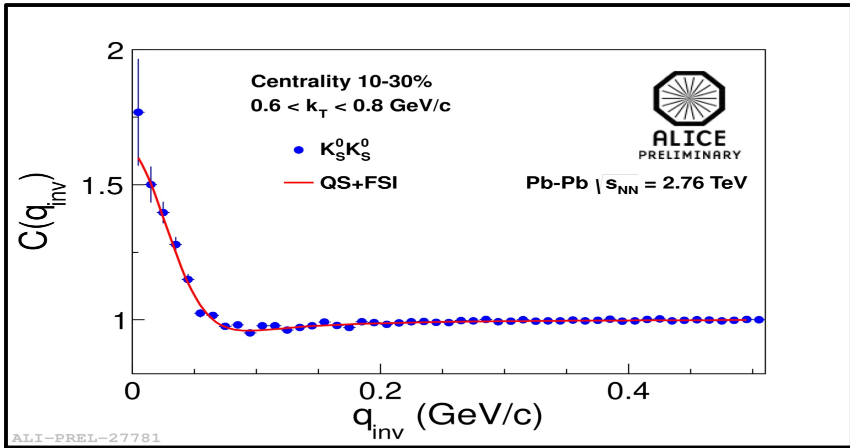
- PID via $\pi+\pi-$ decay channel (purity~95%), p_T up to 2.0 GeV/c
- **strong FSI and QS** lead to femtoscopic effect, both included in the fit (Lednicky &Lyuboshitz model, Sov.J.Nucl.Phys. 35(1982)770)
- **no Coulomb suppression**

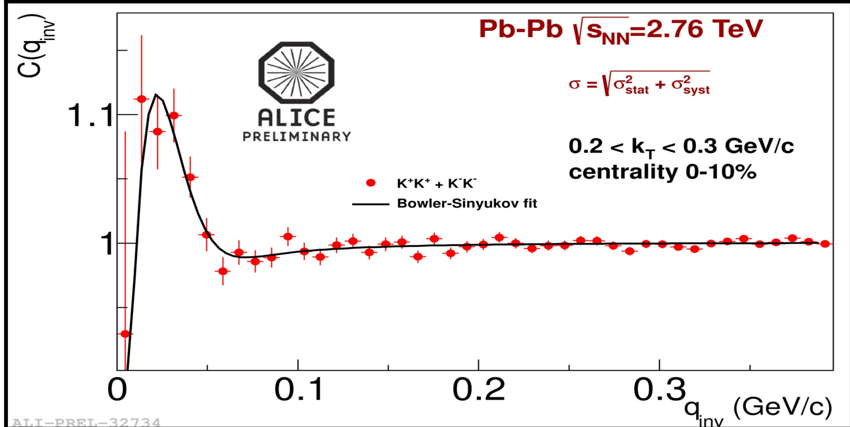
Charged kaons:

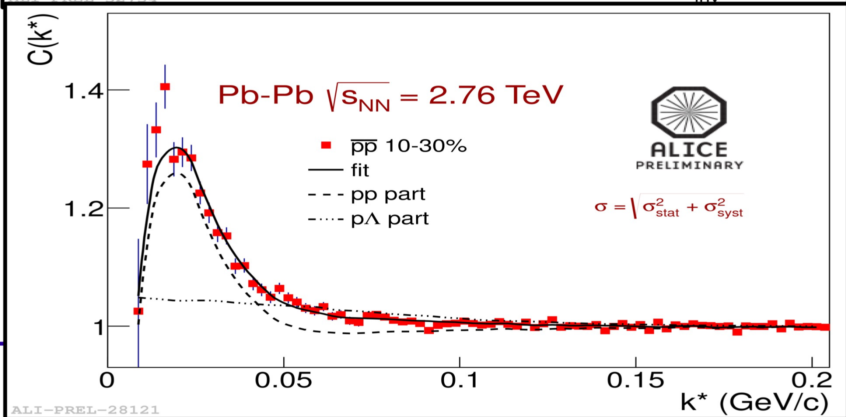
- PID: TPC+TOF, p_T range up to 1.5 GeV/c
- **QS and Coulomb repulsion**, Bowler-Sinyukov fit: $C(q_{inv}) = (1 - \lambda) + \lambda K(q_{inv})(1 + exp(-R^2 q_{inv}^2))$, $K(q_{inv})$ - Coulomb function,

Protons ((anti-) protons]

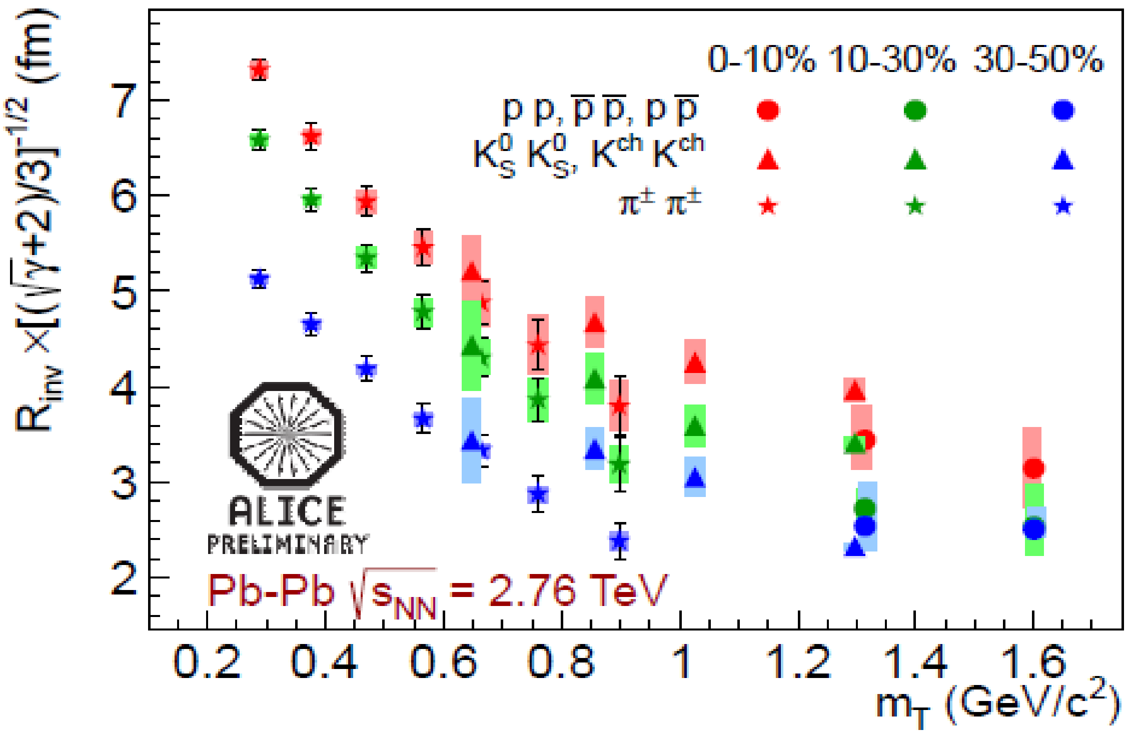
- PID: TPC+TOF
- **QS, Coulomb and Strong FSI** included in the fit, fit includes also residual pΛ correlations







m_T scaling with different masses in Pb-Pb at 2.76 TeV



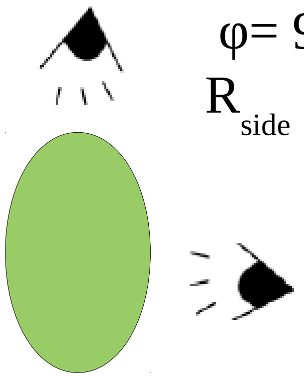
Approximate m_T scaling after taking into account kinematics.

(see THERMINATOR: A. Kisiel, T. Taluc, W. Broniowski, W. Florkowski: Comput.Phys.Commun. 174 (2006) **669-687**; and also Maciej Szymanski's QM2012 talk "Meson and baryon femtoscopy in heavy-ion collisions at ALICE").

Non-central collisions: azimuthally sensitive femtoscopy (az-femtoscopy)

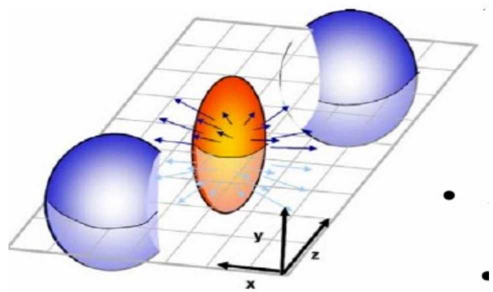
Azimuthally sensitive femtoscopy measures the space-time asymmetry by measuring radii vs. reaction plane. Specific oscillations are observed.

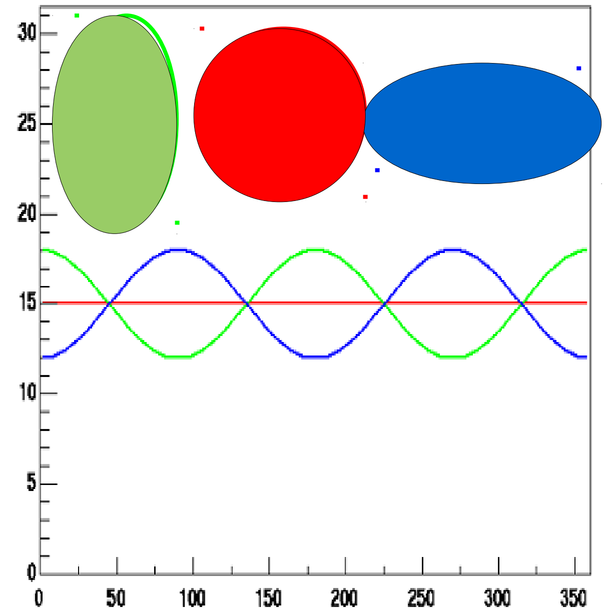
out-of-plain source



φ= 90, R_{side} small

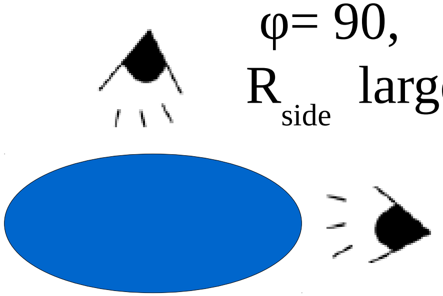
φ= 0, R_{side} large





in-plain source

φ= 90, R_{side} large



φ= 0, R_{side} small

$$R_\mu^2 = R_0^2 + 2R_{\mu,n}^2 \cos\left[n\left(\phi_{pair} - \Psi_n\right)\right] \quad (\mu = s,o,l)$$

$$R_\mu^2 = R_0^2 + 2R_{\mu,n}^2 \sin\left[n\left(\phi_{pair} - \Psi_n\right)\right] \quad (\mu = os)$$

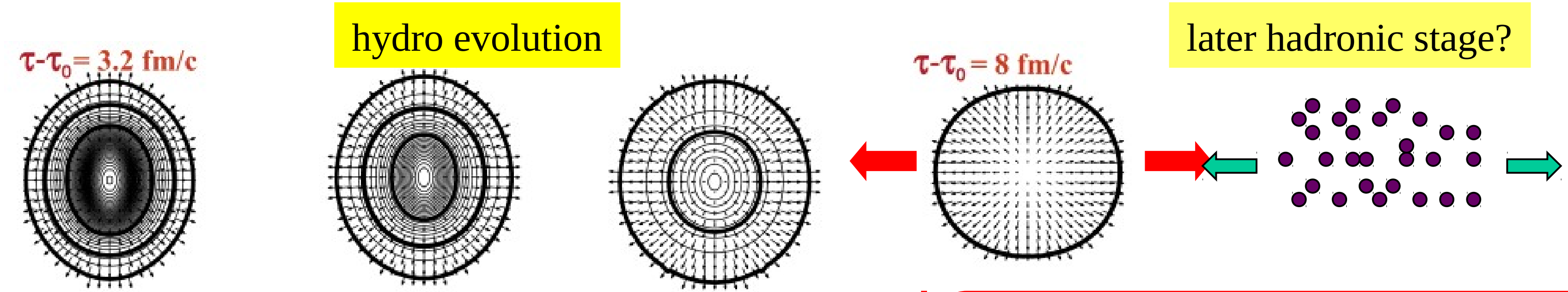
n : harmonic number

$$\Psi_n = \frac{1}{n}\arctan\left(\frac{Q_y}{Q_x}\right) + \Delta\Psi_n$$

$$Q_x = \frac{1}{N}\sum_i \left(w_i \cos(n\phi_i) - \langle Q\rangle_x\right)$$

$$Q_y = \frac{1}{N}\sum_i \left(w_i \sin(n\phi_i) - \langle Q\rangle_y\right).$$

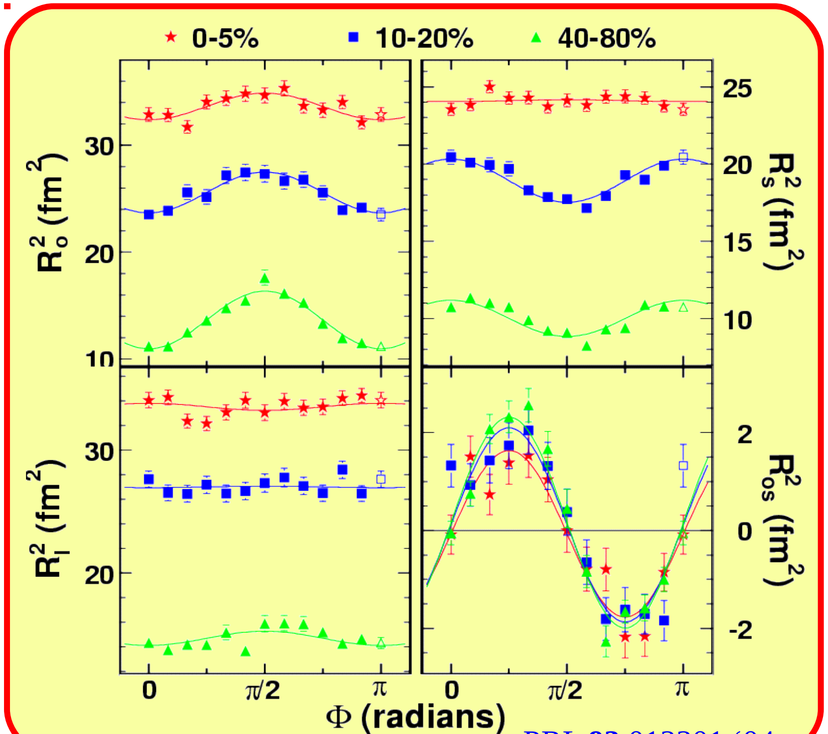
Non-central collisions: azimuthally sensitive femtoscopy (az-femtoscopy)



Kolb & Heinz

- Azimuthal anisotropy evolves towards a spherical shape;
- Anisotropic pressure gradients cause elliptic flow (v_2);
- Au-Au 200 GeV : STAR observed oscillations similar to out-of-plain source
- Short evolution time:

R_{long} & radii *vs* reaction plane: $\tau \sim 10$ fm/c

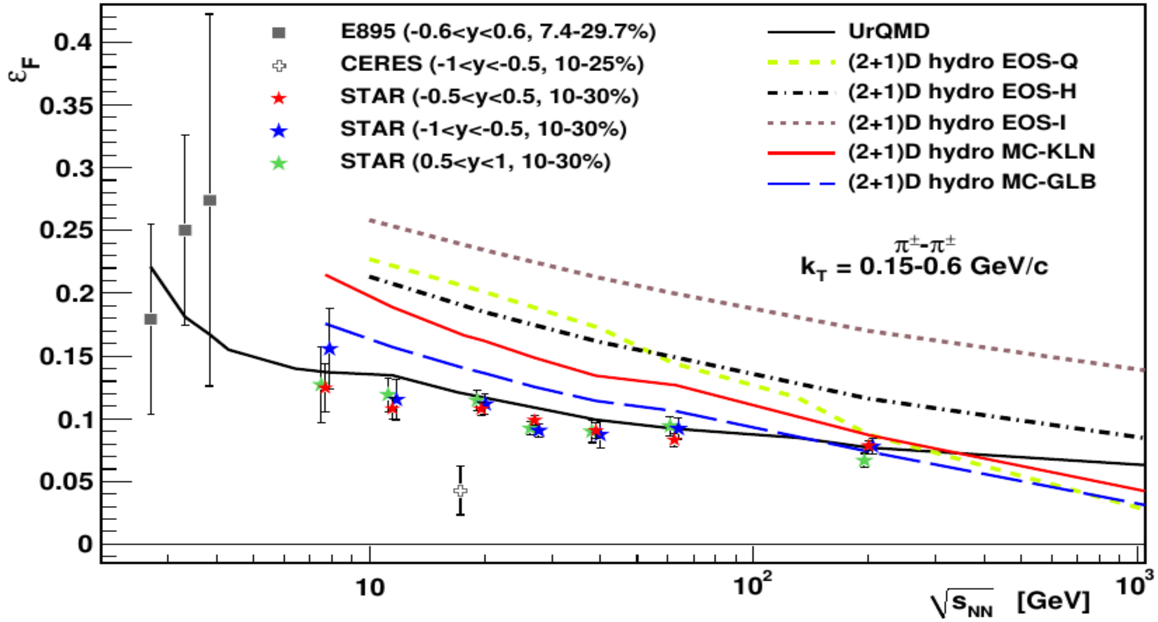


PRL **93** 012301 '04

Az-femtoscopy

STAR arxiv 1403.4972 [hep-exp]

Dependence of the kinetic freeze-out eccentricity of pions on collision energy



$$\varepsilon_F = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} \approx 2\frac{R_{s,2}^2}{R_{s,0}^2}$$

From: F. Reti`ere and M. A. Lisa, Phys. Rev. C 70, 044907 (2004)

$\sigma_x^2 = \{x^2\} - \{x\}^2$ in-plane

$\sigma_y^2 = \{y^2\} - \{y\}^2$ out-of-plane

The prediction of the Boltzmann transport model, UrQMD matches most closely the freeze-out shape at all energies. UrQMD does not require assumptions about how freeze-out occurs; the model is 3D and does not require boost-invariance, therefore it is equally applicable at all the studied energies.

Femtoscopy in pp & p-Pb

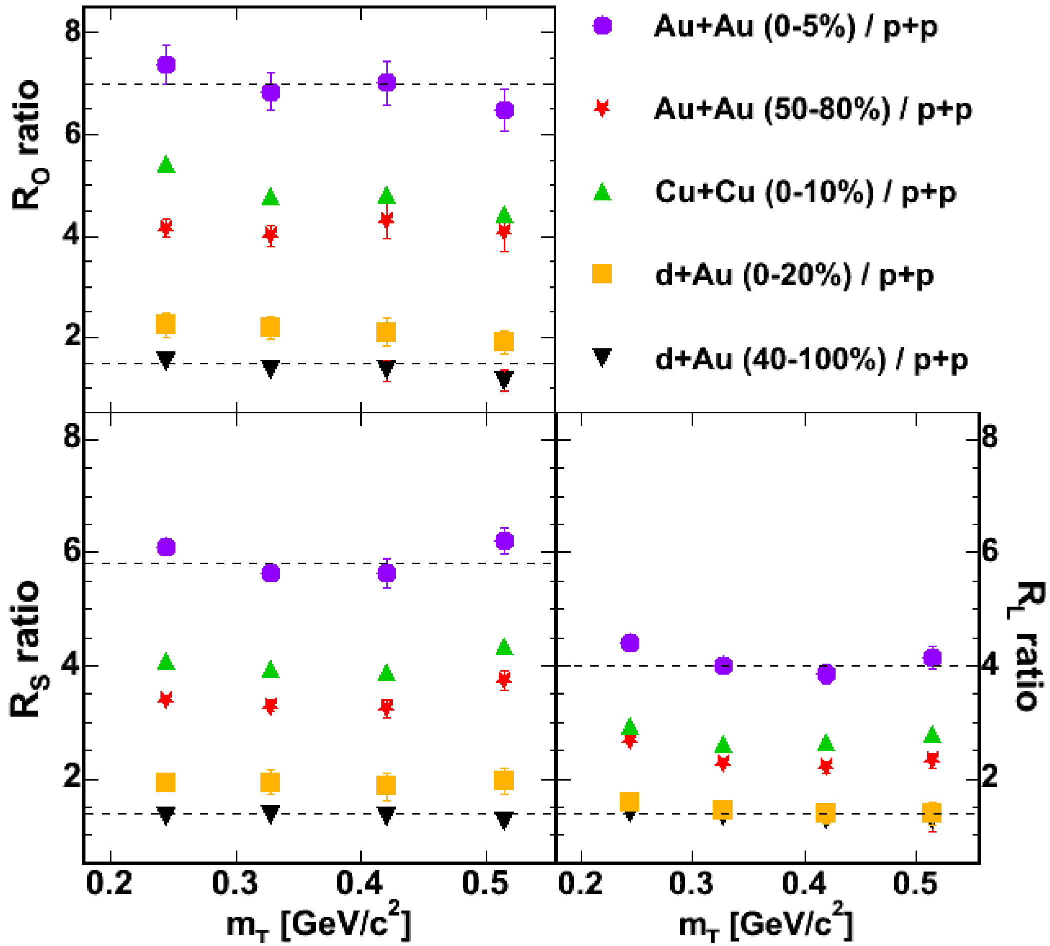
RHIC lessons: femtoscopy in pp collisions at 200 GeV

- STAR reports that 3D HBT radii scale in p+p in a way very similar to HI

- mT dependence in elemenatary (pp, e+e-) collisions is usually attributed to
  - -string fragmentation
  - -resonance contribution
  - -Heisenberg uncertainty

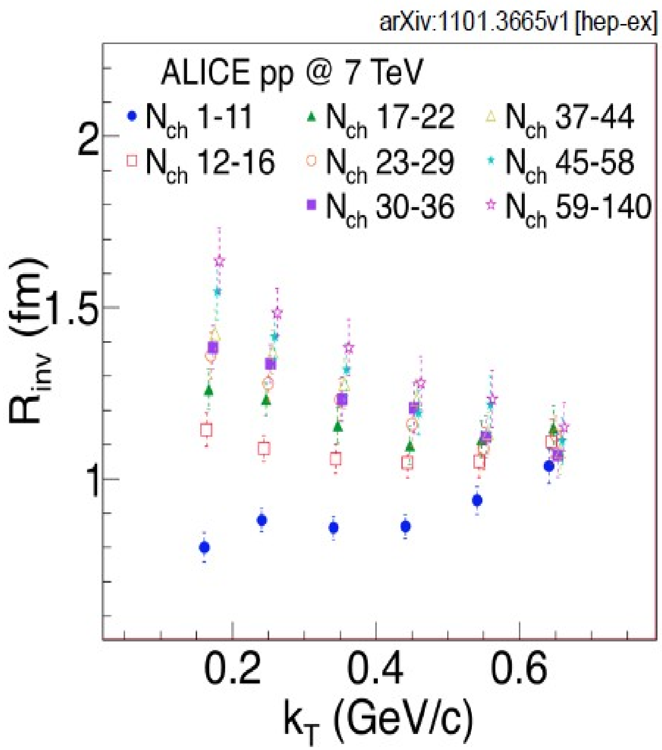
- Is the scaling between p+p and Au+Au a signature of the universal underlying physics mechanism (collective flow) or a coincidence?

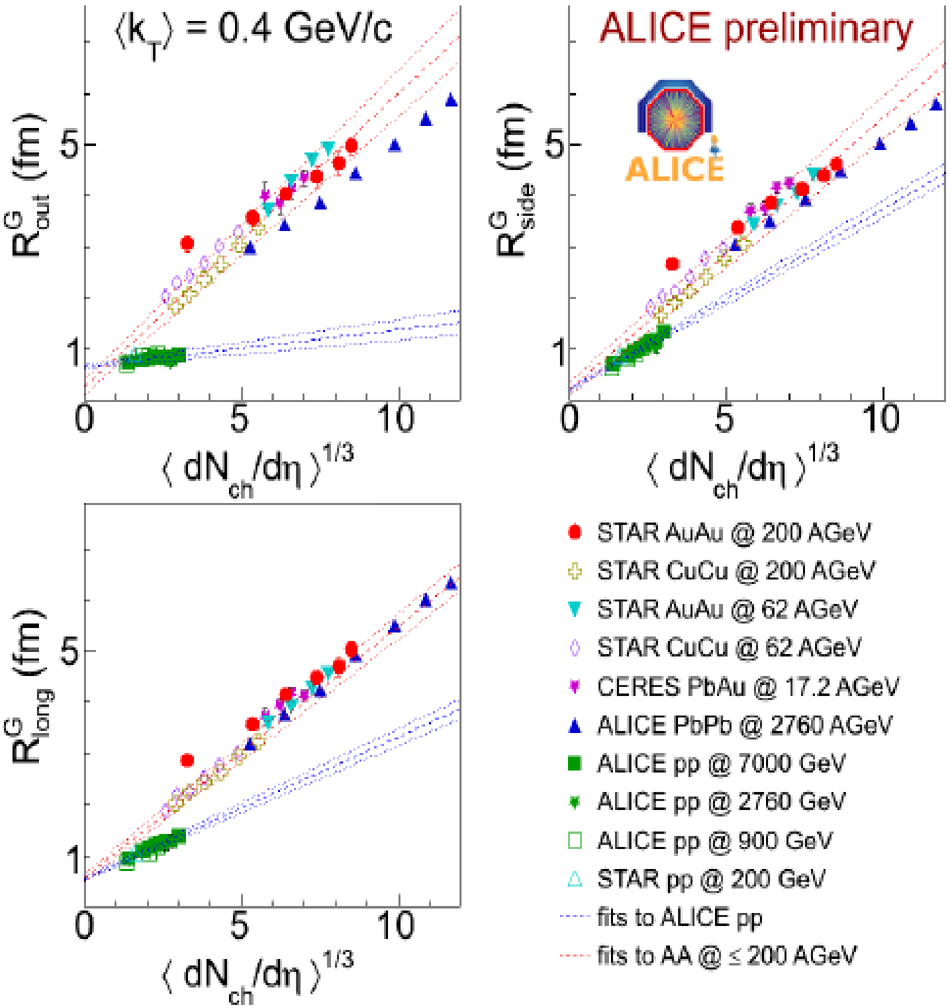
STAR 1004.0925 [hep-ex]



ALICE data on pion correlations in pp collisions at 7 TeV

From: Aamodt, et al., Phys. Rev. D 84 (2011) 112004.

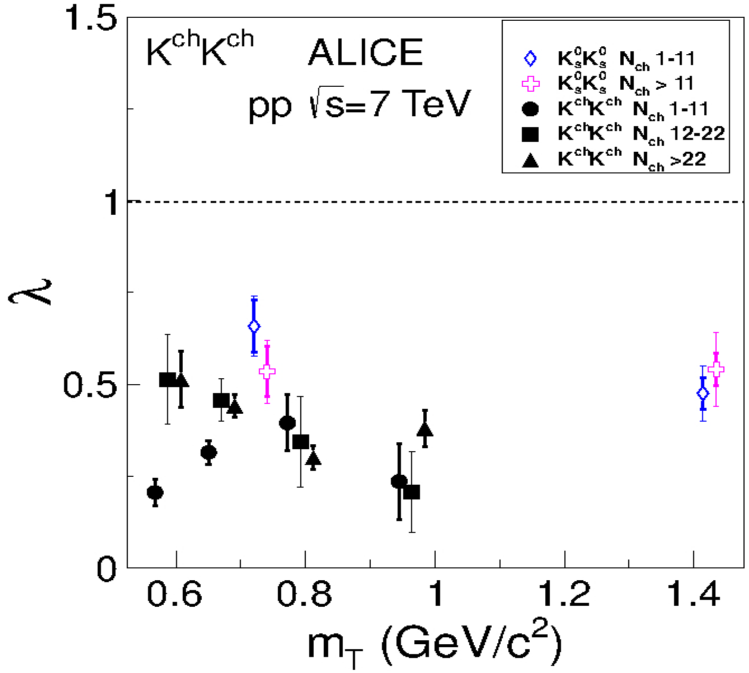


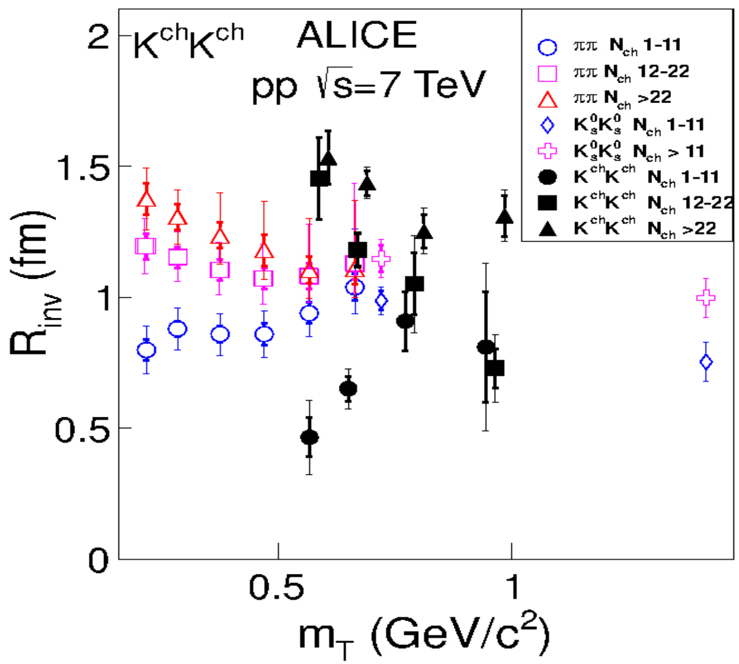


- In pp k_T dependence of radii is observed at large multiplicity bins
- Decrease of size with decreasing multiplicity
- Radii increase with multiplicity both in pp and Pb-Pb but with different slopes

m_T-dependence in pp @ 7 TeV

B. Abelev et al. (ALICE Collaboration) Phys. Rev. D 87, 052016 (2013)



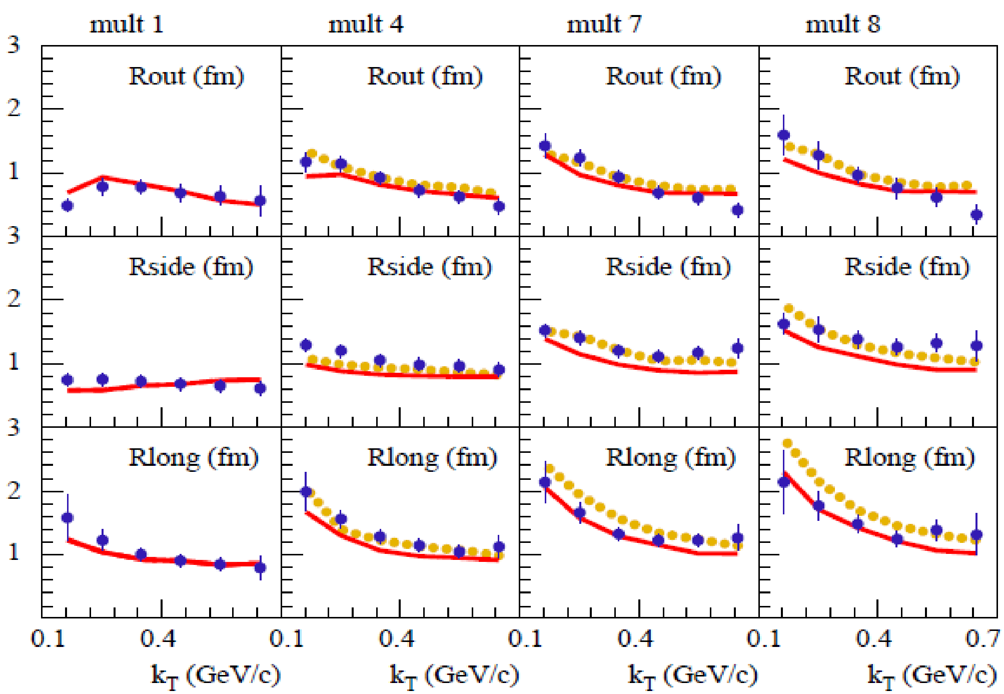


- k_T dependence of radii is different at small and large multiplicity bins
- decrease of size with decreasing multiplicity
- indication on breaking of m_T scaling $R_K>R_\pi$

Theoretical interpretations: EPOS

K. Werner, K. Mikhailov, Yu. Karpenko, T. Pierog arXiv:1104.2405

Modified EPOS model combining string dynamic, hydrodynamics and hadron cascade



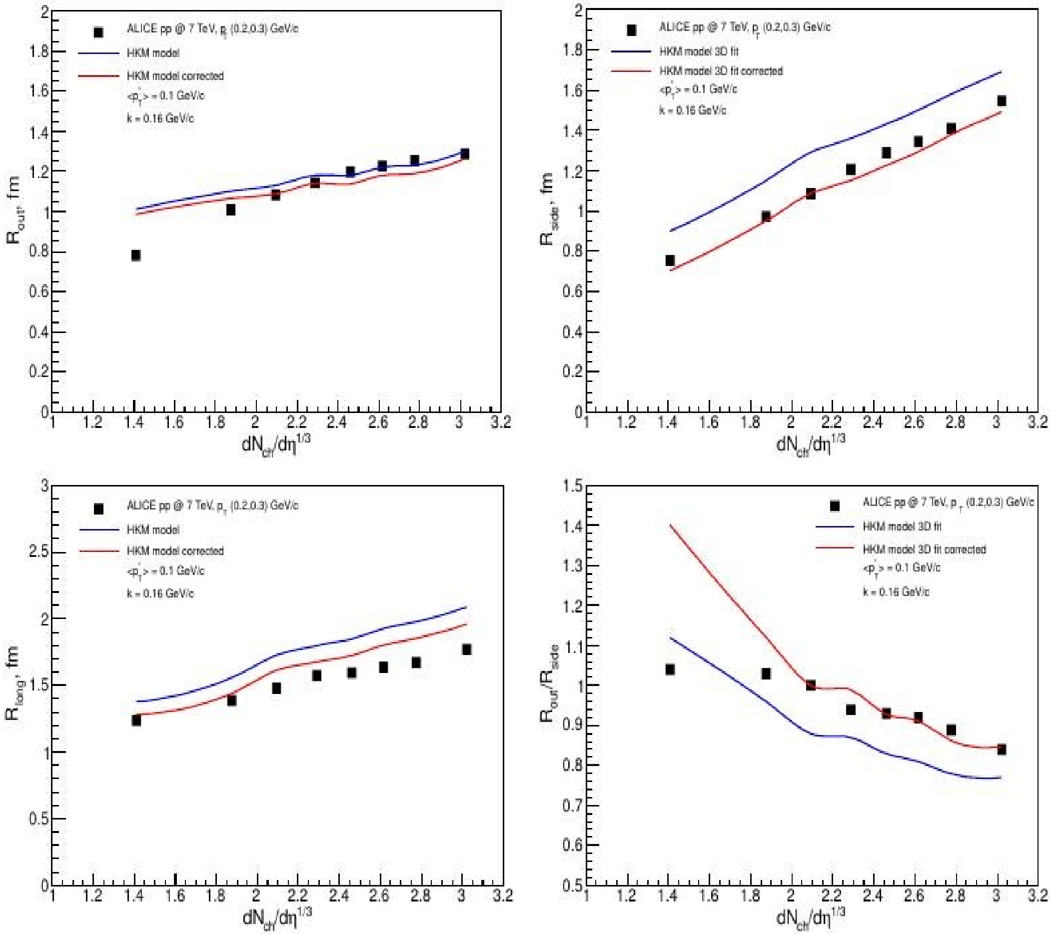
	N_{ch}	$dN_{ch}/d\eta$
mult1	1-11	3.2
mult4	23-29	13.6
mult7	45-57	24.3
mult8	58-149	31.1

At large multiplicity bins in pp high string density => the usual string models has to be modified ! Rather than breaking independently, the strings will constitute multiple flux tubes matter used as initial conditions for hydrodynamical evolution

Theoretical interpretations: HKM

ALICE data from: Aamodt, et al., Phys. Rev. D 84 (2011) 112004.

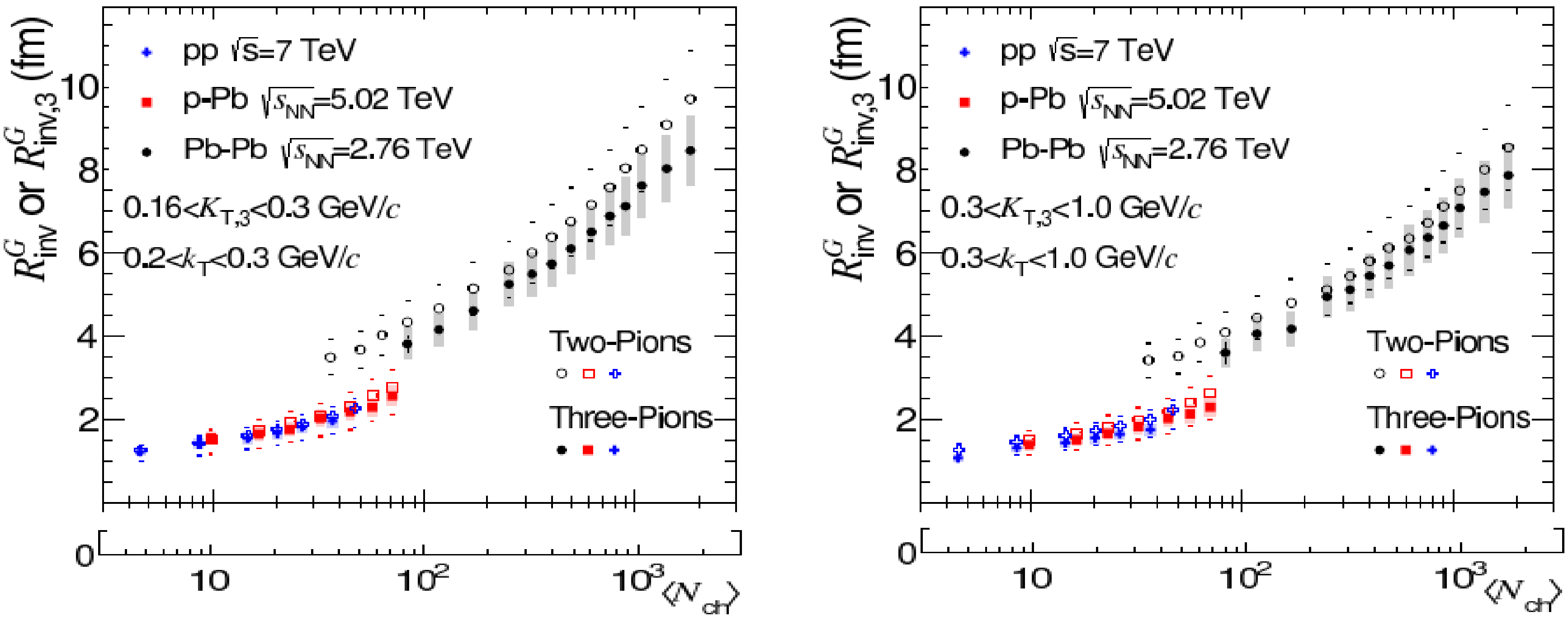
New observations concerning femtoscopy of small systems were done in [Sinyukov et al. Phys. Rev. D 87 094024 (2013), Phys. Lett. B 725 (2013) 139:



- If the source size is ~1 fm the standard femtoscopy model of random sources is inapplicable. Uncertainty principle leads to the partial indistinguishability & coherence of closely located emitters -> reduction of R & suppression of λ
- positive R-λ correlation
- factorization property for the contributions of femtoscopic and non-femtoscopic correlations (minijets & initial state fluctuations) into complete CF

Two & three pion Gaussian radii in pp, p-Pb and Pb-Pb

B. Abelev et al. (ALICE Collaboration) 1404.1194[nucl-ex]



At similar multiplicity, R_{inv} in p–Pb ~ 5–15% larger than those in pp, while those in Pb–Pb are 35–55% larger than those in p–Pb. ALICE measurements disfavor models which incorporate substantially stronger collective expansion in p–Pb as compared to pp collisions at similar multiplicity. The smaller radii in p–Pb then in Pb–Pb may demonstrate the importance of different initial conditions on the final-state, or indicate significant collective expansion already in peripheral Pb–Pb collisions.

Summary

- **Femtoscopy provides different tools to study collectivity:**

  -study of m_T dependence of radii for different particle types,

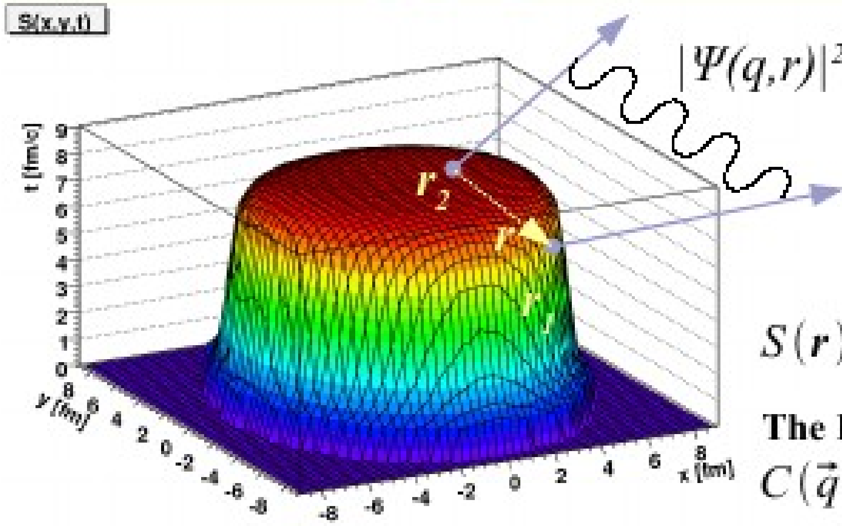
  -oscillation of radii vs. reaction plane orientation,

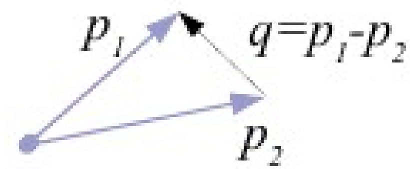
  -emission point differences.

- Femtoscopy provides a strong constrains on the physical assumptions of the models describing dynamics of different collisions .

Additional slides

Measuring space-time extent: femtoscopy





$$S(\boldsymbol{r})=\int S_a(\boldsymbol{r_1})S_b(\boldsymbol{r_2})\,\delta(\boldsymbol{r}-(\boldsymbol{r_1}-\boldsymbol{r_2}))\,d^4r_1\,d^4r_2$$

The Koonin-Pratt Equation:

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

Femtoscopy uses the correlation between two particles, reflected in the pair wave function Ψ. It comes from a combination of the quantum statistics (anti-)symmetrization, Coulomb and strong interactions. Using the Koonin-Pratt equation, one tries to learn as much as possible about the source (i.e. the source emission function S), from the measured correlation C.

Fitting a 3D CF

- The Koonin-Pratt equation:

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

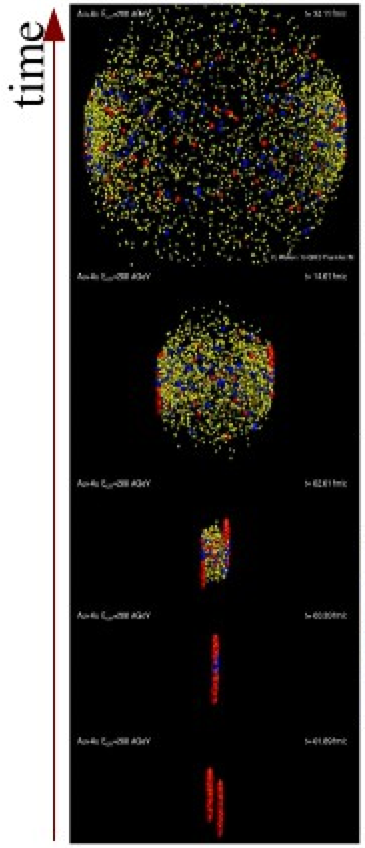
  requires the functional form of the source S to be postulated.
- The 3D Gaussian is commonly used in heavy-ions.
- Coulomb K is factorized out of Ψ, it is then $1+\cos(q\boldsymbol{r})$. This gives the femtoscopic part of the CF:

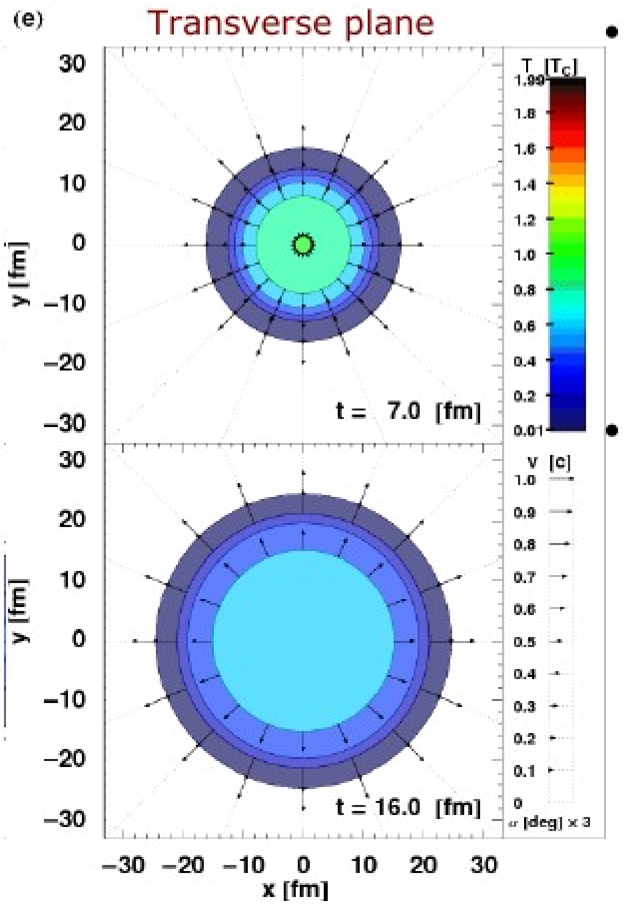
$$C = (1-\lambda) + \lambda K \left(1 + \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2)\right)$$

  where the radii R and q can be in Pair Rest Frame (PRF) or LCMS (this study)
- We need to add the non-femtoscopic background and normalization for the final version of the fit function:

$$C = N\left[(1-\lambda) + \lambda K \left(1 + \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2)\right)\right] B$$

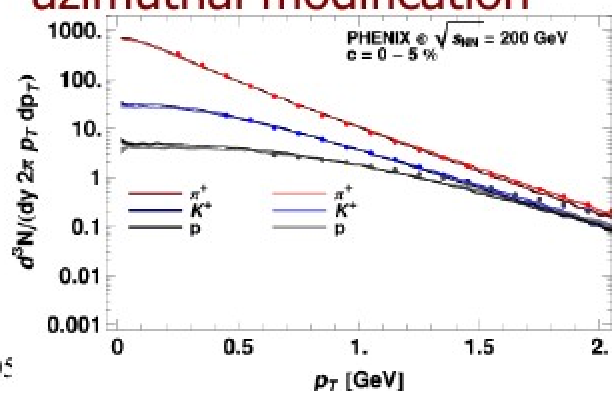
Heavy Ion collision evolution





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



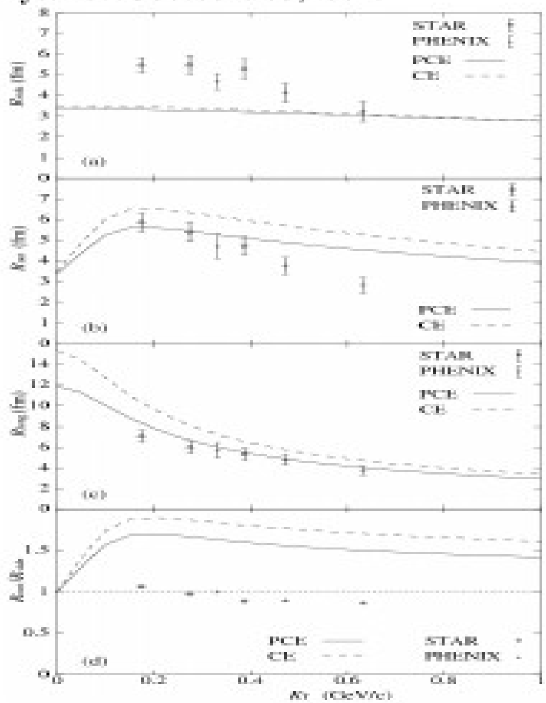
RHIC "HBT-HYDRO puzzle"

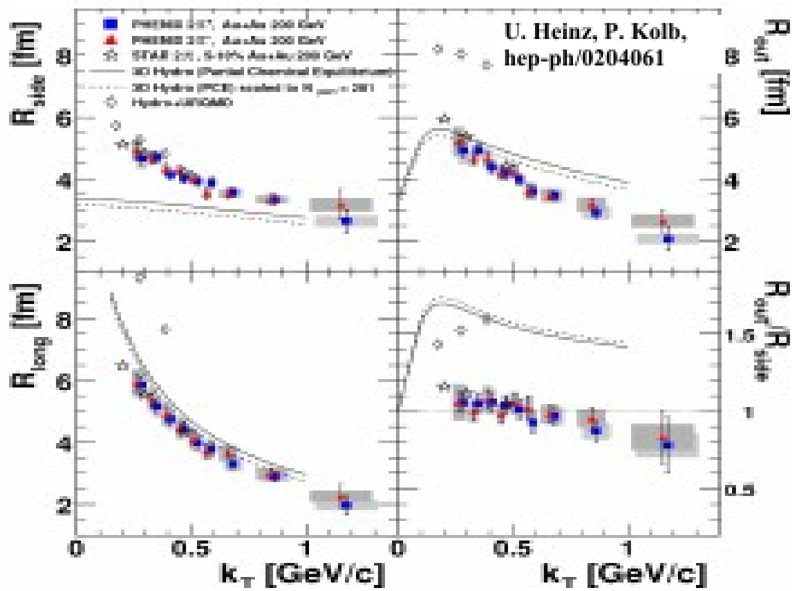
- First hydro calculations describing well momentum observables failed to describe femtoscopic data.

- Predicted too small Rs too large Rout – too long emission duration

- No evidence of the first order phase transition

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



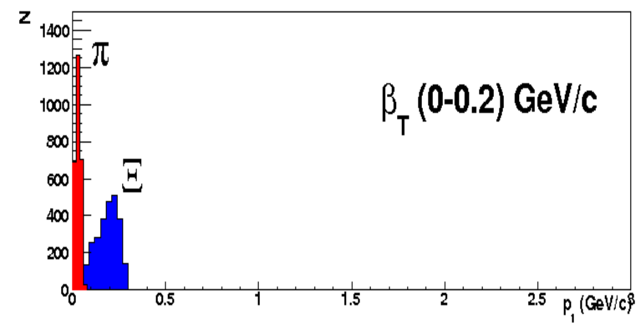


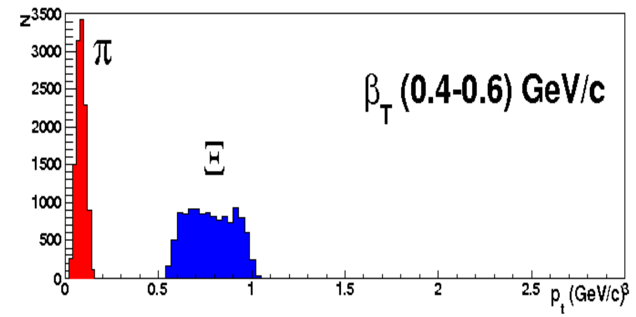
Femtoscopy with non-identical particles: average space-time differences

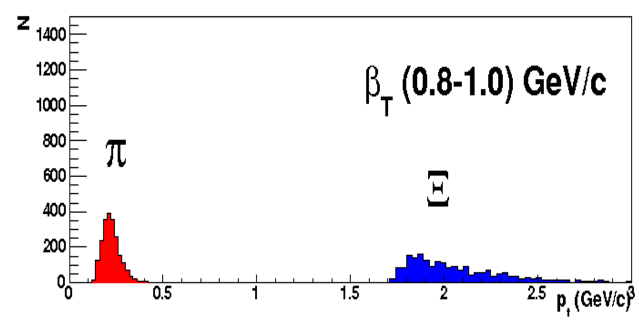
HYDJET++ model calculations
Spectacular example: π Ξ

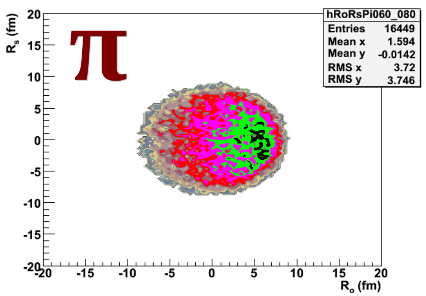
Particles interact if they are close in the phase space in the PRF --> relative momentum in pair rest frame is small.
It means that in laboratory rest frame they have close velocities. But for the particles with such a different masses the corresponding momenta will be very different:
to large Ξ momentum corresponds the small π momentum

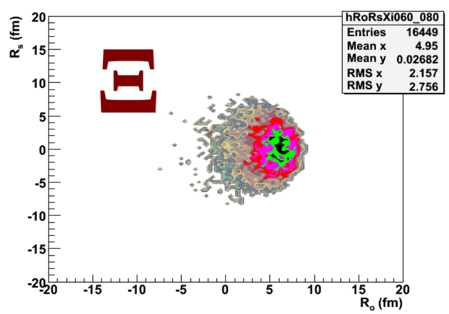
Random smearing is maximal for particle with low mass and momentum--> the system region emitting particles with given momentum shrinks and moves to edge of the system as mass/momentum increases











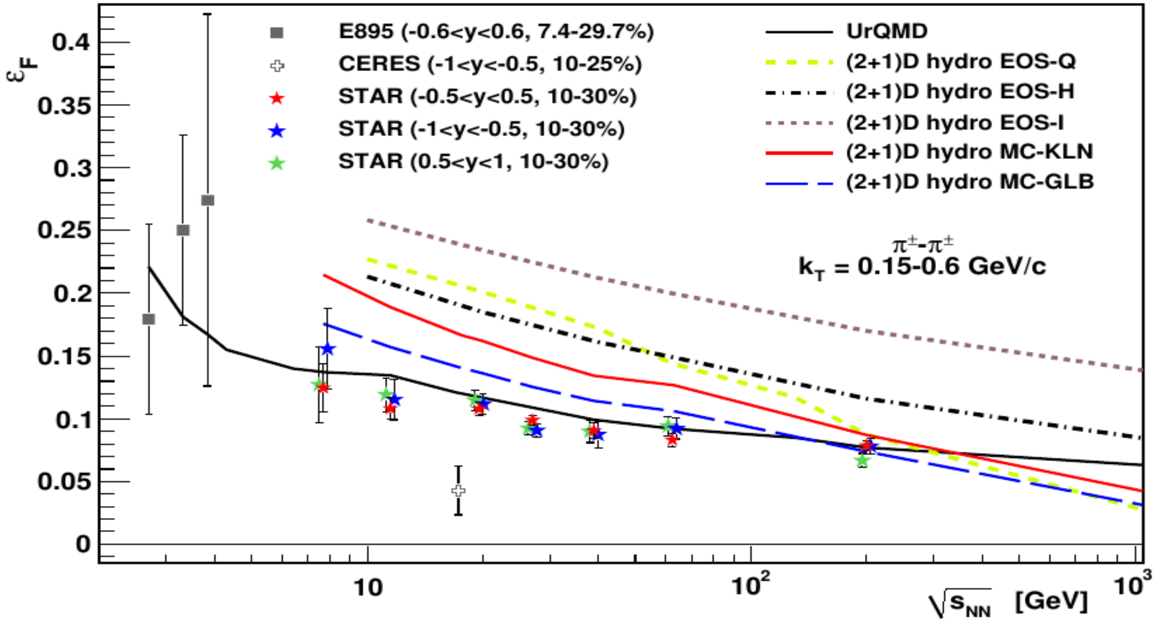
Az-femtoscopy

• Just as the pT -dependence of azimuthally-integrated femtoscopy radii gives access to the geometric substructure generated by radial flow, az-femtoscopy measured relative to the first and second-order event plane are the spatial analogs of **directed and elliptic** flow, respectively, and contain important information not accessible in momentum space alone.

• These measurements can be sensitive to a softening in the equation of state, related to a first-order phase transition, or rapid crossover --- useful instrument for the beam energy scan.

STAR arxiv 1403.4972 [hep-exp]

Dependence of the kinetic freeze-out eccentricity of pions on collision energy



$$\varepsilon_F = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} \approx 2\frac{R_{s,2}^2}{R_{s,0}^2}$$

From: F. Reti`ere and M. A. Lisa, Phys. Rev. C 70, 044907 (2004)

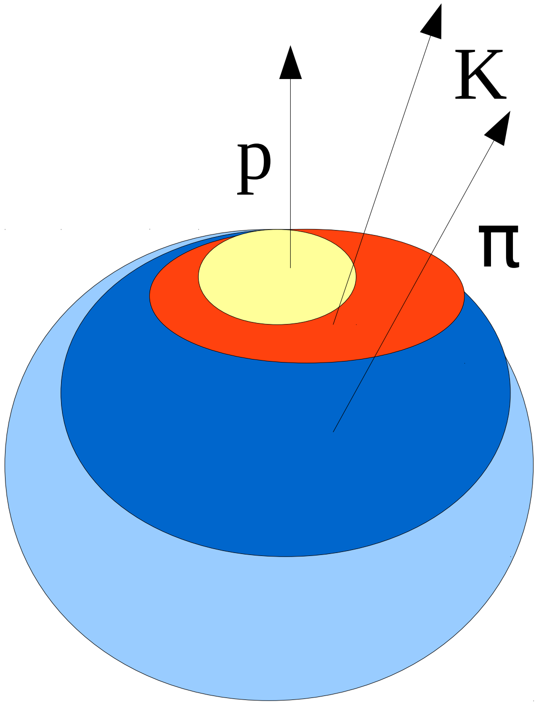
$\sigma_x^2 = \{x^2\} - \{x\}^2$ in-plane

$\sigma_y^2 = \{y^2\} - \{y\}^2$ out-of-plane

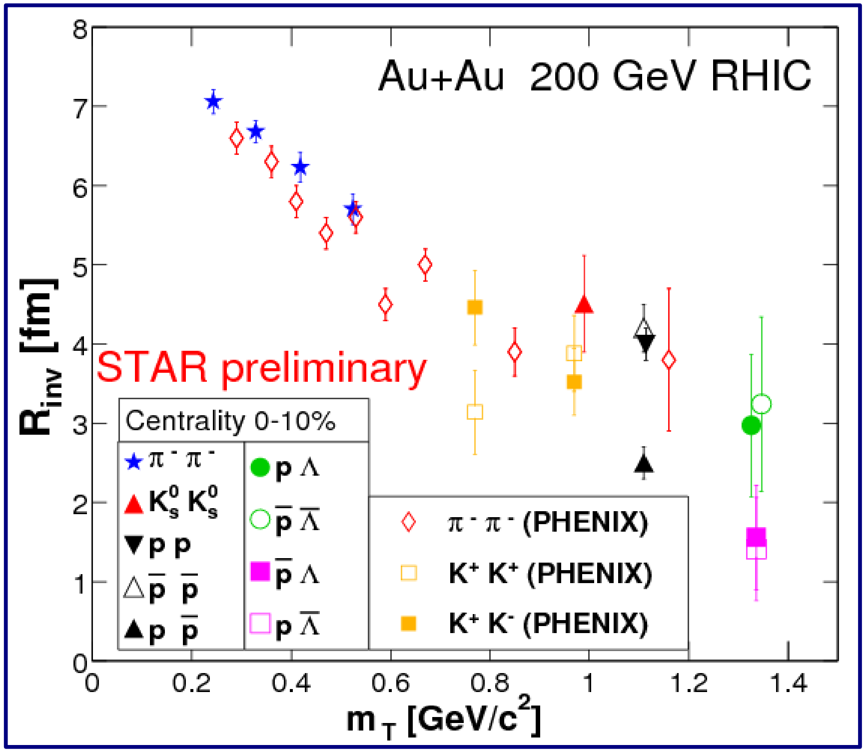
The UrQMD model provides an alternative explanation for the minimum in the volume measurement in terms of a change from a hadronic to a partonic state. Including interactions between color string fragments early in the collision, it not only can explain the minimum in the volume, but is also able to find R_{out}/R_{side} values close to unity as observed from AGS through RHIC energies and improves the agreement between UrQMD and other observables at the same time. It is interesting that such an interaction potential may somewhat mimic an increase in the pressure gradients, which may correlate with the observation that v_2 increases rapidly with $\sqrt{s_{NN}}$ in this region also.

Femtoscopy: expanding source

- Study of m_T-dependence of correlation radii. In heavy ions collisions at RHIC & SPS approximate m_T-scaling was observed: $m_T(KK) > m_T(\pi\pi)$, $R(KK)<R(\pi\pi)$ – indication on effects of hydrodynamic expansion.
- Emission point asymmetries with non-identical particles: πK, pK, πp...



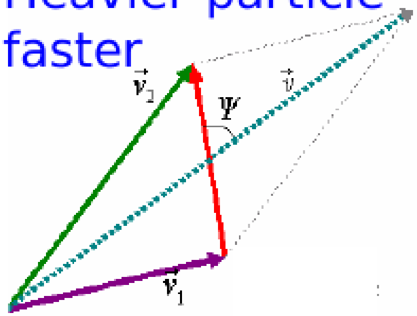
Eur. Phys. J. C 49, 75 (2007)

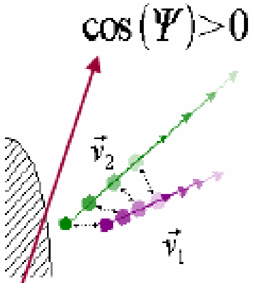


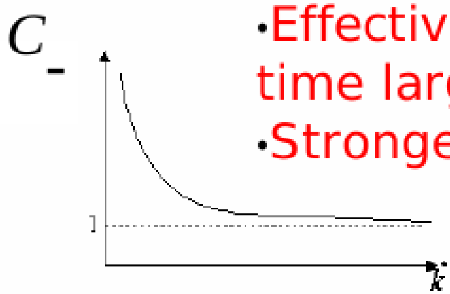
Adam Kisiel,
Fabrice Retiere

Nonidentical particle correlations – the asymmetry analysis

Heavier particle faster

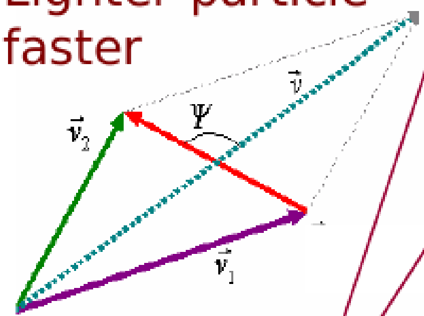


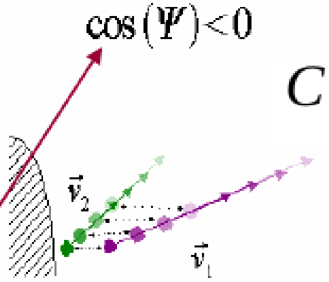


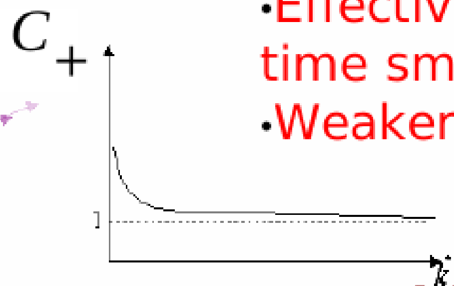


Catching up
- Effective interaction time larger
- Stronger correlation

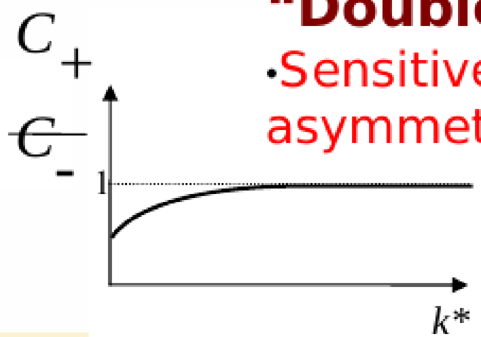
Lighter particle faster







Moving away
- Effective Interaction time smaller
- Weaker correlation



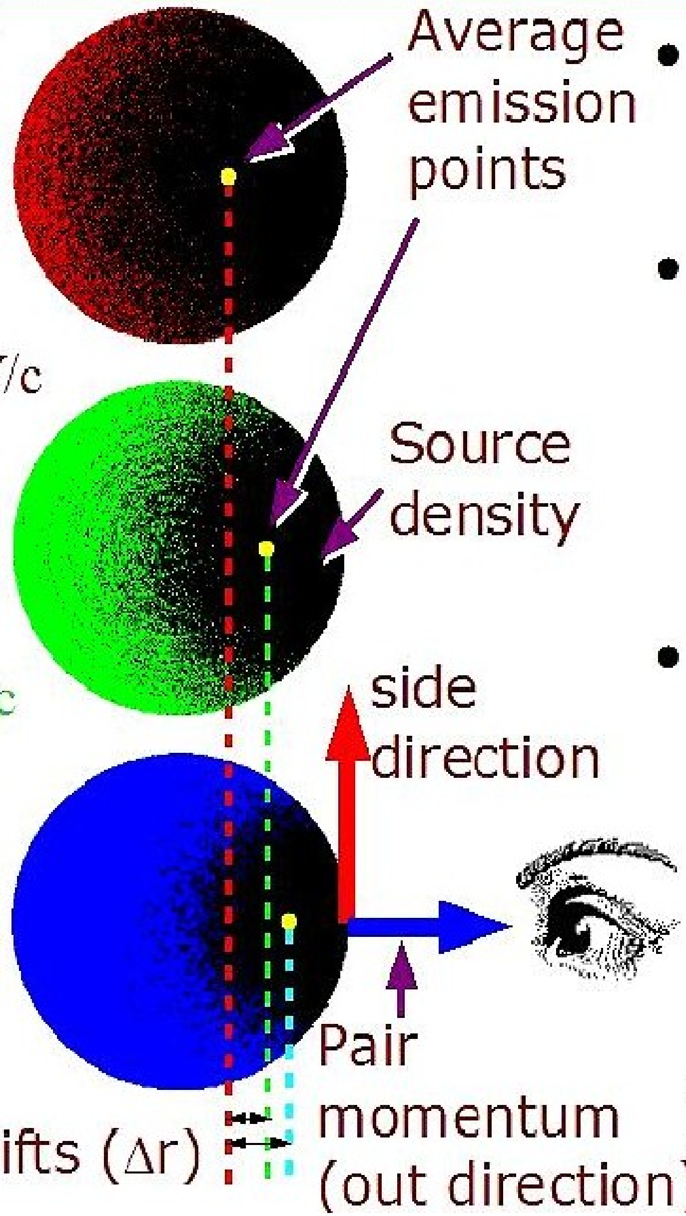
"Double" ratio
- Sensitive to the space-time asymmetry in the emission process

Kinematics selection along some direction
e.g. k_{Out}, k_{Side}, $\cos(v,k)$

R.Lednicky, V. L.Lyuboshitz, B.Erazmus, D.Nouais, Phys.Lett. B373 (1996) 30.

Flow in the transverse plane

nucl-th/0312024
F. Retiere,
M. Lisa



- Flow produces emission asymmetries in space Δr
- Observed asymmetry r^* can come from emission time difference Δt too

$$\langle r^* \rangle = \gamma \left(\langle \Delta r \rangle - \beta_T \langle \Delta t \rangle \right)$$

- We expect asymmetry in "out" direction, but not in "side", due to symmetry

S.Voloshin, R.Lednicky, S. Panitkin, N.Xu, Phys.Rev.Lett.**79**(1997)30

R. Lednicky, nucl-th/0305027

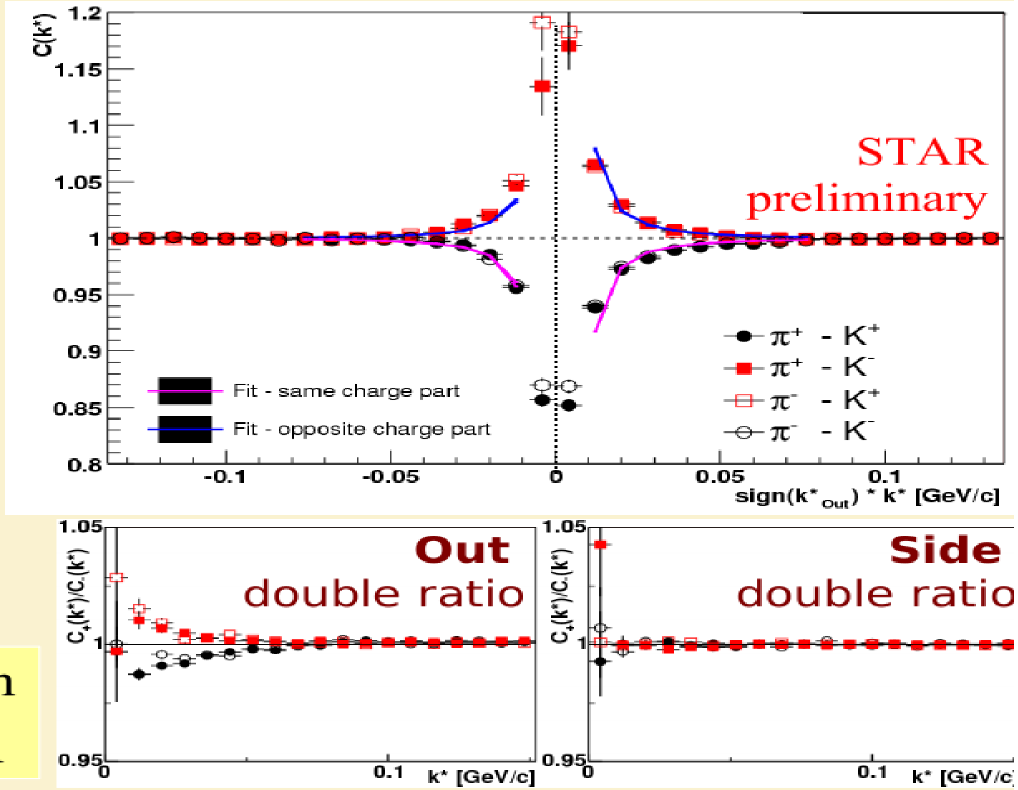
Femtoscopy with non-identical particles: average space-time differences

In experiment the information about space-time asymmetries $<\Delta x^*> = \gamma_t(\Delta x - v_t\Delta t)$ was extracted using method :$CF_{+x}/CF_{-x} \rightarrow 1+2 <\Delta x^*> /a$ suggested in

Lednicky, Lyuboshitz et al. PLB 373 (1996) 30

Pion-Kaon at 200 AGeV

- **Clear emission asymmetry signal**



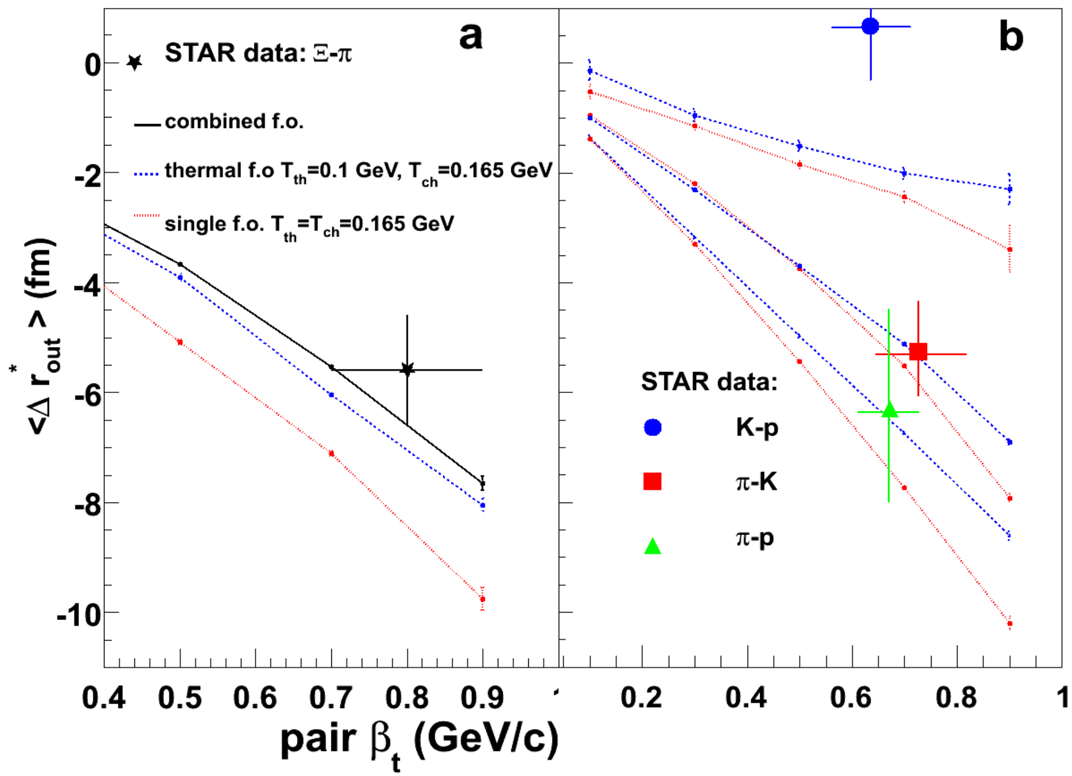
Sigma: **17.3** ± **0.8** $^{+0.9 \text{ syst.}}_{-1.6 \text{ syst.}}$ fm

Mean: **-7.0** ± **1.2** $^{+6.1 \text{ syst.}}_{-4.0 \text{ syst.}}$ fm

Space-Time shifts in PRF: πΞ, πK, πp, Kp

As particle mass (or p_T) grows, average emission point moves more "outwards" - origin of the effect the same as m_T scaling:
due to collective transverse flow & higher thermal velocity of lighter particles
Consistent with hydrodynamic model predictions, strong evidence against competing explanations

HYDJET++ model calculations



STAR, J.Phys. G30 (2004) S1059-S1064

Good review of non-ident particle femtoscopy: A. Kisiel, Phys.Rev. C81 (2010) 064906