Femtoscopy of Pb-Pb and pp collisions at the LHC with the ALICE experiment

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for the ALICE collaboration

Overview

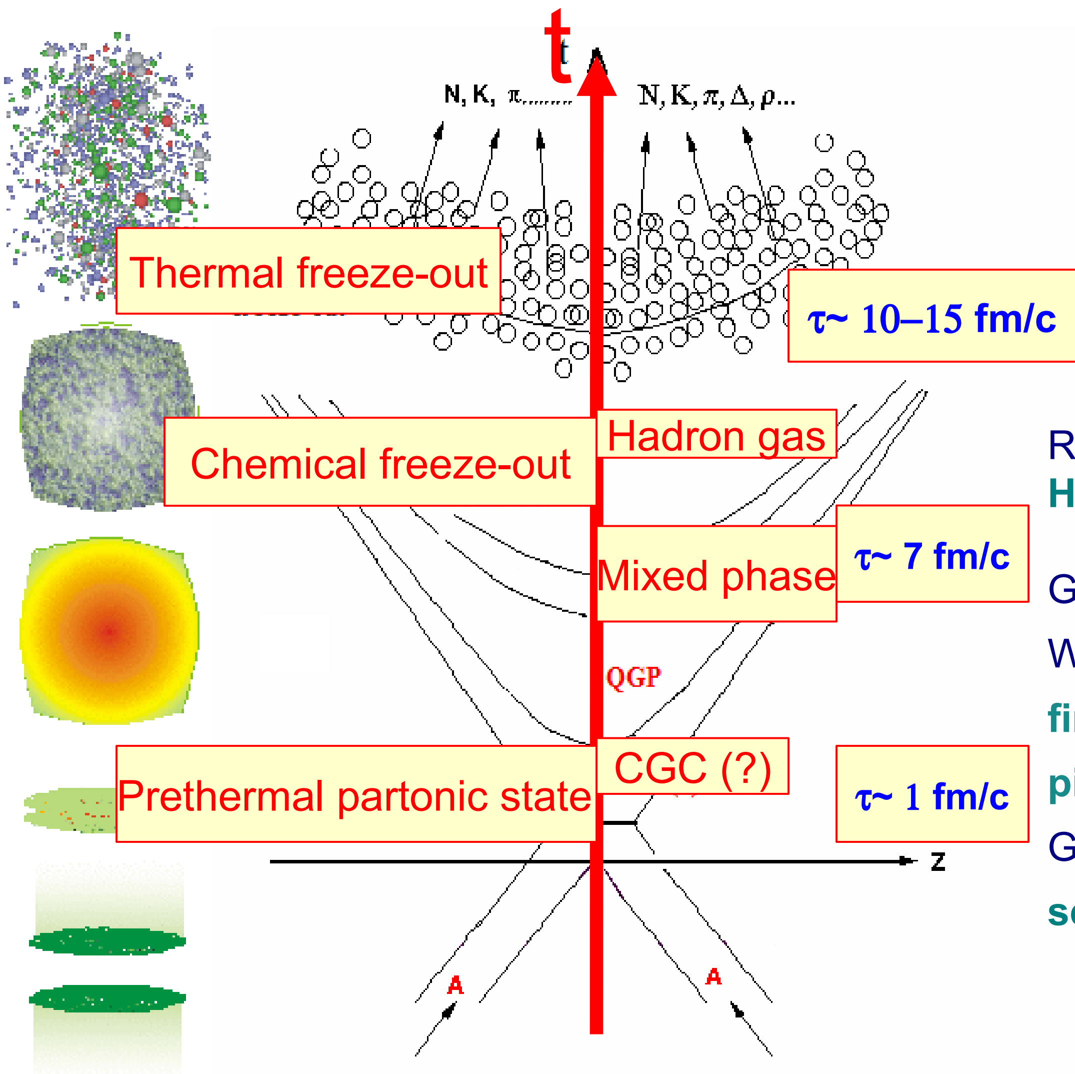
- **Introduction**
  - What is correlation femtoscopy ?
  - Physical motivation in HI & pp collisions

- **ALICE experiment at LHC**

- **Pion femtoscopy in Pb-Pb collisions**
  - Correlation radii dependence on kt, multiplicity
  - Theoretical interpretations

- **Femtoscopy in pp collisions**
  - Correlation radii dependence on kt, multiplicity
  - Theoretical interpretations
  - Comparison of ALICE pp, Pb-Pb and world systematics
  - Kaon femtoscopy in pp collisions

Evolution of matter in HI collisions



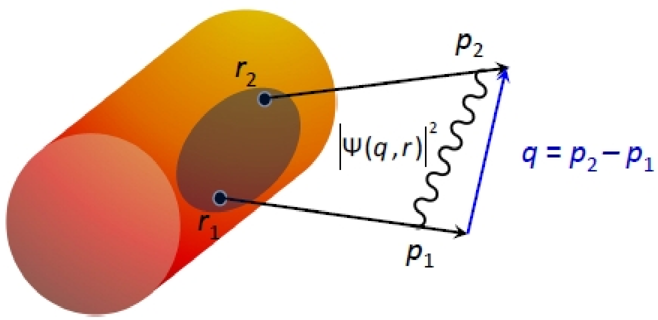
Correlation femtoscopy : measurement of space-time characteristics R, cT ~fm of particle production using particle correlations due to the effects of QS and FSI

R. Hanbury-Brown and R.Q. Twiss (1956)-
HBT effect in astronomy

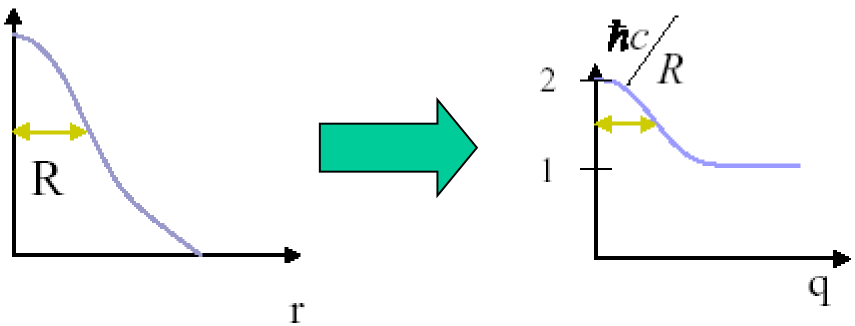
G. Goldhaber, S. Goldhaber,
W-Y Lee, A. Pais (1960)
firstly shown BE correlation of identical pions in ap-p collisions

G.I. Kopylov and M.I. Podgoretsky (71-75)
settled basics of correlation femtoscopy

FEMTOSCOPY: QS Momentum correlations



The idea of the correlation femtoscopy is based on an impossibility to distinguish between registered particles emitted from different points
Two boson (fermion) correlation function $\Psi(q, r)$ reflect source dimensions



The theoretical correlation function is expressed through source emission function S(q,r) and square of pair wave function Ψ(q,r):

$$C(q) = \int d^4 r \, S(q, r) \, |\Psi(q, r)|^2 .$$

Experimentally:

C(q) = A(q)/B(q)

A(q) from same event pairs (with BEC)

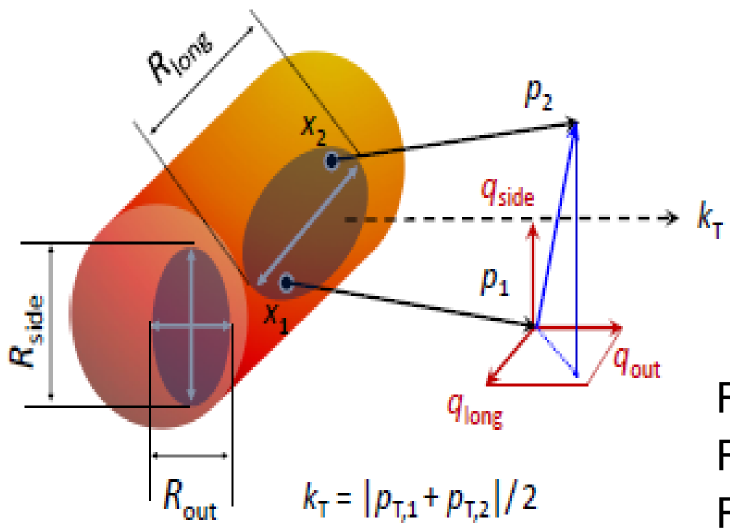
B(q) – from different event pairs (without BEC)

FEMTOSCOPY: Coordinate systems

Usually *S(q,r)* is approximated as Gaussian, the corresponding correlation widths are parametrized in terms of the Gaussian correlation radii R_i,

$$C(q) = N(1+\lambda\exp(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2)B(q)$$

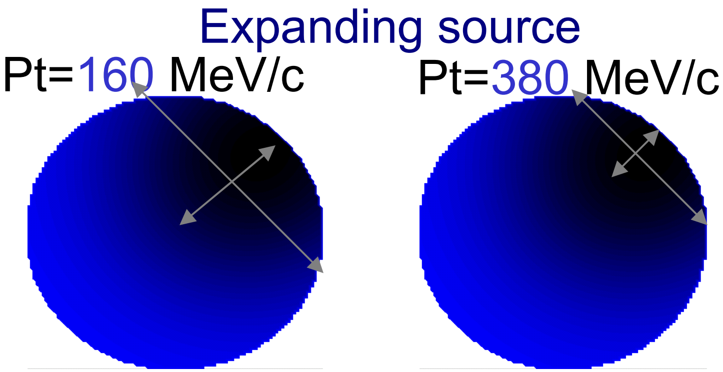
where both *R* and *q* can be in Pair Rest Frame (PRF) or Longitudinally Co-Moving Frame. PRF is used for 1D analysis, LCMS for 3D



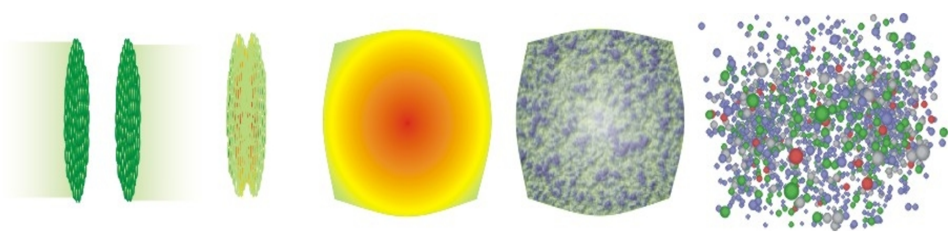
long || beam;
out || transverse pair velocity **v**t;
side normal to out,long

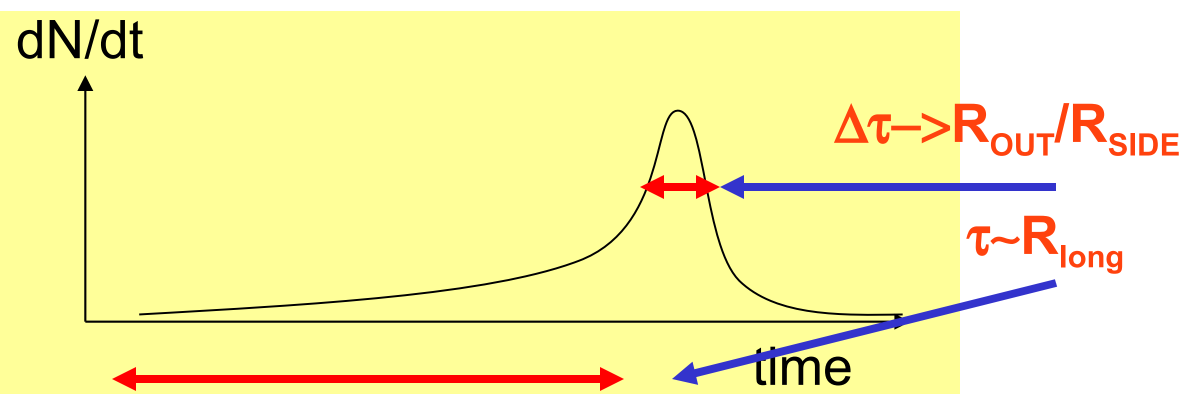
Rside sensitive to geometrical transverse size.
Rlong sensitive to time of freeze-out.
Rout / Rside ~ sensitive to emission duration.

Physics motivation: heavy ion collisions



Interference probes only a part of the source - homogeneity region; radii decrease with pair velocity





Pion femtoscopy in Pb-Pb collisions

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

– Transverse momentum dependence of the radii a manifestation of strong collective motion of matter

– Strong constraints on timescales and sensitivity to the EOS in dynamic models

RHIC lessons: EOS with no first-order phase transition; "Pre-thermal flow": strong flows already at τ_0=1 fm/c

Physics motivation: pp collisions

– Study spacetime characteristics of particle production in "elementary" systems

– Multiplicities, comparable to peripheral AA collisions. p+p and A+A measured in same experiment with same method great opportunity to compare physics

what causes p_T-dependence in p+p?

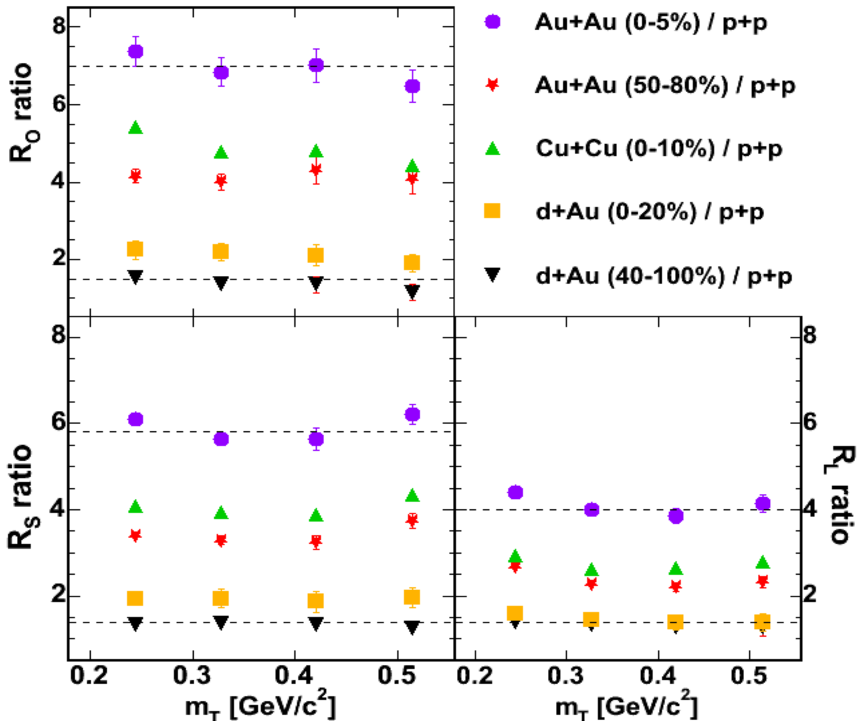
same cause as in A+A??

m_T dependence ("x-p" correlations) in very small systems (pp, e+e-) is usually attributed to:

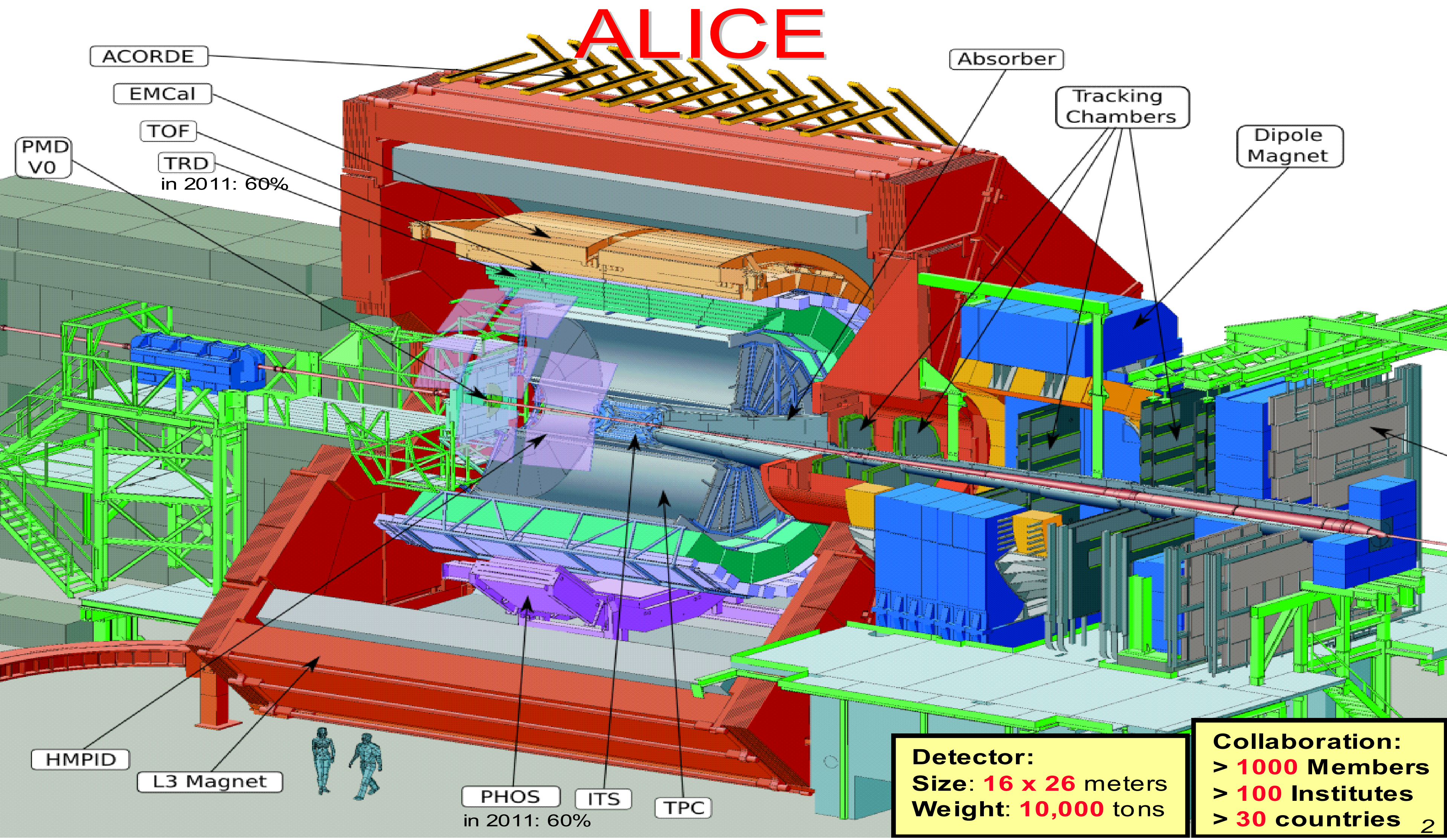
-string fragmentation
-resonance contribution
-Heisenberg uncertainty
-jets

The correlation radii measured by STAR show similar $p_T(m_T)$ dependences in heavy ion and pp collisions.

STAR data



ALICE experiment at LHC



Main ALICE data sets

year	system	energy(TeV)	trigger	events / 10^6
2009	pp	0.9	min bias	0.3
2009	pp	2.36	min bias	0.04(no stable beam)
2010	pp	0.9	min bias	8
2010	pp	7.0	min. bias	800
2010	PbPb	2.76	min.bias.	30
2011	pp	2.76	min. bias	70
2011	pp	7.0	min.bias	700
planned				
2011	PbPb	2.76	Central central(30-50)	5-10 25

Pion correlations functions in Pb-Pb

- Correlation functions measured in three dimensions (out, side, long) at 2.76 TeV

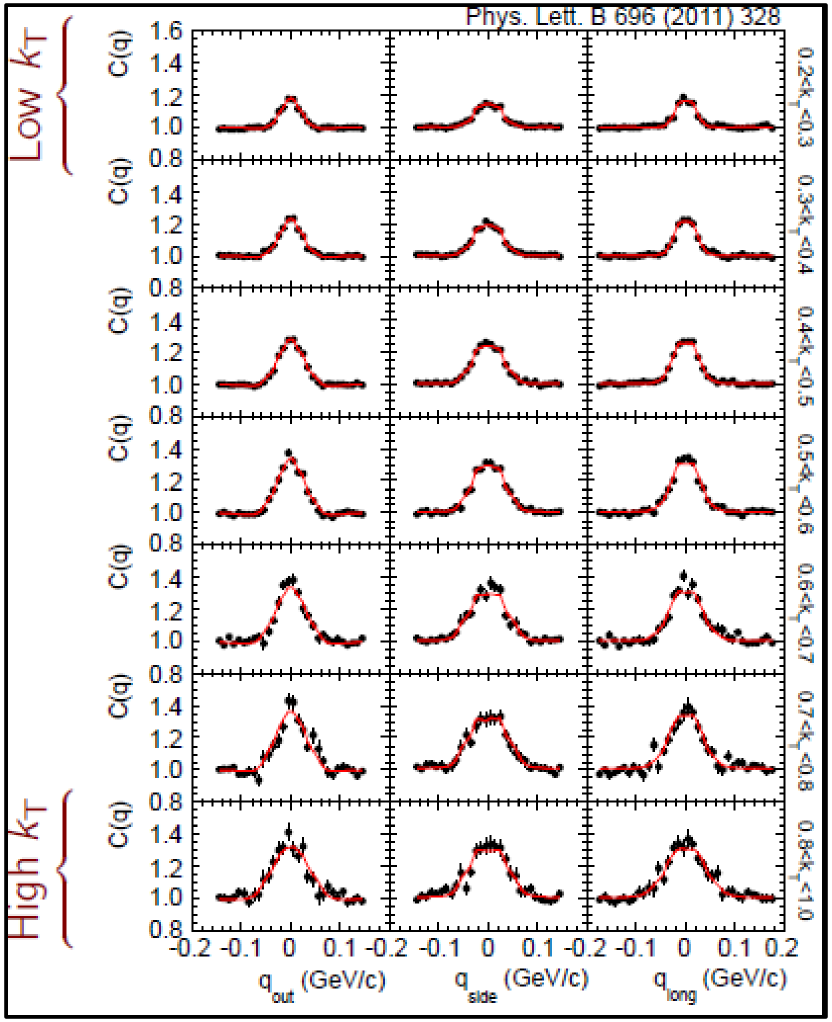
- Seven k_T (0.2 - 1.0) GeV/c

- Fitted using the Bowler-Sinyukov formula:

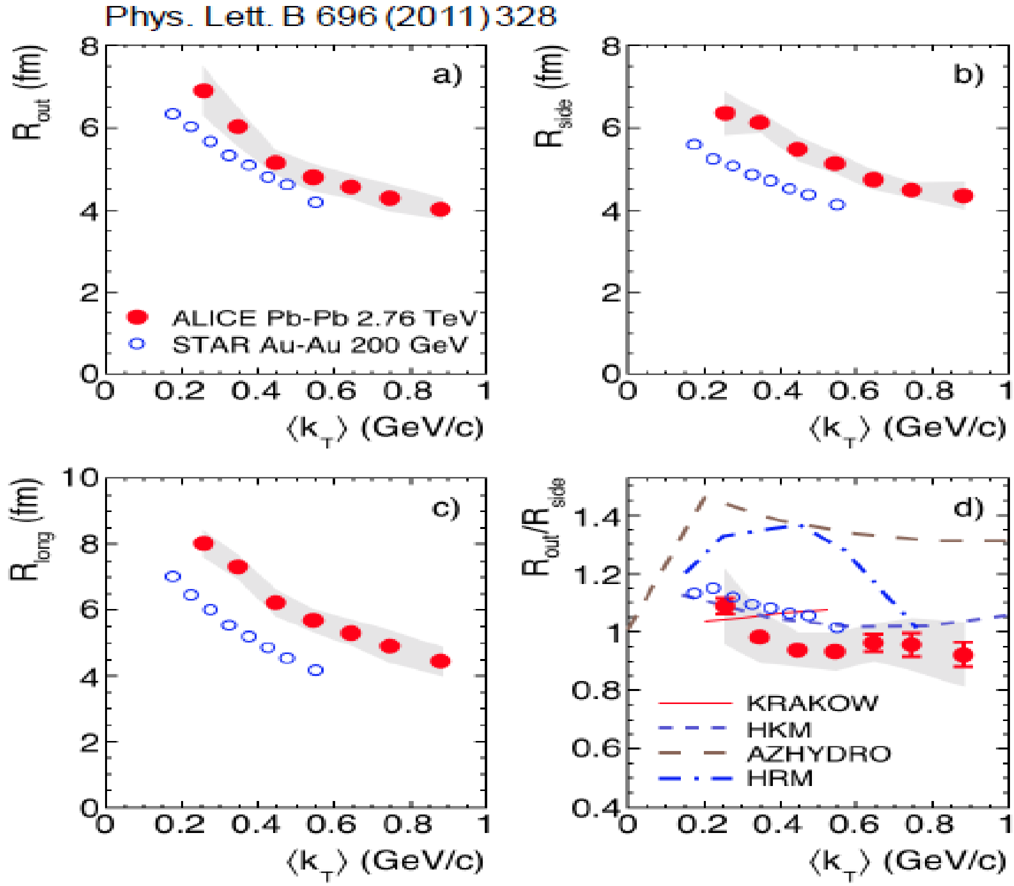
$$C(q) = \mathcal{N}\{(1-\lambda) + \lambda K(q_{inv})[1+G(q)]\},$$
$$G(q) = \exp\left[-(R_{out}^2 q_{out}^2 + R_{side}^2 q_{side}^2 + R_{long}^2 q_{long}^2)\right],$$

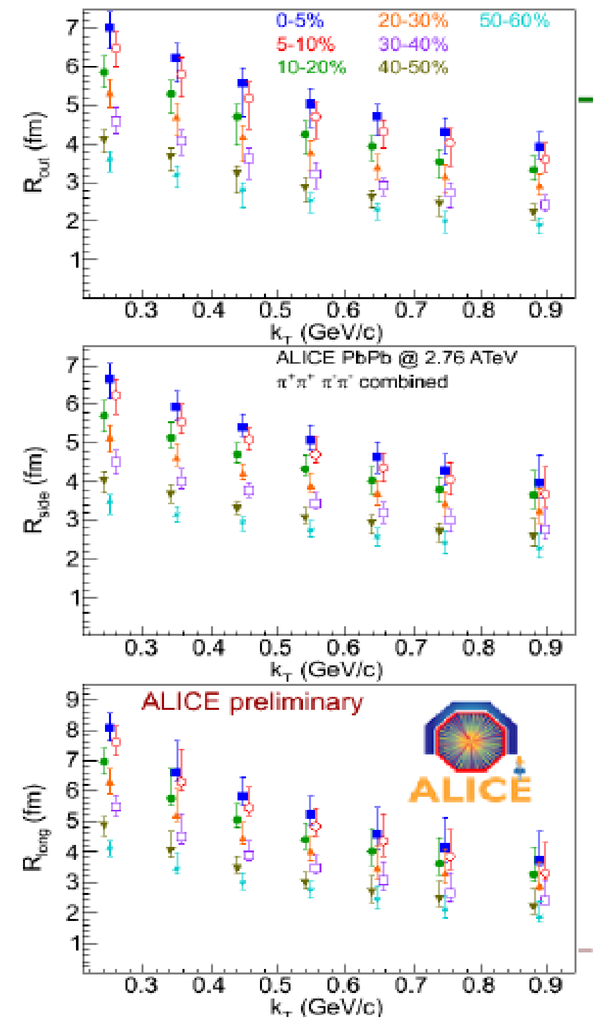
with λ the correlation strength and K(qinv) the Coulomb factor.

- BE peak width increases with kT.



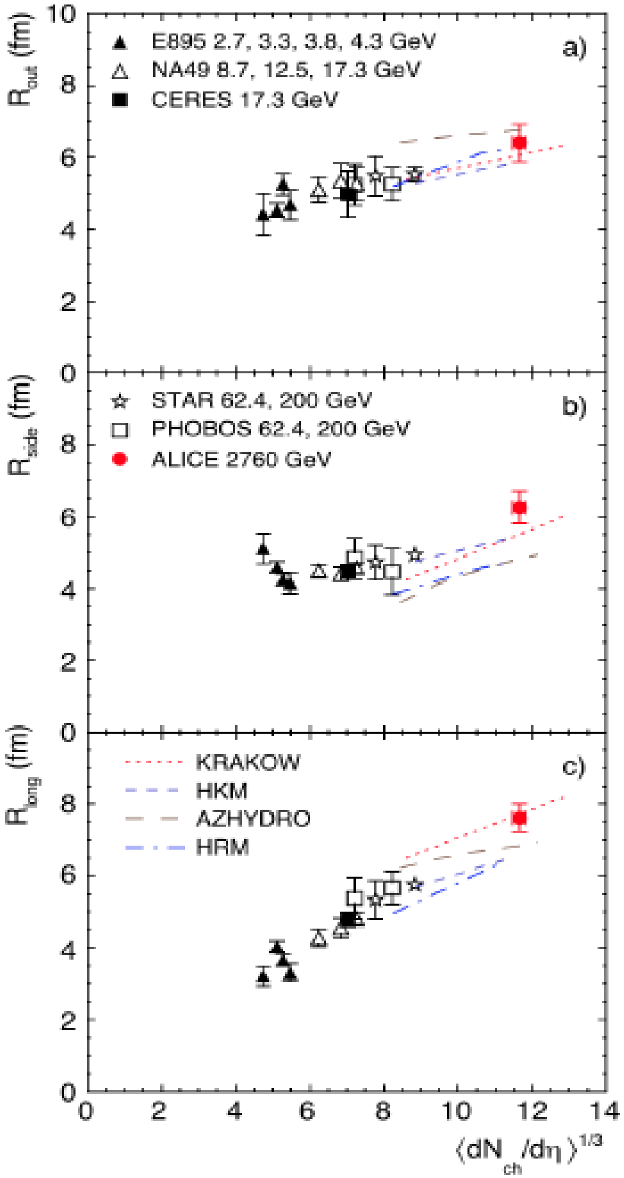
Radii transverse momentum dependence

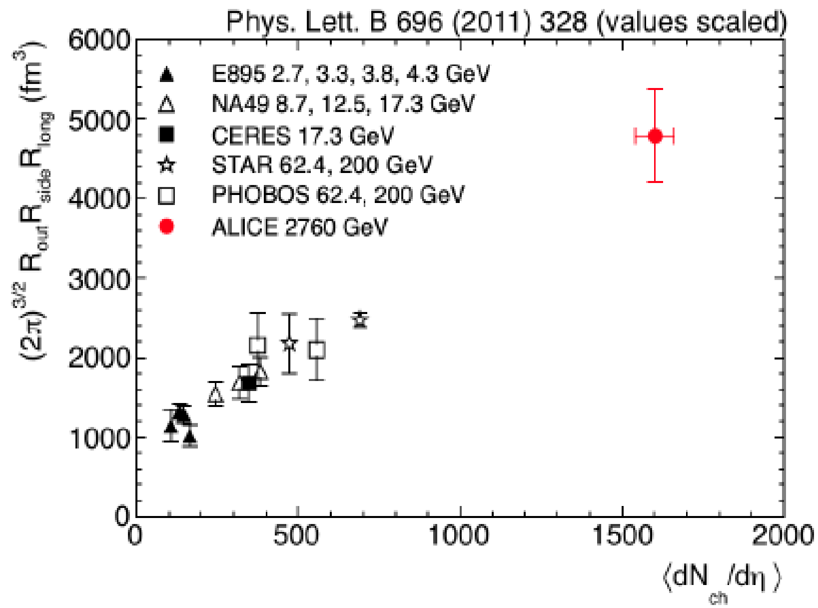




- Strong k_T dependence of radii - sign of transverse flow
- Decrease of size with decreasing multiplicity
- Linear scaling of radii with $dN_{ch}/d\eta$ – similar to hydrodynamic
- Rout/Rside smaller then at RHIC

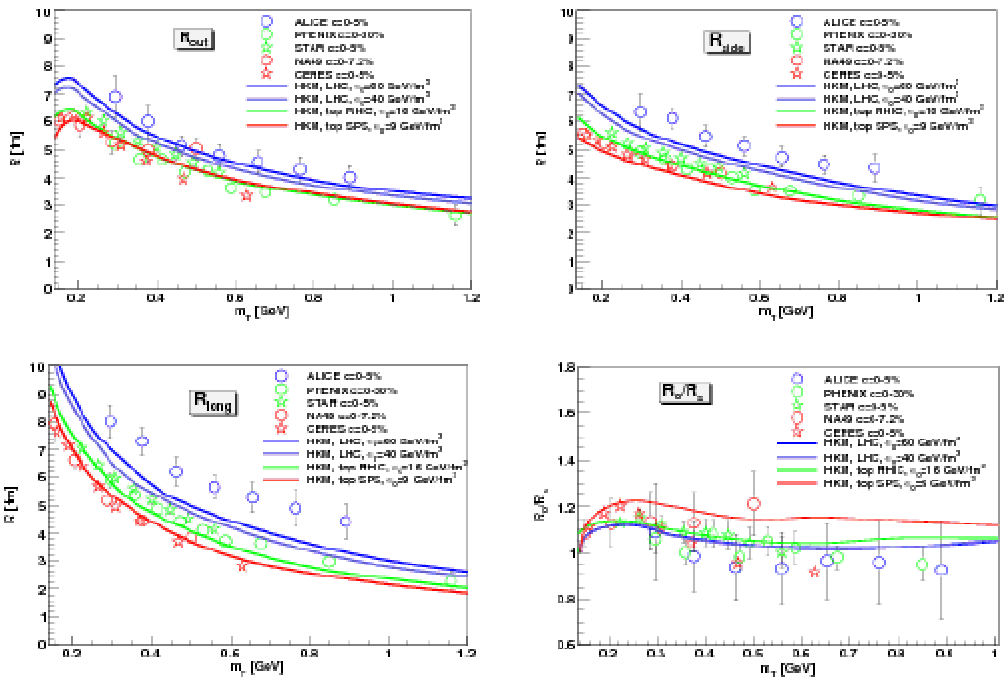
Radii versus $dN_{ch}/d\eta$

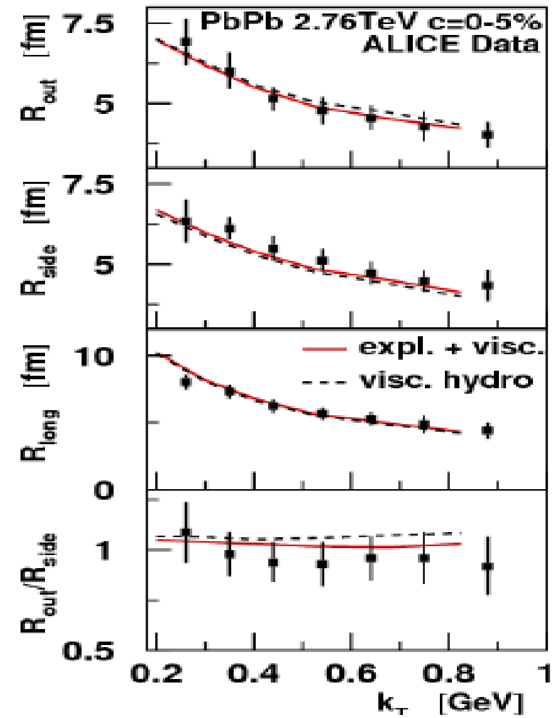




- Homogeneity volume 2 times larger than at RHIC
- Scaling of the radii with(dNch/dη)$^{1/3}$\
- ALICE significantly extends the range of the radii world systematics.
- Rlong is proportional to the total duration of the longitudinal expansion.
- The measured decoupling time τ is about 40% larger than at RHIC.

Theoretical interpretations





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

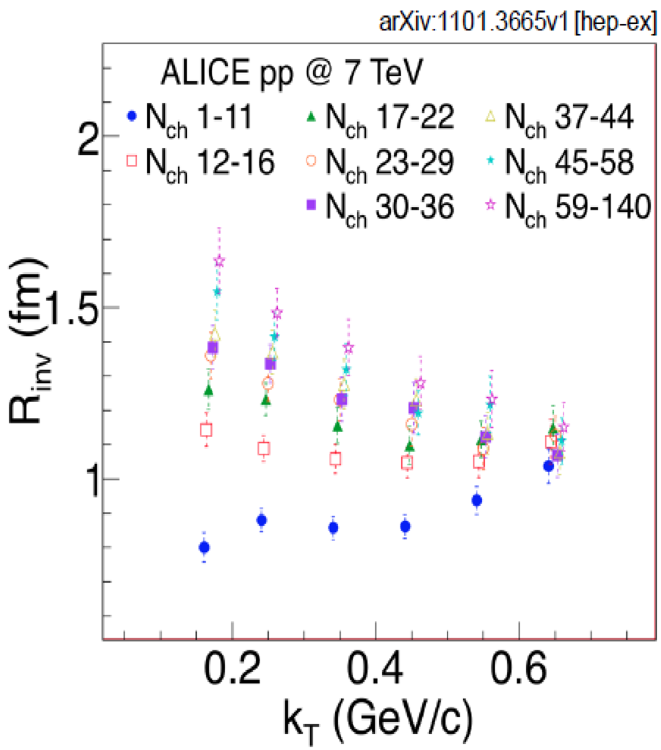
3D relativistic viscous hydrodynamics

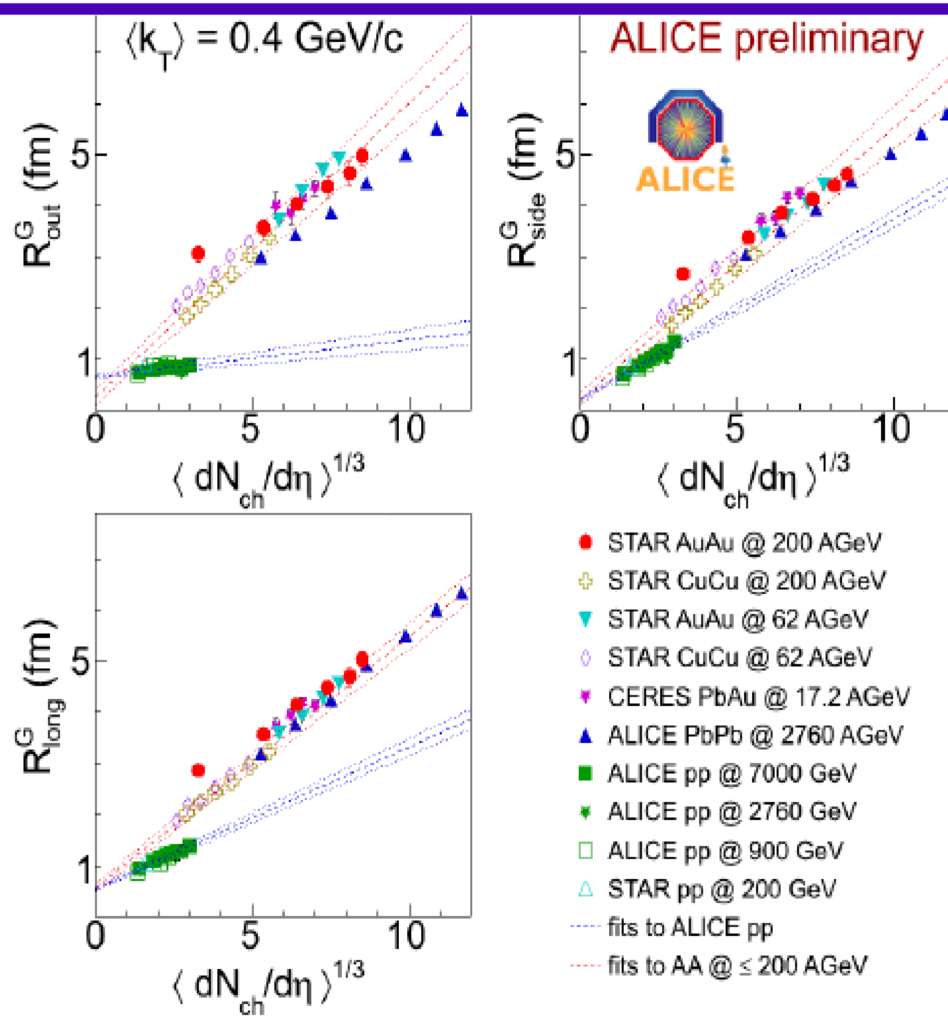
Glauber model initial conditions

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

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

ALICE data on pion correlations in pp





In pp k_T dependence of radii is observed at large multiplicity bins

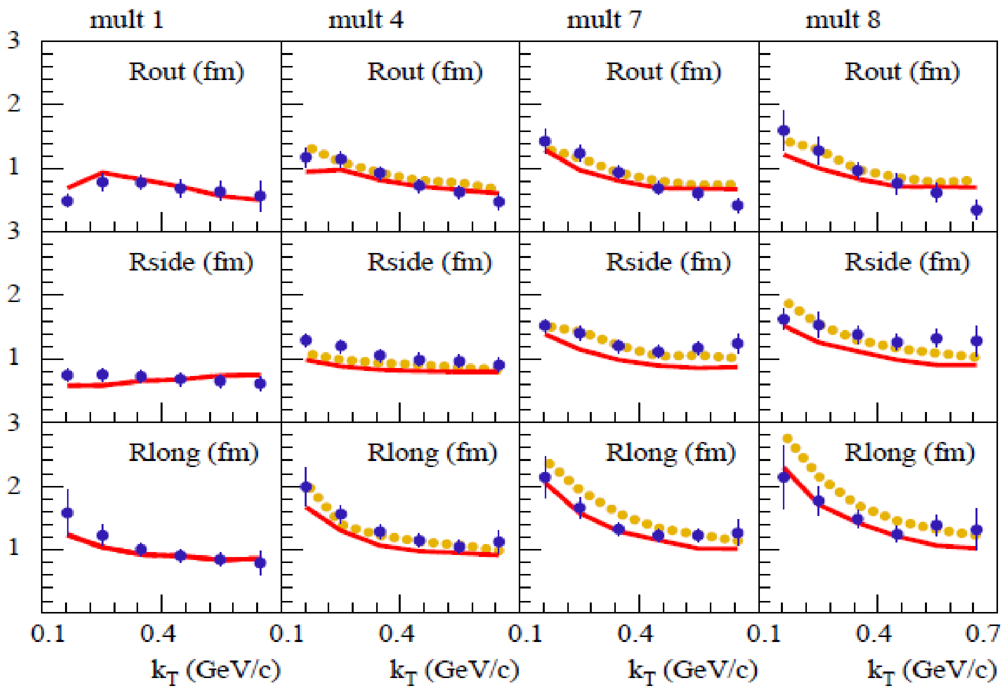
Decrease of size with decreasing multiplicity

Radii increase with multiplicity both in pp and Pb-Pb but with different slopes

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

Kaon femtoscopy: motivation

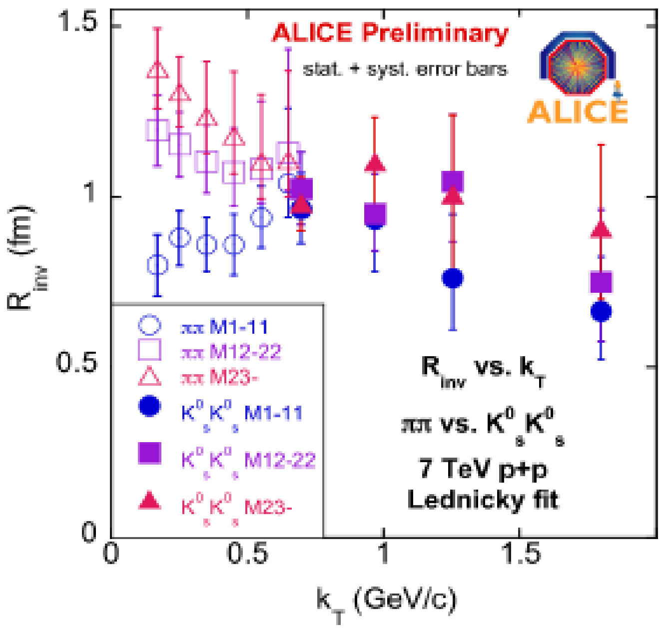
- Study of m_T-dependence of correlation radii.
  In heavy-ions collisions at RHIC was observed $m_T(KK) > m_T(\pi\pi)$,
  $R(KK)<R(\pi\pi)$ – indication on effects of hydrodynamic expansion

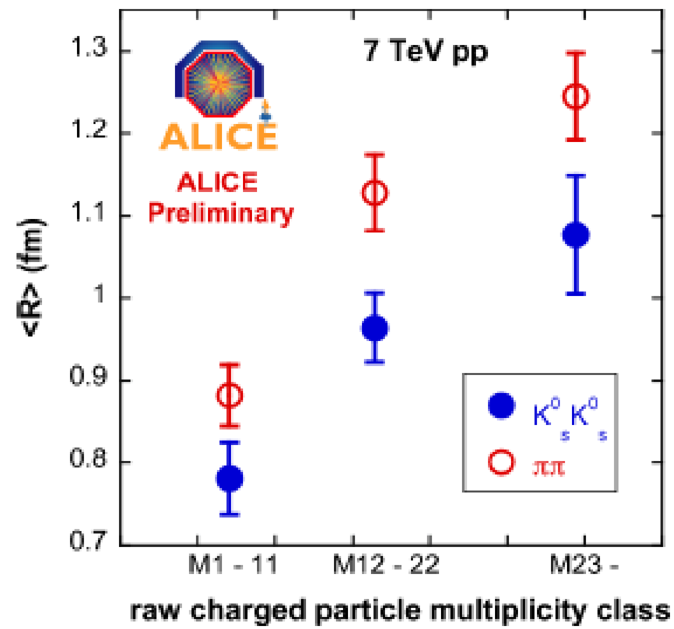
- KK suffer less from the resonance contributions then ππ -> more clear signal

- Neutral K analysis presently limited to 1D radii, but extends the pair momentum range

- Correlation of neutral kaons strong: comes from a combination of Bose-Einstein symmetrization and strong interaction, helps to reduce systematic uncertainties

$K^0_s K^0_s$ & $\pi\pi$ k_T and multiplicity dependence





- Pair momentum range extended 3 times (w.r.t. pions)
- Decrease of radii with k_T
- Increase of radii with multiplicity

Summary

- ALICE measurements significantly expand the range of the existing radii world systematics
- Homogeneity volume 2 times larger than at RHIC
- The fireball formed in nuclear collisions at LHC lives longer; decoupling time exceeds the one measured at RHIC by 40%.
- Scaling of the radii with$(dN_{ch}/d\eta)^{1/3}$
- Hydrodynamic models describe well the Pb-Pb data, similar EoS as at RHIC, strong argument for the correctness of this description

- Pion radii in pp show factorization of scaling into linear dependence on multiplicity (with parameters different from AA), non-trivial dependence on pair momentum, independence of collision energy
- Pion correlation radii in pp are well reproduced within EPOS model combining string dynamics, hydrodynamics and hadron cascade

- More demanding analyses are started, e.g. kaon femtoscopy,