Femtoscopy with ALICE at the LHC

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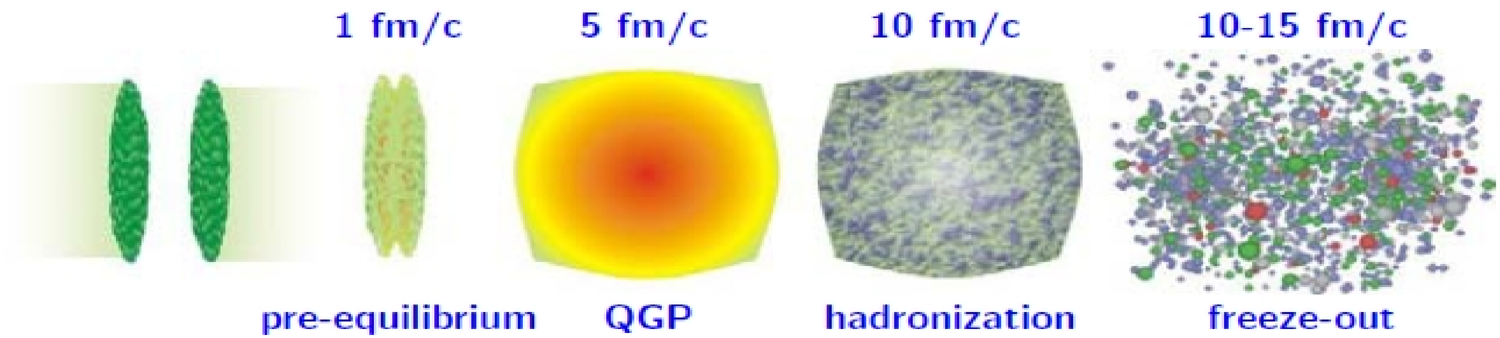
for the ALICE collaboration

Introduction



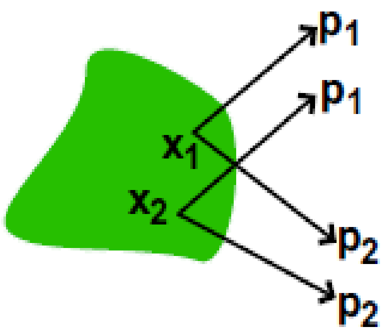
Correlation femtoscopy : measurement of space-time characteristics R, $c\tau$ ~fm of particle production region using particle correlations due to the effects of QS and FSI

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

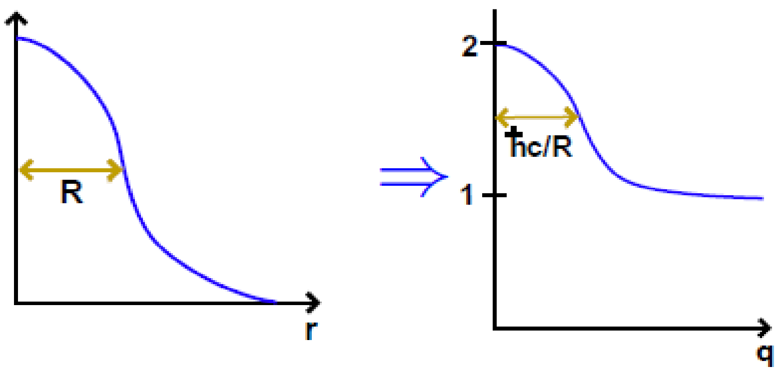
V.G. Grishin, G.I. Kopylov, and M.I. Podgoretsky showed analogy (Sov.J.Nucl.Phys. 13 (1971) 638) and difference (G.I. Kopylov and M.I. Podgoretsky, Sov.J.Nucl.Phys. 15 (1972) 219) between femtoscopy in particle physics and HBT effect in astronomy (R. Hanbury-Brown and R.Q. Twiss, Phil.Mag. 45 (1954)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

Introduction



Correlation femtoscopy : measurement of space-time characteristics R, $c\tau$ ~fm of particle production region using particle correlations due to the effects of quantum statistics (QS) and final state interactions (FSI)

- Two-particle Correlation Function (CF):



Theory: $$C(q)=\frac{N_2(p_1,p_2)}{N_1(p_1)\cdot N_2(p_1)}, C(\infty)=1$$

Experiment: $$C(q)=\frac{S(q)}{B(q)}, q=p_1-p_2$$

S(q) – pairs from same event

B(q) – pairs from different events

Femtoscopy: frequently used parametrizations

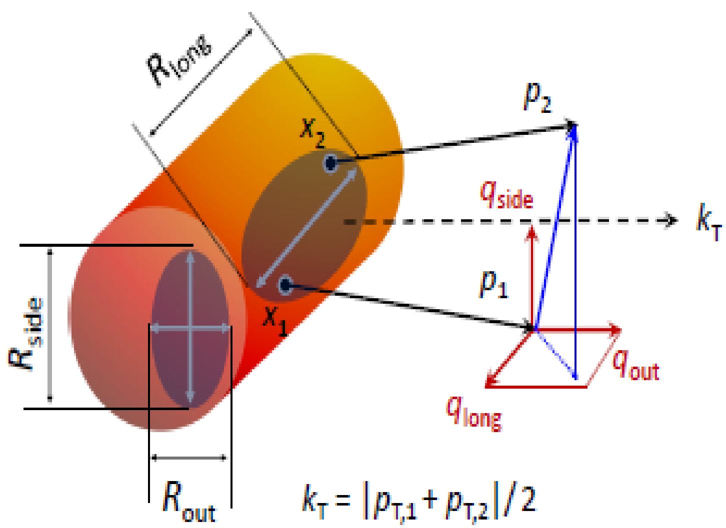
$$C(q) = 1+\lambda\exp(-R_{inv}^2 q_{inv}^2),$$ λ- correlation strength,

R_{inv}, 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 (**LCMS**)



long || beam;
out || transverse pair velocity $\mathbf{v}_T$
side normal to out,long

3D- analysis

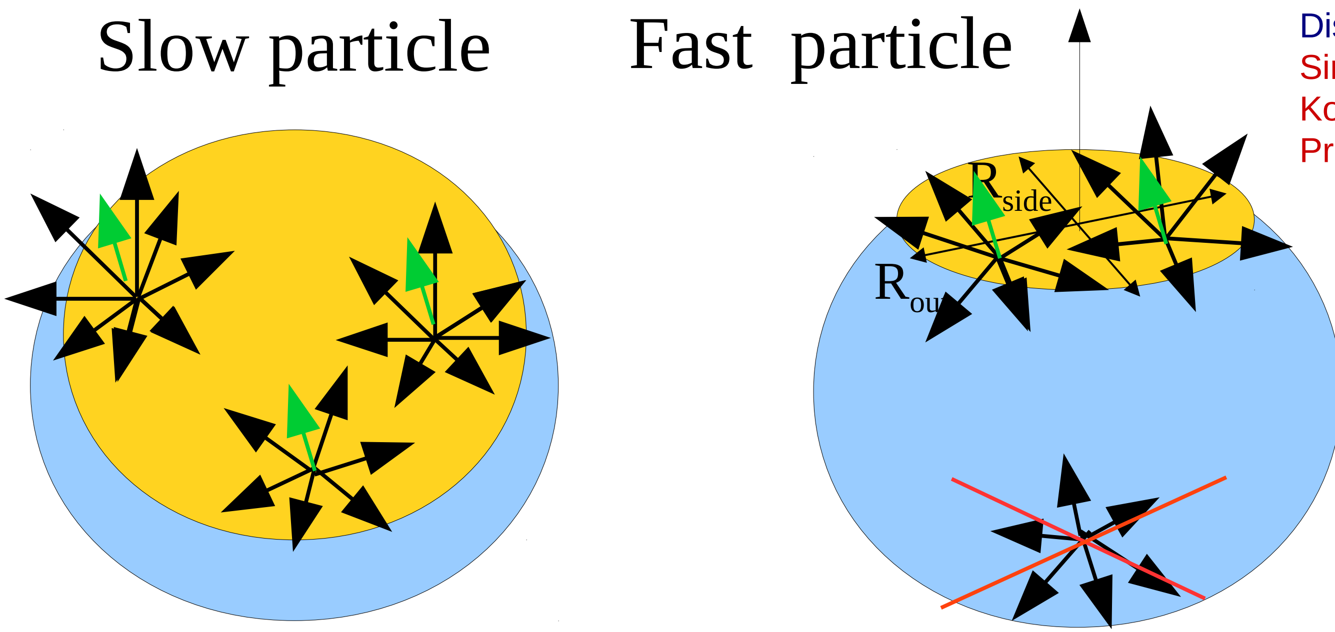
R_{side} sensitive to geometrical transverse size.

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

R_{out} / R_{side} ~ sensitive to emission duration.

Introduction: study of source dynamics

- Particle emitted from the source has a thermal (random) and collective (flow) velocities.
  At small $p_T(m_T)$ the emission points are distributed within large region,
  as p_T grows → iemission points move "outwards" and size decreases
- Interference probes only parts of the source at close momenta – **homogeneity regions**.
  (Yu.M. Sinyukov, Nucl. Phys. A 566, 589 (1994);)



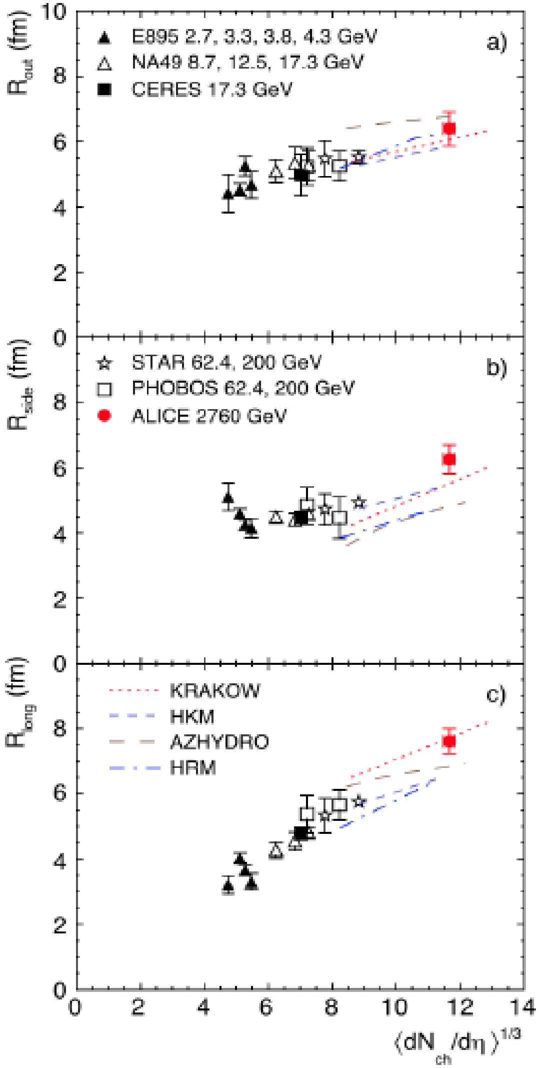
Discussed in e.g.:Makhlin-Sinyukov'87
Kolehmainen, Gyulassy'86
Pratt, Csörgö, Zimanyi'90

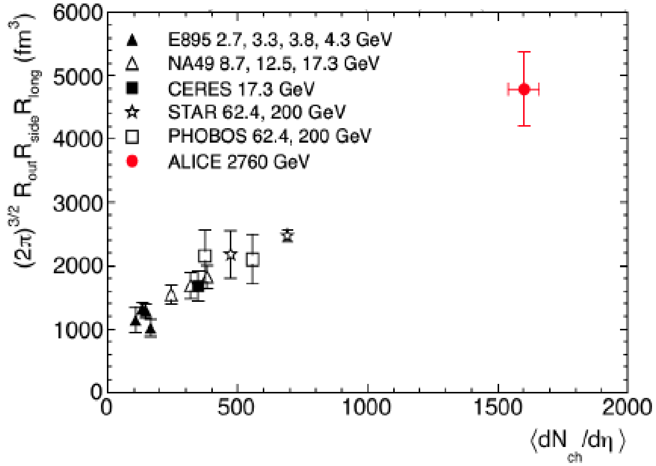
$R_{side} \sim R/(1+m_T\beta_T^{\,2}/T)^{1/2}$ $\qquad$ β_T collective transverse flow

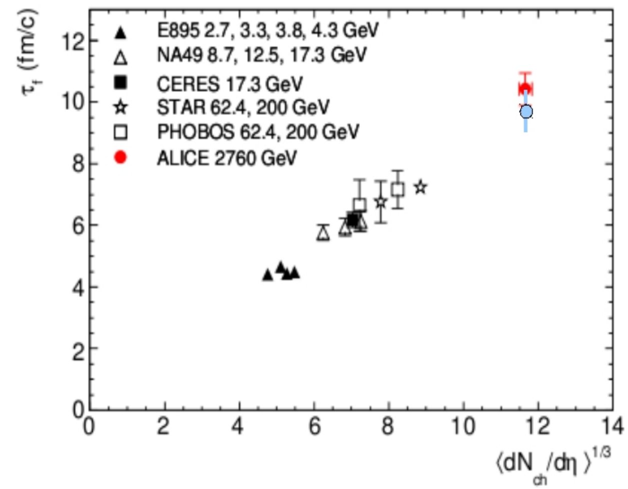
$R_{long} = \tau\ (T/m_T)^{1/2}$, assuming a longitudinal boost invariant expansion

Pion femtoscopy in Pb-Pb at 2.76 TeV

ALICE, Phys.Lett.B 696 (2011) 328



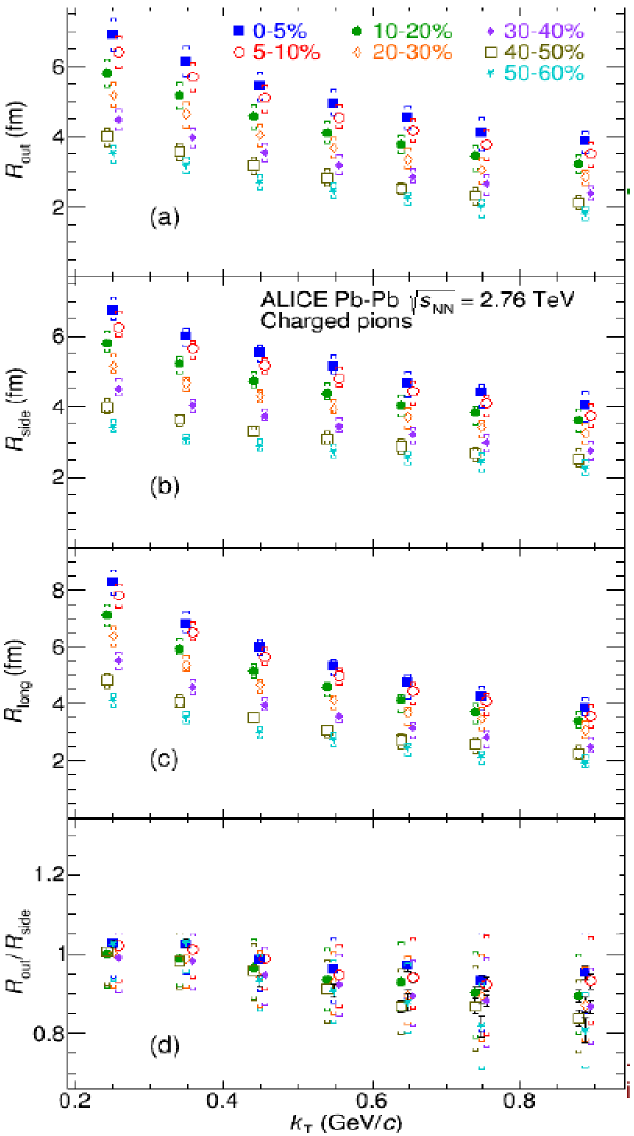


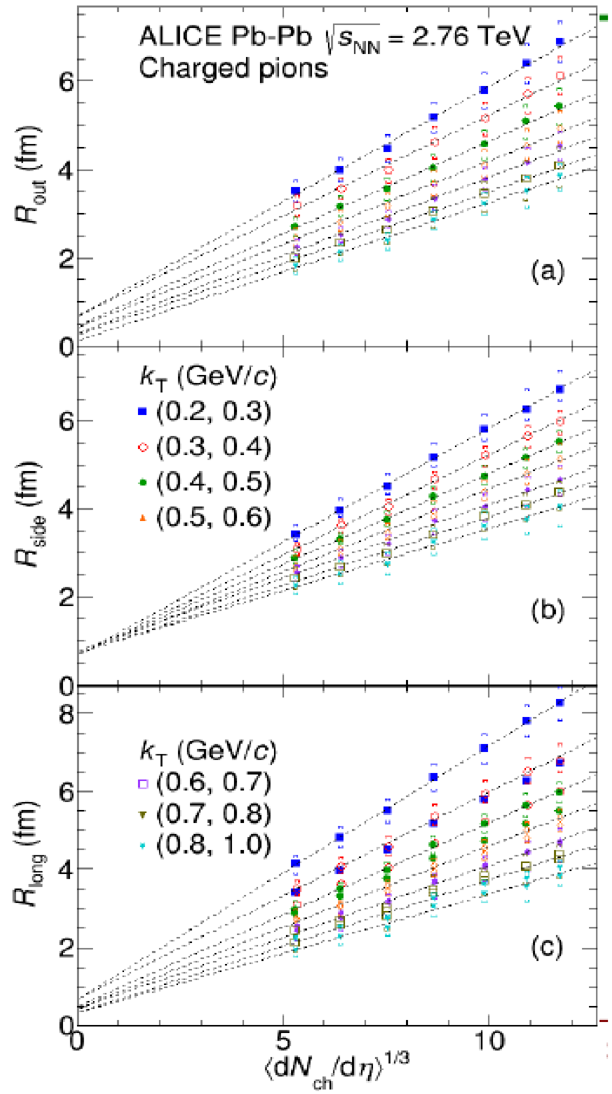


- Homogeneity volume 2 times larger than at RHIC
- Scaling of the radii with($dN_{ch}/d\eta)^{1/3}$
- ALICE significantly extends the range of the radii world systematics.
- R_{long} is proportional to the total duration of the longitudinal expansion.
- Decoupling time τ ~ 40% larger than at RHIC.

Pion femtoscopy: radii versus k_T & $dN_{ch}/d\eta$

ALICE, Phys.Rev.C93 (2016) 2, 024905



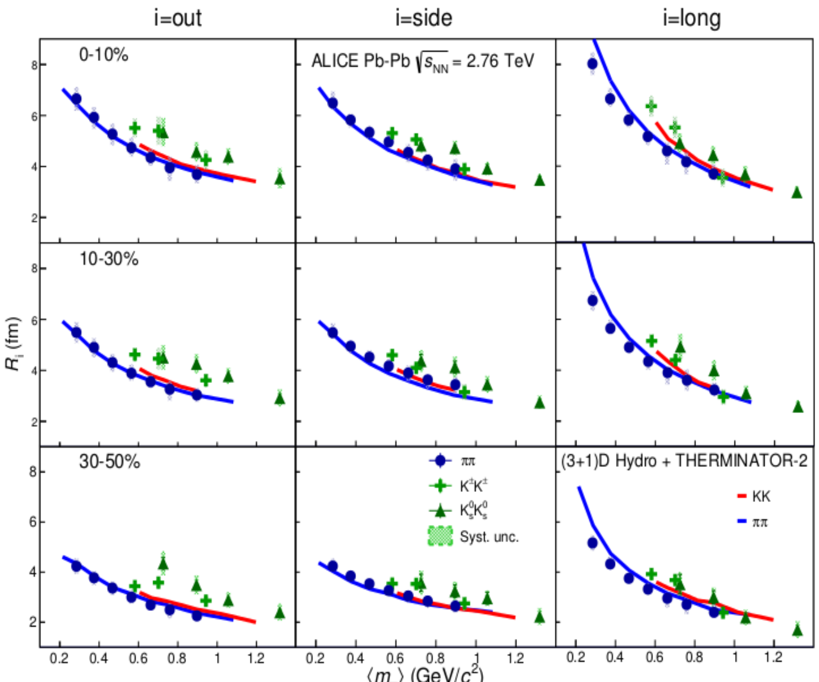


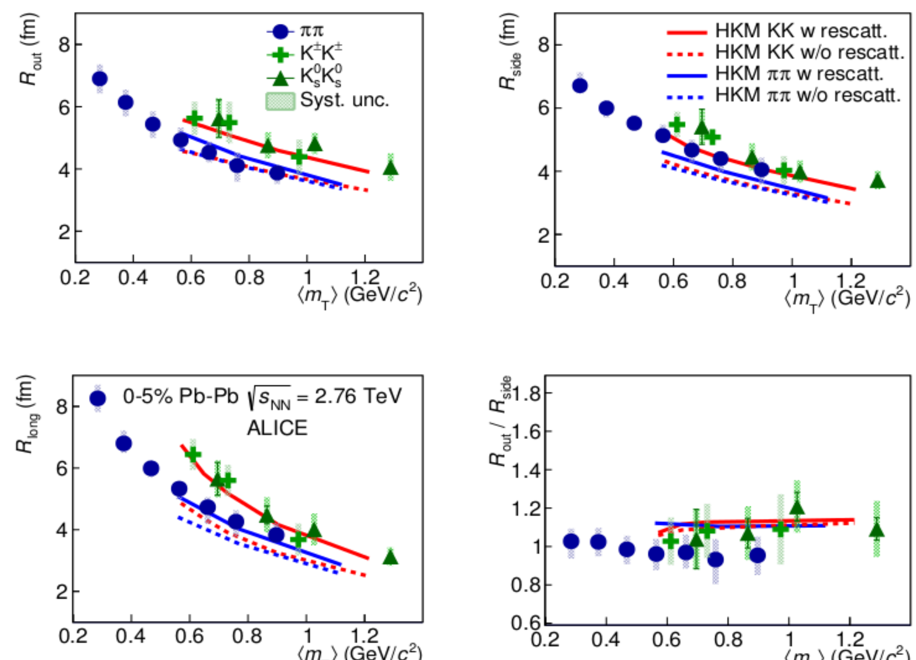
- Strong k_{T}-dependence of radii - sign of transverse flow
- Decrease of size with decreasing multiplicity
- Linear scaling of radii with cube root of final state multiplicity – similar to hydrodynamic (AK, M.Gałażyn, P.Bożek; Phys.Rev.C90 (2014) 6, 064914)
- $R_{out}/R_{side} < 1$ - smaller than at RHIC

3D $K^{\pm}K^{\pm}$ & $K^{s}_{0}K^{s}_{0}$ radii in Pb-Pb

- m_T – scaling : Ideal 1D hydro predicts exact m_T scaling
- 3+1D hydro + viscosity (no rescatterings) (AK, M.Gałażyn, P.Bożek; Phys.Rev.C90 (2014) 6, 064914) → approximate scaling in LCMS
- "Hydro" + rescatterings → strong breaking of m_T scaling (M. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov; Nucl.Phys. A 929 (2014))

ALICE, "Kaon femtoscopy in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV", arXiv:1709.02743





It was shown that pion 3D radii can be reproduced by pure hydro approach, but kaon radii can be described only if the hadronic rescattering phase is incorporated in the model.

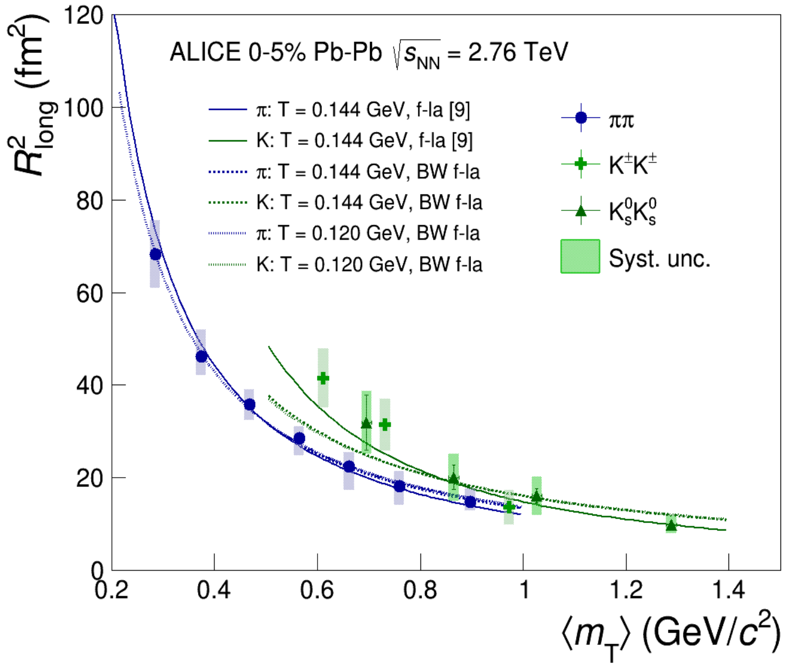
Extraction of emission time from fit $R_{long}^2(m_T)$

- The new formula for extraction of **the times of maximal emission** for the case of strong transverse flow was used (Yu. Sinyukov, V.Shapoval, V.Naboka, NPA 946 (2016) 227, arxiv:1508.01812)

$$R_{\rm long}^2 = \tau^2 \frac{T}{m_{\rm T}} \frac{K_2(m_{\rm T})}{K_1(m_{\rm T})},$$ BW formula

$$R_{\rm long}^2 = \tau^2 \frac{T}{m_{\rm T}\cosh y_T}\left(1 + \frac{3T}{2m_{\rm T}\cosh y_T}\right),$$

where $\cosh y_T = (1 - v_T^2)^{-1/2}$, $v_T = \frac{\beta p_{\rm T}}{\beta m_{\rm T} + \alpha}$, $\beta =$

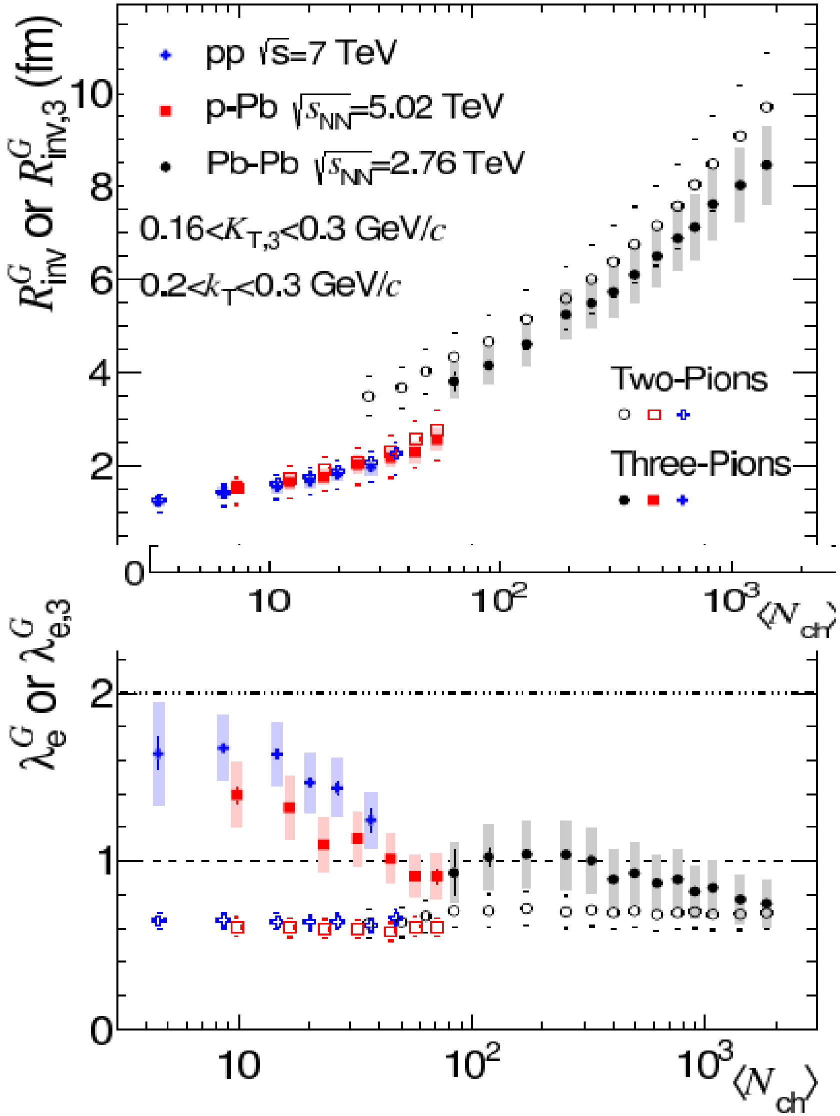


- The parameters: T and "intensity of transverse flow", α were fixed in (NPA 946 (2016) 227) by fitting π and K spectra (ALICE, Phys. Rev. C88 (2013) 044910,):
  T = 0.144 GeV , α_π = 5.0, α_K = 2.2

Longer time for kaons $\tau_K = 11.0 \pm 0.1\,^{+0.5}_{-0.1}$ fm/c than for pions $\tau_\pi = 9.3 \pm 0.2\,^{+1.8}_{-0.5}$:
model interpretation – rescatterings via K*(892) influence on kaons

1D Pion radii in pp, p-Pb and Pb-Pb

ALICE, Phys. Lett. B 739 (2014) 139



- Study space-time characteristics of particle production in “**elementary process”**
- **collectivity in pp as in AA ?**
- Is size difference significant or just multiplicity ?
- **p-Pb** collisions closer to **pp** or to **Pb-Pb** ?

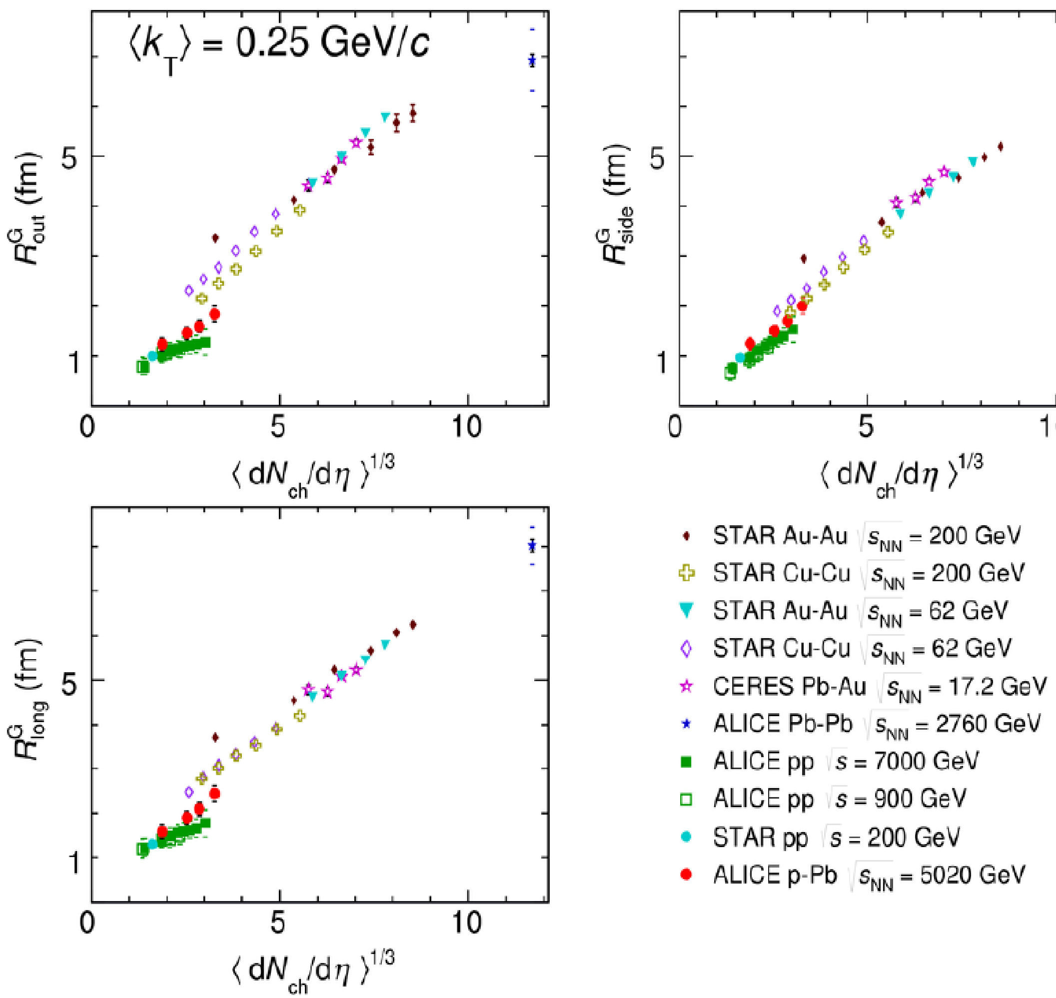
- 1D analysis performed for **pp**, **p-Pb** and **Pb-Pb** using 2-pion and 3-pion correlations.

- At similar multiplicity R_{inv} in **p–Pb** ~ **5–15%** larger than those in **pp** → disfavours models which incorporate essentially stronger collective expansion in pp than in p-Pb

- R_{inv} in **Pb–Pb** are **35–55%** **l**arger than those in **p–Pb** **→** importance of different initial conditions.

3D Pion radii in pp, p-Pb and Pb-Pb

ALICE, Phys. Rev. C 91, 034906 (2015)

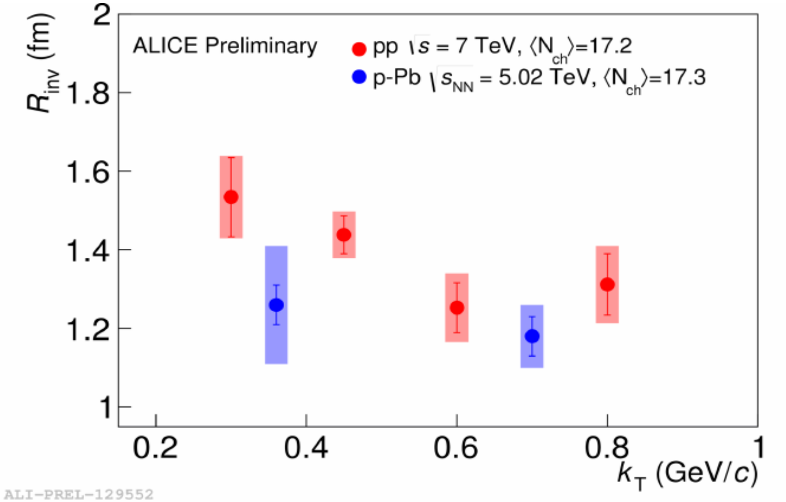


- p-Pb radii agree with those in pp at low multiplicities; with increasing multiplicity they start to diverge
- Femtoscopic radii demonstrate approximate linear scaling with cube root of final multiplicity.
- Slope for pp is clearly different from heavy ions
- The conclusion of this analysis is consistent with the 2-pions & 3-pion cumulant analysis

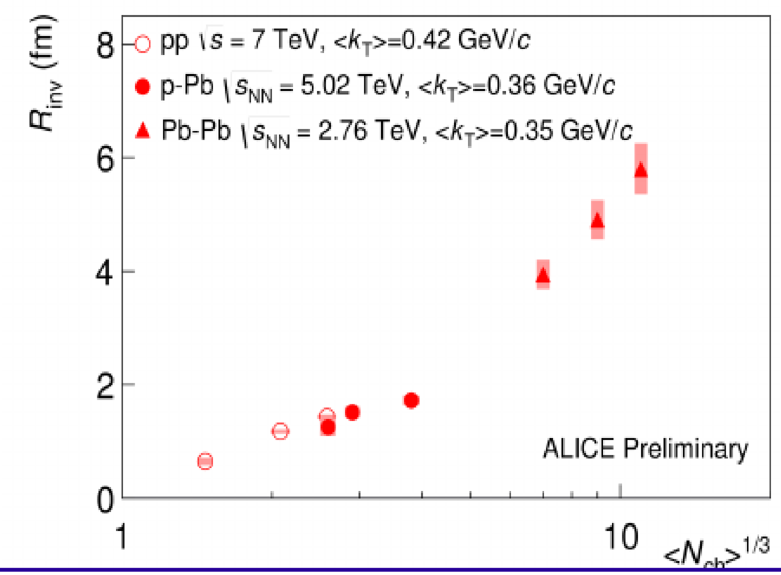
ALICE Collaboration , Phys. Lett. B 739 (2014) 139-151

1D Kaon radii in pp, p-Pb and Pb-Pb

E. Rogochaya for ALICE Collaboration, WPCF2016



- **pp**: CFs from (Phys. Rev. D87 (2013) no.5, 052016) refitted
- **p-Pb**: current analysis with EPOS baseline
  Pb-Pb: (Phys. Rev. C92 (2015) no.5, 054908)
- At the same multiplicity p-Pb radii are equal to pp ones within errors



- p-Pb radii increase with N_{ch} close to pp trend with multiplicity
- p-Pb radii practically equal to pp;
- hard to say anything for Pb-Pb because of a big gap in multiplicity gap
- No indication of strong collective expansion

Summary

- Femtoscopy allows measurements of space-temporal sizes of the systems created in different types of collisions

- Femtoscopy provides different tools to study collectivity:
  e.g. m_T (k_T) dependences of radii for different particle types

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

ALICE femtoscopy: diversity of directions

ALICE

- traditional QS femtoscopy correlations with π,K (our group), p for pp, p-Pb, Pb-Pb at different collision energies

- "**baryon-antibaryon** " correlation functions are sensitive to strong interaction potential, including annihilation; ALICE EPJ Web Conf. 71 (2014) 00130 (2014); structure of baryons
- **pp**, $\mathbf{p\bar{p}}$, test of matter - antimatter symmetry

- $\mathbf{K^0_s K^\pm}$ femtoscopic correlations were measured for the first time: FSI gives a possibility to distinguish between different a0(980) resonance parameters and properties (ALICE, arXiv:1705.04929)

- $\mathbf{K^+K^-}$ femtoscopic correlations – possibility to study KK scattering properties & phi-meson production mechanism (our group)

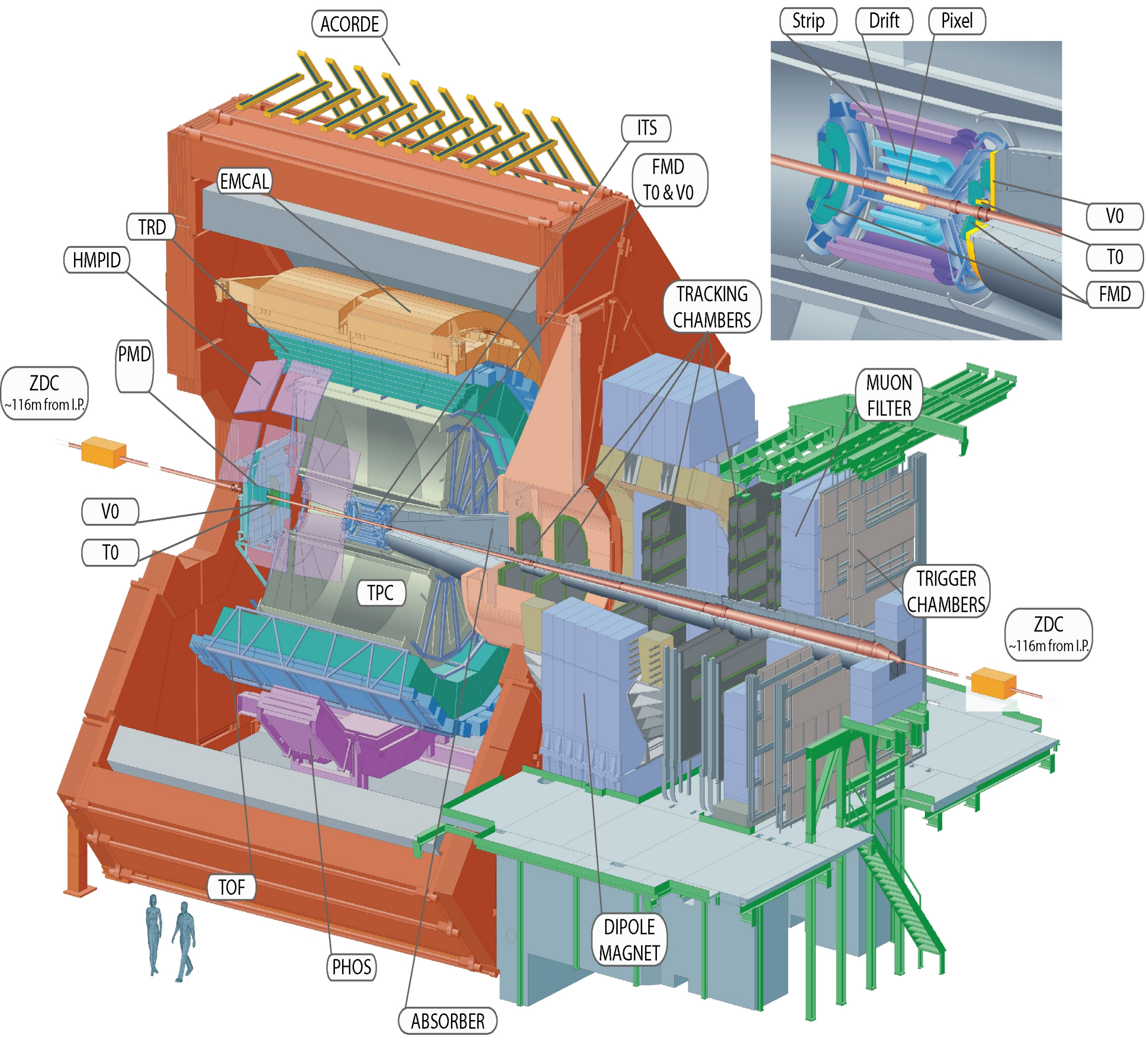
- πK, πp, πΛ, pΞ, pΛ, ΛΛ - possibility to study properties of exotic scatterings not available by experiments with beams

- Azimuthally differential pion femtoscopy (ALICE, Phys. Rev. Lett. 118 (2017) 222301)

- Multipion Bose-Einstein correlations (extraction of chaoticity parameter) (Phys.Rev. C93 (2016) no.5, 054908)

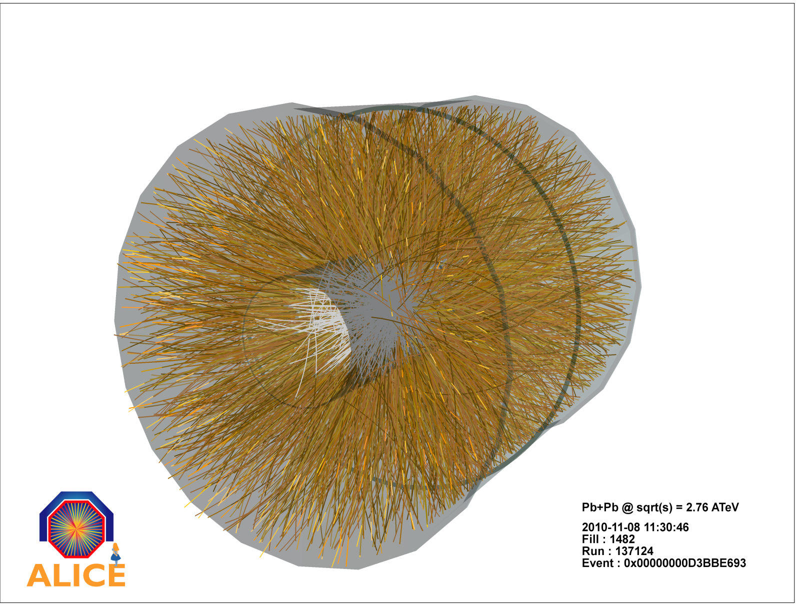
Additional slides

ALICE at LHC

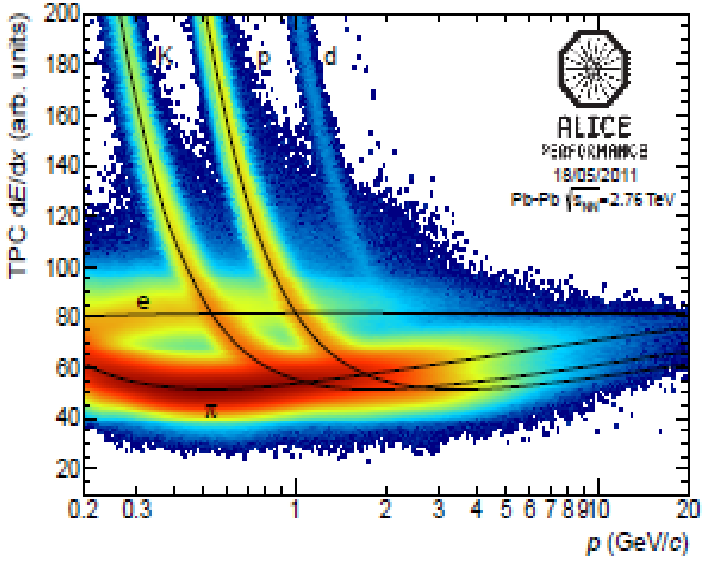


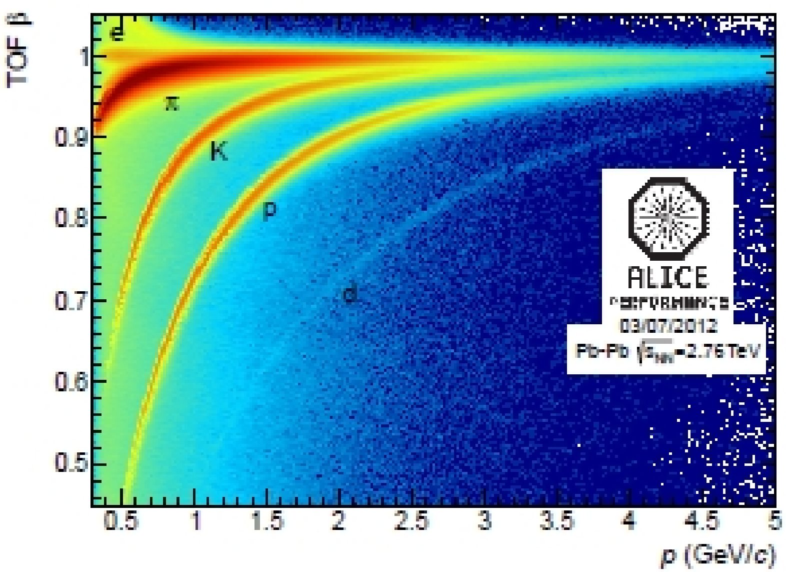
- Main tracking detector:
  Time Projection Chamber(TPC)
- Vertexing and tracking:
  Inner Tracking System (ITS)
- Trigger and centrality:
  VZERO, ZDC, ITS
- Particle identification (PID):
  TPC & ITS (energy loss)
  Time-of-Flight (TOF)

ALICE experiment at LHC



- Low momentum 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

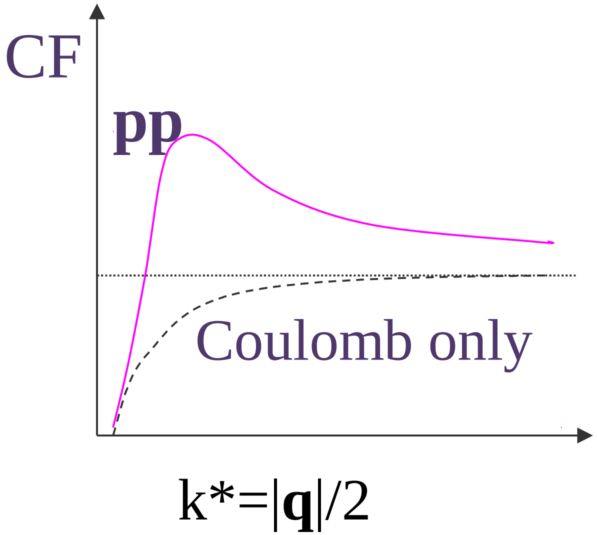




Introduction: non-identical particles correlations FSI

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

Cross section



Final State Interaction (FSI) is sensitive to source size and scattering amplitude. It complicates CF analysis but makes possible:

- femtoscopy analysis of nonidentical particle correlations: πK, πp, πΛ, πΞ , K+K-, $K^{ch}K_s^0$

- 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)

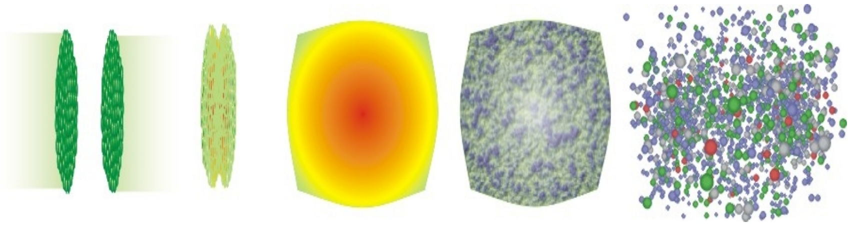
3D kaon femtoscopy analysis: motivation

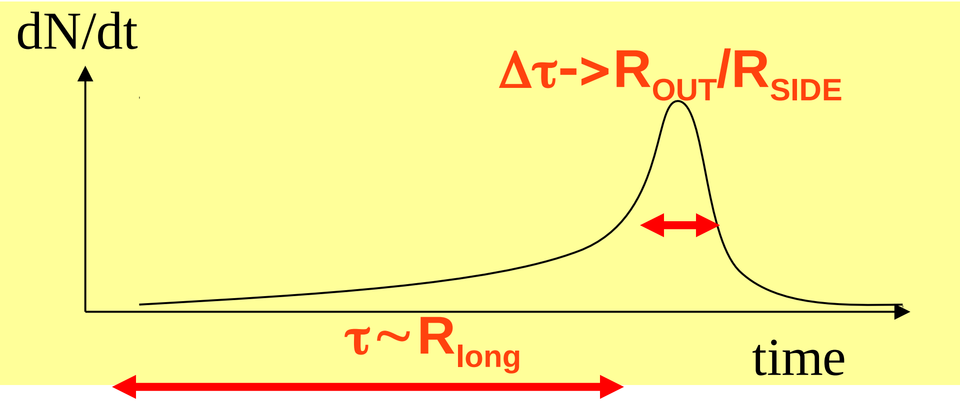
- "m_T-scaling" **:** $R \sim m_T^{\,a}$, $m_T = \sqrt{m^2 + p_T^2}$
- Hydrodynamics predicts exact "m_T-scaling" for R_{long} with **a** =-1/2 (A.N. Makhlin, Yu.M. Sinyukov, Sov. J. Nucl. Phys.46 (1987) 345; Z. Phys.C 39 (1988) 69.. Yu. M. Sinyukov, Nucl. Phys. A 498 (1989) 151.):
  - Negligible transverse flow
  - Longitudinal boost invariance
  - Common freeze-out
- Approximate "m_T-scaling" for different particle species for R_{long}, R_{side}, R_{out} with different **a** was predicted in (A. Kisiel, M. Galazyn, P. Bozek, Phys.Rev. C90 (2014) 064914)
  - Indication of flow dominated freeze-out scenario
- Strong violation of "m_T-scaling" was predicted in (V.M. Shapoval, P. Braun-Munzinger, Iu.A. Karpenko, Yu.M. Sinyukov, Nucl.Phys. A 929 (2014) 1.) due to :
  - Strong transverse flow & resonance decays influence & rescattering phase
  - "k_T-scaling" was predicted instead
- Extraction of emission time from fit $R_{long}^2(m_T)$ using formula generalized for any strong transverse flow (Yu. Sinyukov, V.Shapoval, V.Naboka, arxiv:1508.01812),
  - Once more indication on importance of rescattering phase

Femtoscopy with heavy-ion collisions

Femtoscopy allows to

- measure the size of the "homogeneity regions" → volume of the QGP
- extract the total evolution time & particle emission duration;
- study of radii k_T-dependence o → manifestation of collective motion of matter;





- study of m_T-dependence for different particle types (π, K, p, ...) → hydrodynamic type of expansion
- put strong constraints on model parameters.