Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Femtoscopy results from ALICE

Małgorzata Janik
for the ALICE Collaboration

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Status of femtoscopy in ALICE

- **Previous results**
  - Multipion Bose-Einstein correlations in pp, p-Pb, and Pb-Pb collisions at the LHC, Phys. Rev. C 93 (2016) 054908
  - Centrality dependence of pion freeze-out radii in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV Phys. Rev. C 93 (2016) 024905
  - 1D pion, kaon , proton femtoscopy in Pb-Pb Phys. Rev. C 92 (2015) 054908
  - Pion femtoscopy in p-Pb Phys. Rev. C 91 (2015) 034906
  - Freeze-out radii extracted from three-pion cumulants in pp, p-Pb and Pb-Pb collisions at the LHC, Phys. Lett. B 739 (2014) 139-151
  - Two and Three-Pion Quantum Statistics Correlations in Pb-Pb Collisions at $\sqrt{s_{NN}}$=2.76 TeV at the LHC Phys. Rev. C 89 (2014) 024911
  - Charged kaon femtoscopic correlations in pp collisions at $\sqrt{s}$=7 TeV, Phys. Rev. D 87 (2013) 052016
  - K0sK0s correlations in pp collisions at $\sqrt{s}$=7 TeV from the LHC ALICE experiment Phys. Lett. B 717 (2012) 151-161
  - Femtoscopy in pp a 0.9 and 7 TeV: Phys. Rev. D 84 (2011) 112004,
  - Two-pion Bose-Einstein correlations in central Pb-Pb collisions at $\sqrt{s_{NN}}$= 2.76 TeV Phys. Lett. B 696 (2011) 328-337
  - Two-pion Bose-Einstein correlations in pp collisions at $\sqrt{s}$=900 GeV, Phys. Rev. D 82 (2010) 052001
- **Newly published papers:**
  - Azimuthally-differential pion femtoscopy relative to the third harmonic event plane in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, arxiv: 1803.10594
  - Azimuthally differential pion femtoscopy in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV, Phys. Rev. Lett. 118 (2017) 222301
  - Kaon femtoscopy in Pb-Pb collisions at $\sqrt{s_{NN}}$= 2.76 TeV, Phys. Rev. C96 (2017) 064613
  - Measuring K0SK± interactions using Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV, Phys. Lett. B 774 (2017) 64
- **Preliminary results:**
  - Baryon results:
    - $p\overline{p}$, $\overline{pp}$, pp from Run2
    - Baryon-baryon correlations ($p\Lambda$, $\overline{p}\overline{\Lambda}$, $\Lambda\Lambda$, and $\overline{\Lambda\Lambda}$) from Run1 and Run2
    - Baryon-antibaryon correlations ($p\overline{p}$, and $p\overline{\Lambda}$, $\overline{p}\Lambda$, and $\Lambda\overline{\Lambda}$) from Run1 and Run2
    - Analysis of heavier baryons (eg. $p\Xi$, $\overline{p}\Xi$)
  - Lambda-K+, Lambda-K-, and Lambda-K0s
  - Kaon-proton

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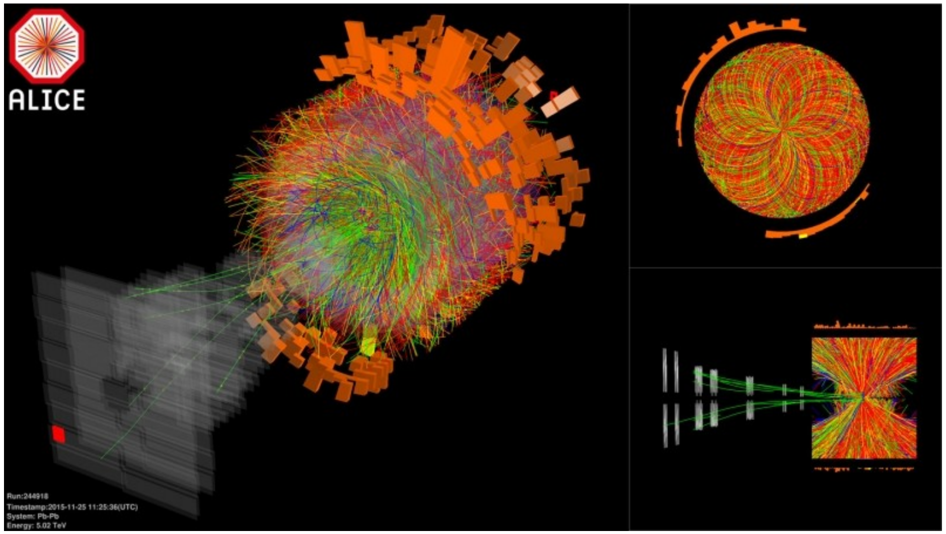
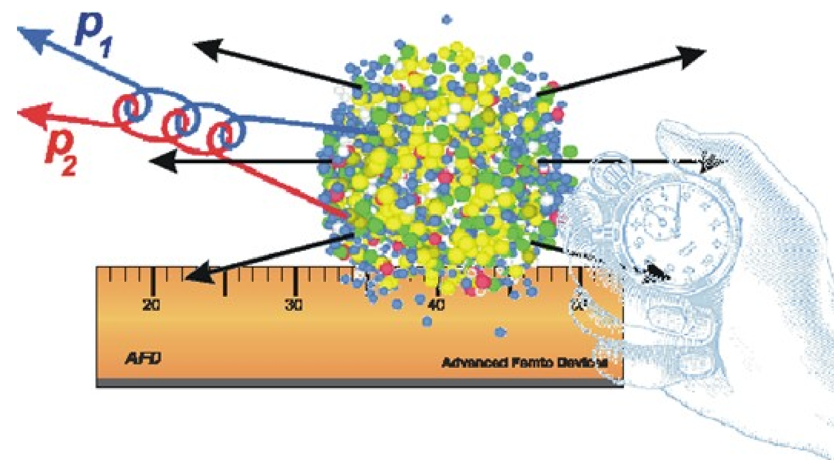
New since last WPCF

Femtoscopy technique



from M. Lisa and S. Pratt



- Femtoscopy – measures space-time characteristics of the source using particle correlations in momentum space

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

measured correlation

emission function (source size/shape)

two-particle wave function

Correlation function

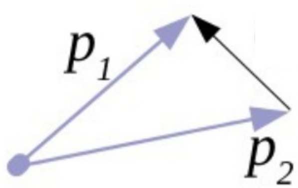
$$C(\vec{q})=\int S(\vec{r})|\Psi(\vec{q},\vec{r})|^2 d^4 r$$

measured correlation

emission function
(source size/shape)

two-particle
wave function

Variables:



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

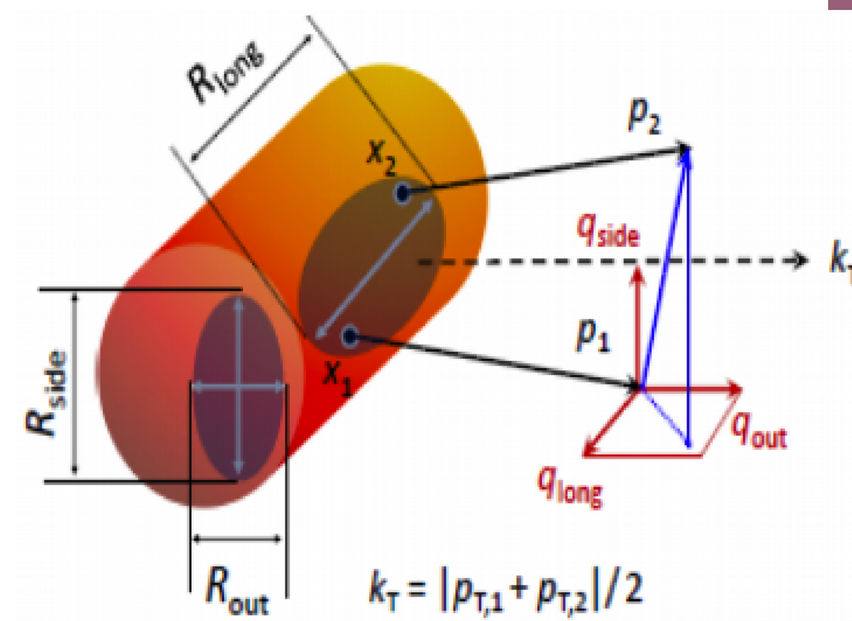
In the experiment:

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

$A(q)$ - signal distribution ("same" events)

$B(q)$ - background distribution ("mixed" events)

3D femtoscopy:



q_{out} – along pair transverse momentum

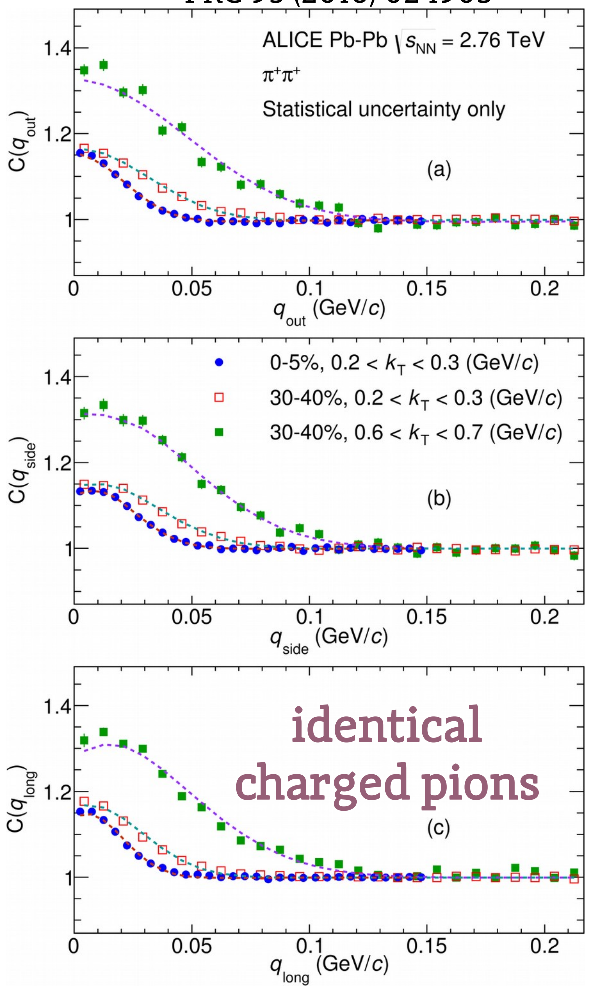
q_{long} – along the beam axis

q_{side} – perpendicular to the other two

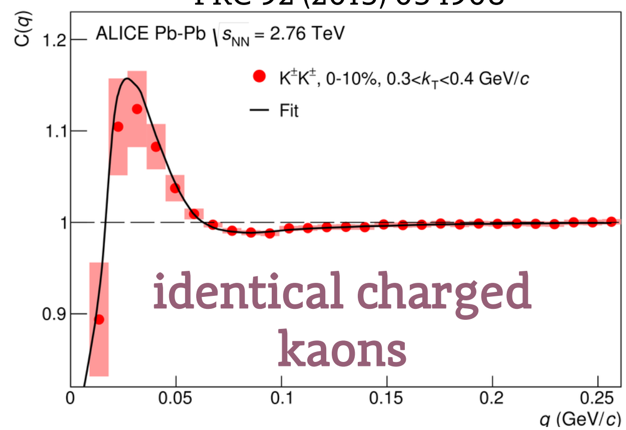
How does it look like?

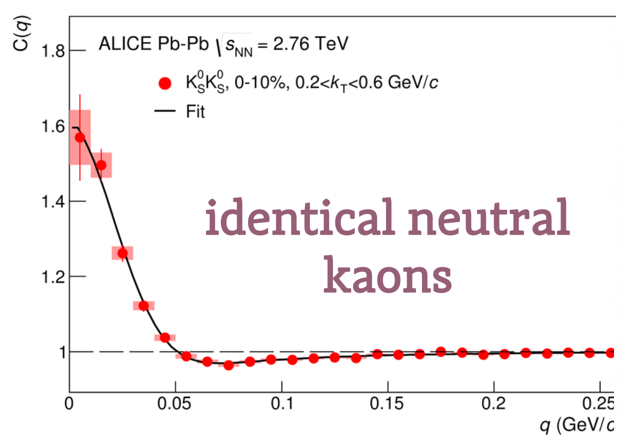
Correlation functions have different shapes, depending on the pair type (interaction involved), collision system and energy, pair transverse momentum, etc.

PRC 93 (2016) 024905



PRC 92 (2015) 054908





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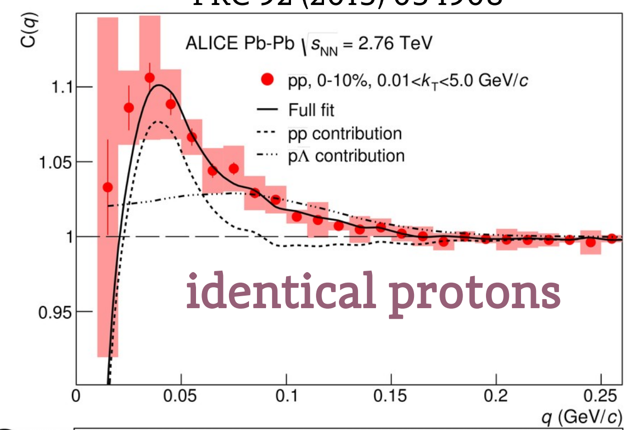
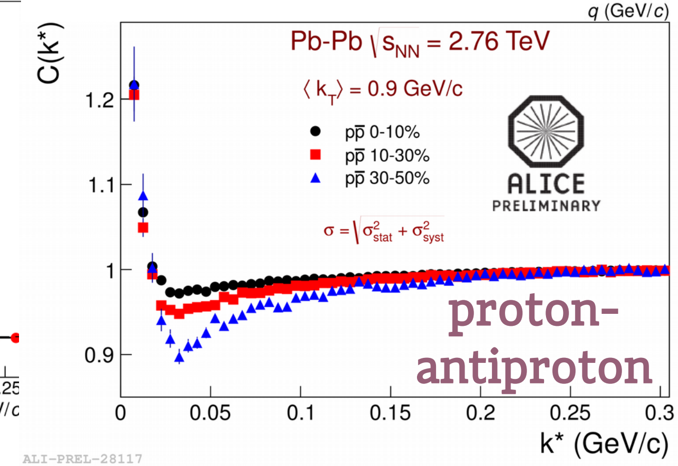
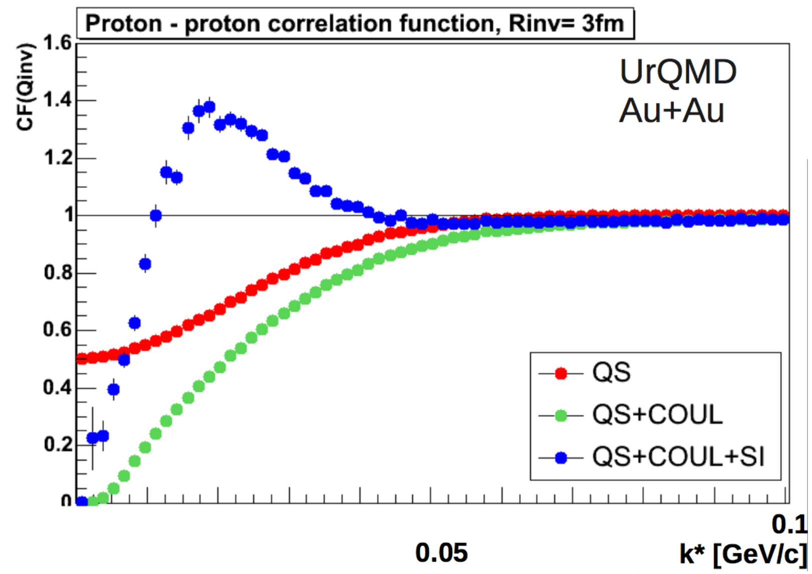


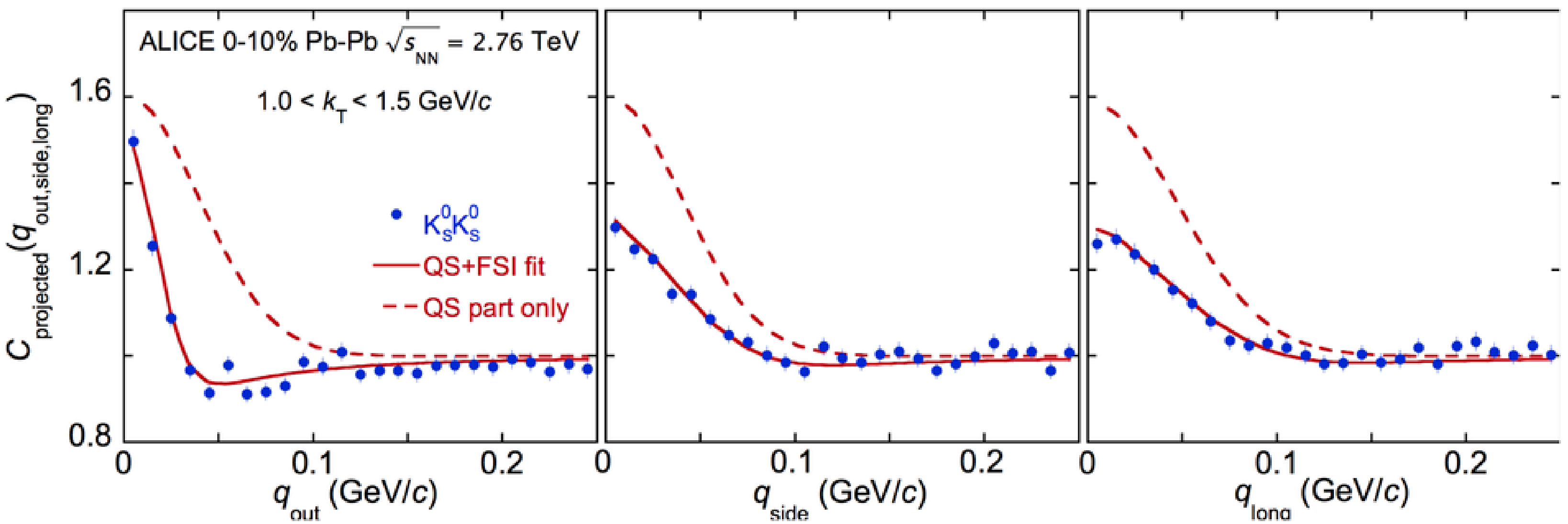


Sources of correlations

- Main sources of correlations:
  - Quantum statistics (QS)
    - bosons (i.e. pions) – Bose-Einstein QS
    - fermions (i.e. protons) – Fermi-Dirac QS
  - Final-state interactions (FSI)
    - strong interaction
    - Coulomb repulsion or attraction

H. Zbroszczyk, Ph.D. thesis





Traditional femtoscopy

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

measured correlation

emission function (source size/shape)

Two-particle wave function

We measure in the experiment

Unknown

Interaction known (e.g. analytical formula)

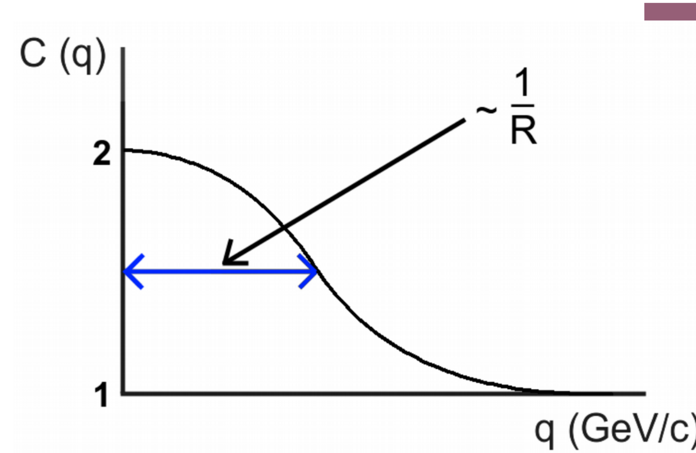
We parametrize the source:

$$S(\vec{r}) \sim \exp\left(-\frac{r_{out}^2}{4R_o^2} - \frac{r_{side}^2}{4R_s^2} - \frac{r_{long}^2}{4R_l^2}\right)$$

$$|\Psi(\vec{q},\vec{r})|^2 = 1 + \cos(\vec{q}\,\vec{r})$$

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

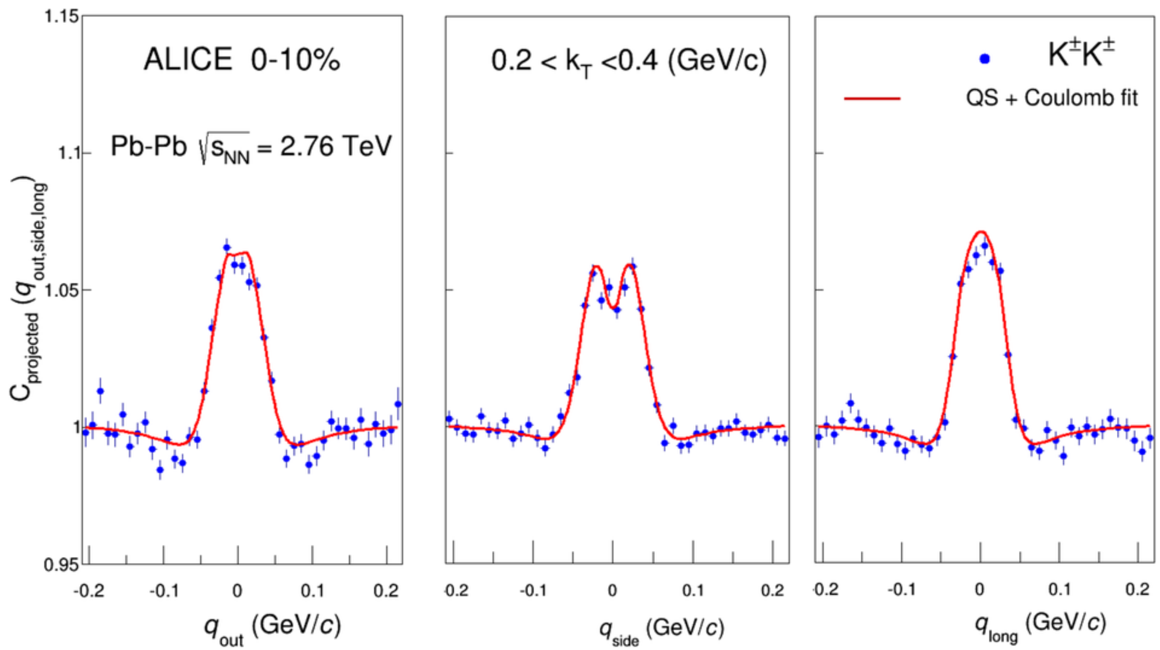
- The size (or sizes in 3D) R is referred to as the **"HBT radius"**

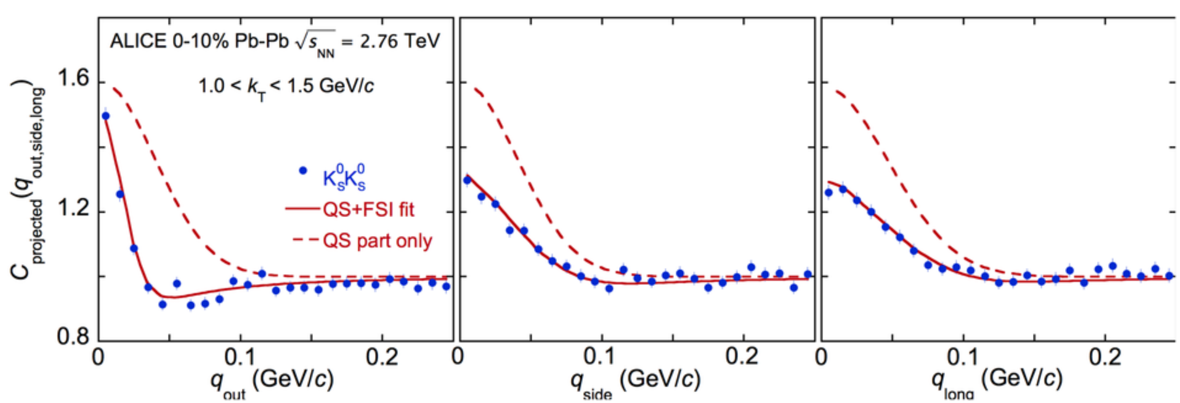


Kaon femtoscopy

Phys. Rev. C96 (2017) 064613

- Cleaner signal compared to pions (less affected by resonances)
- Studying neutral and charged kaons together provides a convenient consistency check (different experimental techniques)
  - Charged Kaons: QS + Strong and Coulomb FSI
  - Neutral Kaons: QS + Strong FSI (including resonances)
- Models which describe pions well, should describe kaons with equal precision
- Rescattering phase has different influence on pions and kaons → can lead to broken m_T-scaling → good probe of the rescattering phase effects

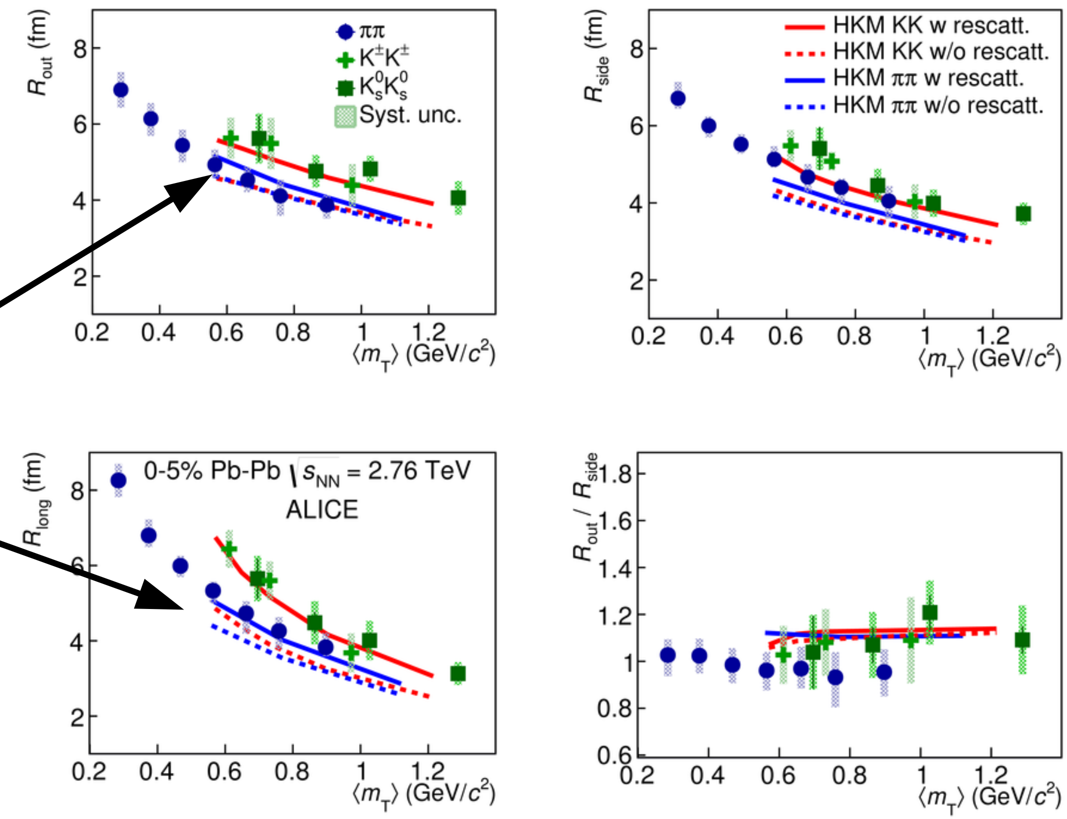




Kaon femtoscopy

Phys. Rev. C96 (2017) 064613

- Results:
  - Data are compared to models with and without rescattering phase. Broken m_T-scaling indicates the importance of the hadronic rescattering phase at LHC energies



- Emission times for pions and kaons extracted
  - $$R^2_{\rm long} = \tau^2_{\rm max}\frac{T_{\rm max}}{m_{\rm T}\cosh y_{\rm T}}\left(1+\frac{3T_{\rm max}}{2m_{\rm T}\cosh y_{\rm T}}\right)$$

    Y. Sinyukov, *et al* Nucl. Phys. A946 (2016) 227–239
  - The measured emission time of kaons is larger than that of pions.

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

More on emission times: A. Kisiel

Pion-kaon femtoscopy

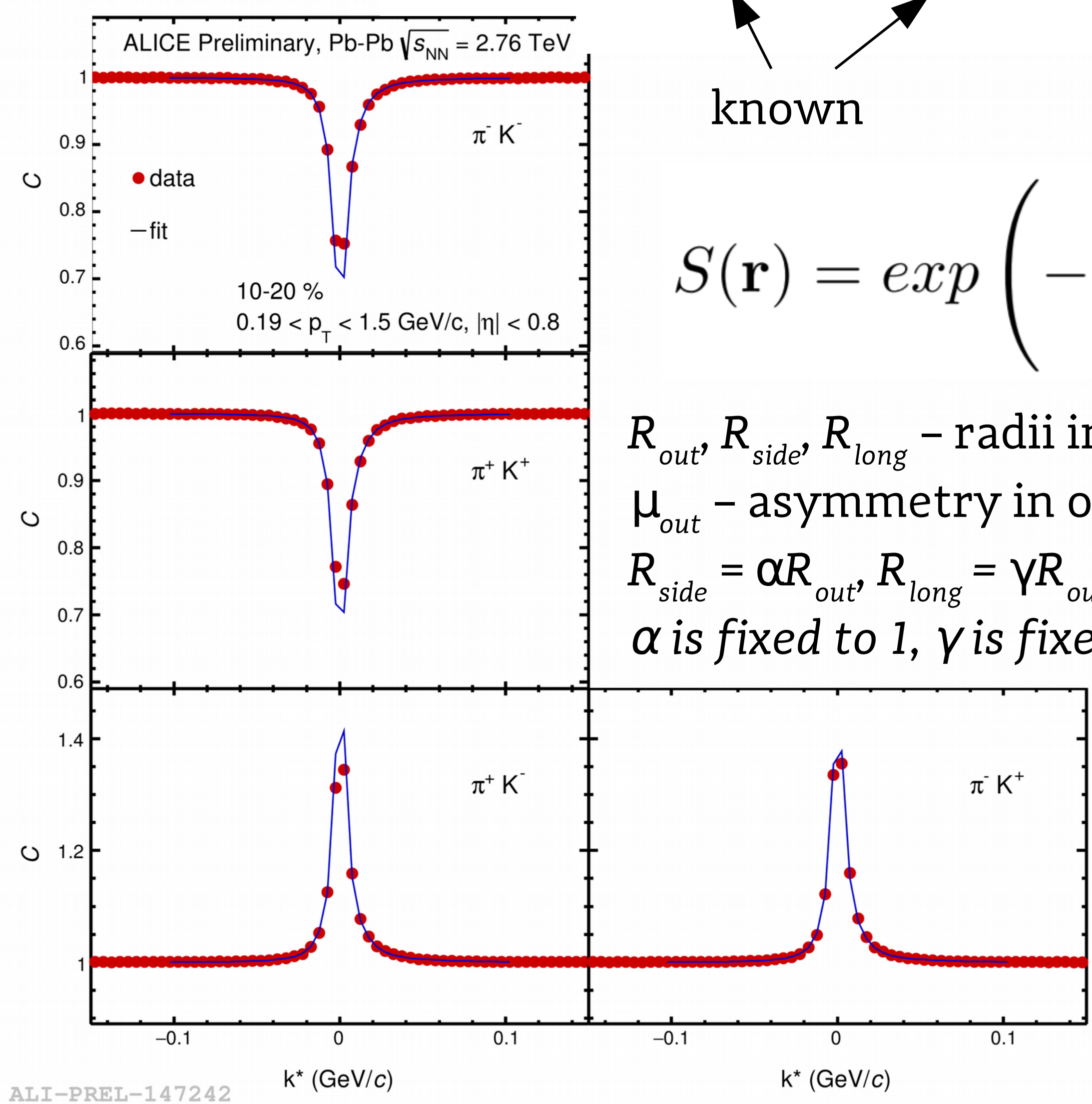
QM2018, Ashutosh Pandey

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

known

unknown

$$S(\mathbf{r}) = exp\left(-\frac{(r_{out}-\mu_{out})^2}{R_{out}^2} - \frac{r_{side}^2}{R_{side}^2} - \frac{r_{long}^2}{R_{long}^2}\right)$$



R_{out}, R_{side}, R_{long} – radii in out, side, long

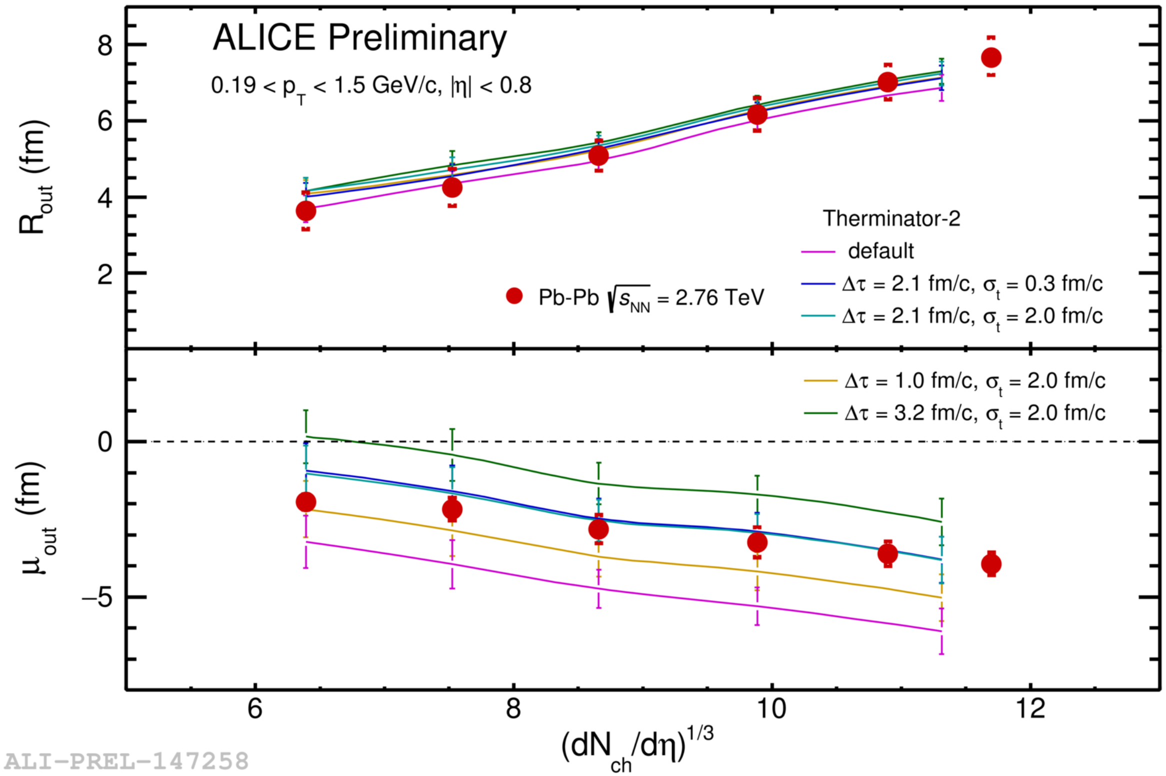
μ_{out} – asymmetry in out direction

$R_{side} = \alpha R_{out}$, $R_{long} = \gamma R_{out}$

α is fixed to 1, γ is fixed to 1.3 based on pion measurements

Pion-kaon femtoscopy

QM2018, Ashutosh Pandey

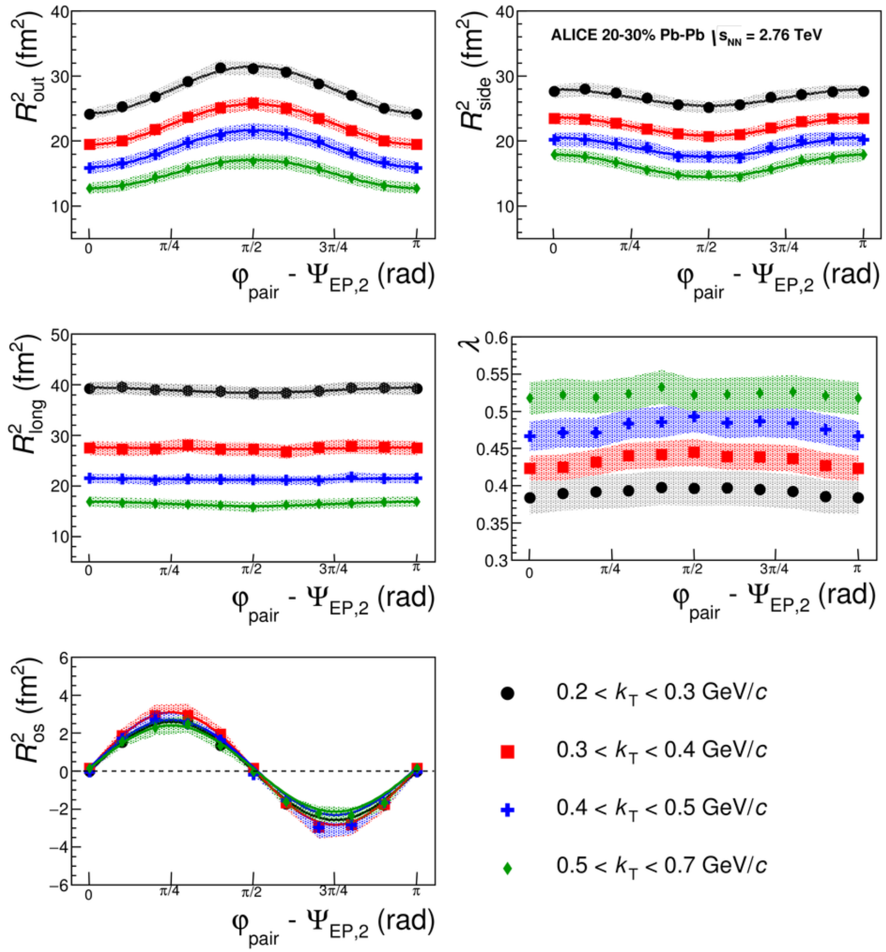


- Data points: significant negative pion-kaon emission asymmetry is observed which increases with centrality
  - on average, pions are emitted closer to the centre/later than kaons
- Model studies: the pion-kaon data is consistent with delay seen by pion-pion & kaon-kaon analysis. It is independent and possibly more precise measurement of such delay
  - different particle species freeze-out at different times

More on emission times:
A. Kisiel, WPCF2018

Azimuthally differential pion femtoscopy

Phys. Rev. Lett. 118, 222301



- First azimuthally differential measurements of the pion source size **relative to the second harmonic event plane** in Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV.
- Reflects spatial geometry.
- R_{side} and R_{out} oscillate out of phase, similar to what was observed at RHIC.
- Pion source at the freeze-out is elongated in the out-of-plane direction.

RHIC results:
Phys. Rev. Lett. 112, 222301 (2014)
Phys. Rev. C 92, 01494 (2015)

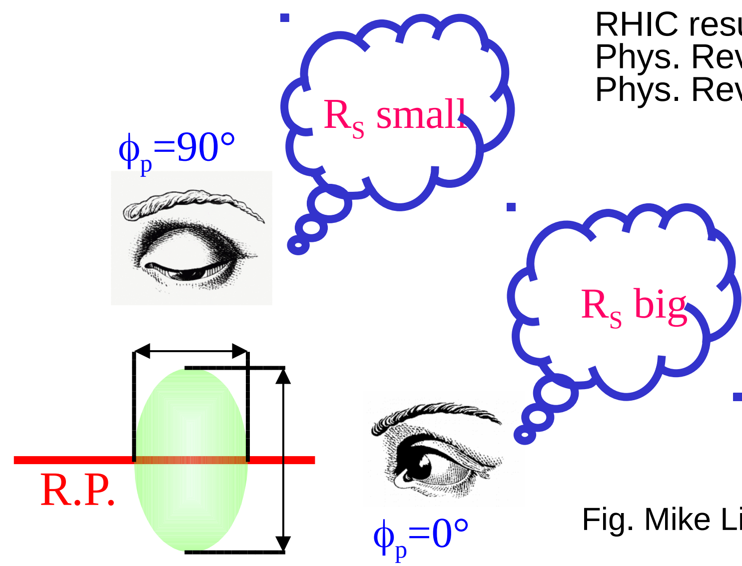
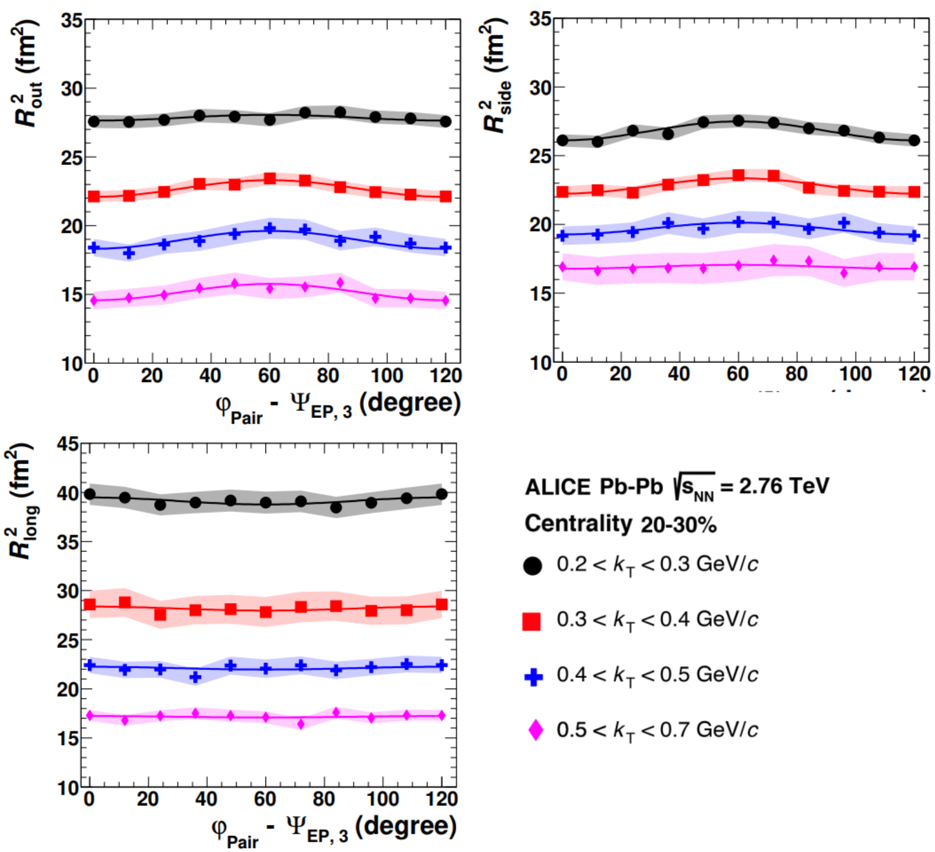


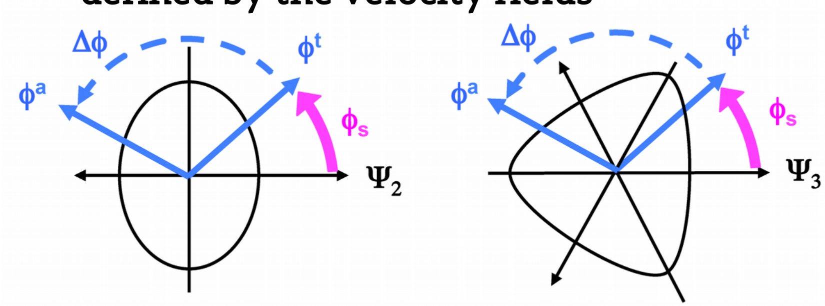
Fig. Mike Lisa

Azimuthally differential pion femtoscopy

arXiv:1803.10594



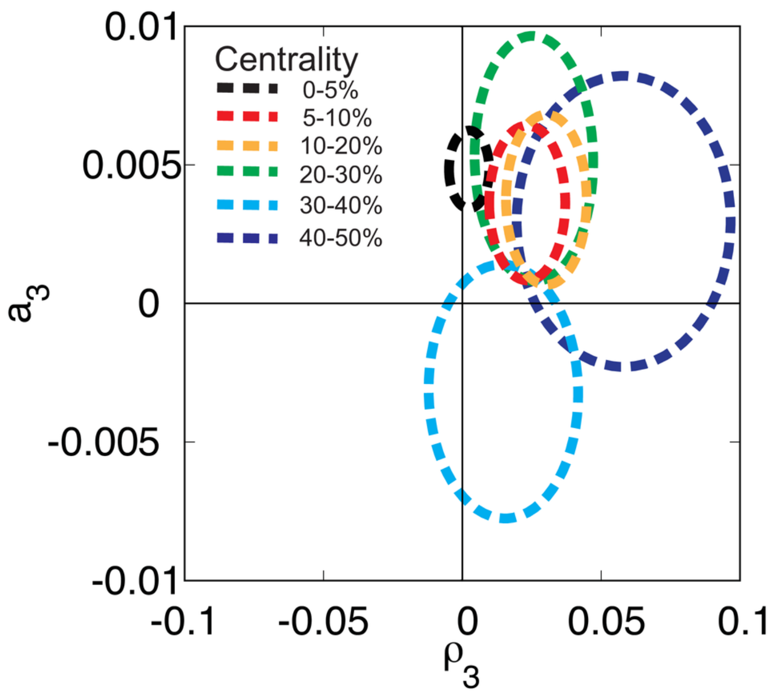
- First azimuthally differential measurements of the **pion source size relative to the third harmonic event plane** in Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV
- HBT radii oscillations relative to the
  - 2nd harmonic event plane: reflect the spatial geometry of the source,
  - 3rd harmonic event plane: **predominantly defined by the velocity fields**



- The observed radii oscillations signal a **collective expansion and anisotropy in the velocity fields**

Azimuthally differential pion femtoscopy

arXiv:1803.10594



Blast-Wave source parameters:
a_3 – final source anisotropy
ρ_3 – transverse flow

a_3 is close to zero, significantly smaller than the initial triangular eccentricities that are typically of the order of 0.2–0.3

- First azimuthally differential measurements of the **pion source size relative to the third harmonic event plane** in Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV
- HBT radii oscillations relative to the
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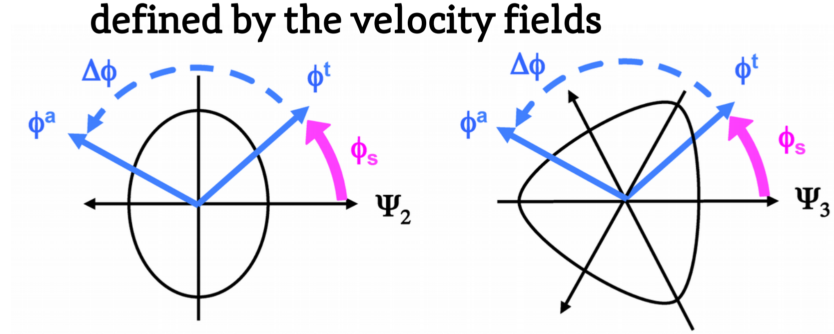


- The observed radii oscillations signal a **collective expansion and anisotropy in the velocity fields**
- **A comparison of the measured radii oscillations with the Blast-Wave model calculations indicate that the initial state triangularity is washed-out at freeze out**

Beyond the system size

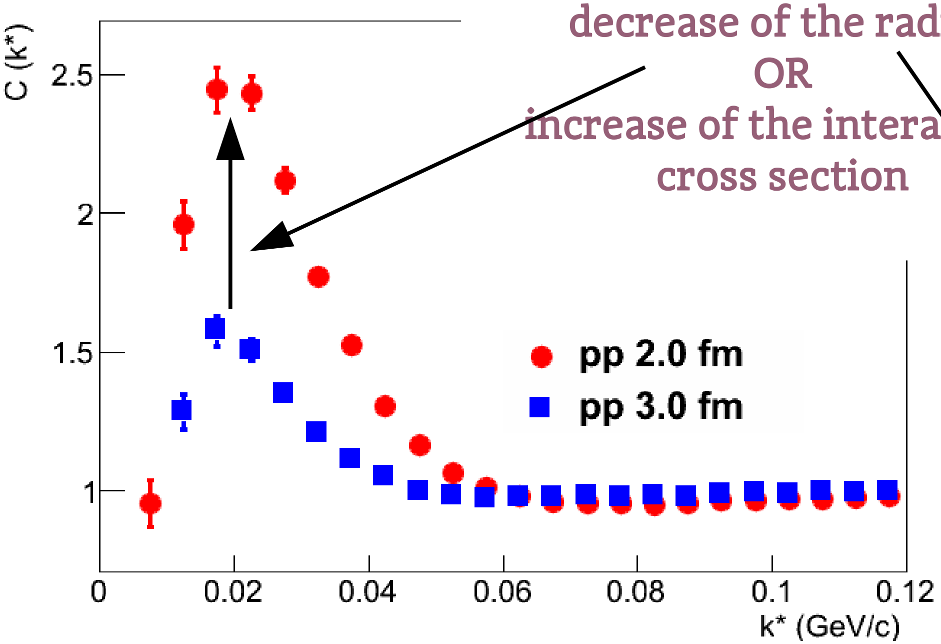
$$C(q) = \int S(r) |\Psi(q,r)|^2 d^4 r \qquad q = 2 \cdot k^* = p_1 - p_2$$

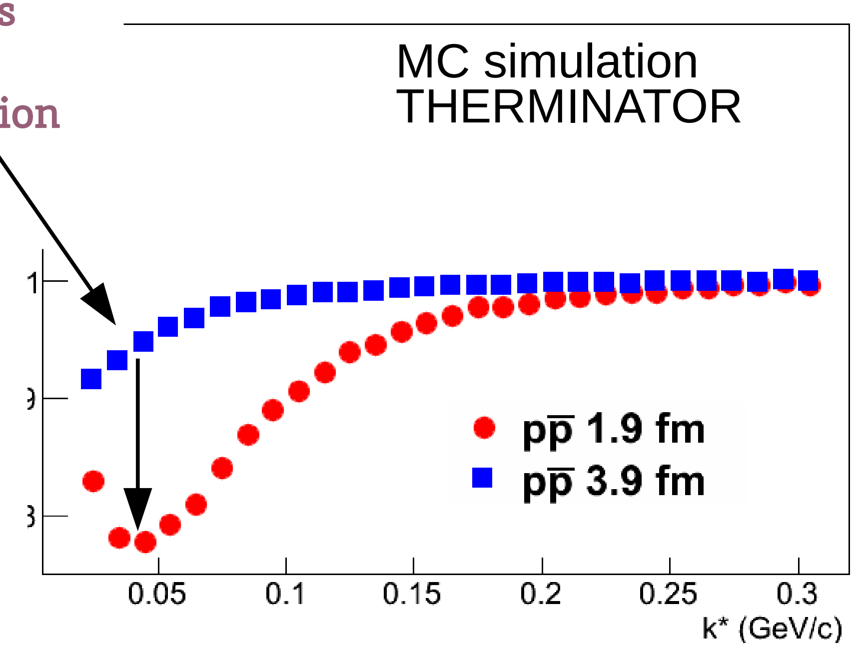
measured correlation

emission function
(source size/shape)

pair wave function
(includes cross section)

increase of (anti)correlation
=
decrease of the radius
OR
increase of the interaction
cross section





Beyond the system size

$$C(q)=\int S(r)|\Psi(q,r)|^2 d^4 r \qquad q=2\cdot k^{*}=p_1-p_2$$

measured correlation

Measured

emission function
(source size/shape)

Constrained from previous measurements

pair wave function
(includes cross section)

Unknown

- Pair wave function Ψ can be parametrized with **scattering length** f_0, and **effective radius** d_0 parameters.

- The correlation function is characterized by **three parameters**:
  - **radius** R, **scattering length** f_0, and **effective radius** d_0
  - **cross section** σ **(at low** k^***)** is simply: $\sigma=4\pi|f|^2$

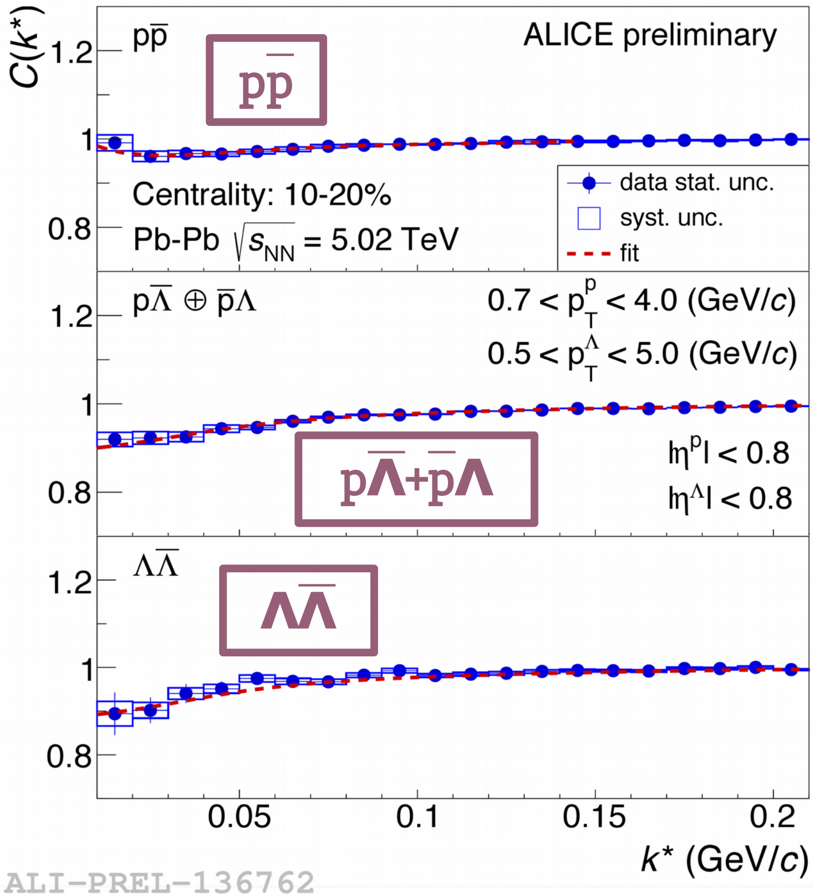
Potential applications

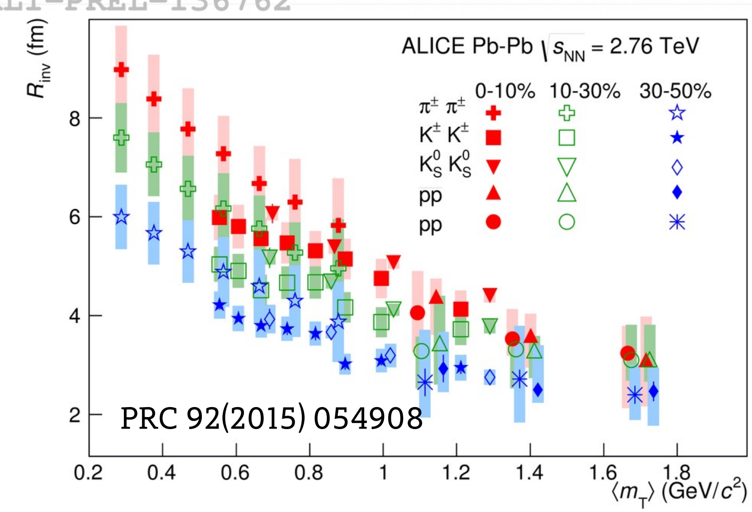
- Input to models with re-scattering phase (eg. UrQMD):
  - annihilation cross sections only measured for $p\bar{p}$, $\bar{p}n$, and $\bar{p}d$ pairs – UrQMD currently **guesses it for other systems** from $p\bar{p}$ pairs
- Structure of baryons/search for CPT violation
  STAR, Nature 527, 345-348 (2015)
- Search for H-dibaryon
  ALICE, PLB 752 (2016) 267-277
- Hypernuclear structure theory
  Nucl.Phys. A914 (2013) 377-386
- Neutron star equation of state
  Nucl.Phys. A804 (2008) 309-321

- Relativistic heavy-ion collisions at LHC or RHIC produce very similar number of baryons and antibaryons, "matter-antimatter pair factories"

Baryon-antibaryon correlations

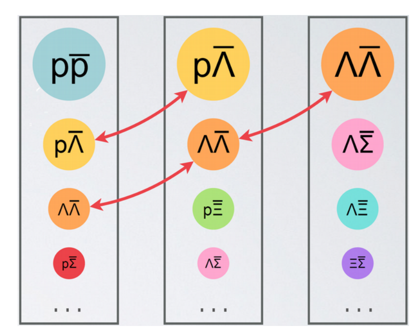
Jeremi Niedziela, PhD thesis



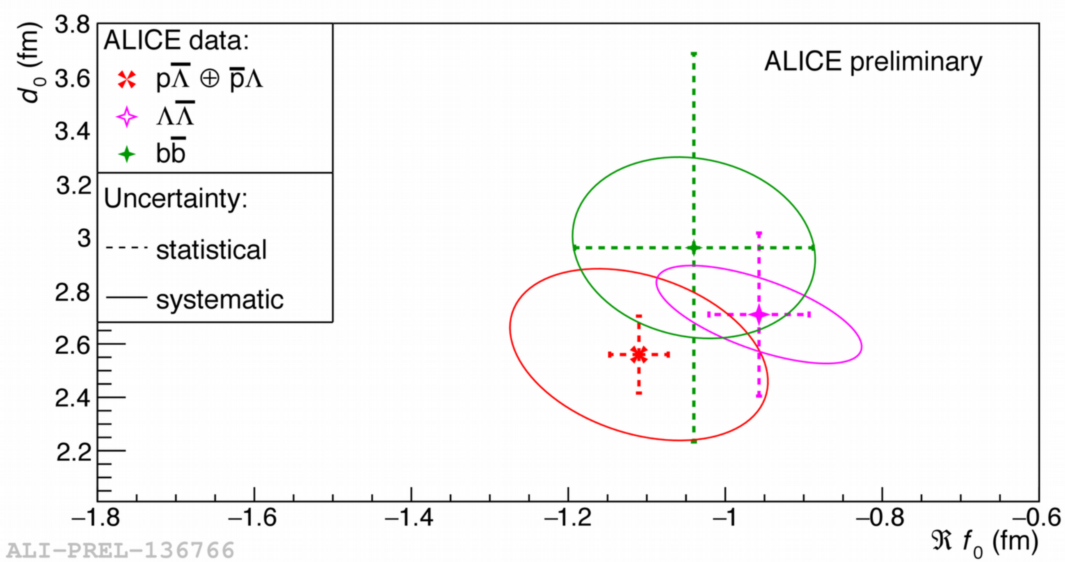


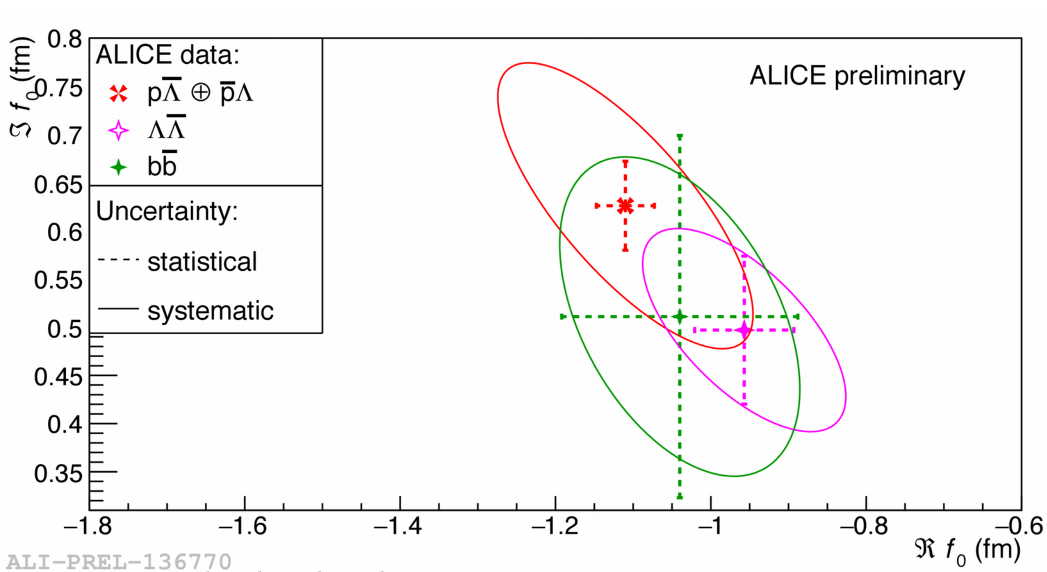
Explanation of the fitting procedure:

- χ^2 is calculated from a "global" fit to all functions:
  2 data sets, 3 pair combinations, 6 centrality bins (**total 36 functions**)
- simultaneous fit accounts for parameters **shared** between different systems (such as $\Lambda\bar{\Lambda}$ scattering length)
- **radii scale with multiplicity** for a given system $R_{inv} = a \cdot \sqrt[3]{N_{ch}} + b$
- for different systems we assume **radii scaling with** m_T
- Fractions of **residual pairs** taken from AMPT



Baryon-antibaryon correlations





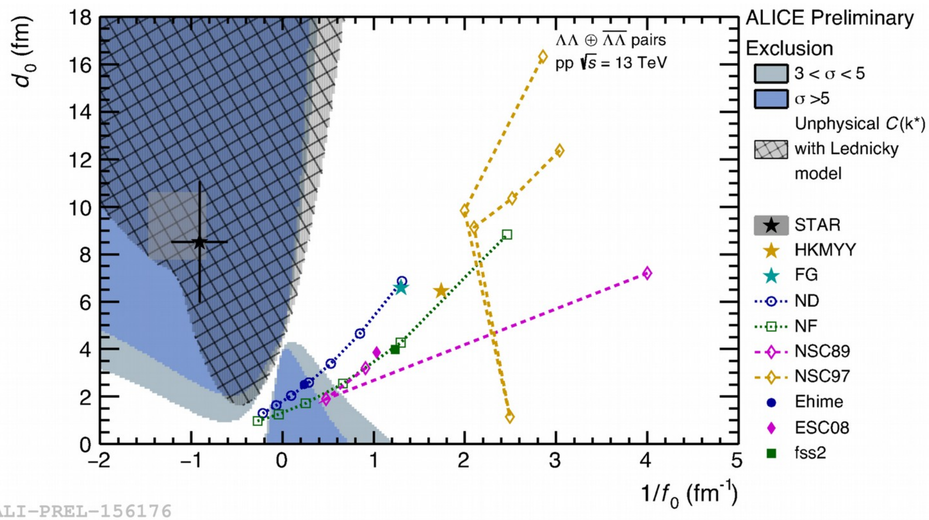
Jeremi Niedziela, PhD thesis

Conclusions from fitting:

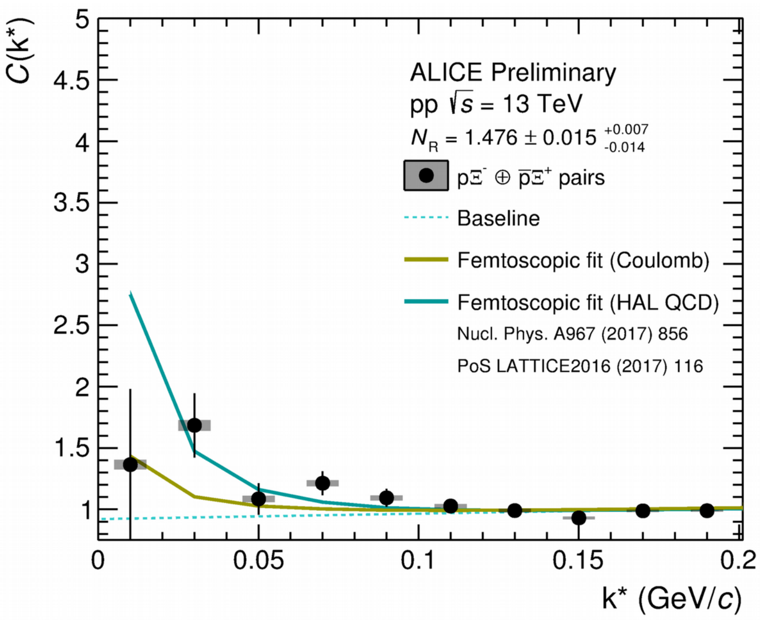
- Interaction parameters are measurable
- Scattering parameters for **all baryon-antibaryon pairs are similar to each other** (UrQMD assumption is valid)
- We observe a **negative real part of scattering length** → repulsive strong interaction or creation of a bound state (existence of baryon-antibaryon bound states?)
- Significant **positive imaginary part of scattering length** – presence of a non-elastic channel – annihilation

Baryon-baryon correlations

ΛΛ+$\overline{\Lambda\Lambda}$



pΞ⁻+$\overline{\text{p}}$Ξ⁺



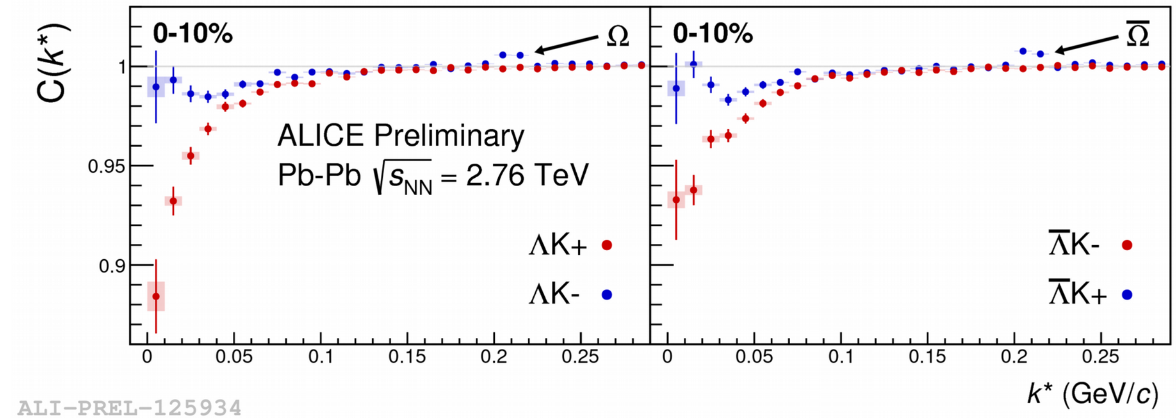
- ALICE particle identification capabilities allow us to measure correlations of different baryons
- Except for pairs like proton-proton or proton-neutron, cross sections for other baryons practically not known
- more accurate results with 13 TeV LHC Run2 data → See talk by Bernhard Hohlweger, Wed 17:30

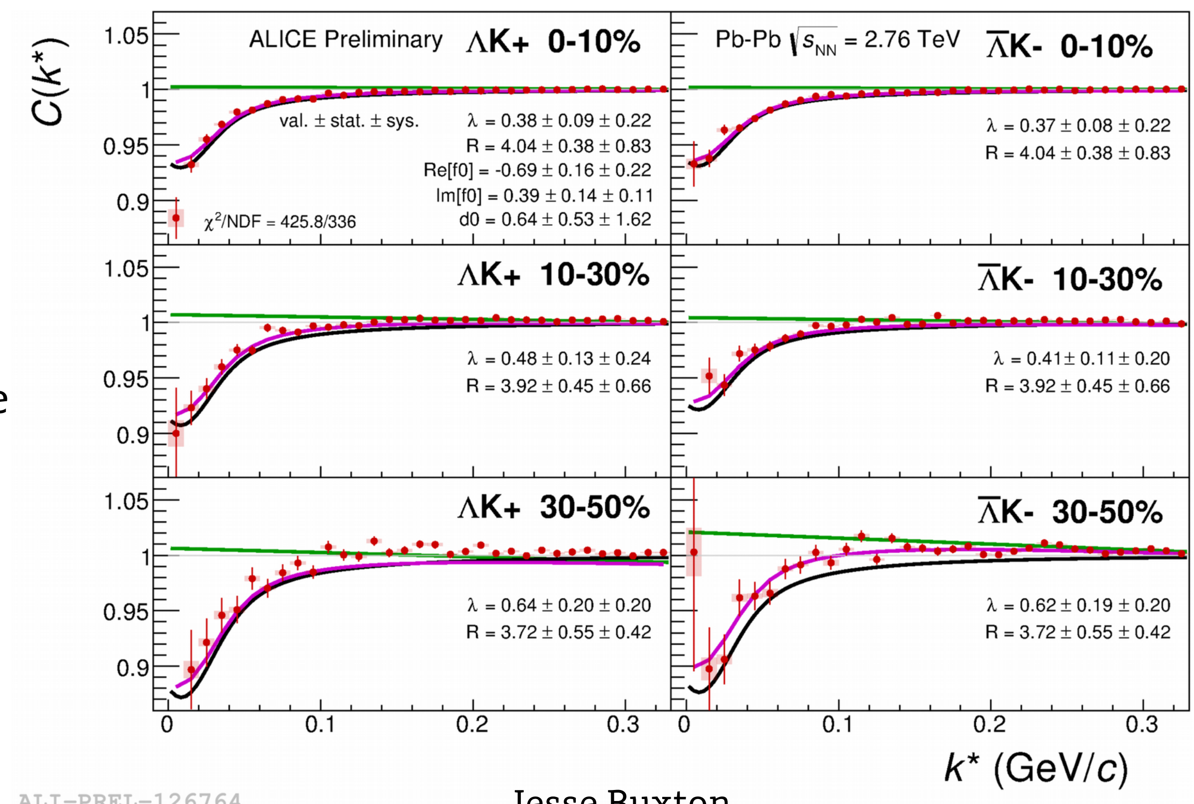
New results from following systems:

- Proton-proton
- Proton-lambda
- Lambda-Lambda
- Proton-Xi

Other interesting pairs

- Many other interesting correlations are currently studied by ALICE
- Lambda-kaon (both charged and neutral) pairs
  - scattering parameters measured for the first time
- ΛK^+ shows greater suppression at low k* compared to: ΛK^-:
  - effect arising from $s\bar{s}$ annihilation compared to $u\bar{u}$?
  - or S=0 ΛK^+ system has more interaction channels than S=-2 ΛK^-?
- For details see Quark Matter 2017 poster by J. Buxton http://cern.ch/go/qwF7





Jesse Buxton

Summary

- **"Traditional" femtoscopy results from ALICE:**
  - Kaon and pion-kaon femtoscopy suggest that kaons are emitted later than pions. Data show 2.1 fm/c delay between pion and kaon average emission time.
  - Pion source at the freeze-out is elongated in the out-of-plane direction. Initial state triangularity is washed-out at freeze out.
- **ALICE can probe strong interaction cross sections with femtoscopy**
- **Correlations of baryons reveal interesting features and baryons in general seem to be of great importance:**
  - Unique experimental environment at RHIC and LHC → "matter-antimatter pair factories"