Femtoscopy results from ALICE

Małgorzata Janik
for the ALICE Collaboration

WPCF 2018
Kraków, Poland
22-26/05/2018
Status of femtoscopy in ALICE

• Previous results
  - Centrality dependence of pion freeze-out radii in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV Phys. Rev. C 93 (2016) 024905
  - 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 femtoscopy in pp collisions at $\sqrt{s}=7$ TeV, Phys. Rev. D 87 (2013) 052016
  - $K_0sK_0s$ 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,

• 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 $K_0S$K± interactions using Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV, Phys. Lett. B 774 (2017) 64

• Preliminary results:
  - Baryon results:
    - $\bar{p}p$, $\bar{p}p$, pp from Run2
    - Baryon-baryon correlations ($p\Lambda$, $p\Xi$, $\Lambda\Lambda$, and $\Lambda\Xi$) from Run1 and Run2
    - Baryon-antibaryon correlations ($p\bar{p}$, and $p\bar{\Xi}$, $\bar{p}\Lambda$, and $\Lambda\bar{\Lambda}$) from Run1 and Run2
    - Analysis of heavier baryons (eg. $p\Xi$, $\bar{p}\Xi$)
  - Lambda-K+, Lambda-K-, and Lambda-K0s
  - Kaon-proton
Status of femtoscopy in ALICE

- **Previous results**
  - Centrality dependence of pion freeze-out radii in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV, Phys. Rev. C 93 (2016) 024905
  - 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 at a 0.9 and 7 TeV: Phys. Rev. D 84 (2011) 112004,

- **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:
    - $\bar{p}p$, $\bar{p}p$, pp from Run2
    - Baryon-baryon correlations ($p\Lambda$, $p\Xi$, $\Lambda\Lambda$, and $\Lambda\Xi$) from Run1 and Run2
    - Baryon-antibaryon correlations ($p\bar{p}$, and $p\bar{\Xi}$, $p\bar{\Lambda}$, and $\Lambda\bar{\Xi}$) from Run1 and Run2
    - Analysis of heavier baryons (e.g. $p\Xi$, $p\Xi$)
    - Lambda-K+, Lambda-K-, and Lambda-K0s
    - Kaon-proton

New since last WPCF
Femtoscopy technique

- 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)

from M. Lisa and S. Pratt

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:**

\[ C(\vec{q}) = A(\vec{q})/B(\vec{q}) \]

\[ A(\vec{q}) \] - signal distribution ("same" events)

\[ B(\vec{q}) \] - background distribution ("mixed" events)

**3D femtoscopy:**

\( q_{\text{out}} \) – along pair transverse momentum
\( q_{\text{long}} \) – along the beam axis
\( q_{\text{side}} \) – perpendicular to the other two
Correlation functions have different shapes, depending on the pair type (interaction involved), collision system and energy, pair transverse momentum, etc.
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

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

measured correlation
emission function
(source size/shape)

Two-particle
wave function

Interaction known
(e.g. analytical
formula)

We measure in the experiment

We parametrize the source:

\[ S(\vec{r}) \sim \exp \left( -\frac{r^2_{\text{out}}}{4 R^2_o} - \frac{r^2_{\text{side}}}{4 R^2_s} - \frac{r^2_{\text{long}}}{4 R^2_l} \right) \]

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

\[ C = 1 + \lambda \exp(-R^2 o q^2_o - R^2 s q^2_s - R^2 l q^2_l) \]

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

- 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

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

$$R_{\text{long}}^2 = \tau_{\text{max}}^2 \frac{T_{\text{max}}}{m_T \cosh y_T} (1 + \frac{3T_{\text{max}}}{2m_T \cosh y_T})$$


- The measured emission time of kaons is larger than that of pions.

More on emission times: A. Kisiel

<table>
<thead>
<tr>
<th>method</th>
<th>$T$ (GeV)</th>
<th>$\alpha_\pi$</th>
<th>$\alpha_K$</th>
<th>$\tau_\pi$ (fm/c)</th>
<th>$\tau_K$ (fm/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fit with Eq. (9)</td>
<td>0.144</td>
<td>5.0</td>
<td>2.2</td>
<td>$9.3 \pm 0.2$</td>
<td>$11.0 \pm 0.1$</td>
</tr>
<tr>
<td>fit with Eq. (9)</td>
<td>0.144</td>
<td>$4.3 \pm 2.3$</td>
<td>$1.6 \pm 0.7$</td>
<td>$9.5 \pm 0.2$</td>
<td>$11.6 \pm 0.1$</td>
</tr>
</tbody>
</table>
Pion-kaon femtoscopy

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

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

- \( R_{out}, R_{side}, R_{long} \) - radii in out, side, long
- \( \mu_{out} \) - asymmetry in out direction
- \( R_{side} = \alpha R_{out}, R_{long} = \gamma R_{out} \)
- \( \alpha \text{ is fixed to 1, } \gamma \text{ is fixed to 1.3 based on pion measurements} \)
Pion-kaon femtoscopy

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

- 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.
- $R_{\text{side}}$ and $R_{\text{out}}$ 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:
Azimuthally differential pion femtoscopy

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

arXiv:1803.10594
Azimuthally differential pion femtoscopy

- 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
- 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

Blast-Wave source parameters:
- $a_3$ – final source anisotropy
- $\rho_3$ – 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

arXiv:1803.10594
Beyond the system size

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

measured correlation

emission function
(source size/shape)

pair wave function
(includes cross section)

\[ q = 2k^* = p_1 - p_2 \]

increase of (anti)correlation

= decrease of the radius

OR

increase of the interaction cross section

MC simulation
THERMINATOR

\[ q = 2k^* = p_1 - p_2 \]
Beyond the system size

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

- Measured correlation
- Emission function (source size/shape)
- Pair wave function (includes cross section)

- Pair wave function \( \Psi \) 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** \( \sigma \) (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 $p\bar{p}$, $p\bar{n}$, and $p\bar{d}$ pairs – UrQMD currently **guesses it for other systems** from $pp$ pairs

- **Structure of baryons/search for CPT violation**

- **Search for H-dibaryon**
  ALICE, PLB 752 (2016) 267-277

- **Hypernuclear structure theory**

- **Neutron star equation of state**

- **Relativistic heavy-ion collisions at LHC or RHIC produce very similar number of baryons and antibaryons, “matter-antimatter pair factories”**
Baryon-antibaryon correlations

Explanation of the fitting procedure:

- $\chi^2$ 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
  \[ R_{inv} = a \cdot \sqrt{3N_{ch}} + b \]

- for different systems we assume radii scaling with $m_T$

- Fractions of residual pairs taken from AMPT

**Equation:**

\[ R_{inv} = a \cdot \sqrt{3N_{ch}} + b \]
Baryon-antibaryon correlations

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

- 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
- $\Lambda K^+$ shows greater suppression at low $k^*$ compared to $\Lambda K^-$:
  - effect arising from $s\bar{s}$ annihilation compared to $u\bar{u}$?
  - or $S=0$ $\Lambda K^+$ system has more interaction channels than $S=-2$ $\Lambda K^-$?
- For details see Quark Matter 2017 poster by J. Buxton
  http://cern.ch/go/qwF7
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”